Preparatory Study on

Eco-design of Water Heaters

Task 4 Report (FINAL)

Technical Analysis

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CONTENTS

1 INTRODUCTION

1.1 Scope

This is the Draft Final Report on Task 4 of the preparatory study on the eco-design of Water Heaters for the European Commission, in the context of the Ecodesign of Energy-Using Products Directive 2005/32/EC.

The scope of Task 4 is Product System Analysis, describing technical features of Water Heaters and the system they form part of. Much of the information presented here will be used in the subsequent Task 5 (Definition of Base-case) and Task 6 (Design options - including modelling of water heater system).

1.2 Approach

Annex VII.4 of the Ecodesign Directive concerns the interaction of the EuP with the installation/system in which it operates and implies that the possible effects of the EuP being part of a larger system and/or installation are identified and evaluated.

This task includes therefore a functional analysis of the system to which the water heater belongs. Given that the technical modelling of the water heater itself will be subject of Task 6, the main system considerations in a strict sense will relate to the inputs (cold water temperature, piping lay-out, ambient conditions of the water heater), the system and its infrastructural aspects (chimneys, pipe lengths) and the outputs (as influenced by mixing valves, water saving shower heads, sewage systems with waste heat recovery, etc.).

The hot water comfort is an important performance characteristic and manufacturers are making design concessions in energy efficiency to reach certain comfort levels. E.g. the capacity (expressed as litres of water of 'x' degree Celsius per minute) determines the applicability (kitchen only, bath, bath + kitchen, etc.) and the comfort level. The convention is that policy measures rate energy efficiency, which means not only energy consumption but energy consumption per performance. The inclusion of performance characteristic should therefore be mandatory.

In principle, the consumer habits (tapping patterns) will determine the load (see Task 3). Task 4 will have to deliver the inputs for the technical model of the water heating system. These may cover energy losses in the appliance itself as well as heat losses in the piping (waiting time, water and/or heat wasted) and aspects related to the chimney (options for replacement / renovation). So the system also defines the overall net heat load (energy input).

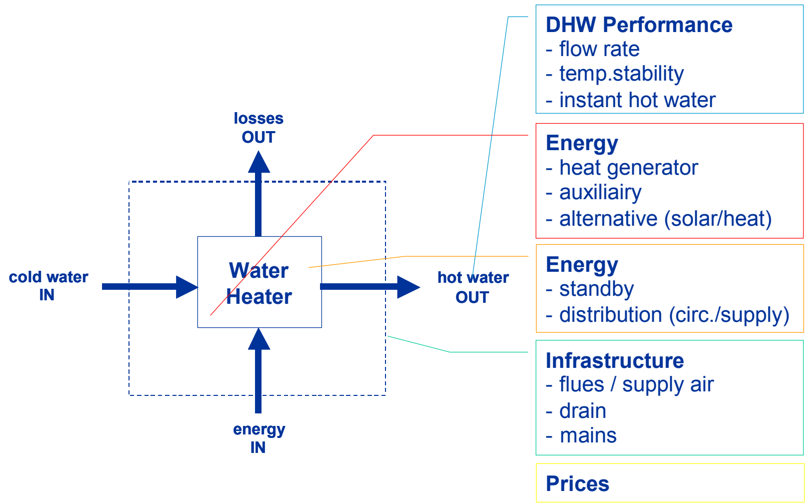
As regards the position of the water heater in the house, e.g. close to the most frequently used outlet in the kitchen, this can have a significant influence on energy use and emissions. It is often the reason for consumers (waiting time) to purchase or not to purchase a second water heater just for the kitchen outlet (or other outlets further away from the primary water heater). Also in that context the EPBD standards will have something to say on these issues, that may will very well be of influence on Ecodesign measures for the water heater.

A negative effect (from the energy point of view) of long waiting times may be the use of so-called 'comfort-switch' found on many types of water heaters. This switch, that the consumer may or may not use, maintains the temperature of the appliance (heat exchanger, etc.) in order to reduce waiting times. And it may lead to an extra energy use of 50-100 m^3/year.

Finally, it should not be forgotten that –in a wider sense—a large hot water tank represents an energy buffer to fill the gap between periods of energy supply (e.g. solar) and demand. And this demand may not only be for water heating, but also products are known where the thermal storage capacity of the tank contributes to the space heating system in the house. A study of the state-of-the-art in that area may also contribute in making a legislation that doesn't discourage this type of innovation (if the solutions are valid from cost and environmental point of view).

The figure below indicates the elements considered.

Figure 1-1
The outline of the water heating system described in Section Two. To the right are mentioned the items that are part of the system considered.



1.3 Structure of report

The report is divided into four sections.

Section One - Chapter 2-5

Describes the basic principles of heat generation in gas- and oil-fired water heaters and the major components involved in this. It includes a description of a basic mass and energy balance, emissions, types of burners and heat exchangers.

Emissions of electric water heaters are considered in subsequent tasks and modelling (see also the EcoReport results in Task 5).

Section Two - Chapter 6-13

Describes the main water heating products (following Task 2 market categories) and certain system aspects related to inputs (energy, water), outputs (hot water, energy losses) and the system environment (technosphere = infrastructure, constraints).

Section Three- Chapter 14-15

Describes two 'alternative' water heater(s) (systems) using renewable energy in the form of solar heat and ambient heat.

Section Four - Chapter 16-19

Describes aspects of the water heater system that are not really water heaters but can be relevant for the modelling of a Water Heater system, Task 5 (Definition of Base-case) and Task 6 (Design options). Described are systems to prevent Legionellosis, to prevent scalding and to recover heat from warm waste shower water.

Annex A

The Annex includes a section on vacuum insulation panels (VIPs) which is relevant for Task 6 (Design Options).

SECTION ONE - HEAT GENERATION

2 BASIC ENERGY AND MASS BALANCE

[This Chapter primarily applies to the heating operation of gas-/oil-fired boilers but the physics also apply to gas- and oil-fired water heaters. Note that wherever 'boilers' are mentioned in the text, this could be read as 'gas-/oil-fired water heaters' as well].

2.1 Introduction

In most energy policy studies on water heating appliances, the combustion process and the detailed energy- and mass balance of gas- and oil-fired water heaters are not explained. The scientific background is not very easy and in general it is not needed for readers in the policy field to go beyond the level of the gas- and oil-fired water heaters being a 'black-box' with a certain efficiency level according to a product test standard.

Yet, this approach has also led to a number of notions, myths and half-truths regarding efficiency and emissions in practice which can only be understood (and partially denied) when looking inside the black-box. For this reason we have made an attempt, as part of the system analysis, to provide some guidance for policy makers regarding the basics of the energy and mass balance with a boiler. We have taken methane, the main component of natural gas but also a fuel with a relatively simple structure, as an illustration of a fuel, although references to other fuels also occur. The mass- and energy values should be seen as illustrations, although also here we add results from research that is based on tests with actual water heaters.

Starting off with the global chemical reaction which mainly produces carbon dioxide and water vapour (paragraph 2.2), this chapter looks at the:

Mass balance (paragraph 2.3), including:

- Stoichiometric volume balance (the 'ideal' theoretical volume balance);
- Air factor/ lambda (excess air);
- Humidity of combustion air;
- Influence of CO, NO_x, C_xH_y, SO2 and dust (PM) emissions (fraction of incomplete combustion);
- Conversion of volume to mass balance.

Subsequently, we are discussing the energy balance of the heat generator, looking at the energy parameters of the combustion process, such as the flame temperature, combustion heat, latent heat of condensation, heat loss through excess combustion air and finally the energy loss concerned with incomplete combustion (paragraph 2.4). The approach is basic (secondary school) and pragmatic (focused on heat generators found in combi-boilers etc.), largely by-passing the many tools that exist at academic research level to numerically model and predict the combustion process.

Paragraphs 2.5 to 2.8 deal with the energy losses in the main heat generator components: the burner (paragraph 2.5), the primary heat exchanger (paragraph 2.6), secondary and tertiary 'condensing' heat exchangers (paragraph 2.7) and finally the energy penalties involved in storage components (paragraph 2.8). The most extensive report is on the efficiency of the primary heat exchanger in paragraph 2.6, where we will be looking at flue gas losses, generator losses and start-stop ('cycling') losses both in on-mode and off-mode.

Paragraph 2.9 gives a brief estimate of losses in auxiliary components such as pump, fan and controls (to be expanded in other parts of the study). Paragraph 2.10 presents an overview of energy flows through a heat generator during the heating process.

2.2 Global chemical reaction

In gas- and oil fired water heaters (and combi-boilers) the combustion is the ***stationary***, ***rapid, medium to high-temperature oxidisation***[1] of a hydrocarbon with the oxygen in air. With gas- and oil-fired (combi-)boilers the combustion products of an ideal combustion process are always carbon dioxide (CO_2) and water vapour (H_2O) [2]. For instance, in the case of methane (CH4), which is the main component of natural gas in Europe, the global chemical reaction can be summarized as:

$$CH_4 + 2O_2 \text{ ®} \rightarrow CO_2 + 2H_2O$$

The equation for e.g. heating oil is different but follows the same principle, but with the hydrocarbon being more complex also the equations become more complex. Still, the outcome is again (mainly) CO_2 and H_2O.

2.3 Mass balance

2.3.1 Stoichiometric volume balance

Using *Avogadro's Law* [3] and assuming that air is made of ca. 1 part of oxygen (O_2) and 4 parts of nitrogen (N_2) we can derive the theoretical volume of air that is needed for the reaction and the volumes of carbon dioxide and water vapour produced.

$$\mathbf{1\ vol.}CH_4 + \mathbf{2\ vol.}O_2 + \mathbf{8\ vol.}N_2 \text{ ®} \rightarrow \mathbf{1\ vol.}CO_2 + \mathbf{2\ vol.}H_2O + \mathbf{8\ vol.}N_2$$

9,1% CH4 + 90,9% air ®→ 9,1% CO_2 + 18,2% H_2O + 72,7% N_2

The above is known as ***stoichiometric*** combustion, i.e. assuming a perfect mixing of fuel and air at perfectly controlled pressure and temperature.

2.3.2 Air factor/ lambda

In reality, the stoichiometric volume balance is theoretical. Manufacturers build in a safety factor, called ***air factor*** or ***lambda (λ),*** to make sure that there is always enough air/oxygen to guarantee a complete combustion. The air factor is actually intended to compensate for:

- inhomogeneous mixing of air/fuel (oil-fired 'blue burner' 5%, good 'yellow burner' 10%, less good burners 15%). In general the particle size of the fuel (with atomising

[1] ***'Stationary'*** as opposed to non-stationary combustion in motors.. ***'Rapid'*** as opposed to slow, low-temperature oxidisation processes in biochemistry (rotting, etc.) and medicine (glucose in muscle power, etc.). ***'High-temperature'*** is also referred to as 'flame-combustion' (>1500 K). ***'Medium-temperature'*** is referred to as 'flameless' combustion (700-1500 K). Medium-low temperature combustion (400-1000 K reaction temperature) is e.g. 'catalytic combustion'. The chemical oxidisation in a fuel cell is classified as 'catalytic combustion of hydrogen'.

[2] Note that the quantity of water vapour depends on the fuel with its specific combustion reaction. For instance solid fuel combustion does not produce water.

[3] "Equal quantities of gases and vapours at the same pressure and temperature have the same number of molecules, i.e. $N_A = 6{,}022137 \cdot 10^{-23}$ per mol."

oil burners this is the size of the droplets) is a very important factor for the air factor [4].

- fluctuations in atmospheric pressure of the incoming air (around 6%);
- fluctuations in relative humidity of air (from 0,1 to 3,5%);
- fluctuations in fuel supply (between 5 and 10%, depending on maintenance, varying gas grid pressure, etc.);
- fluctuations in fuel quality/ combustion value (e.g. in the Netherlands the Wobbe-index[5] can vary between 40,4 and 44,6 MJ/m³, requiring 8% extra air. In the EU these fluctuations are expected to increase with Russian gas imports);
- wind influence on chimney (up to 20% for atmospheric burners, 5% for premix burners with deflectors/ draught limiters).

For instance, an air factor of 1,2 means that 20% extra air is added with respect of the stoichiometrically needed volume. Another way of describing the air factor is the oxygen content (O_2) of the flue gases. For instance an air factor ***λ=1,2*** for natural gas equals around **3% O_2** in the flue gases.

So, with an air factor of ***λ=1,2*** there is some 16,6% (0,2/1,2) extra air that goes into the process and the mass balance of the combustion of methane changes as follows:

83,4% * (9,1% CH_4 + 90,9% air) + 16,6% air →

83,4% * (9,1% CO_2 + 18,2%H_2O +72,7% N_2) + 16,6% air

or, substituting 'air' with 20% oxygen and 80% nitrogen in the result:

7,59% CH_4 + 92,41% air → 7,59% CO_2 + 15,18% H_2O + 73,93% N_2 + **3,3% O_2**

So the 16,6% air in the flue gases equals an oxygen content of ca. 3,3% (20% oxygen in air). Normalizing this volume balance to the fuel input, we can say that for the combustion of 1 m³ of methane 12,17 m³ of air is used, resulting in 13,17 m³ of flue gases with the composition as mentioned above: 1 m³ carbon dioxide, 2 m³ water, 9,73 m³ nitrogen and 0,43 m³ oxygen.

To convert these results from methane to natural gas, we must consider that natural gas contains only some 95% of methane and therefore the oxygen content of the flue gases drops to close to **3% O_2.**

2.3.3 Humidity of combustion air

Not only the combustion reaction produces water vapour as one of the outputs, but also a —relatively small— fraction of the water vapour in the flue gases comes from the humidity of the combustion air input. The EN standard prescribes a relative humidity (RH) of 70% and ambient temperature (20°C) for the air input. The look-up table 2-1 shows that the maximum water content (100% RH) of air at 20°C is 2,4 volume%. At 70% RH this is 1,68 vol.%. At 12,17 m³ of air that goes into the combustion, this results in 0,2 m³ of water vapour or around 0,16 litres of water that needs to be added.

Table 2-1. Max. volume % Water of air (1013 mbar) and saturation pressure (psat) at various temperatures (Temp.) ***[source: Farago, 2004]***

Temp.	- 20	-10	0	10	20	30	40	50	60	70	80	90	100
%water	0,16	0,31	0,61	1,2	2,4	4,2	7,4	12,3	19,1	31,2	47,4	70,1	100
psat	155	308	611	1227	2367	4242	7375	12334	19919	31161	47359	70108	101325

[4] In fact, the preparation of the fuel, especially the heating oil, is a discipline in itself whereby the viscosity and other physical properties of the oil are a limiting factor in themselves in decreasing droplet size when atomising the oil before combustion. Also the preheating of the oil up to 60°C is a factor. For more details see www.iwo.de

[5] Natural gas is a mixture of gases. In the EU it is mostly it is methane, but there are also smaller fractions of propane, butane, etc.. The Wobbe-index is a measure of the combustion value of the mixture.

2.3.4 *Influence of emissions*

The balance is also incomplete because it does not contain the emissions of unburned fuel (CH4) and pollutants: carbon monoxide (CO_2), nitrogen oxides (NO_x) and total organic compounds (TOC).

Pfeiffer 2001 of the University of Stuttgart [6] has done extensive tests of emissions of oil- and gas-fired (combi-)boilers, looking not only at the stationary (combi-)boiler operation —as is done in EN standard tests— but especially during cycling (D. *Taktbetrieb*). For the latter he used the (combi-)boiler loads as described in DIN 4702-8 and calculated the emissions for around 14000 start/stop cycles per year [7]. This description of 'Taktbetrieb' applies to space heating operation, but also applies to water heaters when producing hot water at lower flow rates (e.g. below the minimum flow rate) of course with a different number of cycles.

As the tables below show, the emissions during cycling were much higher –on an annual basis—than during stationary operation, despite the fact that mainly above-standard pre-mix burners were tested In terms of environmental impact –which will be elaborated at a later stage—these are significant numbers.

In terms of actual mass, the numbers are small. In our calculation of the methane combustion we will use a value of 100-120 mg/MJ: CO 24, CH_4 26, NO_x 25-30 mg/MJ + TOC 23 mg C/MJ (say 30 mg hydrocarbons). At 39,8 MJ/m³ for methane this comes down to a total 4-5 gram. This mass does not come on top of the emissions, but replaces a minute part of the other combustion products.

Table 2-2. Emissions gas fired boilers (source Pfeiffer, 1)

Gas fired appliance	Ref.	CO [mg/MJ]		CH_4 [mg/MJ]		TOC [mgC/MJ]	
		Steady state	*Cycling**	*Steady state*	*Cycling**	*Steady state*	*Cycling**
Boiler with premix burner	H1-G1	2,2	32	0,42	19	0,59	16
Premix condensing, flat burner	G2	0,43	21	0,49	36	0,68	31
Premix condensing, flat burner	G3	3,9	10	2,6	33	2,0	28
Instantaneous boiler, flat burner	G7	14	16	0,89	16	0,99	14
Instantaneous boiler, flat burner	G8	6,5	15	0,45	23	0,99	19
Average		***5***	***19***	***0,97***	***25,4***	***1,05***	***21,6***

* Cycling operation based on relative boiler load acc. DIN 4702 / Part 8

[6] Dipl.-Ing. Frank Pfeiffer ; Bestimmung des Emissionen klimarelevanter und flüchtiger organischer Spurengase aus Öl- und Gasfeuerungen kleiner Leistung;; Fakultät Energietechnik der Universität Stuttgart; 2001

[7] For a regular boiler this is fairly close to the German average (other sources like Farago mention 16000 cycles). For instantaneous combi-boilers, with on average 50-60 draw-offs per day, the amount of cycles can triple (e.g. 40000 per year).

Table 2-3. Emissions oil fired boilers (source: Pfeiffer, 1)

Oil fired boiler	Ref.	CO [mg/MJ]		CH_4 [mg/MJ]		TOC [mgC/MJ]	
		Steady state	*Cycling**	*Steady state*	*Cycling**	*Steady state*	*Cycling**
Boiler 1 with jet burner 1	H1-B1	< 0,33	2,3	< 0,40	0,49	< 0,56	1,5
Boiler 1 with jet burner 2	H1-B2	< 0,35	1,9	< 0,43	0,48	< 0,60	1,0
Boiler 1 with jet burner 3	H1-B3	< 0,34	3,7	< 0,41	0,45	< 0,58	1,2
Boiler 1 with jet burner 4	H1-B4	0,34	2,4	< 0,41	0,44	< 0,58	1,6
Boiler 2 with jet burner 5	H2-B5	1,2	43	< 0,42	1,5	< 0,59	17
Boiler 3 with jet burner 6	H3-B6	4,0	7,3	< 0,40	2,0	< 0,56	6,9
Boiler 3 with jet burner 3	H3-B3	5,4	7,8	< 0,41	0,61	< 0,57	1,9
Boiler 3 with jet burner 7	H3-B7	4,3	3,3	< 0,38	0,74	< 0,53	2,4
Average		*2*	*9*	*0,4*	*0,84*	*0,57*	*4,18*

* Cycling operation based on relative boiler load acc. DIN 4702 / Part 8

Please note, that the values measured by Pfeiffer on commercially available boilers in 2001 were already much lower than the ones mentioned in the EN standards.

Having said that, the above tables also do not take into account a number of emissions in practice. In the paragraph 1.4.5 on energy contained in lost fuel this will be discussed in more detail. In short:

- The measurements were done in a laboratory and did not take into account real-life fluctuations in combustion air (pressure, temperature, enthalpy), fuel supply and quality, flue gas duct pressure (wind), etc. In analogy with the air factor we add an extra 25% for all emissions
- The measurements were done with DIN 4702-8 conditions (39% load →14000 cycles/year) for regular boilers. Correcting for the lower load factor in practice (9%) and the fact that most boilers deliver hot sanitary water (40 000 cycles) this gives a factor 2,8.
- Gas leakage at (combi)boiler level was not taken into account. Following prEN 13836:2005 this adds another 0,1% of methane emissions.

All in all, we estimate that around 10-11 g of fuel is lost per m³ of methane input, or around 1,5 weight %.

2.3.5 Converting volume into mass balance

To convert the volume balance into a mass balance, we can use the atomic mass of the elements involved (O=16, N=14, C=12, H=2), also knowing that the mol-volume at ambient conditions is ca. 22 litres [8]. For instance, 22 litres of CH_4 would then weigh 20 (=atomic weight) grams or 0,909 g/l. = 0,909 kg/m³. Table 2-3 gives the conversion from volume to mass balance of the methane combustion.

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[8] From Avogadro: In the reference situation of 0 ºC and 1013 mbar the mol-volume is 22,41 litres and the kilomol volume around 22,41 m³. At ambient conditions the mol-volume is ca. 22 litres. Furthermore, it is assumed that the ultimate flue gas temperature and pressure equals the temperature and pressure conditions of the fuel and air inputs.

Table 2-4. Conversion from volume to mass balance of 1 m³ methane combustion

	volume	ato.mass	calc. density	mass
Input	***m³***	***#***	***kg/m³***	***kg***
CH_4	1,00	16	0,73	0,73
air 12,17 m³			*(1,31)*	
- O_2, 21%	2,56	32	1,45	3,72
- N_2, 79%	9,61	28	1,27	12,24
H_2O in air*	0,20	18	0,82	0,16
Total	13,37			16,84
Output				
CO_2	1,00	44	2,00	2,00
H_2O combustion*	2,00	18	0,82	1,64
H_2O in air*	0,20	18	0,82	0,16
N_2	9,74	28	1,27	12,39
O_2	0,44	32	1,45	0,63
$CO/CH_4/TO_x/NO_x$				0,01
Total	13,37			16,84

*= water vapour, not liquid —> density < 1

As mentioned, this mass balance is for 100% methane and not exact for natural gas.

2.4 Energy balance combustion

2.4.1 Introduction

During the combustion the chemical energy of the fuel reacting with the oxygen is transformed into three types of heating energy:

- Radiation energy of the flame/burner
- Convection energy of the combustion products (temperature of the flue gases) and
- Latent heat of the water vapour (the heat released when the vapour condenses into liquid)

Furthermore, the combustion process has to carry the ballast of the excess air, due to the air factor., and at the most parts of the emissions –the ones containing carbon [9] — count as lost fuel.

All in all, the general mass balance for the inputs in the methane combustion in our previous example looks like this:

[9] For oil this also includes sulphur.

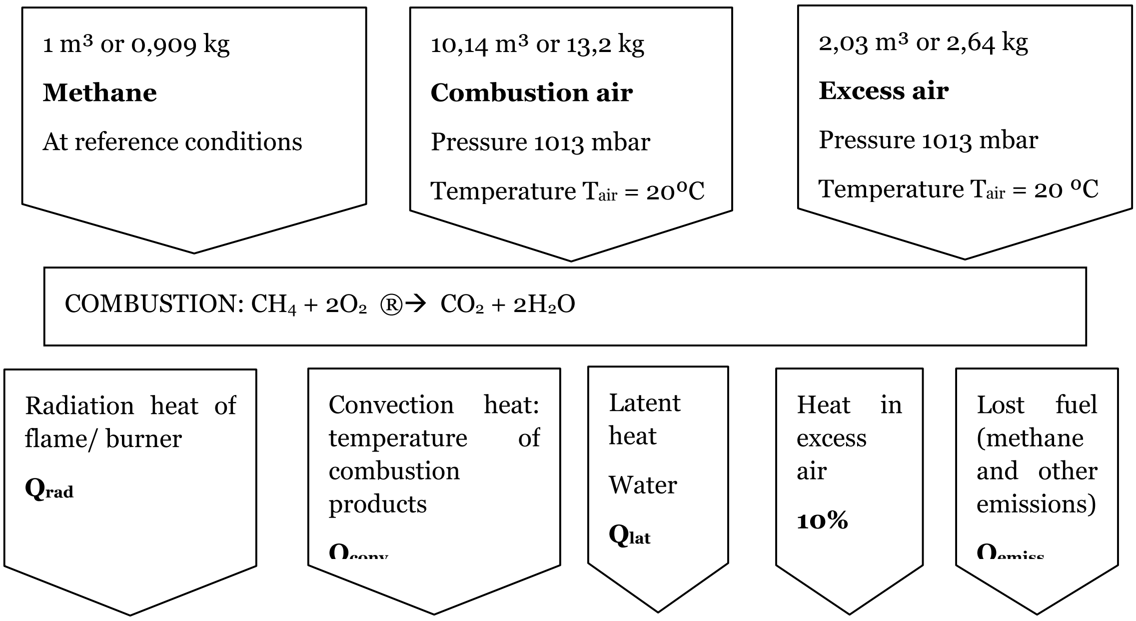


Figure 2-1. Mass balance methane combustion

The total heat heat released by the combustion process is the ***combustion heat***, also known as combustion energy or enthalpy, symbol ΔH. The unit is MJ (megajoules, 10^6) or kWh of heating energy, often expressed as the ***Gross Calorific Value GCV*** or the ***upper heating value uhv*** (D. *Brennwert*) of the fuel. The equation for methane (at 273 K, 1013 mbar [10]) is:

$$\Delta H_{methane} = Q_{flame} + Q_{latent} + Q_{xsair} + Q_{fuel\text{-}loss} = 39{,}8\ MJ/m^3$$

If we leave out the latent heat contained in the water vapour, i.e. the heat released when the water condenses, we find a value known as the ***Net Calorific Value***, the ***'dry gas' combustion value*** or the ***lower heating value ulv*** (D. *Heizwert*). In the global combustion reaction the ΔH has a negative connotation in the right-hand side of the equation, indicating that the reaction is ***exothermic*** (produces heat, as opposed to an ***endothermic*** reaction which consumes heat).

The table below gives the enthalpies for some fuels:

Table 2-5. Energy levels of different fuels at 273 K and 1013 mbar

	Gross calorific value Hs [MJ/m³]	Net calorific value Hi [MJ/m³]	Hs/Hi	Hs – Hi [MJ/m³]	Volume of condensate (theoretical) [kg/m³]
Town gas	19,73	17,53	1,13	2,20	0,89
Natural gas LL	35,21	31,79	1,11	3,42	1,53
Natural gas E	41,25	37,26	1,11	3,99	1,63
Propane	100,87	92,88	1,09	7,99	3,37
Fuel oil (fig.relate to 1 ltr)	38,45	36,29	1,06	2,16	0,88

[10] Note that for gases the temperature is an important parameter, e.g. at 25°C the GCV of methane is 36,3 MJ/m³.

In the rest of the paragraph we will explore to see what is the share of Q_{flame} , Q_{latent} , Q_{xsair}, $Q_{fuel\text{-}loss}$ and what temperature levels are associated with these heat energy outputs.

Note that the energy balance of the combustion process is only the first step of the total energy balance, but we will deal with the heat transfer in the burner, heat exchanger(s), etc. in the following paragraphs.

2.4.2 Combustion heat Q_{rad} + Q_{conv}

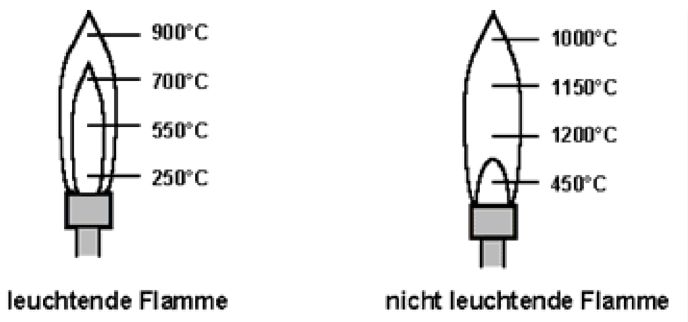
Flames

Starting point of a high-temperature combustion is the flame. In a 'normal' flame, e.g. of a candle, there are three zones:

- A ***fuel-preparation*** zone where the gaseous fuel is heated up to a temperature – the ***'ignition temperature'***–starting the dissociation process (breaking up the hydrocarbon molecules in smaller fractions) leading up the combustion chain reactions. When the gas reaches the ignition temperature (around 300-500°C) it attracts the minimum amount of air necessary from its surroundings (e.g. air factor of 0,5) and starts combustion. In the case of a liquid fuel (oil) this process is preceded by a step where the oil is atomised into droplets, which are then vaporized.
- A ***'rich combustion'*** zone where the flame is above the ignition temperature and minimal air factor but has too little oxygen/air with respect of the stoichiometric combustion (0,5 < air factor < 1). In this zone very small soot particles are formed and burnt, emitting a yellow light. Rich combustion is also usually accompanied by higher emissions of CO.
- A ***'lean combustion'*** zone (air factor > 1) with a blue flame colour. At a certain temperature the flame temperature attracts so much air/oxygen that the air factor becomes too high (e.g. higher than 2) and the flame has reached its visible boundaries. Lean combustion is also usually accompanied by higher emissions of NO_x.

Such a flame is known as a ***'diffusion flame'***, where the air input to the combustion process is dependent on the flame-temperature and the mixing of air/fuel takes place concurrently with the combustion. This flame is typical of candles, matches, etc. but also to a large extend of ***partial pre-mix burners*** (a.k.a. *'atmospheric burners'*, type B_{11}) in simple combi-boilers and many gas-fired instantaneous water heaters, where the primary air flow is regulated (pre-mixed) through a venturi with the fuel flow and secondary air completes the job during combustion.In contrast, in ***pre-mix burners*** the air input to the combustion process is independent of the flame-temperature and a combustion fan gives an exact dosage of air to the mixture. The fuel/air is fully pre-mixed before entering the burner and produces a flame with a very different temperature distribution profile (see picture) but also a more favourable emission profile.

Figure 2-2.
Temperature distribution in a diffusion-flame (left) and a pre-mix flame (right) of a Bunsen-burner [Farago, 2004]



Flame temperature

Calculating the temperature of the flame is not an easy task. A first theoretical value called the ***calorific flame temperature*** can be calculated from the enthalpy of the fuel under the simple assumption that all energy is converted into hot combustion products. The temperature increase (above ambient) of the combustion products ΔT comes from the ***enthalpy*** of the fuel ΔH, the ***mass*** of the combustion products ***m*** and their ***specific heat cp***:

$$\Delta H_{methane} = m * cp * \Delta T$$

The reaction temperature $T_{reaction}$ is then defined as $T_{reaction} = T_a + \Delta T$, where T_a is the start temperature of the combustion products (usually ambient, i.e. 20°C).

The enthalpy of the fuel is known (see paragraph 2.4.1: 39, 8 MJ/m³), the mass of the combustion products is taken from the mass balance in the previous paragraph 2.3 and the specific heat is a look-up materials property (see table below).

Table 2-6. Density and specific heat of some substances

Substance (properties at 293K and 1013 mbar)	formula	density ρ kg/m³	specific heat c_p kJ/(kgK)
water	H_2O	1	4,18
air	79% N_2, 21%O_2	1,29	1
oxygen	O_2	1,43	1,4
nitrogen	N_2	1,25	1,25
methane	CH_4	0,72	2,21
propane	C_3H_6	2,02	1,53
(iso-) butane	C_4H_8	2,67	1,61
carbon monoxide	CO	1,25	1,05
carbon dioxide	CO_2	1,98	0,82
sulphur dioxide	SO_2	2,93	0,64
acetylene	C_2H_2	1,18	1,67

Table 2-7. Calculating calorific flame temperature for 1 m³ methane at air factor = 1,2

Output	**mass** *kg*	**spec. heat** *kJ/(kgK)*	**mass*spec. Heat** *kJ/K*	**Temperature increase at fuel enthalpy in K** *Hs= 39,8 MJ*
CO_2	2,00	0,82	1,64	
H_2O combustion*	1,64	4,18	6,84	
H_2O in air*	0,16	4,18	0,68	
N_2	12,39	1,04	12,89	
O_2	0,63	1,40	0,89	
CO/CH4/TOx/Nox	pm		pm	
Total	16,84		22,94	1735

This calorific flame temperature is in practice never reached, because of dissociation effects (incomplete combustion), especially at air factor=1 (stoichiometric combustion). Another value that takes into account the dissociation process is the ***adiabatic flame temperature***. Especially for gases the adiabatic flame temperature is fairly close to the calorific flame temperature at practical air factor values. The adiabatic flame temperature is independent of the size of the flame and the dimensions of the combustion chamber and the power output of the burner.

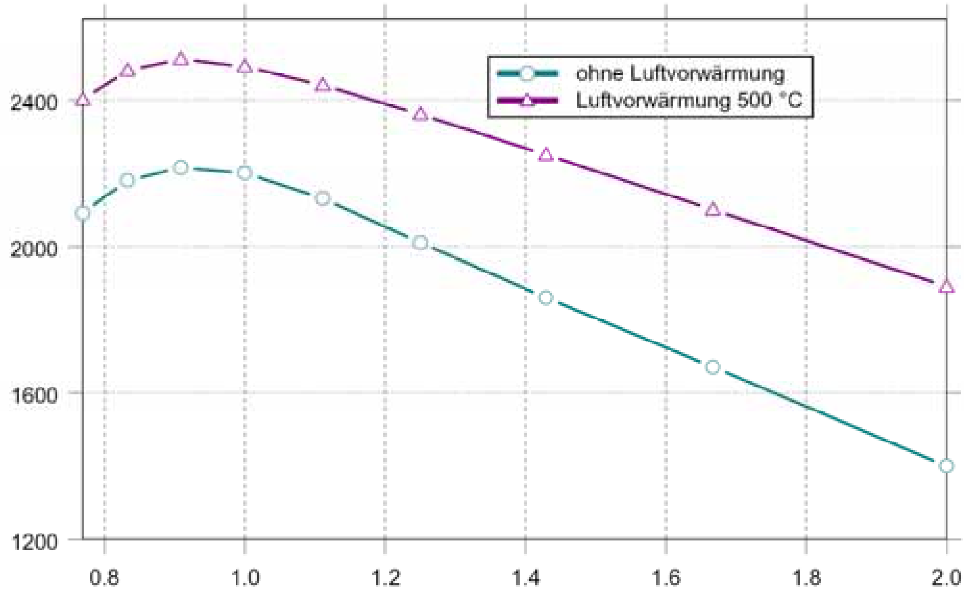


Figure 2-3.
Adiabatic flame temperature in K =ºC +273 of methane-air mix at various air factors 0,8 to 2.0. The highest temperature is reached at air factor=0,9. *[source Farago, DLR]* Please note that temperatures are given in Kelvin (K =ºC +273). The adiabatic temperature at air factor =1,2 is around 2000K or 1730°C, which is close that what we calculated earlier.

2.4.3 Latent condensation heat Q_{latent}

As mentioned in the introduction, the ***latent condensation heat*** is the heat contained in the water vapour from combustion when condensing. Numerically it is the difference between ***Gross and Net Calorific Values (GCV and NCV)*** of the fuel.

In the case of our example of methane combustion around 1,8 kg of water vapour is produced per m³ of methane (see mass balance: 1,64 kg from combustion, 0,16 kg from humidity in the incoming air at air factor 1,2). The specific latent condensation heat of water is 2,27 MJ/kg, so per m³ of methane 4,09 MJ of condensation heat is available. Compared to the GCV of methane of 39,8 MJ/ m³, this is 10,2%. Compared to the NCV it adds an extra 11%. As natural gas consists mostly of methane, the same numbers apply roughly to natural gas.

For other fuels, the stoichiometric combustion equations are different and therefore the water vapour and the maximum amount of latent heat is different. For oil-fired (combi)boilers this is around 6% and for propane it is 8-9%.

In theory, the latent condensation heat can be fully recovered, if somewhere in the water heater before the flue gases go up the chimney or flue duct the flue gases are cooled to ambient temperature (<20°C).

In a ***non-condensing heater*** the flue gases –after flowing through the heat exchanger— leave the water heater at a temperature of somewhere between 200 and 300°C still in the form of water vapour. Somewhere in the atmosphere the water vapour will condense against the cooler outside air, but in principle all the latent heat of the condensation process is lost for the water heater.

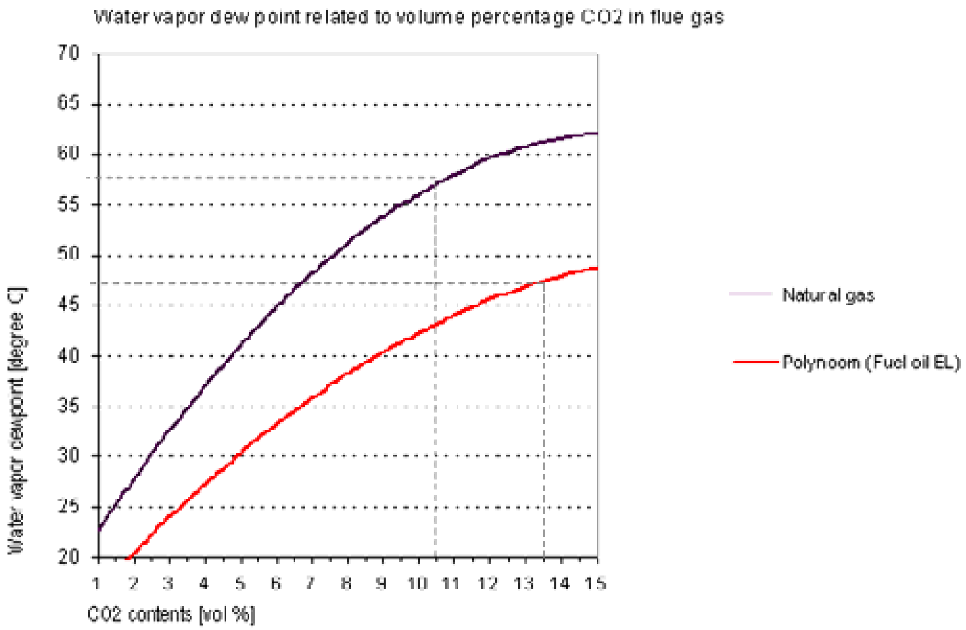
To establish where this point of total-loss is, we can use the EN standards that define that if the flue gas temperature stays above 160°C there is no risk of condensing. This is a technical level, taking into account extreme circumstances.

The EN standards speak of a dedicated '***condensing boiler***' (same applies to water heaters) at flue gas temperatures of lower than 80°C. 'Condensing' relates to the fact that the water vapour in the flue gas comes into contact with a cold surface of the heat exchanger and than turns into liquid, releasing the latent heat of condensation. This condensation of air with a 100% ***relative humidity (RH)*** takes place at a temperature level that is known as the ***'dew point'***. This dew point also depends on other parameters, but in general one can say that condensing starts at a surface temperature of the heat exchanger (=boiler temperature) of just below 57°C for gas and

46°C for oil. At a boiler return temperature of 30°C some 70-80% of all latent heat is recovered. At 35°C boiler return temperature around 50% is recovered.

The graph below gives the water vapour dew point at (near) stoichiometric combustion. At higher lambda's, the dew point will even be lower. Natural gas starts condensing at 57°C and oil at 47°C. At lamdba's of 1,25 the CO_2 content decreases and with it also the dew point to approximately 53°C for gas and 44°C for oil.

Figure 2-4.
Dew point water vapor for gas- and oil flue gasses



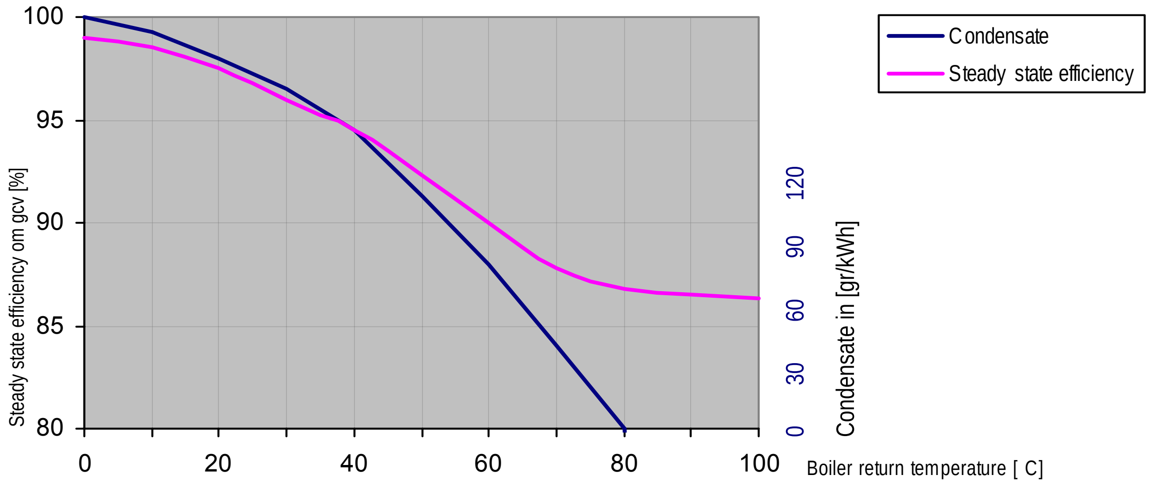


Figure 2-5. Steady state efficiency and amount of condensate related to return temperature of gas fired boiler.

2.4.4 Heat loss in excess combustion air Q_{xsair}

To complete the picture of the energy balance of the combustion process we include the excess air that is the consequence of the air factor.

Obviously, the extra air into the combustion process comes at a penalty. For instance, in a 10 kW gas-fired heat generator with an air factor $\lambda=1,3$ this means that an extra 3 m³ is heated from ambient temperature to e.g. 1000°C combustion temperature. With respect of the stoichiometric process this initially costs some 9% extra[11], of which of course in the heat exchanger a large part is recuperated. But still, 'losses' in the order of magnitude of 2% remain. A rule-of-thumb is that *every 1% O_2 extra results in 0,5% efficiency loss*. This is of course only true when measuring flue gas exit temperatures, but it gives an order of magnitude for the partitioning.

All in all, as described in the EN standards, an air factor of 1,2-1,25 is standard practice for higher power outputs of gas- or oil fired premix burners. For lower outputs (<10 kW) or not-premix burners it can be 1,3 or higher (up to 1,5-1,6).

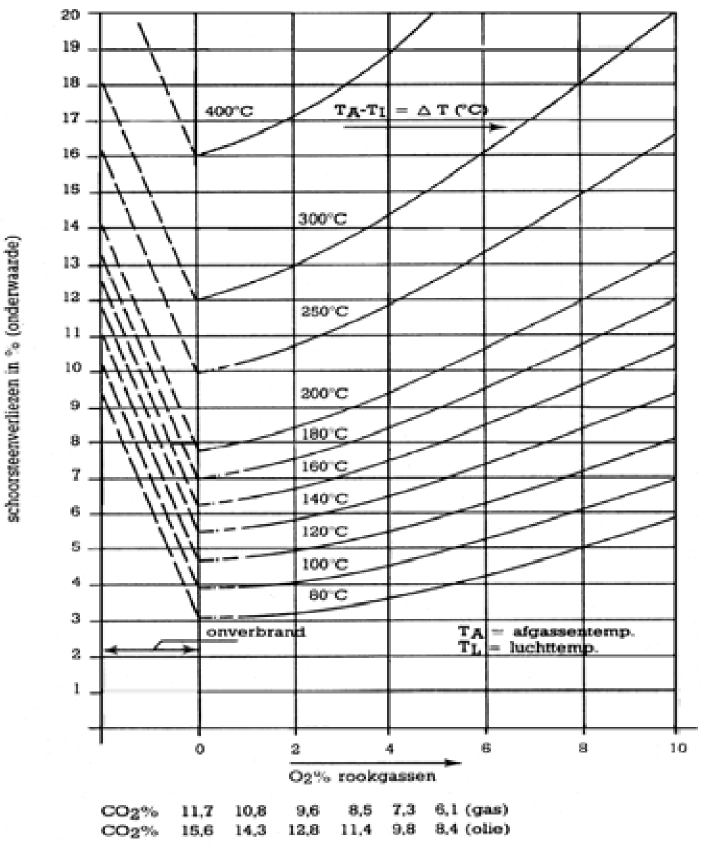


Figure 2-6.
Flue heat losses due to the air factor, expressed in % O2, showing that every 1% O2 leads to 0,5% efficiency loss. Source: Stooktechnologie, 2005]

2.4.5 *Fuel loss $Q_{fuel\text{-}loss}$*

The research by Pfeiffer, as mentioned in the mass balance, allows us to quantify the energy lost because of incomplete combustion. In principle, we can say that all carbon (C) that ends up in the emissions comes from the methane and quantifies the fuel lost. This leaves out the NO_x emissions, but we are still left with 24 mg/MJ CO (ato.mass 28), 16 mg/MJ CH4 (ato. mass 16) and 12 mg carbon/MJ TOC (carbon ato. mass is 12). Calculating these numbers on a mass basis this means that the equivalent of ca. 3 g of methane is lost per m³ methane of carbon-containing emissions. At a density of 0,73 kg/ m³ this means that some 0,4% of fuel energy is lost.

Obviously, this was measured in a laboratory, which means that the fluctuations in combustion air (atmospheric pressure, temperature, etc.), fuel (pressure, wobbe-index), etc. were not taken into account. Following an analogy with the air factor, we can assume that in real-life the emissions are some 25% higher, i.e. 0,5%.

Furthermore, it has to be considered that Pfeiffer did his measurements at DIN 4702-8 conditions, which means on average a heat load of 39% (space heating). In reality, as a

[11] Air at 1 kJ/K.m³ for a 3 m³ with a temperature increase of 1000 K → 3000 kJ = 3 MJ= 0,9 kWh/h = 0,9 kW → 9% of 10 kW.

study of Wolfenbüttel pointed out, the heat load in the heating season is more in the area of 9%. At a modulation ratio of 30% this still means that the average number of on-off cycles in reality is higher than the 14000 cycles assumed by Pfeiffer. No statistics on average cycling behaviour are available, but anecdotal evidence suggests numbers in the range of 16000 - 20000 cycles. This then leads to an annual loss of 0,65% for a regular heating boiler at say 18000 cycles/year.

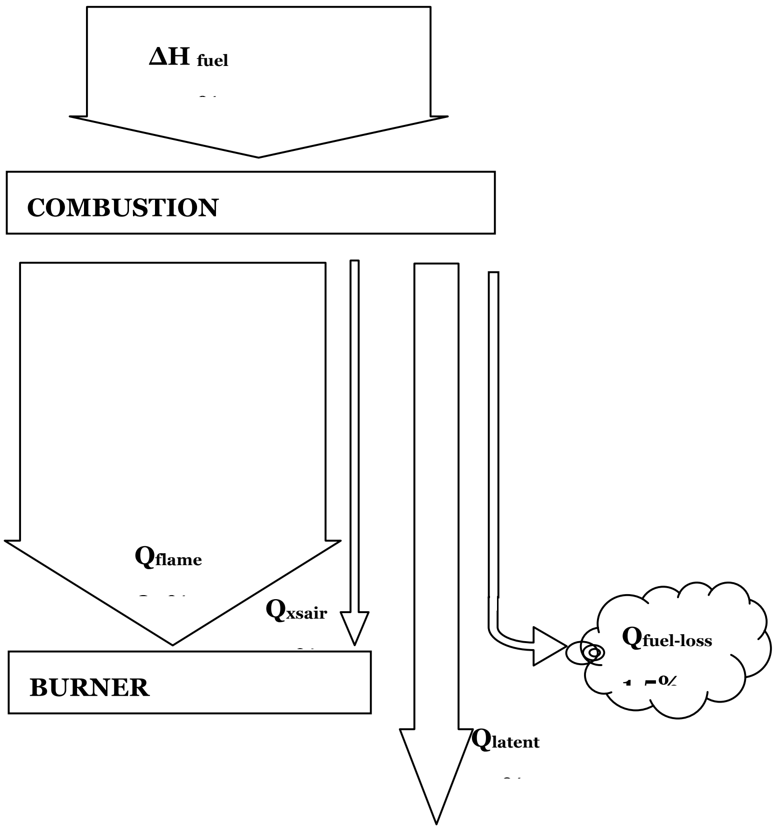
Pfeiffer tested regular boilers, i.e. without the sanitary hot water function. In case of an instantaneous combi-boiler that switches at every draw-off, the number of cycles is much higher, e.g. in the range of 40-50 000 cycles. The corresponding fuel-loss in that situation is almost triple, say 1,5%. According to the BED Market study 2006 by BRG Consult around 90% of the gas-fired boilers are operated with a sanitary hot water function, either as a combi or with an external cylinder, and the vast majority of these are instantaneous.

Pfeiffer did not take into account gas leakage. No statistics on the subject are known, but the prEN 13836 specifies that a boiler satisfies the requirements if the leakage is of the gas valve is less than 0,06 dm^3/h (upstream gas pressure 150 mbar) and 0,14 dm^3/h for the whole boiler. One might argue that these are maximum values; on the other hand these are laboratory measurements where no inaccuracies in installation practice should occur. Per annum (8760 hours) this equals some 0,5 to 1 m^3 per annum. At an average consumption of 1000 m^3 /year (example for space heating) this adds another 0,1% energy loss.

All in all, we estimate for average EU combi-boilers, a figure of 1,5% of energy in fuel losses (combi boiler, largely instantaneous, 40000 cycles/a).

In summary, the heat balance for the combustion process of a gas-fired boiler methane with air factor 1,2 looks like this. Please note that the latent heat includes not only the water vapour from combustion, but also the potential condensation heat of the water from the incoming air.

Figure 2-7.
Energy balance of combustion process methane

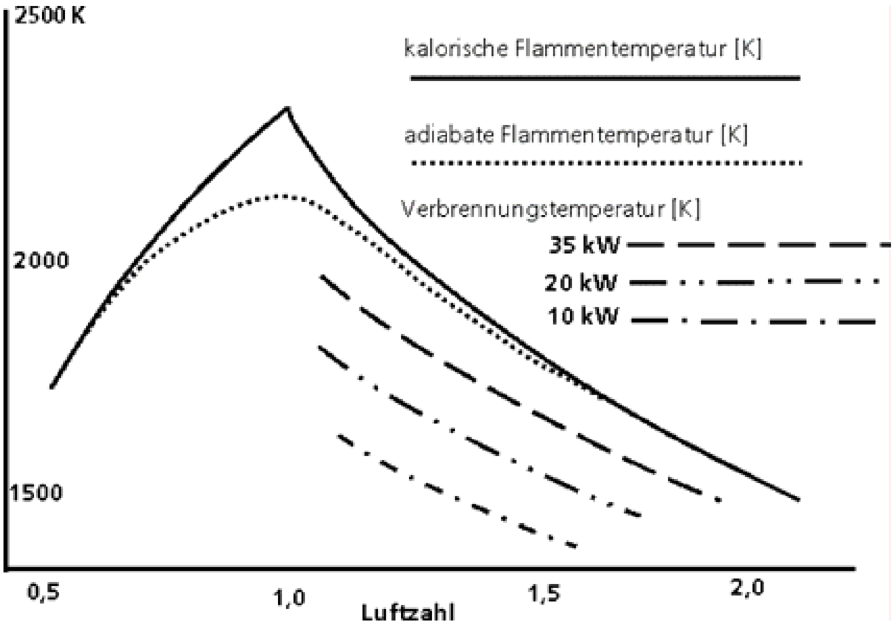


2.5 Energy balance burner

Many authors do not distinguish between the energy balance of combustion and the burner, because in terms of actual measurements it is very difficult to measure the flame temperature without some sort of burner. Yet, in explaining the heat balance of the whole process it is functional, because in the interaction between the flame and the burner construction there is much more going on than meets the eye.

For starters, when you measure the temperature of the combustion products at the burner, the so-called ***combustion temperature*** (D. *Verbrennungstemperatur*), there always seem to be 100-200°C missing compared to the adiabatic flame temperature. The graph below gives an illustration of the above in an actual combustion chamber and burner operated at 10, 20 and 35 kW.

Figure 2-8.
Flame and combustion temperatures in an oil-fired boiler (*D. Blaubrenner*) at 70°C boiler temperature, according to various definitions.
[source: Farago, Brennstoffkunde, DLR 2004]



If we assume the power output of the burner as a measure of the flame size, the picture shows that at a smaller flame size (10 kW on a 35 kW burner), the combustion temperature, i.e. the temperature of the combustion products, is significantly lower than at nominal power/ flame size. Between 35 and 10 kW power the temperature difference is some 350 K. Assuming this is proportional to the temperature difference with the ambient (ca. 1700°C) this means that at 10 kW (30% load) the share of radiation energy has increased by 20% with respect of 35 kW (100% load). On average, every 10% decrease in load has yielded around 2,5-3% more radiation share. It may seem contra-intuitive that a smaller flame gives off relatively more radiation heat, but the keyword here is 'relative', because in fact the size of the burner bed and the combustion chamber do not change. In other words, one could also say that with a larger burner plate (compared to its nominal capacity in W/cm²) the radiation share increases (and the convection share, i.e. the temperature of the combustion gases, decreases) [12].

Of course there is a limit to decreasing the burner load, which has to do with air and flame velocity, flame stability, laminar and turbulent flame fronts, etc.. We will not go into that complex matter[13], but stick to the more profane thermodynamics.

[12] Electro-magnetic waves in the visible light spectrum, but also in the UV (ultra-violet) and IR (infra-red) spectrum. In fact, the radiation in the UV-spectrum of the flame is the basis for optical flame-ignition control sensors.

[13] Dietzinger 2006 gives a good overview of the latest insights in flame modelling techniques and numerical tools available.

On the next page there are several illustrations of research concerning temperature levels inside a burner, showing that there is more to be considered.

The university of Eindhoven has done experiments of a 'flame in a box', which amongst others give a detailed insight into the temperature fields of a pre-mix burner. The picture shows temperatures near a nozzle of a conventional nozzle, showing that the flame temperature at the burner nozzle is around 600-800 K (300-500°C). From this we assume that the temperature of a conventional burner plate, made of perforated thin refractory steel plate (surface around 240 cm² for 24 kW burner → weight ca. 80-100 g.) is on average around 400°C. The flame temperature itself rises to around the adiabatic flame temperature of 2000 K (1730°C).

Dietzinger [2006] at the university of Stuttgart has done several experiments on the propagation of the temperatures of a methane/air mixture in a porous ceramic burner, showing the propagation of the temperature at the Z-axis of the burner. In the area between the hole plate ('flame barrier') and burner bed the temperature rises to the ignition temperature (550-600°C) and then —at the bottom of the 20 mm thick burner bed— jumps to a temperature of around 1600°C. Inside the burner bed of this 'flameless burner' the temperature then decreases to around 1100-1200°C before leaving the burner. Already at a height of 5 mm above the burner bed the temperatures have dropped to below 1000°C and laboratory measurements of the flue gases may lead to believe that this is a low temperature burner, whereas in reality the high temperatures are there, but inside the burner. In fact, in this case the average temperature of the burner bed is 1300°C.

The results from Eindhoven and Stuttgart represent two extremes in pre-mix burners. Somewhere in between we find ceramic surface burners, where in fact the flames 'sit' halfway inside the burner nozzles. There, the burner plate reaches temperatures up to 1000°C and the temperature of the combustion products is around 1100°C.

The table below gives an estimate of temperature levels between burner bed, flame and combustion products.

Table 2-8. Estimated temperatures and loads for pre-mix burners (at air factor 1,2, no preheat air)

Pre-mix burner type	Burner plate temperature [°C]	Combustion products temperature at 10 mm [°C]	Radiation share [%]	Max. load [W/cm²]	Surface for 20 kW [cm²]
Steel plate	400	1300	5%	100	200
Radiation burner (ceramic/steel)	900	1100	20-25%	300-400	70
Porous ceramic burner	1200	900-1000	25-30%	300 (>1000, experimental)	70

The table also gives typical burner loads in terms of watts burner output per surface area, showing that the radiation burners can be much more compact for the same output power.

Figure 2-9.
Numerical result of a 2D temperature field of a flame in a box
[source: TU Eindhoven, faculty Mechanical Engineering, 2006]

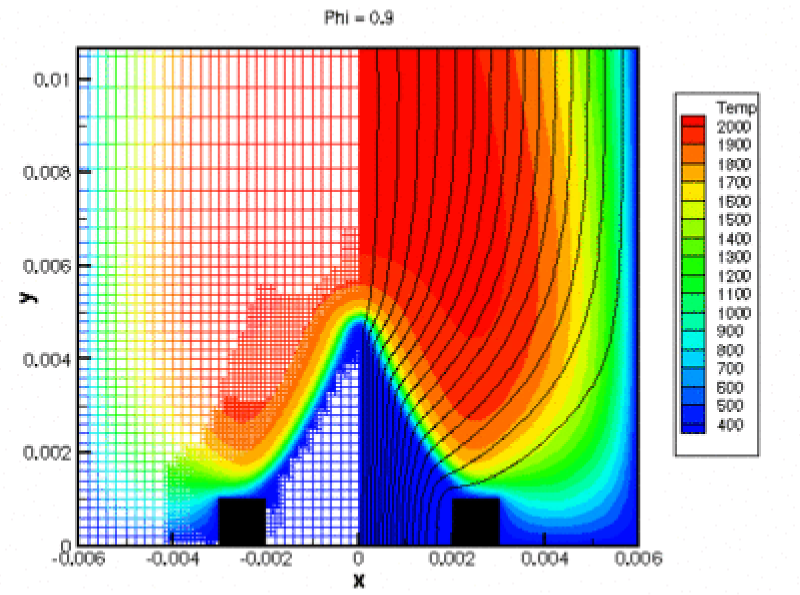
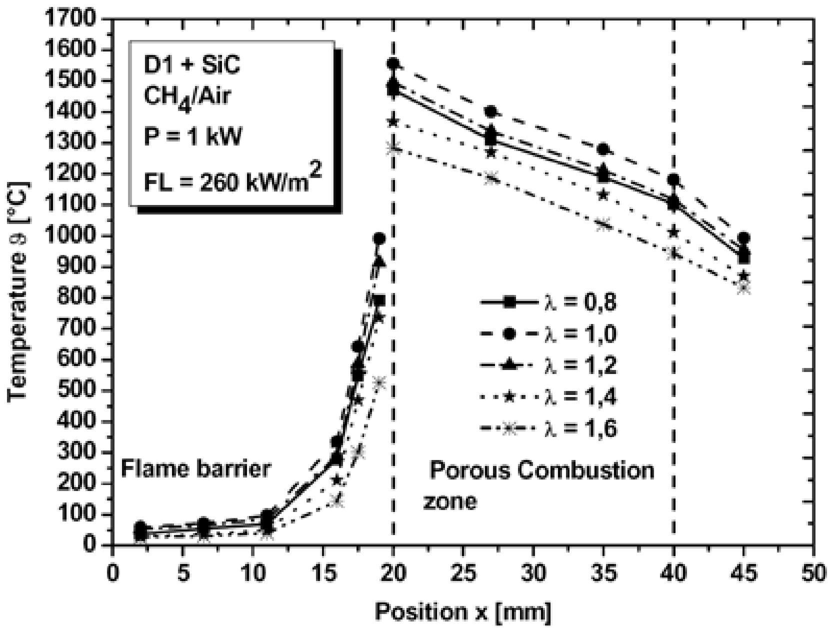


Figure 2-10.
Ceramic porous burner: Propagation of temperature with a methane/air mix. The graphs show an experiment whereby the temperature is measured in the flame barrier and throughout the thickness of a 20 mm porous ceramic burner. Note that the initial temperature after ignition is close to the calculated adiabatic flame temperature and that the combustion products –while giving off their heat to the burner— cool down to a level <1000°C already 10 mm after the burner surface. [Dietzinger, 2006]



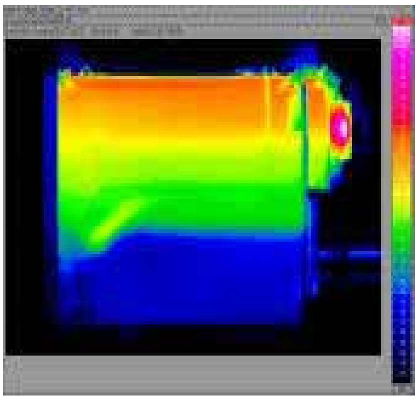
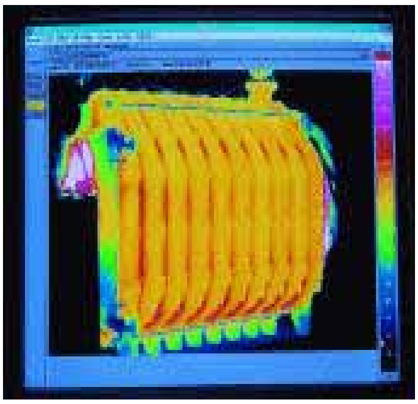
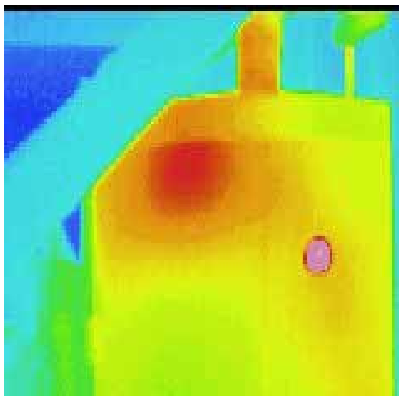




Figure 2-11.
Thermographic pictures of boilers. Left: Steel boiler with jet burner (www.trm.at) Middle: Cast iron boiler (www.trm.at). Right Detail of boiler, burner in red, flue duct in orange.

The wall thickness of a refractory steel plate burner plate is ca. 0,5-0,7 mm, weighing 80-100 g for 20 kW power (+burner frame of 200-250 g). Ceramic radiation burners are 3,5 mm thick and the commercially available porous ceramic burners are now 15 mm thick. For non-stationary (cycling) operation this is relevant, because burner plates cool down in a matter of 3-10 seconds, which means that at every start-up this mass has to be heated.

Calculation example

Assume 350 grams of steel burner+frame with a specific heat of 0,46 kJ/(kgK), to be heated to an average temperature difference dT=300 K. This is 48,3 kJ per cycle. At 40 000 cycles per year, this represents 1932 MJ or 536 kWh. On a total energy consumption of e.g. a combi boiler of 14 000 kWh/year this is around 4%. This energy is not lost. Most of the cooling down will take place during the after-purge at the end of each cycle, where the combustion air will then give off its heat to the heat exchanger and boiler water. If this is then 'useful energy' and not lead to a room temperature overshoot will depend on whether the boiler controls anticipate this extra energy input.

During stationary operation, i.e. during the combustion process, there is also heat transfer.

Steel plate burners are usually fixed to the heat exchanger boiler, which means that a large part of the heat is transferred usefully to the combustion chamber and heat exchanger on the side of the burner. Another part of the heat will be transferred to the space between heat exchanger body and the surrounding casing, where in modern boilers it is picked up to a large extend by the combustion air fan, i.e. it preheats the incoming combustion air. For another part, it will be a major contributor to the heating of the casing, i.e. radiation losses of the boiler to the ambient. The picture at the bottom of the previous page shows thermo-graphic pictures of the boiler casing, showing clearly the 'hot spot' of the burner location.

The following equations summarize the above:

$$Q_b = Q_{b\_conv} + Q_{b\_rad} + Q_{b\_cond}$$

with

$$Q_{b\_conv} = Q_{b\_conv\_combust} + Q_{b\_conv\_case}$$

$$Q_{b\_rad} = Q_{b\_rad\_combust} + Q_{b\_rad\_case}$$

$$Q_{b\_cond} = Q_{b\_cond\_exch} + Q_{b\_cond\_case\_air}$$

where

Q_b = heat out burner

Q_{b_conv} = convection heat burner (combustion temperature* mass combustion products)

Q_{b_rad} = radiation heat burner/ flame

Q_{b_cond} = conduction heat of burner to surroundings

and

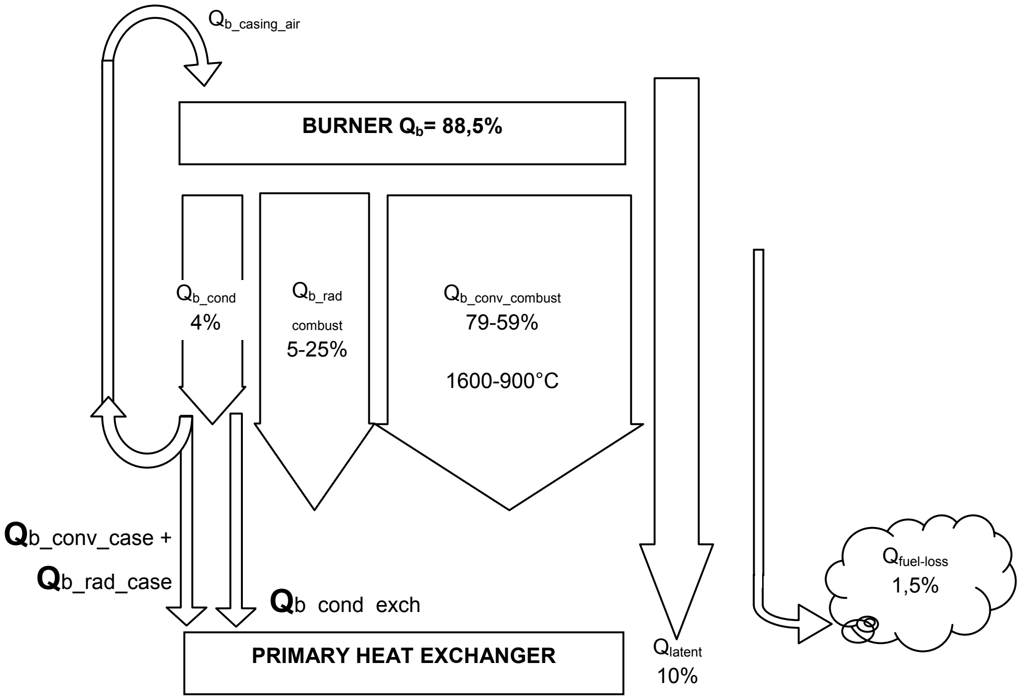
$Q_{b\_conv\_combust}$, $Q_{b\_conv\_case}$ is convection heat transfer to combustion and casing;

$Q_{b\_rad\_combust}$, $Q_{b\_rad\_case}$ is radiation heat transfer to combustion and casing;

$Q_{b\_cond\_exch}$, $Q_{b\_cond\_case\_air}$ is conduction heat to heat exchanger and to the air between casing and heat exchanger.

The picture below gives a Shankey-diagram of the flows. Percentages relate to Q_b = 100%.

Figure 2-12.
Energy balance of gas burner



2.6 Heat balance primary heat exchanger

2.6.1 Introduction

In the primary heat exchanger –and in case of non-condensing heat generators (as in many instantaneous combi-boilers) the only heat exchanger— the radiation heat and convection heat coming from the burner is transmitted to the primary water [14]. This primary water returning from the CH-circuit ('boiler return temperature') has a temperature somewhere between 25 and 70°C to avoid too large heat stress. It is heated by somewhere in the range of 5 to 20°C before it leaves the primary heat exchanger.

In the heat exchanger/ combustion chamber there are the parts that can be 'seen' by the burner and that are subject to the radiation heat. All parts of the heat exchanger are subject to the convection, i.e. the hot flue gases.

Radiation and convection heat transfer are very much linked, but in a publication of the *Verbundnetz Gas AG* [15] an attempt was made at some simplified radiation modelling in an industrial burner, starting from the general Stefan-Bolzman formula:

$$Q_{rad} = A * \varepsilon_{res} * \sigma_s * (T_g^4 - T_w^4)$$

where

Q_{rad}	: the radiation heat energy
A	: the surface of radiation heat transfer in m²,
ε_{res}	: the resulting emission-factor
σ_s	: the constant of Stefan-Bolzmann: **5,67** $* 10^{-8}$ W/m²K⁴,
T_g,- T_w	: temperatures of the gas and the wall in K

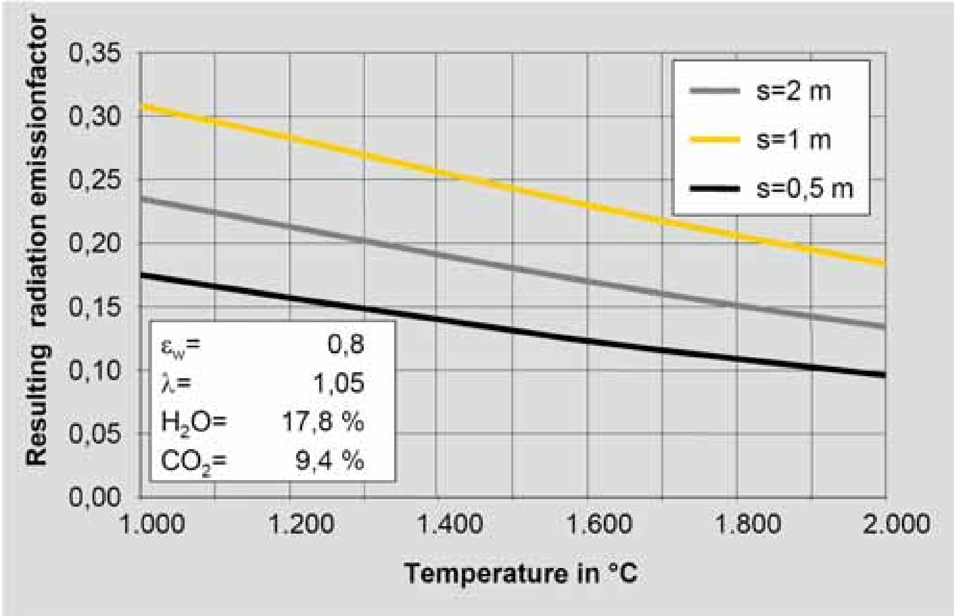
[14] Some instantaneous gas-fired combi's have a dedicated circuit for heating tap water directly (no need for primary water and a heat exchanger) - in this the primary water is the hot water itself.

[15] Erdgas-Report 1/03, *Industrielle Gasbrenner*, Verbundnet Gas AG

The graph below gives an example of the resulting emission factor for an industrial burner/ combustion chamber. It shows that for this burner the maximum radiation is achieved at a height of the combustion chamber of 1 m. At a height of 0,5 m the ε_{res} is almost 50% lower and at 2 m the ε_{res} is around 25% lower. This shows that the dimensions of the combustion chamber are important in maximizing the radiation fraction.

Furthermore, the graph shows that the radiation emission factor increases at a lower temperature from 0,31 at 1000°C to 0,18 at 2000°C.

Figure 2-13
Resulting emission-factor for a combustion chamber, as depending on temperature and the height of the combustion chamber (s= height or 'layer thickness).



The *Erdgas Report 1/03* mentions a value of ε = 0,2 to 0,3 for normal burners and ε = 0,6 for radiation burners.

The convection heat transfer is depending linearly on the temperature difference. A simplified equation for the convection heat tranfer is given by the same source:

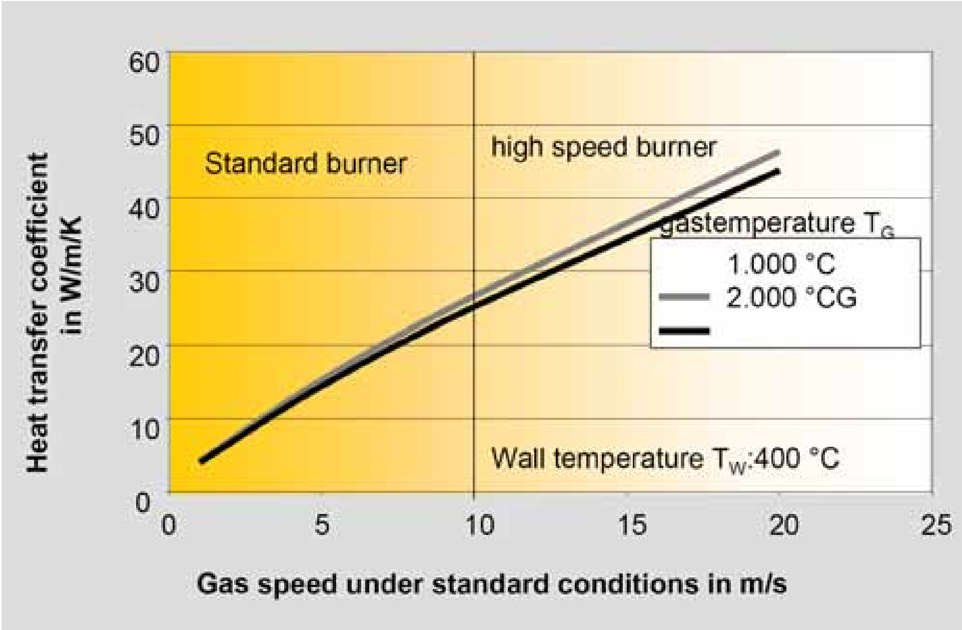
$$Q_{conv} = A * \alpha * (T_g - T_w)$$

where

A	= heat transmission surface
α	= heat transmission coefficient in W/m/K
Tg, Tw	= temperatures of the flue gas and the wall.

The convective heat transmission coefficient depends on the velocity of the flue gas, as shown in the graph below.

Figure 2-14.
Convective heat transfer coefficient
(Erdgas report 1/03, 2003)



Combining the two graphs it is clear that at lower heat output of a modulating boiler (at constant air factor) the convection heat transfer decreases, whereas –given the lower burner load—at the same time the radiation heat transfer increases.

We will not use the formulas for radiation and convection losses directly in describing the heat balance, but they may be useful in describing some of the phenomena in Task 6 (design options).

For the heat balance we will follow the elements of the Boiler Cycle method, distinguishing between energy transfer during 'burner-on' and 'burner off' mode, as well as some additional findings regarding start-stop losses. The important issues are:

'Burner on' operation:

- Flue gas losses;
- Radiation, convection and conduction losses through the generator envelope;

'Burner off' operation:

- Standing losses (radiation, convection (incl. flue gas) and conduction);

'Start-stop' losses:

- Pre-purge losses;
- After purge losses/gains;
- Efficiency losses caused by cycling (German: *Takten*).

2.6.2 Flue gas losses in on-mode

The *primary* heat exchanger is designed to capture the radiation heat from the burner and —after that- to best transfer the heat from the flue gases to the primary boiler water, but without condensation of the flue gases.

The important parameters are the heat exchanger surface (A), the temperature difference between the flue gas and the primary water (dT) and convection coefficients that are typical of a configuration (k' and k"). Most heat exchangers are ***counter flow***, i.e. with the hottest flue gases hitting the hottest boiler water (just before exiting) and the coldest flue gases hitting the coldest part of the heat exchanger, i.e. just where the colder return primary water enters the heat exchanger.

A tap water heat exchanger (as employed in most instantaneous combis) allows the primary water flowrate and temperature regime to be different from the tap water flowrate and temperature regime. At maximum power many combis can produce some 8 l/min of 60ºC tap water. This tap water entered the tap water heat exchanger at approximately 10 to 15ºC. This is however not the same at the primary side of the heat exchanger. Here the temperature difference is limited to what the heat exchanger can withstand (with an average product life in mind): some 5 to 20ºC. The flowrate is governed by an internal circualtion pump (often the same as used for central heating) that sends enough water over the primary heat exchanger to absorb the heat and transfer this to the tap water.

In short, the primary boiler water can be some 80°C with the return water being e.g. 60°C before it goes back into the primary heat exchanger, i.e. above the dew point. Effectively the heat exchanger is working at a 60/80°C (or even 90/70) regime, whereas from the point of view of the tapping point the combi appears to be working at e.g. a 60°C regime. Lower temperatures can be achieved through modulation of burner power, up to the point where cycling (*Takten*) occurs.

The **combustion efficiency η_f** (D. *feuerungstechnischer Wirkungsgrad*) can be explained as measuring the temperature of the flue gasses and then calculating the sensible heat loss, i.e. without taking into account the latent heat (steady state operation):

$$\eta_f = 100\% - Q_f / H_i \text{ (in \%)}$$

where:

Q_f = sensible heat of flue gases [kW] (product of mass flow, specific heat cp and ΔT of the combustion products);

H_i = Heat flow of combustion related to the lower combustion value NCV= (methane 35,89 MJ/m³). As a rule of thumb: 10°C decrease in flue gas temperature represents approximately 0,5% decrease in flue gas losses.

In countries like Germany there is specific legislation regarding the flue gas losses, saying that they should be not higher than 11%, when compared to the net calorific value (NCV).

The Boiler Cycling method gives the following default values for the flue gas losses (applies to heating operation, but indicative for water heating):

Table 2-9. Default flue gas losses of the boiler on-mode as a percentage of nominal power under test conditions (P'ch,on) at typical boiler test temperatures (prEN 15316-4-1, table C1)

Description	θgn,test [°C]	P'ch,on [%]
Atmospheric boiler	70	12
Force draught gas boiler	70	10
Oil boiler	70	11
Condensing boiler (acc. BED)	50	6

Please note that the losses of condensation heat are not included here. Those will be discussed in the paragraph on the secondary heat exchanger.

As the average EU-boiler is moving towards an efficiency on NVC of 90% (82% on GCV), we can take this as a reference for boilers with only primary heat exchangers, meaning flue gas losses of around 6 - 7% (at an average boiler temperature of 50°C and flue gas temperatures of around 150°C).

(To calculate the losses in specific real life situations, corrections on test figures will be necessary to compensate for the differences between the test- and the actual boiler water temperature and cycling behaviour.)

2.6.3 *Losses through the generator envelope in on-mode*

During operation the heat exchanger will transmit heat directly to the casing and the air between heat exchanger and casing. In case of a type C heater (closed system) and an open combustion air fan (D. *'Luftumspült'*), the heated air from the heat exchanger that ends up in the envelope will be picked up by the fan and the heat is recovered.

The heat that is transmitted to the envelope itself (mounting frame and casing) is not recovered for the heat transfer. This heat is mainly lost through radiation and to a smaller extend through convection round the envelope and through conduction (e.g. through wall).

Heat losses through the heater envelope in on-mode can be determined as the difference between the combustion efficiency and the net efficiency of the boiler and can be indicated as a percentage of the input power .

These heat losses through the heater envelope in burner 'on mode' depend on:

- combustion temperatures (type of burner);
- heat-exchanger/burner configuration;
- primary water temperature;
- insulation, material and finishing of heater envelope.

The *Boiler Cycling method* gives default values for these 'envelope-losses' at test conditions with the formula [16]:

$$P'gn,env = A + B * \log Pn$$

A and B are appliance specific parameters, but the following default values are given:

Table 2-10. Value of parameters A and B (heat loss through envelope parameters) [prEN 15316-4-1, table C3]

Generator insulation type	A [-]	B [-]
Well insulated, high efficiency new generator	1,72	0,44
Well insulated and maintained	3,45	0,88
Old generator with average insulation	6,9	1,76
Old generator, poor insulation	8,36	2,2
No insulation	10,35	2,64

Whether the envelope losses are considered as 'recoverable' will depend on the position of the heater. For instance, the *Boiler Cycling method* considers 90% of the radiation losses as useful if a type C (closed system) heater (generator) is in the heated space. See table below.

Table 2-11. Default values of factor kgn,env (reduction factor for recovery of heat losses of envelope) [prEN 15316-4-1, table C4]

Generator type and location	$k_{gn,env}$ [-]
Generator installed within the heated space	0,1
Atmospheric generator installed within the heated space	0,2
Generator installed within a boiler room	0,7
Generator installed outdoors	1

Based on this *Boiler Cycling method* approach and also on the values mentioned in DIN 4702-1, default values for the envelope losses (under test conditions) in the on-mode can be varying from around 2% for the well insulated new appliances to over 14% for old not insulated generators. To calculate the losses in specific real life situations,

[16] Pn is the nominal boiler power in kW. Note that for Pn=20 kW, log Pn= 1,3. At 30 kW, log Pn=1,5

corrections will be necessary to compensate for the differences between the test- and the actual boiler room and primary water temperature. Please note that the room temperature for type B boilers will generally be lower because of the mandatory ventilation provisions.

The average figure for a new well insulated condensing boiler (at average water temperature of 70°C) is estimated at 2% and for the average new boiler at 4% (if no envelope losses are recovered). Half of this was already attributed to the burner, which is much smaller than the heat exchanger, but also much warmer. The other half we will attribute to the heat exchanger.

For an atmospheric standard boiler (or combined water heater) with poor insulation these envelope losses are around 10%.

2.6.4 Standing losses in off-mode

When the burner is switched off, the heat generator still loses heat through radiation, convection and conduction. The convection through the *chimney* attributes largely to these standing losses (most boilers have no flue-valve installed). The other part consist of the radiation, convection and conduction losses of the *boiler envelope*. These standing losses through the boiler envelope and chimney in burner off-mode depend on:

- average primary water temperature;
- average water flow;
- use of a flue valve;
- insulation, material and finishing of boiler envelope;
- use of pilot flame (not very common any more);
- For boilers, the operating time of the pump (continuously running or switched off after each burning cycle) is also important.

For water heaters, after the tap is closed, no more heat is transferred to the system. In most combis the pump stops running after closing the tap. Additional parameters that influence the standing losses are:

- heat capacity of the generator;
- operating time of the pump after burner switch off;
- tappings periods over the day;

Pump continuously running

[This section primarily applies to the heating operation of combined boilers - it is included here to show the methodology and calculations for determining the standing losses in case the heat is transferred to a system]

The standing losses with a primary pump continuously running are measured in the EN 303 standards by using an electric heater in the CH-boiler loop to keep the temperature at a pre-set level (30°C ± 50 above ambient) and are expressed in [kW]. For installations with the pump continuously running, this test figure can be used to calculate the total standing losses in real life, by correcting for the actual average boiler water temperature and actual boiler room temperature.

The *'Case specific boiler efficiency method'* of the prEN 15316-4-1:2005 proposes the following formula for correction (formula nr. 8):

$$\Phi_{\mathrm{gn,l,Po,corr}} = \Phi_{\mathrm{ge,l,Po}} \, [\, (\, T_{\mathrm{gn.w}} - T_{\mathrm{i,gn}} \,) \,/\, 30 \,]^{1{,}25} \qquad \text{[W]}$$

In which:

$\Phi_{ge,l,Po}$ = standby losses according EN 303

$T_{gn.w}$ = actual average boiler water temperature

$T_{i,gn}$ = actual boiler room temperature

The method also gives the following default values for $\Phi_{ge,l,Po}$ in annex B, Table B.1.2 in case the certified test figures for standing losses are not available:

Default stand-by heat losses can be calculated with:

$$\Phi_{gn,l,Po} = \Phi_{Pn} * (E + F \bullet \log \Phi_{Pn}) \qquad \text{[W] (formula B3)}$$

With values of E and F given in the following table.

Table 2-12. Parameters for calculation of stand-by heat losses. [prEN 15316-4-1, table B2]

Generator type	E	F
Standard boiler	25	-8
LT boiler	17,5	-5,5
Condensing boiler	17,5	-5,5

A 24 kW condensing or LT-boiler would have default standing losses of 238 watts; a standard boiler would have 335 watts. To calculate the total real life standing losses per year we would need to correct for the actual average boiler temperature and actual boiler room temperature and then multiply this figure with the operating time of the pump (while burner is off). If average boiler- and room- temperature are identical to test conditions (no corrections necessary) and the additional operating time of the pump is 2/3 of the heating period of 5200 hours, the yearly default standing losses for a condensing 24 kW boiler are:

238 [W] x 2/3 x 5200 [h] x 3600 [s] = 2970 [MJ] or 825 [kWh] (partly recoverable when the boiler is installed in a heated space).

The *'Boiler cycling method'* calculates the *chimney* losses separately from the *envelope* losses in the burner-off mode. If they are not declared by the manufacturer, default values can be used according to annex C table C.6. The default values mentioned in this table are expressed as % of the nominal boiler load. For a 24 kW boiler with premix burner the default value is 0,2% of 24 = 48 watts. A Wall mounted gas fired boiler (24 kW) with fan and wall flue gas exhaust would have 0,4% of 24 = 96 watts.

Atmospheric boilers with long chimneys (>10 m) could go as high as *1,6% x 24* = 384 watts.

According to the '*Boiler cycling method'*, the standing losses through the boiler *envelope* in burner off-mode are the same as in boiler on-mode. As explained in the previous paragraph, the average figure for envelope losses for a new well insulated condensing boiler according to this method is estimated at 2% (480 watts for a 24 kW boiler at 70°C). At an average boiler water temperature of 50°C and a boiler room temperature of 20°C, this 2% can be corrected with the factor *[(50–20) /(70–20)] = 30/50 = 0,6*. Envelope losses will in this case be 1,2% of 24 kW or 288 watts. If we assume the boiler-off period 2/3 of the total heating period of 5200 hours, the yearly default envelope losses for a 24 kW condensing boiler would be: 2/3 x 5200 [h] x 3600 [s] x 288 [W] = 3594 [MJ] or 998 [kWh] (partly recoverable, depending on location of boiler)

A more hands-on approach for the assessment of the standing losses through boiler envelope would be to calculate the radiation and convection losses on the bases of rule of thumb formula's or to compare it with known data from comparable appliances.

Standing losses of electric storage heaters (kept at 60°C) with a volume that is comparable to that of a 24 kW wall hung or standing condensing boiler range from 65 [W] for the best appliance to 123 [W] for the worst appliance (source: Save water heaters, Task 2. Technical Analysis). Of course boilers are not continuously kept at 60°C and the insulation quality differs a lot (water heaters are generally a lot better insulated than boilers), but the figures give some indication on the order of magnitude.

A rule of thumb formula for the calculation of radiation losses is:

$$q_{rad} = A_{env} * \varepsilon_{env} * \sigma \left(T_{env.}^{\ 4} - T_{blr.}^{\ 4} \right)$$

in which

$A_{env.}$	= Surface of the envelope (appr. 2 m² for a wall-hung condensing boiler)
ε_{env}	= Emissivity factor envelope (between 0,1 en 0,9 depending on material and finishing)
σ	= Radiation constant of Stefan-Boltzmann (5,67 * 10-8 [W/m²K⁴])
T_{env}	= Average temperature of boiler enevelope (in degrees Kelvin)
$T_{blr.}$	= Average temperature boiler room (in degrees Kelvin)

With a boiler room temperature of around 15°C, a surface temperature of the envelope of 30°C, and an emissivity factor of 0,9 (white painted steel plate) the radiation according to this formula would be: 158 watts. A 40°C surface temperature of the envelope would give radiation losses of 277 watts.

For heat dissipation through natural convection of the boiler envelope the following rule of thumb formula can be used (formula of Nusselt):

$$q_{conv} = 2{,}6 * A_{env} * \left(T_{env.} - T_{blr.} \right)^{1,25}$$

Using the same temperature values and a convecting surface of 1,5 m², the calculated convection losses of a boiler envelope are approximately 115 watts. A 40°C surface temperature would result in 218 watts of convection losses.

If the conduction losses (e.g. through the wall) are neglected, the calculated total envelope losses (boiler room temperature = 15°C and surface temperature = 30°C) would add up to 273 watts.

Pump switches off 10 minutes after each burning cycle

[This section is applicable to water heating operation of combined boilers with a pump feeding a tap water heat exchanger]

In principle standing losses are lower in case the pump switches off after each burning cycle, since no heat from the system is transported to the boiler and the appliance is allowed to cool down.

In this case the heat capacity of the generator determines how much energy (heat) can be stored, and with that also how much heat can be lost. Depending on the mass of the appliance (mainly heat exchanger and water content) a (combi-)boiler can easily contain 2 to over 4 MJ of heat (40 resp. 80 kg).

The operating time of the pump after burner switch-off in water heating mode is assumed to be zero, meaning that no stored heat is transferred to the tap water.

The number of operating periods per day and the time between operating periods indirectly determine the number of complete cool-downs of the appliance.

During an operating period the radiation and convection losses depend on the average appliance temperature.

The use of a flue valve (valve that switches off the flue duct after each cycle) and the use of insulation for the generators envelope will reduce the radiation and convection losses.

Example

If we assume that a 40 kg generator experiences 10 cool down cycles during a day the annual energy loss can roughly be calculated with the following formula:

$$Q_{rad\&conv;\, p.sw} = a * d_h * c_{av} * m * \Delta T_{appl;avg}$$

In which:

$Q_{rad\&conv;\, p.sw}$: Energy losses through radiation & convection of boiler during pump off –period in [J]

a : Average number of complete cool downs per day (10)

d_h : Number of heating days per year (365 dagen)

c_{av} : Average specific heat of generator (800 [J/(kgK)])

m : mass of appliance (40 [kg])

$\Delta T_{appl;avg}$: average temperature difference between start and end of cooldown period (40 [ºC])

Filling in average values gives:

$Q_{rad\&conv;\, p.sw} = 10 * 365 * 800 * 40 * 40 = 4672$ [MJ]

The *Boiler cycling method* gives a correction on the envelope losses and the chimney losses in burner off mode, for situations in which the pump is switched off.

This correction factor can be calculated, depending on the load factor FC (which is the quotient of the generator-on time and total generator stand-by time) and an exponent 'm', that depends on the type of boiler.

For a wall mounted boiler exponent m = 0,5; for a steel boiler m = 0,4 and for a cast-iron boiler m= 0,3 (see Annex C table C.5 of prEN 15316-4-1).

The correction factor for a wall hung boiler that operates (= burner on) 1/3 of the total time is $0{,}33^{0{,}5} = 0{,}57$. If the envelope losses are 1% of nominal power when the pump is continuously running, in a situation were the pump is switched off, the losses are *1 x 0,57* = 0,57% of nominal power. For a 24 kW boiler this is 137 [W].

If we assume the boiler-off period 2/3 of the total heating period of 5200 hours, the yearly default envelope losses would be: *2/3 x 5200 [h] x 3600 [s] x 137 [W]* = 1707 [MJ] or 474 [kWh] (partly recoverable, depending on location of boiler). For water heating the tapping pattern determines the number of on-hours.

Standing losses increase as the overall standby period is longer. Losses also increase with higher boiler water temperatures. If the pump switches off after each burning cycle, the losses can be reduced with 50% or more, mainly depending on heat capacity of the boiler.

Data from real life measurements for space heating function can be taken from the *Wolfenbüttel study*. In their final report[17] the *Fachhochschule Braunschweig Wolfenbüttel* mentions that the average standing-losses of the 60 condensing boilers that were monitored correspond with a fraction of 0,468% of the input power of the boiler. In other words, a boiler of 24 kW would have 112 W standing losses as an average.

2.6.5 Start-stop losses

The graph below describes the energy profile during start-up and cool-down. It shows that –depending on the burner load and the heat capacity of the boiler— it takes some time before the heater system has reached a steady state situation. During this start-up time, as mentioned earlier, there are the most emissions of fuel and other emissions

[17] Fachhochschule Braunschweig Wolfenbüttel, Felduntersuchung: Betriebsverhalten von Heizungsanlagen mit Gas-Brennwertkesseln, April 2004

causing a fuel loss [18] that –with 40 000 cycles/year—result in some 1,5% of fuel loss. During this time the appliance is heated-up until thermal equilibrium is reached, and from that moment on the steady state efficiency (acc. EN 303) applies.

The graph also shows the so-called purge losses, which come from fan action during 'burner-off', which we will discuss hereafter.

Another issue that needs to be addressed here is the fact that energy is lost when the heat generator starts cycling. This cycling occurs when the supplied heat is higher than the primary water can dissipate and the heat generator is switched off by the boiler thermostat shortly after burner start. Steady-state efficiencies (acc. to NEN 303) are not achieved in those situations. Losses that are related to this phenomena will be further explained.

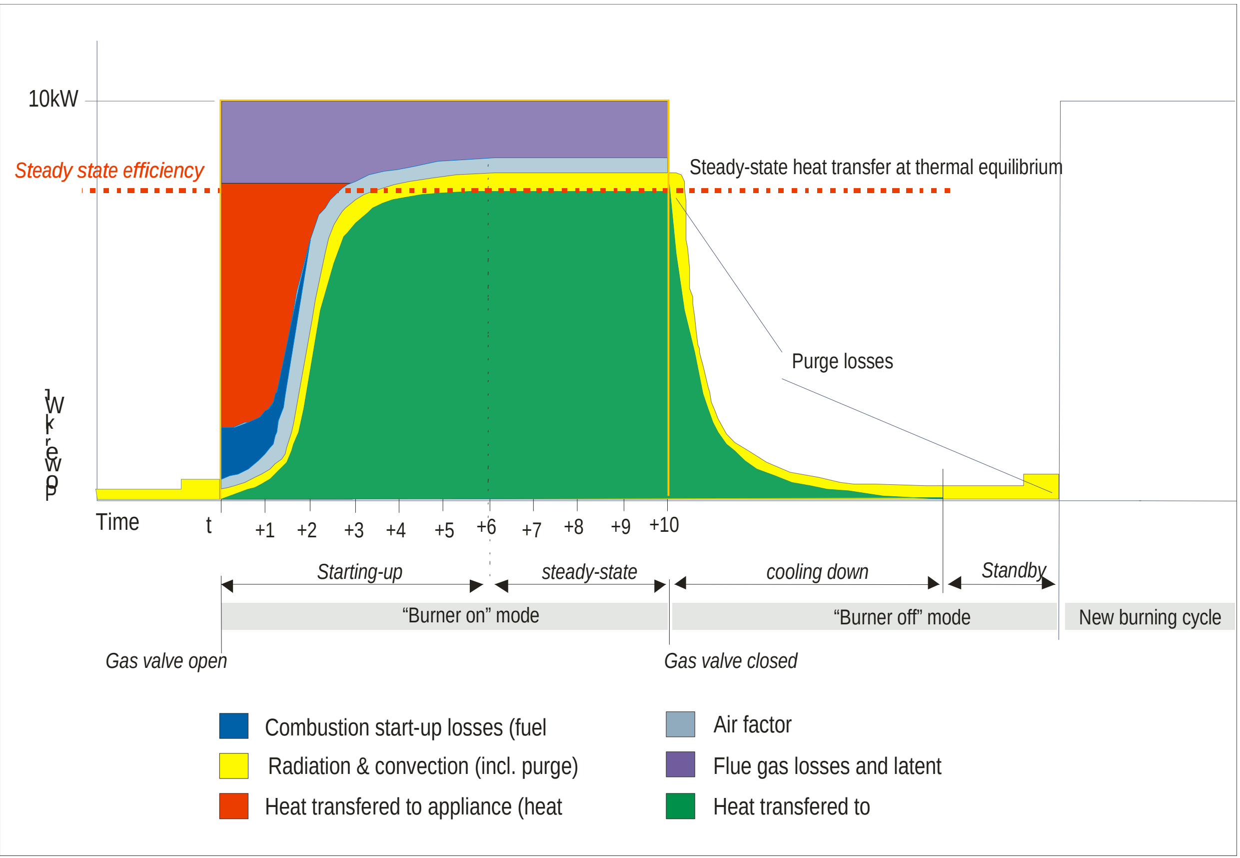


Figure 2-15. Burning cycle and energy losses of boiler

Pre-purge

For safety reasons the combustion chambers of type C boilers need to be purged before each burning cycle. This pre-purging implicates that cold (ambient) air is blown through the combustion chamber and heat exchanger and because of that heat is lost.

According to prEN 13836 a pre-purge period of 30 seconds with an airflow that corresponds to nominal heat generator load would comply.

With the following formula a rough calculation can be made off the energy losses related to these purge cycles:

$$Q_{loss;\ purge} = t_{purge;bf} * \varphi_{fan} * \rho_{air} * c_{air} * \Delta T_{air;avg}$$

---

[18] Please note that "fuel loss" does not equal methane (CH4) emissions and also note that 40.000 cycles per year is a maximum and not an average. To calculate "fuel loss" we took into account the mass balance of all emissions of carbon-compounds (CO, CH4, TOC) as found by Pfeiffer in par. 2.3.4. Marcogaz protests strongly against this value and claims that CH4 emissions from a Ruhrgas/CGB study shows values that are a factor 10 lower. We see no contradiction here, especially if the CGB tests were performed at steady state efficiency or with (Danish) boilers with a high primary store.

In which:

$Q_{loss; purge}$	:Energy losses per burning cycle caused by pre-and after purge of appliance
$t_{purge;bf}$	: pre-purge time in [s]
φ_{fan}	: air flow in [m³/s]
ρ_{air}	: density of air [kg/m³]
c_{air}	: specific heat of air [J/(kgK)]
$\Delta T_{air;avg}$	: average temperature difference of the purge air [s] before and after passing the appliance

If we assume a pre-purge time of 30 seconds, an after purge time of 10 seconds, an air flow of 24 m³/h (6,7 liters per second, e.g. for a 20 kW boiler) and an average temperature difference of the purge air of 30 °C we can make an indicative calculation:

$$Q_{loss; purge} = 30 * 0{,}0067 * 1{,}2 * 1000 * 30 = 7{,}2 \text{ [kJ]}$$

A generator with 40000 starts (heating and hot water) would loose 288 MJ-year (80 kWh).

After purge

At the end of a cycle the EN standards also prescribe an after-purge of around 10 seconds. The reason for this after-purge is safety, e.g. removing fuel from the combustion chamber. However, up to a certain degree where the flue gases are warmer than the boiler water, the after purge is also beneficial to transfer the residual heat of the burner and heat exchanger body to the boiler water. With the burner it was already calculated that this contributed up to 4%. Also with the heat exchanger, typically containing 3-5 litres of hot flue gases and with a heat exchanger surface considerably warmer than the boiler water at the time of shutting down the burner, there may be an extra gain from the after-purge. For heating operation of (combi)boilers we will not consider the heat transfer of 10 s. after-purge as losses, provided of course —as with the residual burner heat— that the extra contribution of the after purge is taken into account in the boiler control. For water heating operation the after purge are losses, assuming the water heaters is left to cool down completely, before the next tapping occurs.

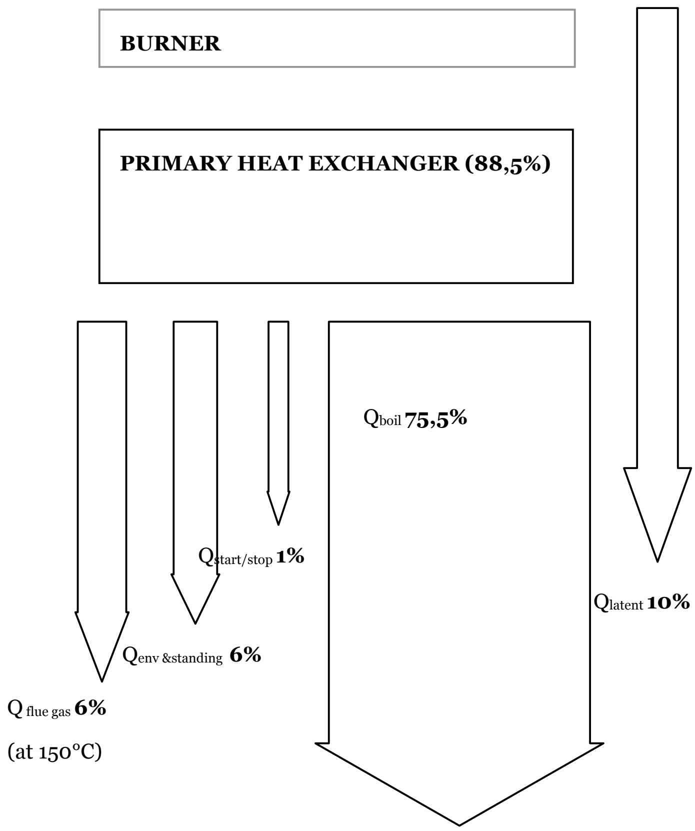
Cycling losses

A boiler starts cycling when the energy input is too high for the heat output realized by primary water flow. These situations especially occur when the water content of the heat generator is small, the minimal load of the heat generator is too high and the heat demand from system side is low. An increase isn start-stop losses can be expected for water heaters.

2.6.6 Primary heat exchanger: Flow diagram

The picture represents an energy flow diagram of the primary heat exchanger. The diagram does not make a distinction between 'burner off' or 'burner on' energy transfer, but sums the flows on an average annual basis.

Figure 2-16.
Simplified energy balance of primary heat exchanger



2.7 Heat balance secondary and tertiary heat exchanger

2.7.1 Secondary heat exchanger

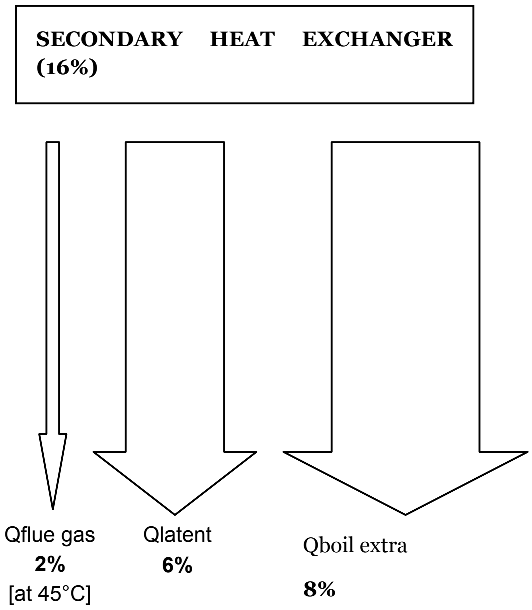
[This section applies to water heaters with condensing heat generators, e.g. condensing gas-fired storage water heaters or combined-boilers with a storagefacility that allows feeding the storage tank with lower temperatures]

In the case of condensing heat generators there is also a secondary heat exchanger. In reality, this can be as simple as an extension of the surface of the primary heat exchanger. In the case of a cylindrical burner and a spiral-tube heat exchanger (round or oval) this may really be a secondary spiral. Or in the case of a jet burner with a plate heat exchanger it may be a second plate heat exchanger. In most cases this secondary heat exchanger is a flue-gas / boiler-water heat exchanger; in some cases (some oil boilers) this can also be a flue-gas / combustions-air heat exchanger in which case it is always a separate (plate) heat exchanger.

In any case, the function of the secondary heat exchanger is to further cool the flue gases to a temperature level where most of the latent heat can be recuperated, alongside of course the remaining sensible heat in the flue gases. The EN standard and the BED foresee that this happens at a primary water return temperature of 30°C, resulting also in flue gases of the same temperature level. If that happens, some 90% of the remaining flue gas losses and of the latent heat can be recovered.

The energy flow diagram of the secondary heat exchanger, neglecting losses to the casing, will look like the picture below.

Figure 2-17.
Simplified energy balance of secundary heat exchanger



With lower average primary water temperatures (around 40°C) and longer operating periods (e.g. for storage water heating), the standing losses in off-mode will also decrease. An additional 2% can be gained compared to the values mentioned in the energy flow diagram of the primary heat exchanger

In case the secondary heat exchanger is a gas / water HE the amount of latent- and flue gas heat that can be regained strongly depends on the return water temperature. If the installation and the control systems do not facilitate low return water temperatures this energy can not fully be regained.

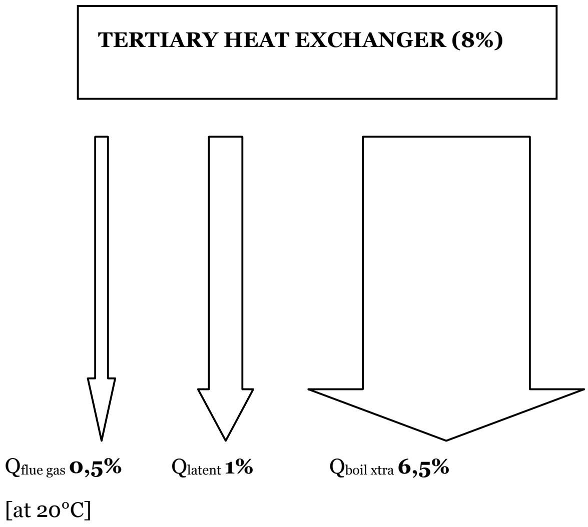
Please note that if the heat exchanging process stops here, the boiler efficiency on GCV is *75,5* + *8* + *2* = 85,5%, which is in line with the results from the Wolfenbüttel study for condensing boilers.

2.7.2 Tertiary heat exchanger

The tertiary heat exchanger is a flue gas to combustion air heat exchanger. This heat exchange can take place in the concentric flue/air duct or in a separate plate heat exchanger. For oil boilers this pre-heating is also functional at higher flue gas temperatures to preheat the incoming air in order to consequently promote the oil vaporisation process. In gas-fired boilers the heat exchange already takes place (to a small extent) through the concentric flue/air tubes, but until now a dedicated counter flow (or cross flow) flue-to-air heat exchanger was not used.

In any case, an effective counter flow tertiary heat exchanger (η=80-90%) allows recouperation of the last bit of latent heat and sensible flue gas losses. We will discuss this further in Task 6 with the design options. For now, we will just present the flow-diagram.

Figure 2-18.
Simplified energy balance of tertairy heat exchanger



Calculation of the effect of the tertiary heat exchanger in case of space heating (including an additional reduction of the standing losses with 1%) gives a total real life efficiency of around 93% on GCV for an average house with a heat load of 7250 kWh. For water heating the effect depends on the applicable tapping pattern. Indicative losses would be:

- fuel losses: 1,5%
- flue gas losses: 0,5%
- latent heat: 1%
- start/stop losses: 1%
- envelope and standing losses: 3%

Whether these envelope & standing losses should be counted as irrecoverable or not, depends on whether the heater is in the heated space. If the heater has a closed flue/air system (Type C), has the right dimensions and answers noise requirements, this type of credit could be appropriate. Furthermore, standing losses in off-mode can be further reduced by prolonging the operation periods. At the same time the fuel losses are reduced to <0,5% and start/stop will be lower (< 0,5%) losses because of the fewer burning cycles.

In any case, even without giving the credit for casing losses to the heated space, the total heater efficiency on GCV could be as high as 96-97% (105-106% on NCV). This is of course without taking into account the auxiliary electrical energy for pump, fan, controls, etc..

2.8 Heat balance with storage facilities

In the previous sections we have often assumed that the heat generator follows the heat demand, when it is needed and at the capacity that is needed (instantaneous mode). These combi boilers are designed for direct hot water delivery.

But the drawback is relatively long waiting times (thermal mass, purge times etc.) and possible cycling (plus subsequent wear of components, noise and cycling losses - see paragraph 2.6.5).

To solve these problems a storage vessel for sanitary hot water (or central heating water - with heat exchanger for tap water). In fact, the primary and/or secondary heat exchanger may already be such a storage vessel. In the Task 1 report most of the currently known configurations with a storage facility are listed and we will not repeat this here.

With proper appliance insulation, cycling losses can be reduced without increasing the envelope and standing losses too much.

However, some practical standing losses are given, to show the penalty of using storage vessels:

- 4 litre combi store: 15-20 W (insulation 30mm, 80-240 kWh/year, 1-2,5% efficiency loss).
- 80 litre at 65°C (>100 mm insulation): 55-60 W (500 kWh/year = 5% efficiency loss/ year).
- 150 litre (120mm insulation): 65-70W (600 kWh/year, 6% efficiency loss).
- 350 litre solar (110mm insulation): 100 W, 870 kWh/year (8-9% efficiency loss).

Please note that these values are already much lower (ca. factor 3) than the maximum values suggested by e.g. EN 303-6.

2.9 Auxiliary energy

Many gas- or oil-fired water heaters, especially the combined ones (combi-boilers), use electrical components for their operation. Practically all premix modulating combi-boilers use an electronic control unit, a pump (to circulate primary water through the heat exchanger), a fan and electrically powered gas valves.

Oil boilers use in addition to the above, electricity for preheating the oil and an oil pump for pressurizing or atomizing the fuel.

Gas and oil igniters also use electricity but only for a short period (10 – 35 seconds). The electricity consumption related to this will be neglected.

Table 2-13 gives an overview of the typical power consumption for the various components from the Boiler Savelec study. Please note that these values may be subject to change later in the underlying, e.g. following the preparatory study on the CH circulators.

Table 2-13. Auxiliary energy consumption (electrical) [Source: Boiler Savelec Study, WP3]

Component	Typical instantaneous power [W]	Consumption during system *off* mode	Consumption during system *on* burner *off* mode	Consumption during system *on* burner *on* mode
Pump	55 – 80	Depends on type of T control system	Yes	Yes
Fan	30 – 50	No	No	Yes
Control unit	2 - 6	Yes	Yes	Yes
Gas valve	6 - 10	No	No	Yes
Stand-by consumption	5 - 15	Yes	Yes	Yes
Oil preheat	40 - 150	No	No	Yes, during 50s. for cold start only
Oil pump / atomization	75 - 200	No	No	Yes

2.10 Total energy balance

Based on the previous paragraphs, the figures below give an illustration of the total energy balance for some characteristic heat generators in (gas-fired) water heaters (e.g. a combi-boiler).

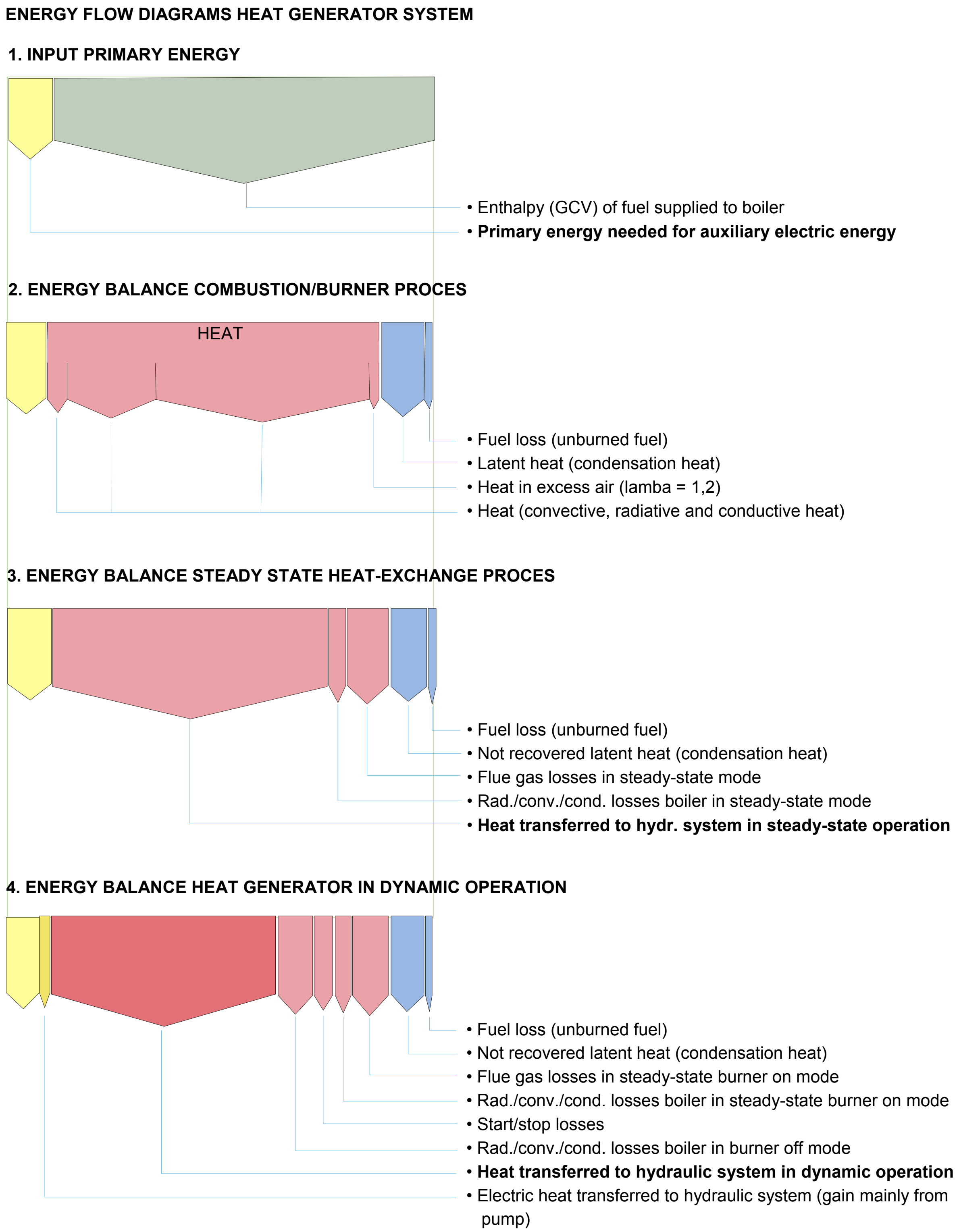


Figure 2-19. Energy flow diagrams of the heat genertator in gas-fired water heater (e.g combi-boiler)

3 EMISSIONS

3.1 Introduction

Emissions of air pollutants from the combustion process in gas- and oil-fired CH boilers and water heaters are carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO) and methane (CH4). In oil-fired boilers or water heaters you have these emissions plus sulphur oxides (SO_x), Volatile Organic Compounds (C_xH_y) and "soot" (Particulate Matter, PM).

In the MEEUP methodology study (VHK 2005) 'default values' for the emissions per GJ of heat output were presented for a number of heat generators. An extract (excluding water and waste) is given in the table below.

Table 3-1. Use phase: Energy and emissions per GJ heat out CH boiler, (excl. Electricity for fossil fuel based heating) [VHK 2006, based on Öko-institut GEWIS database]

	HEATING	Energy	Emissions: To Air						To Water	
		primary	GWP	AP	VOC	POP	PAH & HM	PM	HM	EUP
nr.		MJ	kg	g	mg	i-Teq	mg	g	mg	g
66	Electric, η 96%, per GJ	3045	132,9	784	1147	20	180	17	6	0,1
68	Gas, η 86%, atmospheric	1163	64,3	19	846	0	0	0	0	0
69	Gas, η 90%, atmosph.	1111	61,4	18	809	0	0	0	0	0
70	Gas, η 101%, condens.	990	54,7	16	721	0	0	0	0	0
71	Gas, η 103%, condens.	971	53,7	16	706	0	0	0	0	0
72	Oil, η 85%, atmosph.	1176	87,8	110	1519	0	0	2	0	0
73	Oil, η 95%, condens.	1053	78,5	98	1360	0	0	2	0	0
78	Extra for fossil fuel extraction & transport: Gas +7% (row 68-73), Oil +10% (row 72-73), for Wood pellets and logs add 5% of row 72									

Please note that all efficiency values are given in NCV

Data for fossil-fuel fired boilers were taken from GEMIS 4.2 for fossil fuel powered 10 kW Central heating (CH) boilers in GJ heat produced at the heat generator exit. These data are assumed to apply to water heaters as well (GJ heat produced at tap water outlet). They do not include the auxiliary electricity consumption for pump, fan and controls. The table below gives some details for the specific operating conditions [19].

Table 3-2. Boiler operating conditions (GEWIS 4.2)

	Gas CH				Oil CH	
Row nr.	**68**	**69**	**70**	**71**	**72**	**73**
% O_2	3%				3%	
% CO_2 in flue	9,96%				13,11%	
Nm³/h flue	11,7	11,2	10,0	9,8	12,2	10,9

[19] The tables are from GEMIS 4.2. More recent information on emissions from oil- and gas-fired appliances are found in the updated GEMIS 4.3 software packagein which emission values for GWP and AP are considerably more favourable than in GEMIS version 4.2 (information supplied to VHK by Eurofuel).

VHK has taken this into account in its final recommendation (Task 7), but for the underlying study we used the MEEuP values, as of contract.

In this chapter we will not discuss the emissions from electricity production because their composition cannot be influenced by an (electric) boiler designer. The ‘only’ problem he or she has to face is to use the electric kWh as efficiently as possible.

First we will look at the environmental impacts of oil- and gasfired boilers and water heaters following the MEEUP methodology and expanding on that. Subsequently, we will look at the emissions from the angle of their origin and some basic design measures. Next the focus is on two most interesting groups from the design point of view: The non-CO_2 hydrocarbon emissions (CO, CH4, C_xH_y, soot) and especially the nitrogen oxides (NO_x). Finally, it is examined where the contrast and the similarities between energy-efficient and environmentally-friendly design of boilers lies.

3.2 Environmental impact

When looking at the combustion emissions from the angle of their relative environmental impact. there are a number of categories.

Global Warming Potential (GWP). These include CO_2, CO and CH_4 emissions. Legal basis is the Kyoto protocol[20] and the weighting factors for the GWP-100 are prescribed by the Intergovernmental Panel on Climate Change (IPCC). The unit of GWP-100 is CO_2-equivalent (CO_2=1). Carbon monoxide has –per weight unit— a CO_2-equivalent of 1,57. Methane (CH_4) has a significantly higher GWP at CH_4=21.

Acidification Potential (AP). These include SO_x and NO_x emissions. The policy framework for regulating acidification consists of several European Community directives and the so-called Gothenburg Protocol[21]. This protocol considers SO2 to be 50% more harmful in terms of acidifaction than NO_x (weighting factor 1 versus 0,7 respectively. This relationship is also reflected in the emission limit values of the 1999/30/EC daughter directive of the Ambient Air Quality Directive (AAQD)[22]. The AAQD is an interesting framework directive, because the collection of –so far— 4 daughter directives show the relative importance that the legislator gives to very different types of emissions, which are all assessed in a similar (grid-based) method.

From this comparison (see table 3) it is clear that the legislator thinks **NO_x some 50 times more harmful than CO-emissions** from the viewpoint of ambient air quality. This is very significant, because up till now the boiler and (gas/oil-fired) water heater sector has mostly treated the emission limits for CO as equivalent to NO_x (see Task 1 report). This is not in line with EU environmental policy. If the sector —and the governments in Member States—have treated CO equally stringent this must be due to other reasons, e.g. historical safety reasons when boilers and water heaters were not room sealed and CO-poisoning was a real danger with open (not room-sealed) units.

Table 3-3. Target/Limit values in EC Ambient Air Quality directives (VHK, MEEUP, 2006)

Pollutant	Target/ limit values* in ng/m³	EC Air Quality directive
Benzo(a)pyrene (as a measure for polycyclic aromatics PAHs)	**1**	2004/107/EC
Cadmium (Cd)	**5**	2004/107/EC
Arsenic (As)	**6**	2004/107/EC
Nickel (Ni)	**20**	2004/107/EC
Lead (Pb)	**500**	1999/30/EC
Particulate Matter (PM10)**	**50 000**	1999/30/EC

[20] Council Decision 2002/358/CE of 25 April 2002 concerning the approval on behalf of the European Community of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCC) and agreed upon by the Conference of the Parties at its third session.

[21] The United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP).

[22] Another piece of EU legislation that is relevant is the National Emissions Ceiling Directive (NECD, 2001).

Sulphur dioxide (SO_2)***	**125 000**	1999/30/EC
Nitrogen dioxide (NO_2)***	**200 000**	1999/30/EC
Ground-level ozone****	**120 000**	2002/3/EC
Benzene (aromatic HC, C_6H_6)	**5 000**	2000/69/EC
Carbon monoxide (CO)	**10 000 000**	2000/69/EC

sources:

DIRECTIVE 2004/107/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and poly-cyclic aromatic hydrocarbons in ambient air.

DIRECTIVE 1999/30/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air.

DIRECTIVE 2000/69/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 November 2000 relating to limit values for benzene and carbon monoxide in ambient air.

DIRECTIVE 2002/3/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 12 February 2002 relating to ozone in ambient air.

notes:

* For directive 2004/107/EC these are "target values" for the total content in the PM10 fraction averaged over a calendar year. For directive 1999/30/EC these are 24-h "limit values" for human health.

** Particulate Matter is a separate impact category/ indicator in our methodology

*** SO_2 and NO_2 are included in the separate category of acidifying agents with more or less the same relative weighting factor (1 vs. 0,7 for eco-toxicity, 1 vs. 0,62 here)

**** Ground-level ozone is not a direct anthropogenic emission but the result of a photochemical reaction (see text)

Volatile Organic Compounds (VOC). These include the C_xH_y emissions from oil-fired boilers/water heaters. Strictly also methane (CH_4) is part of VOCs, but because the effect on the environment is different it is excluded. For this reason VOCs are often called NMVOCs (non-methane VOCs).

VOCs appear in Directive 2002/3/EC of 12 Feb. 2002 due to their role in (ground level) ozone and in Directive 1999/13/EC dealing with organic solvents. Furthermore, the European IMPEL network is monitoring fugitive NMVOCs, amongst others from combustion processes. There are no weighting factors mentioned and the MEEUP study proposes to simply make an inventory on a weight basis.

Formation of VOCs in commercial and industrial boilers (e.g. feeding separate hot water storage cylinders) primarily result from poor or incomplete combustion due to improper burner set-up and adjustment. To control VOC emissions from commercial and industrial boilers, no auxiliary equipment is needed; properly maintaining the burner/boiler package will keep VOC emissions at a minimum. Proper maintenance includes keeping the air/fuel ratio at the manufacturer's specified setting, having the proper air and fuel pressures at the burner, and maintaining the atomizing air pressure on oil burners at the correct levels. An improperly maintained boiler/burner package can result in VOC levels over 100 times the normal levels. Furthermore, as VOC emissions mainly occur at start-up and the end of a burning cycle, a very important measure is a reduction of the number of cycles.

Heavy Metals (Toxicity). Although not a Heavy Metal, the MEEUP classifies CO as a toxic agent, albeit –as an outdoor emission—with a very low weighting factor. Carbon monoxide is a pollutant that is readily absorbed in the body and can impair the oxygen-carrying capacity of the hemoglobin. Impairment of the body's hemoglobin results in less oxygen to the brain, heart, and tissues. Even short-term over exposure to carbon monoxide can be critical, or fatal, to people with heart and lung diseases. It may also cause headaches and dizziness in healthy people.

Particulate Matter (PM). This refers to 'soot' from oil-fired boilers/water heaters. Emission limit values are mentioned in Directive 1999/30/EC, which indicate that the European legislator takes PM 10-emissions very serious indeed (see table 4). In fact, the emission limits on a weight basis are 4 times more stringent than the ones for NO_x.

PM emissions are primarily dependent on the grade of fuel fired in the boiler/water heater. Generally, PM levels from natural gas are significantly lower than those of oils. Distillate oils result in much lower particulate emissions than residual oils.

When burning heavy oils, particulate levels mainly depend on four fuel constituents: sulfur, ash, carbon residue, and asphalenes. These constituents exist in fuel oils, particularly residual oils, and have a major effect on particulate emissions. By knowing the fuel constituent levels, the particulate emissions for the oil can be estimated.

Methods of particulate control vary for different types and sizes of boilers/water heaters. For utility boilers, electrostatic precipitators, scrubbers, and baghouses are commonly utilized. For industrial and commercial boilers, the most effective method is to utilize clean fuels. The emission levels of particulate matter can be lowered by switching from a residual to a distillate oil or by switching from a distillate oil to a natural gas. Additionally, through proper burner set-up, adjustment and maintenance, particulate emissions can be minimized, but not to the extent accomplished by switching fuels.

The above refers to emissions to air. To complete the picture it must be mentioned that in some regions of the EU there are strict regulations regarding the emissions to water, which –when using heating oil with a higher sulphur content—can apply to affluent of condensate to the sewer.

3.3 Emissions grouped by origin

Taking the angle of their origin, the emissions from gas-and oil-fired boilers can be split into four groups:

Unavoidable products from the combustion reaction. As already explained in the previous chapter water vapour and carbon dioxide (CO_2) are the main combustion products from the reaction between a hydrocarbon and oxygen. The CO_2 production is completely linked with a) the specific fuel and b) the energy efficiency of combustion. Regarding the fuel the CO_2 emissions per MJ gas are 20-30% lower[23] than with oil. Regarding the efficiency, it depends very much on the design. At best the oil-fired heat generators in the top-end of the market can keep up (but not surpass) the best gas-fired heat generators.

Pollutants that are unavoidable because they are already contained in the fuel. This is the case with SO_x production from sulphur. In principle, without end-of-pipe measures, the sulphur emissions are independent of the design of the combustion process. If we use heavy fuel oil with 3% sulphur, this amount will also result from the combustion process. If we use low-sulphur (<50 ppm) gas heating oil the corresponding lower amount will result. The only design-measure that a boiler designer can take is to make sure that the boiler/water heater (also) works with low-sulphur oil, but it is the user —or the regulations on the sulphur content of heating oil in a particular country— that will determine the outcome.

Emissions that are a consequence of incomplete combustion. Basically, these are all other carbon-containing compounds, besides CO_2: Carbon monoxide (CO), Methane (CH_4), hydrocarbons (C_xH_y) and soot (PM). The carbon in these compounds comes from the fuel and is an indicator of how much fuel was subject to incomplete combustion. The most well known cause of this is the lack of sufficient air/oxygen. But there may be other causes, such as the temperature of the fuel is too low to permit oxidation (combustion) to occur. It can occur as a result of flame impingement (flame in contact with metal) because parts of the flame are cooled—quenched—below the burn temperature of the fuel. For instance, on a gas range burner, flame impingement always occurs when a pot is on a burner. As the pot becomes hotter, the carbon monoxide production decreases because the flame is not cooled as much by the impingement. This

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[23] Eurogas mentions a figure of 24%, citing the International Gas Union. The MEEUP table shows even higher differences (>30%) for comparable boilers.

makes measurement of carbon monoxide difficult; as impingement surfaces change temperature, the carbon monoxide emissions change. Quenching of a flame can also occur if air blows across a flame rapidly enough to cool it to below its burn temperature. A rule of thumb is that –in order to keep the CO-emissions low—the combustion temperature should be well above 900°C. Finally, the most obvious cause of non-CO_2 carbon emissions is during start- and stop of combustion, i.e. when unburned fuel remains in the combustion chamber. This causes of course a considerable amount of unburned fuel emissions (CH_4 or C_xH_y), but also gives peaks in CO-emissions as the circumstances at start-up (cold heat exchanger) are so favourable for CO-formation. As mentioned in chapter 2, 80-90% of the non-CO_2 carbon emissions occur not during steady-state but during start-up and stop.

Emissions that do not involve the fuel, but are chemical reactions between air molecules triggered by the specific combustion conditions. This relates to emissions of nitrogen oxides (NO_x), NO and NO_2, from the reaction between the oxygen and nitrogen molecules in the air. This occurs only when there is enough air around (excess air, e.g. air factor > 1,4), when the temperature is high enough (above 1200°C) and when there is enough time for the reaction to take place at this high temperature (the so-called 'residence time' should be long enough).

Basically the above is about all there is to tell about the amount of CO_2 and SO_x emissions (point 1 and 2). Once the fuel is chosen[24], the amount of SO_x and CO_2 emissions follow directly from the fuel input per functional unit.

We will now expand on the points 3 and 4 mentioned above.

3.4 Low non-CO_2 Carbon Emission

3.4.1 Formation

The ***global*** chemical reaction just shows the **results** of what in reality is a complex series of simultaneous and consecutive chemical reactions. The picture below gives an impression of that complexity during methane combustion, whereby the molecules are first dissociated into smaller fractions before entering the chain reactions and finally the end-stage.

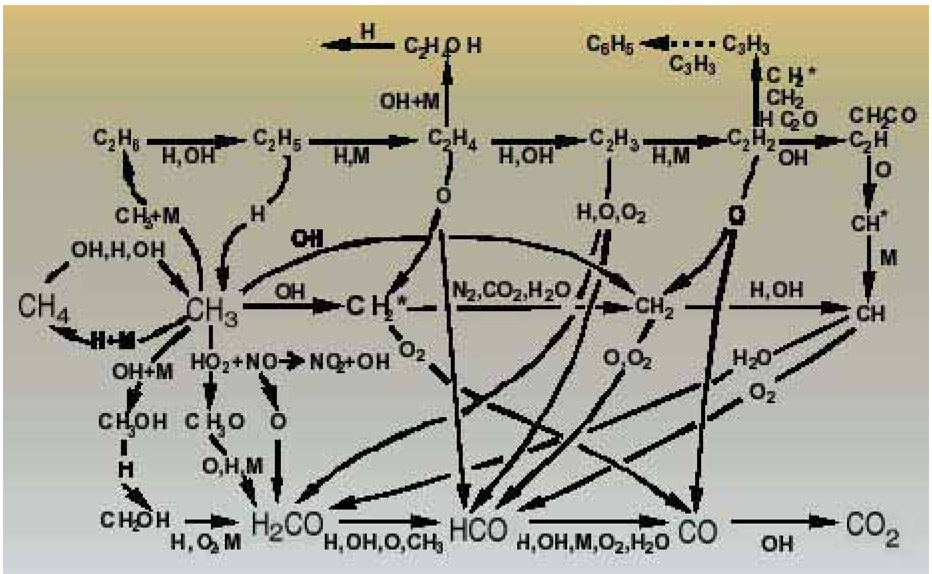

Figure 3-1.
Possible reactions during methane combustion (for natural gas) (Farago)

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24 And a minute amount is subtracted for unburned fuel (<1,5%, see Chapter 2)

The picture shows the steps in the methane combustion. From left to right it presents the oxidisation steps whereby hydrogen (H) is split off. From top to bottom it represents the oxidisation through taking up oxygen and splitting larger hydrocarbon molecules into smaller parts. In a ‘rich combustion’ (air factor < 1) the reactions predominantly follow the steps in the upper lines. In a ‘lean combustion’ (air factor >1) the reactions predominantly follow the steps in the lower lines of the picture. In the lower line the intermediate products are formaldehyde (H_2CO) and aldehyde (HCO) before arriving at carbon monoxide (CO) and finally carbon dioxide (CO_2). In the upper line acetylene (C_2H_2) is the most important intermediate product.

From this it will also be clear that in case of imperfect combustion CO is a combustion by-product. In case of rich combustion there will be a high C_2H_2 – concentration, which increases the tendency for soot-formation. In case of lean combustion there is a concentration of H_2CO, which reduces the formation of soot, but favours the formation of aldehyde.

3.5 Low NO_x technology

[This is a non-applience specific text: Where the text states 'boilers' one may read this as 'water heaters' as well]

3.5.1 Introduction

In the discussions of nitrogen oxide combustion products and their impact to environment, the major nitrogen oxide species of concern are nitric oxide (NO) and nitrogen dioxide (NO2).

Under high temperature combustion conditions, the formation of NO is favoured and consequently, less than 10% of the NO_x in typical exhaust is in the form of NO2 (Pereira and Amiridis, 1995). However, a higher percentage of NO_x in the form of NO2 has been experienced in domestic applications. NO when it cools down in the atmosphere combines with oxygen in air to form NO2 (Eqn. 1).

$$2NO+O_2 \leftrightarrows 2NO_2 \qquad [Eqn. 1]$$

In warm, sunny days the NO2 breaks down into NO and a nascent oxygen atom (Eqn. 2) which can combine with a molecule of oxygen to form ozone (Eqn. 3). The ozone reacts with NO to yield back NO2 almost as fast as it is formed.

$$NO_2 \leftrightarrows NO + O \qquad [Eqn. 2]$$

$$O + O_2 \leftrightarrows O_3 \qquad [Eqn. 3]$$

When volatile organic compounds (VOC) exist in the air, they combine with the NO in the present of sunlight to change it back to NO2. Less NO is then available to remove the nascent oxygen, and hence ozone accumulates, resulting in photochemical smog.

The term low NO_x technology used in the industry has a broad range in terms of the NO_x emission level achieved. In some instances, an emission of 70 - 80 ppm at 0% O_2 on dry basis is regarded as "low". In other instances, it may be down to 10 - 15 ppm or less. In the EU the threshold level of <40 ppm (70 mg/kWh) seems the most appropriate, being used in the German Blue Angel labelling scheme and the Dutch ‘Low- NO_x’ label and it is the lowest class limit (class 5) in the European Standard prEN 267.

Conversions:
Europe: 1 ppm (at 3% O_2) = 1,83 mg/kWh = 0,508 mg/MJ = 0,508 ng/J.
US: 100 ppm (at 3% O_2) = 0,118 lb/MMBtU (1 lb= 0,4535 kg; 1 Btu= 1,0546 kJ) = 183 mg/kWh.
ppm (at 3% O_2) = (21-3)/(21 – O_2 actual) ppm actual.
1 ppm (at 3% O_2) = 18/21= 0,857 ppm (at 0% O2).

This section is based on a study for the Australian government by environmental consultant Bob Joynt and combustion engineer Stephen Wu, which gives a good overview of the subject, also mentioning technology not strictly from a European angle.

3.5.2 Formation of NO_x

NO_x formed during combustion is the predominant source of NO_x to atmosphere. The source may be mobile or stationary, cars or boilers. NO_x consists of NO and NO2. For the convenience of discussion on a theoretical basis, only NO is discussed in this section.

NO can be categorised into the following:

- Thermal NO;
- Fuel NO;
- Prompt NO.

For gas combustion burners such as Bunsen burners and flat flame burners which have a high flame temperature (> 1550°C), the NO formed is predominantly thermal NO, with a small fraction as prompt NO.

Thermal NO

Thermal NO is found mainly in the high-temperature post-flame zone. It is formed by the oxidation of molecular nitrogen in combustion air and fuel gases by the extended Zeldovich mechanism:

$$O + N_2 \leftrightarrows NO + N \qquad \text{[Eqn. 4]}$$

$$N + O_2 \leftrightarrows NO + O \qquad \text{[Eqn. 5]}$$

$$N + OH \leftrightarrows NO + H \qquad \text{[Eqn. 6]}$$

where the nascent oxygen atom in Eqn. 4 is formed (with a large activation energy) from the H_2-O_2 radical pool or possibly from the dissociation of O_2 (Glassman, 1996).

The hydroxyl (OH) radical in Eqn. 6 may come from the following reaction, which obtains the hydrogen atom from the dissociation of hydrocarbon fuel:

$$H + O_2 \leftrightarrows OH + O$$

Eqn. 4 is rate-determining. To reduce thermal NO formation, O (nascent oxygen atom) must be reduced. The formation of O, and hence thermal NO, is more dependent on the combustion temperature and less dependent on the oxygen concentration. It increases with temperature. For combustion systems like those obtained on Bunsen and flat flame burners, the temperature, and hence the mixture ratio, is the prime parameter in determining the quantities of thermal NO formed.

Fuel NO

Fuel NO is formed by the oxidation of nitrogen chemically bound in fuel. In the production of natural gas and liquid petroleum gas, combustible gaseous nitrogen compounds such as ammonia and amines have been removed to insignificant levels and little or no fuel NO would be formed.

Prompt NO

Prompt NO is most frequently observed in fuel-rich flames and at low temperatures, and its formation is found to be relatively independent of temperature. There are three possible sources of prompt NO (Glassman, 1996):

Non-equilibrium nascent oxygen (O) and hydroxyl (OH) radical concentrations in the reaction zone and burnt gas, which accelerate the rate of thermal NO (Zeldovich) mechanism.

A reaction sequence initiated by reactions of hydrocarbon radicals, present in and near the reaction zone, with molecular nitrogen (Fenimore prompt NO mechanism):

$$CH + N_2 \leftrightarrows HCN + N \qquad [Eqn.\ 8]$$

$$C_2 + N_2 \leftrightarrows 2\ CN \qquad [Eqn.\ 9]$$

The nascent N atom can yield NO by reactions such as Eqn. 5 and Eqn. 6, and CN can form NO with a nascent oxygen atom or oxygen molecule.

Reaction of nascent oxygen (O) with molecular nitrogen to form nitrous oxide (N_2O) via the three-body recombination reaction (Eqn. 10) and the subsequent reaction (Eqn. 11) to form NO:

$$O + N_2 + M \rightarrow N_2O + M \qquad [Eqn.\ 10]$$

$$N_2O + O \rightarrow NO + O_2 \qquad [Eqn.\ 11]$$

The non-equilibrium O and OH concentration mechanism is more important for non-pre-mixed flames, stirred reactors for lean conditions, or low pressure premixed flames.

The Fenimore prompt NO mechanism is dominant in fuel-rich pre-mixed hydrocarbon combustion.

The nitrous oxide mechanism becomes more important when the fuel-air ratio decreases, when the burnt gas temperature decreases, or when the pressure increases.

At common combustion temperatures, increase in aeration can reduce prompt NO formation.

Formation of NO_2

Despite the favoured formation of NO dictated by thermodynamics and reaction kinetics, high concentrations of NO_2 have been experienced in domestic applications, e.g., Glassman (1996) cited that high concentrations of NO_2 were reported in the exhaust of range-top burners.

It was observed that NO_2 was formed by HO_2 and NO in the low-temperature regime of visible flames (Eqn. 12) and suggested that the conversion of NO_2 to NO and oxygen in the near-post-flame zone (as given by Eqn. 11) was quenched.

$$NO + HO_2 \rightarrow\ \ \hookleftarrow O_2 + OH \qquad [Eqn.\ 12]$$

3.6 Principles of Primary Control of NO_x Emissions

[This is a non-applience specific text: Where the text states 'boilers' one may read this as 'water heaters' as well]

NO_x control may be:

- Primary - to reduce NO_x formation.
- Secondary - to remove NO_x formed.

There are three basic principles of primary NO_x control to reduce NO_x formation:

- Reduction of high combustion/flame temperature since more NO_x will be formed at higher temperatures under thermodynamic equilibrium conditions.
- Reduction of residence time at high combustion temperature to resist the NO_x formation approaches thermodynamic equilibrium concentration.
- Reduction of oxygen concentration and hence the nascent oxygen concentration in the high temperature zone.

It is possible to quench the NO_x reactions, obtain the chemical heat release and prevent NO_x formation (non-equilibrium Zeldovich mechanism) but in practice efficiency often suffers if quenching is done by adding a non-reacting mass such as water or steam to the system.

Any acceptable NO_x control technology should reduce NO_x emissions, at the same time maintain or decrease CO and formaldehyde emissions, and maintain or increase thermal efficiency.

The primary NO_x control technologies involve either or both of the following:

- Modification of fuel/air delivery-burner system.
- Modification of gas burner.

3.6.1 Modification of Fuel/Air Delivery-Burner System

The strategies to modify fuel/air delivery-burner systems can be summarized as follows:

- Increasing the primary pre-mixed air from ~ 50% to more than 100%
- Low excess air (LEA) firing
- Flue gas recirculation (FGR). Recirculating combustion exhaust gases into primary combustion air.
- Staging combustion into more than one discrete step, with heat extracted between steps.
- Delaying, distributing, or dispersing fuel/air mixing within the combustion chamber.
- Humidifying fuel gas, combustion air, or the flame.

Increasing the Primary Premixed Air

This measure applies to an atmospheric (partial pre-mix) burner, which uses both primary ('pre-mix') and secondary air. NO_x emissions from blue flames could be reduced from ~ 100 ppm to < 70 ppm (oxygen (O_2) free) by increasing the primary air from ~ 50% to ~150% of the stoichiometric air required.

Effectively any excess air above 100% stoichiometric dilutes the combustion exhaust and brings down the combustion temperature from a maximum of ~ 1900°C to ~ 1200°C, causing less NO_x to be formed.

Lower combustion temperature would result in longer combustion time at high temperature because of slower burning rate. This would encourage NO_x formation, but this effect was observed to be secondary and a net decrease in NO_x emission would result.

Means to increase the primary air flow to ~ 50% excess are a very large venturi, a fan and higher gas- or air-line pressure. In the EU boilers, the use of fans in a *full pre-mix* burner is the most common measure.

In Japan (Tokyo Gas, Rinnai) and US (Burnham, Gas Research Institute) one would find new designs of aspiration such as alternating burner ports fire with primary air < 100% in one port and up to ~ 85% excess air in the adjacent ports to achieve ~ 70 ppm. Also there are new burner design to accelerate the velocity of the burning pre-mixture and shorten the residence time besides reducing combustion temperature, with a hemispherical bluff body re-stabilises the flame.

Burners designed for excess primary aeration would have deeper ports and thicker walls than the usual stamped metal burners. Secondary aeration would not be required and could be eliminated by closed combustion chamber or baffles.

Low Excess Air (LEA) Firing

As a safety factor to assure complete combustion, boilers are fired with excess air. One of the factors influencing NO_x formation in a boiler is the excess air levels. High excess air levels (>45%) may result in increased NO_x formation because the excess nitrogen and oxygen in the combustion air entering the flame will combine to form thermal NO_x.

Low excess air firing involves limiting the amount of excess air that is entering the combustion process in order to limit the amount of extra nitrogen and oxygen that enters the flame. Limiting the amount of excess air entering a flame is accomplished through burner design and can be optimized through the use of oxygen trim controls. Low excess air firing can be used on most boilers and generally results in overall NO_x reductions of 5-10% when firing natural gas.

Recirculating Combustion Exhaust Gases

Recirculation of flue gases could be achieved by:

- Buoyancy
- Aspiration
- Fan

The cooled combustion exhaust gases (mainly molecular nitrogen and oxygen, carbon dioxide and water vapour) are mixed with air entering the burner. The recirculated gases dilute the primary air and lowers the oxygen concentration of the air mixture from ~ 21% by volume to ~ 18%. Consequently the flame temperature is lowered. Research on larger scale applications has demonstrated that NO_x could be reduced by ~ 75% when the primary air contains ~ 30% recirculated flue gas.

Ducting of the exhaust gases to the fuel/air delivery system would be required. The combustion chamber and heat exchanger of the appliance may become larger to accommodate the higher total gas flow rate and lower flame temperature to maintain baseline thermal efficiency. The burner may have to be upgraded to light and stabilise the fuel-air-exhaust mixture which is more difficult to ignite and slower in combustion, although the warm mixture (if the exhaust gases are mixed at a few hundred degrees C) would alleviate this to some extent. Another concern is that lower flame temperature and oxygen concentration would favour CO formation.

Raghavan and Reuther (1994) pointed out that recirculation of combustion exhaust gases had been used at industrial scale to reduce NO_x emission but not in domestic application, which is still true. Because of the high NO_x reduction potential, they felt that domestic application of this strategy should be explored further. Recirculation often requires a fan driven system that may have to work at elevated temperatures and this would increase the cost of the appliance and its operation.

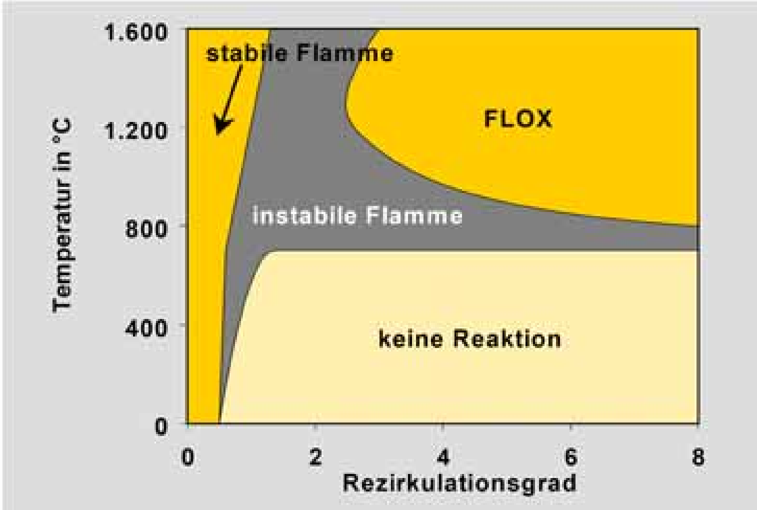
US industrial boiler manufacturer Cleaver Brooks identifies flue gas recirculation (FGR) as the most effective and popular technology for industrial boilers. And, in many applications, it does not require any additional reduction equipment to comply with regulations.

Flue gas recirculation technology can be classified into two types; external or induced.

- **External flue gas recirculation** utilizes an external fan to recirculate the flue gases back into the flame. External piping routes the exhaust gases from the stack to the burner. A valve controls the recirculation rate, based on boiler input.
- **Induced flue gas recirculation** utilizes the combustion air fan to recirculate the flue gases back into the flame. A portion of the flue gases are routed by duct work or internally to the combustion air fan, where they are premixed with the combustion air and introduced into the flame through the burner. New designs of induced FGR that utilize an integral FGR design are becoming popular among boiler owners and operators because of their uncomplicated design and reliability.

Up to a re-circulation ratio of 1, this can be done with conventional flames. Above this ratio of 1, the temperature of the burner/ combustion chamber have to be involved in the process to keep the temperature level above ignition temperature. Between a ratio of 1 to 3,5 it is not possible to realize the combustion process, but at the re-circulation ratio's of 3,5 and higher there is a flameless combustion reaction in a large surface. This flameless combustion process is known as ***FLOX*** (Flameless Oxidisation). The temperature and re-circulation rates are shown in the picture below (see also Chapter on Burners).

Figure 3-2.
Recirculation-rate of FLOX burners



The FLOX technology has been used in industrial burners, but now –through a new collaboration between DLR and WS Wärmeprozesstechnik— will be further developed for gas turbines. [25]

FLOX technology can be combined with the staged combustion (see below and Chapter on burners).

Staging Combustion

Staged combustion can be conducted in two stages, the first is the fuel-rich combustion with < 100% primary aeration and the second is fuel-lean, with inter-stage cooling such as radiant heat loss from a radiant burner, or heat exchange with air or water. In principle, more stages can be used but the design, manufacture and operation will be more complicated and more expensive.

Staging can be achieved by modifying the gas burner or the combustion chamber, or both. The flame temperature at the two stages is lower than the dual flame combustion using the same overall (primary plus secondary) aeration. In a combined approach for a fan-assisted space heater prototype with a radiant burner, a reduction of NO_x emission by ~75% was reported (Raghavan and Reuther, 1994).

Design and manufacture of staged combustion gas appliances are more complicated and expensive. Many of the components such as channels, flame holder, ignition system, combustion chamber and heat exchanger may have to be increased in number or in physical size. This will increase the manufacturing cost of the appliance.

In principle, staged combustion can be performed with stable flame without fan assistance, but the problem of increased CO emission and decreased thermal efficiency must be addressed together with NO_x reduction.

In the US staged combustion techniques are applied in residential low NO_x burners. Reportedly the US Gas Research Institute (GRI) co-developed boilers and furnaces with staged combustion and internal flue gas recirculation with US manufacturers Burnham, Empire Comfort and Trane, reaching a low NO_x level of 25-29 ppm at 3% O2 and CO was found to be less than 50 ppm air-free.

In Europe the use of staged combustion is primarily limited to industrial and commercial boilers.

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[25] Press release, Deutsches Zentrum für Luft und Raumfahrt, *Neuer Brenner verspricht Stickoxidarme Verbrennung –*

DLR und WS Wärmeprozesstechnik schließen Vermarktungsvertrag, 10. November 2005.

Delaying Combustion

Different from staged combustion, delaying combustion allows the combustion process to occur continuously rather than at discrete stages, over lower temperatures, to retard NO_x formation. This is achieved by dispersion, with slower heat release, over larger volumes and time.

Raghavan and Reuther (1994) cited from the literature four examples of burner design to delay combustion, with one suitable for air heaters and the other for water heaters. They recognised that although this approach was effective to lower NO_x emissions (by up to ~75%) and amenable to a variety of atmospheric or powered burners, the development had been limited, which could be related to higher CO emissions and lower efficiency. The fuel/air delivery might need to be pressurised, the burner, combustion chamber and heat exchanger might need enlargement, and the ignition system might require improvement.

In the EU no examples of delayed-combustion technology were found, probably due to the drawbacks mentioned.

Humidifying the Fuel Gas, Combustion Air or Flame

Humidification can be conducted by:

- Spraying water to the combustion air.
- Spraying water to the combustion chamber.
- Spraying steam to the combustion air or fuel gas.
- Spraying steam to the combustion chamber.

Steam dilutes the combustion exhaust in the same way as recirculated combustion exhaust gases. The effect of water is two fold: water evaporates by absorbing a large quantity of heat (latent heat of evaporation) from the combustion system and the steam evolved dilutes the combustion exhaust gases. Both result in cooling the combustion system.

The spraying rate of water to combustion air is restricted by the ambient humidity conditions and the efficiency of water atomisation. The spraying rate of water to the combustion chamber and the spraying rate of steam would depend on flame stability.

The investigation of the humidification for domestic appliances was limited even though the NO_x reduction could be up to ~ 50 - 60% (Raghavan and Reuther, 1994). It has not been attractive probably because the efficiency of the system will decrease with humidification, unless steam in the exhaust gases is condensed and the heat extracted is recoverable. Condensation would complicate the combustion system, create corrosion problem and increase the equipment cost.

Humidification has been used in commercial scale continuous gas turbine operation but not in domestic situations. The loss of efficiency in gas turbine application is traded off with the increase in power output by the higher mass flow through the gas turbine.

Under normal operating conditions, water/steam injection can result in a 3-10% boiler efficiency loss (Cleaver- Brooks).

3.6.2 Modification of Gas Burner

Raghavan and Reuther (1994) identified the major modifications of gas burners as follows:

- Flame Inserts.
- Blue-flame burner redesign.
- Blue-flame burner replacement.

Flame Inserts

A simple means to reduce flame temperature is to insert a foreign object, such as a solid rod or porous screen, into a blue flame and allow the object to radiate red hot. As part of the heat liberated is transferred by radiation, the flame temperature is reduced and hence the NO_x emissions are reduced. The inserts could be made of refractory metals or ceramics.

Raghavan and Reuther (1994) cited five different flame inserts patented for atmospheric burners:

- A ring shaped solid insert for range or water heater burners.
- A rod shaped solid insert for furnace burners.
- A porous screen insert.
- A solid channel insert for furnaces.
- Small solid fin inserts integral with the burner but not in the flame.
- A perforated radiant insert for fan-assisted power burner was also illustrated.

From the literature search, Raghavan and Reuther indicated that most flame inserts could achieve a ~60% reduction but the CO emissions would typically increase, since the combustion conditions remain the same except at a lower temperature which favours CO formation. Adjusting the position of insert or using secondary-air baffles may alleviate CO formation. Thermal efficiency could be an issue, but it may be overcome depending on the application and design.

Compared to other NO_x control techniques, Raghavan and Reuther believed that flame inserts had the least impact on gas appliance component design. However, because of the change in heat transfer and flame shape, heat exchangers, particularly those used in space heaters, might require re-design.

Flame inserts are typical of reducing NO_x in atmospheric burners. In the US, new designs are developed by DSL Technologies and Lennox.

Blue-Flame Burner Redesign

Blue-flame burners could be redesigned either by changing the burner's thermal mass, port loading, or port design to achieve reduced NO_x emissions.

Thermal Mass

Cast iron burners are more "thermal active" than the traditional stamped steel and aluminium burners, and are found to emit less (~30%) NO_x and CO. This is achieved by dissipating more heat via their high thermal mass (and structure).

Cast iron atmospheric or power burners have been applied to ranges and water heaters to lower NO_x (down to < 70 ppm at 0% O_2 dry basis). Thermal efficiency was reported to increase slightly (Raghavan and Reuther, 1994).

Port Loading

NO_x emissions depend on port loading — the heat released per port area per time. It was reported that NO_x emissions from atmospheric blue flames could be reduced by half if the port loading was reduced by one third. Reducing port loading is achieved by increasing burner size if the same heat input rate is maintained. Thermal efficiency may increase or remain the same, but CO emissions could increase and flashback may occur.

Port Design

Port spacing determines the extent of flame aeration and interaction, which affect NO_x formation. If the heat dissipated by the ports is increased and the secondary aeration of flames is improved, NO_x emissions can be reduced.

Raghavan and Reuther (1994) described the Worgas hyperstoichiometric burner as an example. The Worgas burner uses a venturi-burner system with unique port spacing and 80 - 160% stoichiometric air requirement. The burner is larger than the traditional Bunsen type blue flame burner. It has improved secondary-air entrainment, yielding violet flames with low and uniform temperature distribution. The butterfly-wing flame shape has the aerodynamics designed to bring combustion products back to the flame.

Laboratory results indicated that the Worgas burners could achieve 40 ppm NO_x at 3% O_2, dry basis, which is equivalent to 45 ppm at 0% O_2, dry basis. Thermal efficiency is claimed to be high, and the technology can be used in boilers, instantaneous water heaters, storage water heaters, and room/air heaters.

Blue-Flame Burner Replacement

Blue flame burners have been suggested to be replaced with "flameless" burners which adopt radiant combustion, catalytic combustion, or pulse combustion.

Radiant Combustion

Radiant combustion occurs near or within burners which are either porous or ported, and may be fan-assisted. The burners can have different shapes to suit different heat exchangers. In operation, the burners glow in a red-orange colour (> 680°C).

Similar to flame inserts, radiant burners restrict NO_x formation by lowering the combustion temperature, but in a better and more complete manner. NO_x emission < 25 ppm and CO emission < 50 ppm O_2-free have been reported (Raghavan and Reuther, 1994). Facilitated with high excess aeration and reduced port loading, radiant burners could achieve < 10 ppm NO_x O_2-free. In combination with staged combustion, NO_x emissions < 10 ppm O_2-free was experienced. With proper location of heat exchangers, higher thermal efficiency can be obtained.

Radiant burners are normally larger than blue-flame burners. Modification of other components is often required. Pressurisation of the fuel/air delivery system and filtering may be required depending upon burner port size. Usually the combustion chamber is reduced but the ignition system would require upgrading. The heat exchanger would have to be relocated closer to the burner.

In the US Alzeta Corp[26] and Global Environmental Solutions are manuafacturers. In Australia Bowin[27] has developed a patented technology in this respect.

Pre-mix radiation burners are the state-of-the-art in the EU. For instance burner-manufacturer Bekaert in Belgium produces metal fibre burners for premixed gas surface combustion, developed by Acotech[28]. They can be operated in either radiant combustion mode or blue flame surface combustion mode. In the former mode NO_x emission < 10 ppm at 0% O_2 dry basis is claimed to be achieved. In the latter mode, it is claimed that low NO_x levels (30 ppm NO_x) are achieved at 30% excess air. CO emission is claimed to be < 10 ppm. Other advantages such as homogeneous combustion with high modulation rate, high efficiency, low pressure drop, resistance to thermal shock and flashback safety are also claimed. Major boiler manufacturers such as Vaillant, Viessmann and Buderus in Germany, Remeha in Holland, and Ecoflam and Baltur in

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[26] **Alzeta:** Pre-mix radiant burner with a trade name as Pyrocore/Duratherm from alumina-silica fibres fibres which are formed into either cylinders or flat plates with high porosity. This technology has been used by Alzeta's OEM partner, Nuovi Sistemi Termotecnici in Italy on domestic boilers and instantaneous water heaters

[27] Bowin mfg. Pty. Ltd (Australia) Bowin has been manufacturing a number of ultra-low NO_x flued and flueless natural aerated and powered domestic flue heaters using Bowin's patented surface combustion technology. The technology is also applicable to domestic water heaters and cooking appliances (John Joyce, personal communication).

The Bowin low NO_x technology is a hybrid of staged-premixed-radiant combustion technology with a major surface combustion preceded by a minor radiant combustion. In the Bowin burner, air and fuel gas are premixed at a ratio greater than or equal to the stoichiometric combustion requirement.

Combustion is maintained at or adjacent to a combustion surface formed from one or more layers of conductive heat resistant material such as nickel based steel mesh with uniform porosity of 20 - 60% (Australian Patent Document Number: AU-B-64743/90). The porosity provides a flow rate of air-fuel mixture that results in a combustion temperature of 600 - 900°C and radiant heat transfer that maintains the combustion temperature.

Low NO_x (£ 2 ng/J or ~ 4 ppm at 0% O_2 on dry basis) and CO emissions have been achieved (as measured by The Australian Gas and Light Company (AGL)). Further reduction in NO_x emission could be achieved by using baffles, barriers walls or enclosed combustion chamber to restrict or prevent cold secondary air contacting the flame before combustion is completed (Australian Patent Document No.: AU-B-16047/92).

Currently Bowin is collaborating with an Australian water heater manufacturer to develop a prototype low NO_x water heater using Bowin's technology.

[28] A joint Shall/Bekaert company www.acotech.com

Italy have reportedly been using this technology (see Chapter on burners, also for other radiation burner solutions).

Catalytic Combustion

Catalytic combustion may be fully catalytic (or simply catalytic), or partial which is also known as catalytically stabilised (Ro and Scholten, 1997).

In catalytic combustion, a catalyst such as palladium or platinum is used to reduce the activation energy of combustion and allow the fuel gas to be oxidised by air at a low temperature of 500 - 1000°C. The reaction temperature is maintained low by effective removal of heat liberated from oxidation to the heating medium. Because the reaction temperature is low, Ro and Scholten stated that NO_x levels < 5 ppm could be achieved.

In catalytically stabilised combustion, part of the fuel gas is oxidised by catalytic combustion, and the remaining gas is oxidised by homogenous (blue flame) combustion after or during catalytic combustion. Providing heat is removed from the catalytic system, the product gases from catalytic combustion dilute the exhaust gases from the homogenous combustion and lower the overall combustion temperature, and hence NO_x emission, in a way similar to flue gas recirculation.

Ro and Scholten compared the performance of boilers using catalytic combustion and catalytically stabilised combustion. They concluded that catalytically stabilised combustion had a higher reliability because it could be operated as a conventional radiant burner even if the catalyst was poisoned and totally de-activated, and the security and control system required for temperature/combustion control would be more easily developed. Catalytic combustion on the other hand, emitted less NO_x and CO, and its method of catalyst coating was easier.

In the review performed by Raghavan and Reuther three years earlier than Ro and Scholten, a catalytic burner used in a gas-fired appliance was cited. The burner surface was a matrix of ceramic fibres interspersed with chrome (catalyst) fibres. NO_x emission < 15 ppm and CO emission < 10 ppm O_2-free were reported.

Catalytic converters similar to those used in automobiles were also cited by Raghavan and Reuther. The converter completed catalytically the combustion of the products from an earlier fuel-rich combustion with more cool air at a temperature < 540°C. NO_x emission from this two-staged combustion was lower than that from a second stage combustion which was non-catalytic but conducted at a higher temperature.

Raghavan and Reuther suggested that the requirements of fan-assistance to overcome the problem of low temperatures and low heat fluxes, larger heat-exchange areas, and smaller combustion chamber volumes might be the main draw backs of wide application of catalytic combustion to gas appliances.

Pulse Combustion

In this mode, combustion occurs intermittently and the combustion gases experience high temperatures for very short time only. Heat transfer from gases to heat exchange surfaces is fast due to high turbulence, which maintains a lower temperature and hence lower NO_x emissions.

NO_x levels of < 50 ppm were reported, and the technology had been commercialised in residential heating appliances (Raghavan and Reuther, 1994).

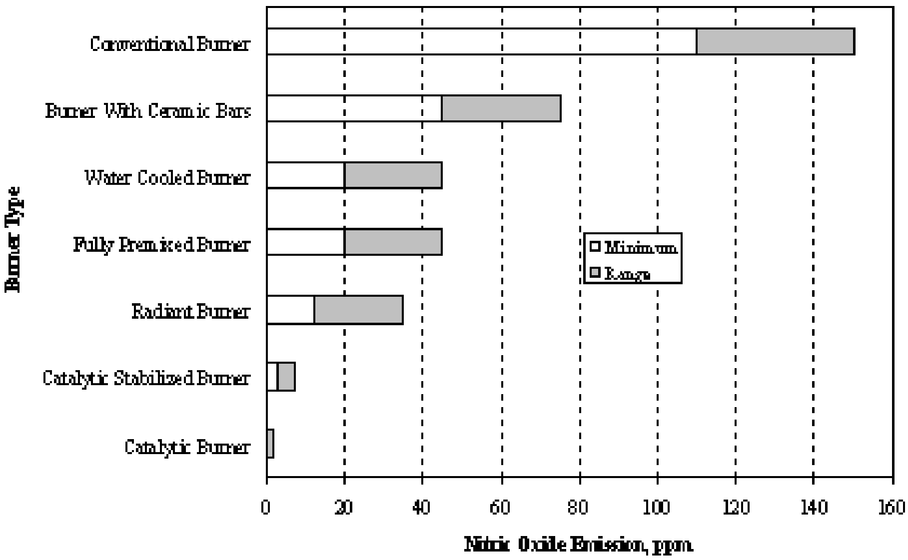
The noise level of pulse combustion systems would be high, and this could limit the application of pulse combustion in domestic situations.

Pulse combustion is used by US manufacturers such as Lennox and Empire Comfort Systems. In Europe it is developed by Auer Gianola in a CH boiler "Pulsatoire", the bulk of the applications however are industrial.

3.6.3 Primary NO_x Control Technology Status

Ro and Scholten (1997) summarised the NO_x emissions achieved by various types of burners. The results are reproduced in Figure 3-3:

Figure 3-3.
Nitric oxide emission levels of various burner types.



On the basis of the above and the summary of Raghavan and Reuther (1994) the status of different primary NO_x control technologies around the year 2000 is reproduced in Table 3-4.

Table 3-4. Comparison of primary NO_x control strategies for residential gas appliances*. (source: Joynt, B, Wu, S., 2000)

Primary NO_x Control Technology	Likely Lowest NO_x (ppm, O_2-free)*	Likely Change in CO Emissions*	Likely Change in Thermal Efficiency*	Technology Status for Domestic Application*
Premixed, High Excess Air	~ 20	Decrease	Decrease	Current
Flue-Gas Recirculation	~ 25	Increase	Decrease	Not Commercialised
Staged Combustion	~ 25	Increase	Decrease	Current
Delayed Combustion	~ 25	Increase	Decrease	Not Commercialised
Humidified Combustion	~ 25	Increase	Decrease	Not Commercialised
Flame Inserts	~ 40	Increase	Decrease	Current
Thermally Active Burner	~ 65	Decrease	Increase	Current
Port-Loading Reduction	~ 50	Increase	Increase	Current
Port Redesign	~ 45	Decrease	Increase	Current
Radiant Combustion	~ 4 - 10	Decrease	Increase	Current
Catalytic Combustion	~ 5	Decrease	Decrease	Not Commercialised
Pulse Combustion	~ 20	Increase	Increase	Current

3.6.4 Secondary Control of NO_x Emission

NO_x can be removed from combustion exhaust gasses in three approaches:

- Selective catalytic reduction (SCR).
- Selective non-catalytic reduction (SNCR).
- Hybrid SNCR/SCR.

These technologies are expensive because consumable reagents and additional NO_x removal systems are introduced. Moreover, the additives such as ammonia if not consumed in the process will escape to the atmosphere which would lead to NO_x. Until now, applications of secondary control are mostly to power generation and other industrial combustion processes.

In the context of the underlying study they are not considered viable and will not be further discussed.

3.7 Low emissions vs heat generator performance / efficiency ?

[This text is primarily non-applience specific: Where the text states 'boilers' one may read this as 'water heaters' as well]

What effect does NO_x control technology ultimately have on a heat generators performance? Certain NO_x controls can worsen heat generator performance while other controls can appreciably improve performance. Aspects of the heat generator performance that could be affected include turndown, capacity, efficiency, excess air, and CO emissions.

Failure to take into account all of the heat generator operating parameters can lead to increased operating and maintenance costs, loss of efficiency, elevated CO levels, and shortening of the heat generator 's life.

The following section discusses each of the operating parameters of a heat generator and how they are related to NO_x control technologies.

Turndown

Choosing a low NO_x technology that sacrifices turndown can have many adverse effects on the heat generator.When selecting NO_x controls, the heat generator should have a turndown capability of at least 4:1 or more, in order to reduce operating costs and the number of on/off cycles. A boiler utilizing a standard burner with a 4:1 turndown can cycle as frequently as 12 times per hour or 288 times a day because the boiler must begin to cycle at inputs below 25% capacity (for water heaters: the outlet temperature is often constant at 60°C, but the flowrate may differ - requiring modulation).

With each cycle, pre- and post-purge air flow removes heat from the heat generator and sends it out the stack. The energy loss can be reduced by using a high turndown burner (10:1), which keeps the heat generator on even at low firing rates.

Every time the heat generator cycles off, before it comes back on, it must go through a specific start-up sequence for safety assurance. It takes between one to two minutes to get the heat generator back on line. If there is a sudden load demand, the response cannot be accelerated. Keeping the heat generator on line assures a quick response to load changes.

Frequent cycling also deteriorates the heat generator components. The need for maintenance increases, the chance of component failure increases, and heat generator downtime increases. So, when selecting NO_x control, always consider the burners turndown capability.

Capacity

When selecting the best NO_x control, capacity and turndown should be considered together because some NO_x control technologies require heat generator derating in order to achieve guaranteed NO_x reductions. For example, flame shaping (primarily enlarging the flame to produce a lower flame temperature — thus lower NO_x levels) can require heat generator derating, because the shaped flame could impinge on the furnace walls at higher firing rates.

However, the heat generator 's capacity requirement is typically determined by the maximum load in the hot water system. Therefore, the heat generator may be oversized for the typical load conditions that may occur. If the heat generator is oversized, its ability to handle minimum loads without cycling is limited. Therefore, when selecting the most appropriate NO_x control, capacity and turndown should be considered together for proper heat generator selection and to meet overall system load requirements.

Efficiency

Some low NO_x controls reduce emissions by lowering flame temperature. Reducing the flame temperature decreases the radiant heat transfer from the flame and could lower heat generator efficiency. The efficiency loss due to the lower flame temperatures can be partially offset by utilizing external components, such as an economizer. Or, the offset technique can be inherent in the NO_x design.

One technology that offsets the efficiency loss due to lower flame temperatures in a firetube heat generator is flue gas recirculation. Although the loss of radiant heat transfer could result in an efficiency loss, the recirculated flue gases increase the mass flow through the heat generator — thus the convective heat transfer in the tube passes increases.

The increase in convective heat transfer compensates for losses in radiant heat transfer, with no net efficiency loss. When considering NO_x control technology, it is not necessary to sacrifice efficiency for NO_x reductions.

Excess Air

A heat generators excess air supply provides for safe operation above stoichiometric conditions. A typical burner is usually set up with 10-20% excess air (2-4% O2). NO_x controls that require higher excess air levels can result in fuel being used to heat the air rather than transferring it to usable energy. Thus, increased stack losses and reduced heat generator efficiency occur. NO_x controls that require reduced excess air levels can result in an oxygen deficient flame and increased levels of carbon monoxide or unburned hydrocarbons. It is best to select a NO_x control technology that has little effect on excess air.

Carbon Monoxide (CO) Emissions

High flame temperatures and intimate air/fuel mixing are essential for low CO emissions. Some NO_x control technologies used on industrial and commercial heat generator s reduce NO_x levels by lowering flame temperatures by modifying air/fuel mixing patterns. The lower flame temperature and decreased mixing intensity can result in higher CO levels.

An induced flue gas recirculation package can lower NO_x levels by reducing flame temperature without increasing CO levels. CO levels remain constant or are lowered because the flue gas is introduced into the flame in early stages of combustion and the air fuel mixing is intensified. Intensified mixing offsets the decrease in flame temperature and results in CO levels that are lower than achieved without FGR. But, the level of CO depends on the burner design. Not all flue gas recirculation applications result in lower CO levels.

Conclusion

There is no contradiction between eco-design for low emissions and eco-design for energy efficiency and good performance. In fact, the most effective design measures, such as pre-mix burners, radiation burners (lower temperature), reduction of the number of cycles (e.g. through deep modulation), etc. are equally effective in lowering emissions as in increasing the energy efficiency. There are some exceptions and limitations, e.g. where there is a trade-off with CO and NO_x emissions in the combustion temperature, but overall if the designer recognizes these boundary conditions and deals with them appropriately they are not problematic. Overall, there is a great deal of synergy, where intelligent design measures contribute not only to one environmental aspect, but to the whole spectrum of environmental, energy and resources impacts.

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4 BURNERS

4.1 Introduction

This chapter gives a hands-on overview of the current EU burners sold for gas- and oil fired CH boilers and water heaters. It discusses the trends and the main types and characteristics.

Current burner production is in the hands of both the boiler manufacturers and specialised burner-OEMs. Boiler manufacturers like Weishaupt, Viesmann, Buderus, etc. are mostly manufacturers of jet burners for floor-standing gas and oil boilers. Specialised burner-producers like Bekaert (Belgium), Worgas (Italy), etc. are mainly producing burners for wall-hung gas (combi-)boilers.

4.2 Trends

Over the last two decades there has been a development from the traditional atmospheric burners towards Low-NO_x pre-mix burners, typically with lower combustion temperatures. This trend was fuelled by the ‘technology push’ of new high-temperature materials becoming available (e.g. ceramics, metal fibres) and the ‘demand pull’ of better energy efficiency (in part load and during cycling), higher heating comfort and lower (NO_x) emissions.

At the moment, this trend seems to have slowed down for a number of reasons.

- In the beginning the new materials had some problems regarding fragility, a too short product life, etc.. Currently this reputation is undeserved[29] when the burners are applied properly. But it is never easy to remedy first impressions.
- Secondly, pushed by the competition and new insights burner-manufacturers found that they could meet large part —at least a sufficient part— of the legislative emission-requirements with traditional materials like perforated refractory steel[30] plate or (half) cylindrical burners.
- Thirdly, although the in the 1990’s the legislators in some countries like Germany and Austria were very active in setting maximum emission limit values for boilers, there have been no updates since and few countries have followed, despite m,easures such as the EU NEC Directive. Furthermore, as already indicated in the Task 1 report, the CEN has hardly updated their emission measurement methods – which were originally meant only for safety—for a practice of environmental impact. For instance, the EN standards measure at stationary (full load) conditions, whereas in practice 80 (oil) to 95% of emissions of CO, CH_4, C_xH_y occur during cycling (start/stop).
- Fourthly, regarding a possible contribution of the burner in improving the energy efficiency heat generator manufacturers have found that they could achieve this also in another, albeit more economical way at the level of the heat exchanger, e.g. recuperating latent heat of condensation.

All in all, this has made the burner into somewhat of a low-interest standard component, where pre-dominantly the most economical pre-mix perforated steel plate version is applied throughout. Prices are in the order of € 8-10, which is hardly more

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[29] Manufacturers have solved these problems and e.g. ceramic burners are successfully being used in –mostly larger—burners

[30] Temperature resistant, low oxidisation e.g. compare stainless steel.

than the price of an atmospheric burner. For integrated heat generators the plate or (half-) cylindrical versions are used the most.

Yet, as has been argued in e.g. the chapter on emissions, for Eco-design the burner may be far more than a low-interest product.

4.3 Types

For the majority of gas- and oil-fired boilers and water heaters there are two types of burners:

- Surface burners
- Jet burners

They can be fan-assisted (pre-mix) or not.

4.3.1 Surface burners

A surface burner is a flat or (half)-cylindrical perforated plate or woven-fibre of metal or ceramic material. Each hole in the plate ('burner port') serves as a flameholder. The geometry of the holes, together with the flow and pressure of the fuel and combustion air (or their mixture), determines the shape and the size of each individual flame. Depending on the position of the flame we can distinguish

- the flame hovers over the burner bed (***'free flame'***),
- the flame sits at the burner surface, i.e. at burner nozzle exit (***'radiation burner'***) or
- the combustion takes place inside the burner nozzles (***'flameless burner', e.g.).***

All these three options —and their intermediate variations— result in a different heat transmission of the flame to the burner bed and thereby a different temperature of the resulting combustion products and a different share of the radiation energy (from flame + burner) and convection energy. E.g. For gas-fired burners some typical values are:

- the free flame burners: around 5% radiation share and flue temperatures of 1300-1500°C;
- metallic pre-mix burners: around 5-15% radiation share and flue temperatures of 1200-1300°C;
- ceramic surface burners: some 20-25% radiation and flue temperatures of 1000-1100°C and,
- flameless burners: 30-35% radiation and flue temperature of the combustion products leaving the burner bed below 1000°C [31].

The maximum burner load of these burners varies between <100 W/cm² for the conventional pre-mix burners, up to 300-400 W/m² for ceramic surface and flameless burners. Experiments with ceramic burners have even shown burner loads up to 1300 W/cm².

Effectively what is happening with the transition of the traditional free flame burner to the flameless burner, is that the flame is cooled by the burner surface. Or, to put it the other way around, the burner is heated. The figures on the following pages show many variations of these surface burners .

[31] Although inside the burner the flue temperatures may be much higher.

Figure 4-1.Selected metallic surface burners.
Atmospheric burners, steel plate [*top row*]:
[top row left]: round, conventional [*left*],
[top row mid]: oval suitable for full pre-mix without fan, lower NO_x
[top row right]: cylindrical, optimised for use with gas-fired storage water heaters.
Pre-mix burners, steel plate & metal fibre [*mid row*]:
[mid row left]: round, refractory steel pre-mix burner, modulation range 1:10, emissions akin to Gaskeur SV/Blue Angel level
[mid row mid]: flat pre-mix burner using metal fibre media, modulation range >1:10, emissions below Gaskeur SV/ Blue Angel (i.e. < 40 mg NO_x /kWh), burner bed dimensions: 70 x 237, 80 x 355 or 90 x 237 mm (or custom made)
[mid row right]: cylindrical pre-mix metal fibre burner, e.g. diameters 63/67, height <400mm.
Pre-mix burner, knitted metal fibre [*bottom row*]:
Compact pre-mix burner, knitted metal fibre welded on foot, optimised for standardisation, low NO_x, CO, noise (no resonance).
[source: http://www.bekaert.com/ncdheating/Home.htm]

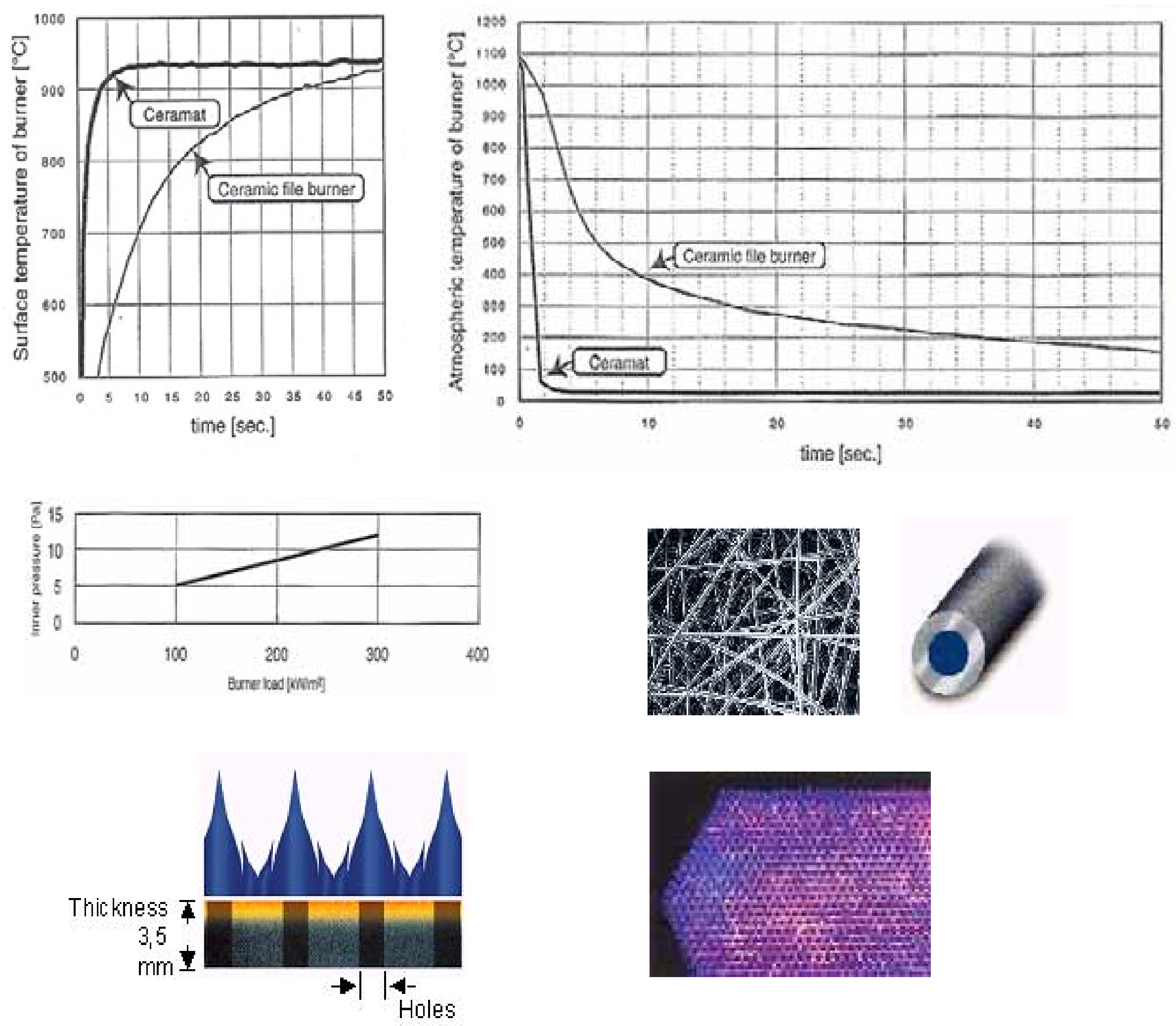


Figure 4-2.
Ceramic radiation burner. Standard size is 250 x 250 mm. Thickness 3,2 +/- 0,5 mm. Standard perforation is 1,4/2,8 or 1,5/3,5 (other sizes and perforation on request. Operating range: Min. 10 W/cm², Max. 400 W/cm². Radiation range: 10 - 75 W/cm². Modulation range 1:35. Maximum surface temperature 1000 ° C.**Pictures** refer to short heat-up time 2-3 s (*top-left)*, quick cool-down 2-3 s(*top right*), low pressure drop +/- 10 Pa (*mid left)*, ceramic fibre material covered with SiC through CVD/PVD-process (*mid right*), small burner plate height of 3,5 mm with holes 1,5 mm → permeability 95% (*bottom left*), front view of burner in action (*bottom-right*) (http://www.schott.com/gasburnersystems/english/)

Figure 4-3.
Radiation burner Viessmann 'off' (left) and in operation (right). Emissions in boilers NO_x: <15 mg/kWh, CO: <15 mg/kWh

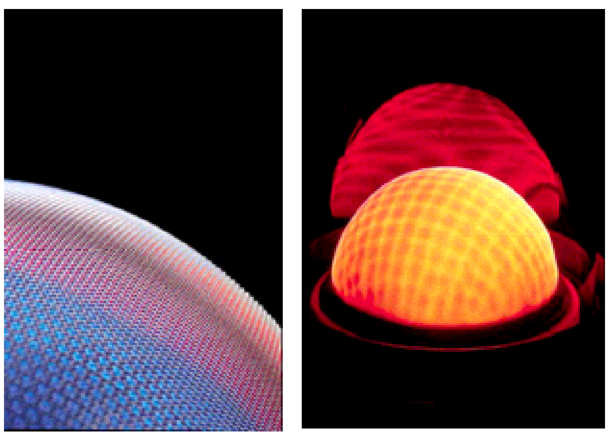


Figure 4-4a.
Porous ceramic burner (SiC). Maximum load: 300 W/cm². Modulation range: 1:20. Thickness 15 mm. Low CO: <20 mg/kWh and low NO_x: <20 mg/kWh, also during burner cycling operations (on/off). Picture left: www.poreos.com

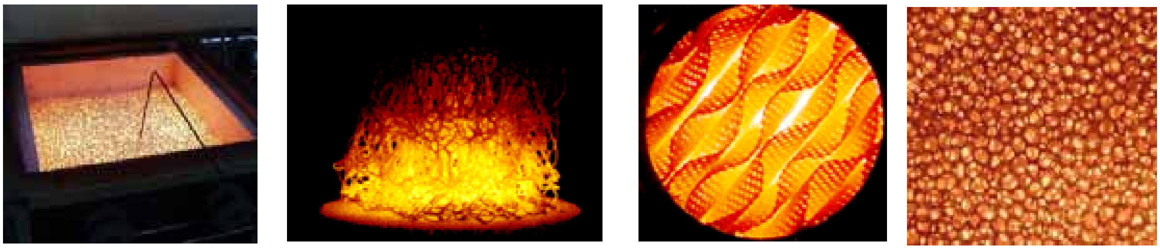


Figure 4-4b.
Ceramic 'flameless' burners. From Left to Right: Ball burner (D. Kugelschüttung), knitted ceramics, mixing/woven burner, ceramic foam [source: Dietzinger, 2006]

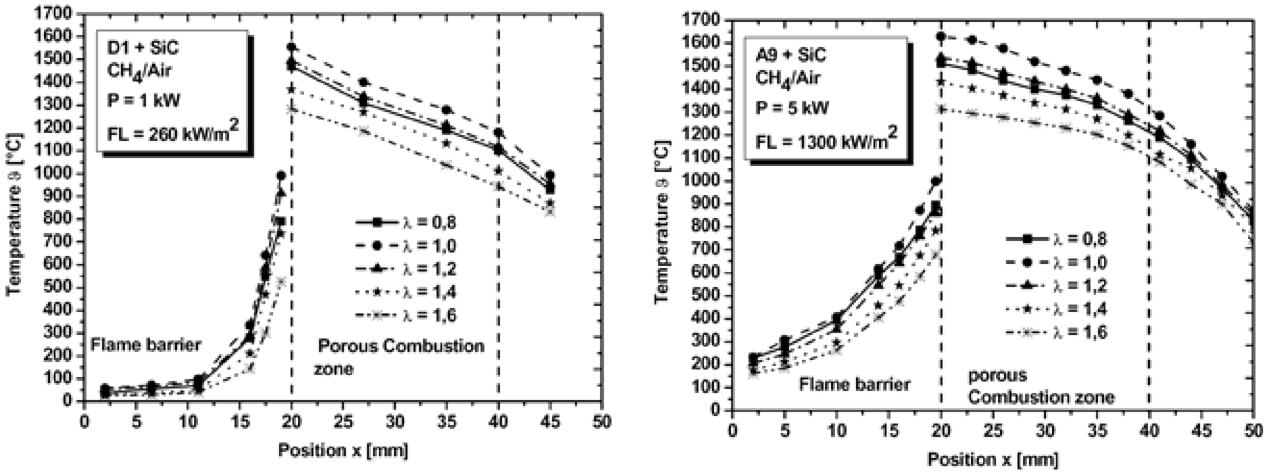


Figure 4-5.
Ceramic porous burner: Propagation of temperature with a methane/air mix. The graphs show an experiment whereby the temperature is measured in the flame barrier and throughout the thickness of a 20 mm porous ceramic burner. Note that the initial temperature after ignition is close to the calculated adiabatic flame temperature and that the combustion products –while giving off their heat to the burner—cool down to a level <1000°C already 10 mm after the burner surface. Left= 1 kW; Right= 5 kW with the same burner but different flame barrie s [source Dietzinger 2006]

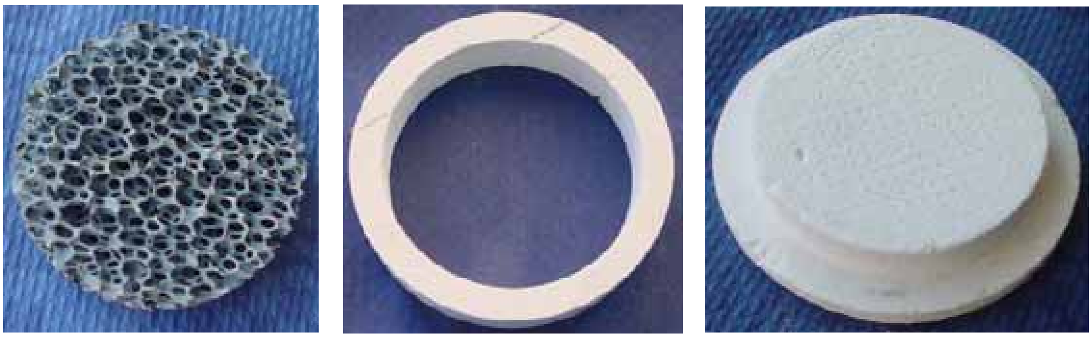


Figure 4-6.
Components of an experimental porous ceramic burner. From left to right: Burner bed in silicium carbide (SiC) foam 10 ppi produced by fa. Erbicol, Al2O3 fibre-based insulation ring, Al2O3 fibre-based hole plate for ceramic burner.
[source: **Diezinger, Stefan**, *Mehrstofffähige Brenner auf Basis der Porenbrennertechnik für den Einsatz in Brennstoffzellensystemen,* dissertation Technical Faculty of the University of Erlangen Stuttgart, 2006 (http://www.opus.ub.uni-erlangen.de)]

Figure 4-2 shows a thin ceramic radiation burner from the German manufacturer Schott. In this design the flames typically sit on top of the burner bed (radiation burner). The graphs show that this particular ceramic fibre burner has a quick heat-up (<5-10s) and cool-down (<2s) compared to competing burners.

Another radiation burner, made of a semi-spherical mesh of stainless steel, is shown in Figure 4-3 (production Viessmann).

Figure 4-4 relates to several types of ceramic 'flameless burners' and in particular a burner made of porous ceramic foam, developed by the University of Erlangen and marketed by the firm Poreos in Germany. The burner can be very compact (high heat load per surface area) and have low NO_x and CO emissions (< 20 mg/kWh = 12-13 ppm at 3% O2). However, because of its price and long heat up time it is probably more suited for industrial applications than for residential boilers or water heaters.

An interesting feature of the thick porous ceramic burner is the fact that the temperature curve through its 20 mm section can be studied. Figure 4-5 shows two examples of such a temperature curve, showing that —although the measured 'combustion temperature' at the burner exit may be as low as 1000°C— in reality inside this flameless burner much higher temperatures of around 1500°C are reached. Figure 4-6 shows the components of the porous ceramic burner.

4.3.2 Jet burners

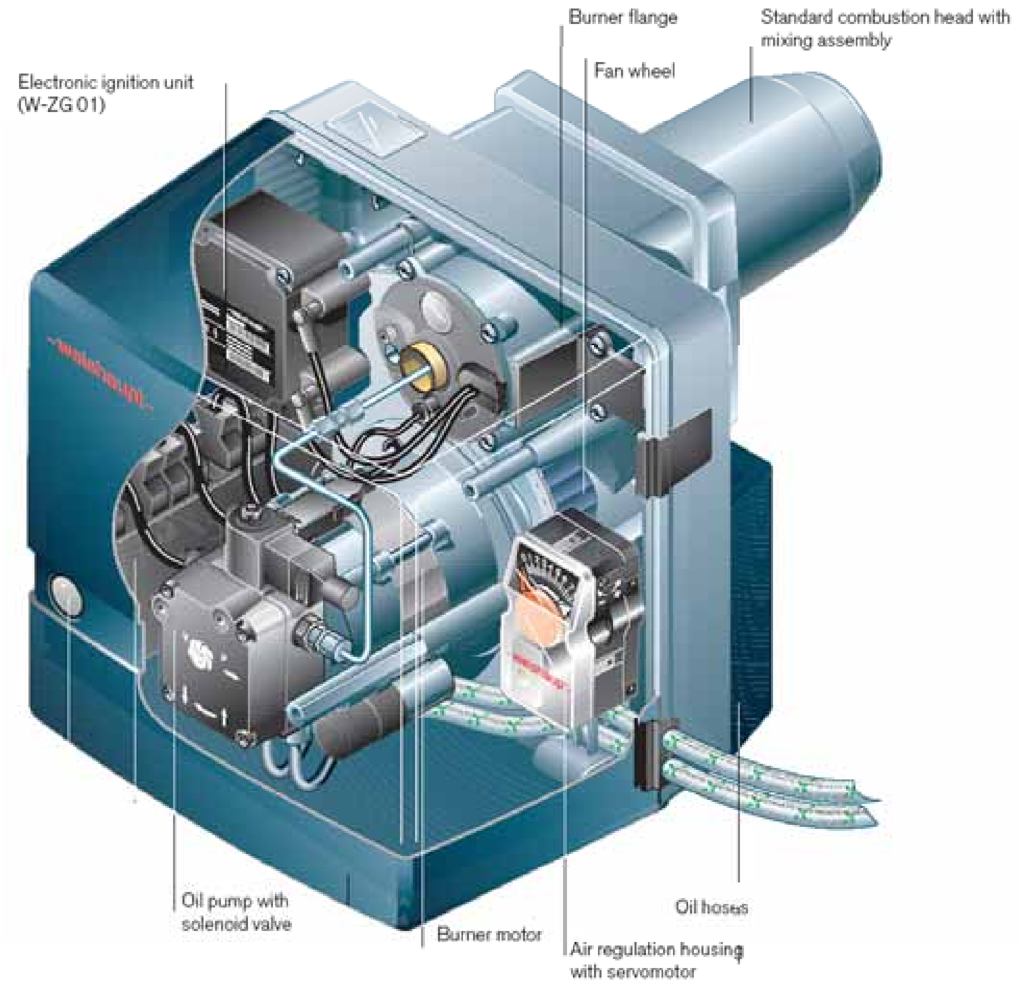
In principle, a jet burner is nothing more than a nozzle for the fuel/air mix. In case of an atmospheric burner the nozzle and preceding induction trajectory creates a venturi effect through which the fuel sucks in a part of the combustion air (the primary air), after which the rest of the air (secondary air) is sucked in by the flame itself. In case of a full-premix burner, the fuel and all the combustion air are already fully mixed in the right proportion before they are being conducted through the nozzle. A pre-mix jet burner usually requires a fan, which —together with the gas valve, ignition and combustion controls— sits in a self-contained unit, which is then often referred to as 'jet burner'.

Figure 4-7 gives an illustration of a jet burner. This particular jet burner is oil-fired, which means that apart from the combustion head, the fan, ignition and combustion control it also contains an oil pump and atomizer to induce the oil droplets into the air stream. Details of the oil nozzle are given in Figure 4-9.

As mentioned, jet burners are fully self-contained and can be mounted on any heat exchanger body with EN standardised attachment for the burner flange (see Figure 4-7). The units cost around € 800 to € 1200,- for the 15-30 kW range and around € 1500,- or more for 100 kW (prices Germany, incl. VAT 16% [32]).

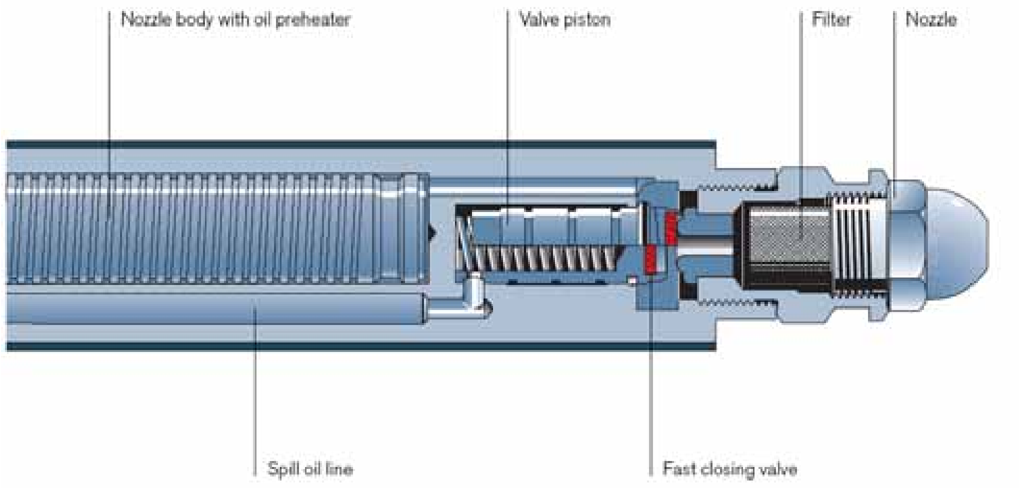
Figure 4-7.
Jet burner assembly
1 = heat exchanger body with control unit
2 = jet burner
3 = indirect cylinder (sanitary hot water)
4-6 = options
(www.viessmann.com)

Figure 4-8.
Weishaupt oil-fired jet burner WL5. Capacity: 16,5-50 kW. Dimensions excl. combustion head 292 x 286 x 308 mm
(www.weishaupt.de)



[32] www.heizungsfachshop.de

Figure 4-9.
Detail of oil nozzle of Weishaupt oil-fired jet burner WL5. Showing nozzle body with oil preheater, spill oil line, valve piston, fast closing valve, filter and nozzle.



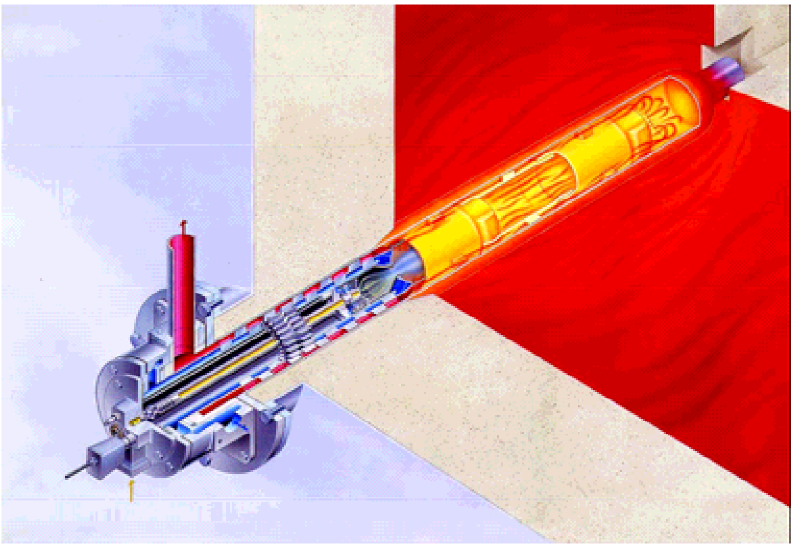
Market trends in the field of jet burners for CH boilers (also feeding separate DHW cylinders) seem to go more in the direction of easthetics, reliability, design, electronic controls, etc. (names: Weishaupt, Buderus, Riello).

In the field of higher energy efficiency and low-emissions most innovations seem to be in the field of industrial burners in Europe. Main developments are in the use of combustion air, i.e. not only through the air factor but also by preheating the incoming air in any number of ways or by mixing the incoming air with the combustion air. These techniques are known as

- recuperator burners (preheating incoming air at burner level),
- regenerator burners (using a heat storage medium and intermittent operation to exchange heat between flue gases and incoming air),
- FLOX burners (high re-circulation rates of flue gases with flameless oxidisation)
- Multi-stage combustion (below-stochiometric pre-combustion)

Especially in the field industrial jet-burners there are new developments regarding the realisation of the cooler flame through recuperator or regenerator techniques. With ***recuperator***-burners the cooler flame and the energy saving is achieved by using/ pre-heating the incoming air with the combustion products.

Figure 4-10.
Recuperation burner whereby there is a heat exchange between incoming air and the outgoing flue gases, allowing the air to be preheated up to 1000°C. The reaction temperature is around 1400°C.

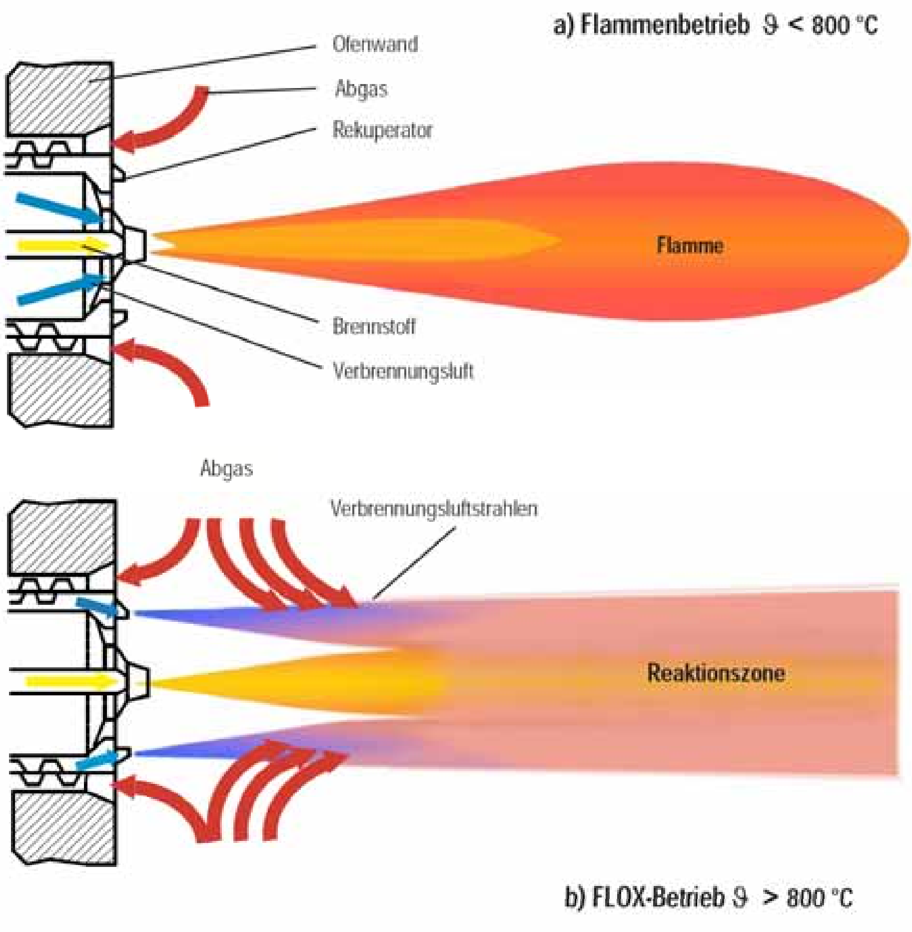


With ***regenerator*** techniques the waste heat recovery is achieved through an intermediate heat storage medium that is intermittently cooled by the air and heated by the flue gases. This technique requires high valve activity and a very integrated construction, which is probably beyond the scope of most domestic burners/boilers.

Another technique is the ***re-circulation of flue gases*** into the combustion process. This has been explained in the chapter on emissions and entails either recirculation rates of 1 with conventional flame technology, or recirculation rates of 3 and higher with the flameless oxidation (FLOX) technology.

The flue gas re-circulation technique, subdivided between internal and external re-circulation, can also be combined with other technologies that reduce NO_x emissions. One such technique is the ***staged combustion*** (D. *Gestufte Verbrennung*), whereby the fuel-air mixture is first combusted at below-stochiometric conditions (air factor < 1) in a pre-combustion chamber and then brought into the main combustion chamber where secondary air is added. This also leads to a reduced flame temperature and lower NO_x. This effect can be vastly increased by a combination with the FLOX operation, where the high flue-gas re-circulation is achieved in two ways: firstly by the impuls of the gas jet and secondly by a delay in mixing the combustion air with the fuel. [33] This is shown in the Figure 4-10.[34]

Figure 4-11.
Principle of a FLOX-recuperator burner, using a conventional flame-mode during start-up and a flameless oxidisation at normal mode [source Erdgasbericht 01/3.]



[33] Note that in a FLOX there is no flame and therefore the conventional UV or ionisation flame sensors cannot be used. Instead the temperature in the combustion chamber is used as a parameter.

[34] Please note that developments in this field are not concluded; especially in the field of emissions of Particulate Matter (PM) with oil-fired FLOX-burners some problems have been reported.[Ökozentrum Langenbruck]

4.4 Control of burner output (power)

4.4.1 Modulation

Controlling the burner-output between the range of 100% back to 30% of the nominal load, is already quite common for gas condensing (combi)boilers. The most common type of boiler is a 24 kW combi boiler. As a result, the minimal power input (30% of 24 kW) is around 8 kW and the boiler may still cycle on and off during low flow DHW demand.

Several companies are already developing techniques to further reduce the modulation range, preferably up to 10% of nominal load. Since most boilers that are either fan assisted or fully premix, the modulation control not only affects the gas valve, but also the fan.

4.4.2 Pneumatic ratio-control

Most commonly applied technique for modulation is the pneumatic ratio control. With this type of control the BCU (boiler control unit) sets the rotation speed of the fan, based on the requested feed temperature or heat demand. The air flow resulting from this fan speed, causes a specific air pressure that is sensed by a *control membrane* or *venturi* of the pneumatic ratio control unit. Based on this pressure-difference the gas valve opening is adjusted. These control techniques compensates for weather conditions like changes in temperature of barometric pressure.

Pneumatic ratio-control systems operate without problem to modulation ranges up until 1 : 4. At increased control ranges, the resolution of the measured pressure differences becomes too small and the control principle becomes unstable.

Figure 4-12.
Increasing pressure difference in pneumatic ratio control devices.

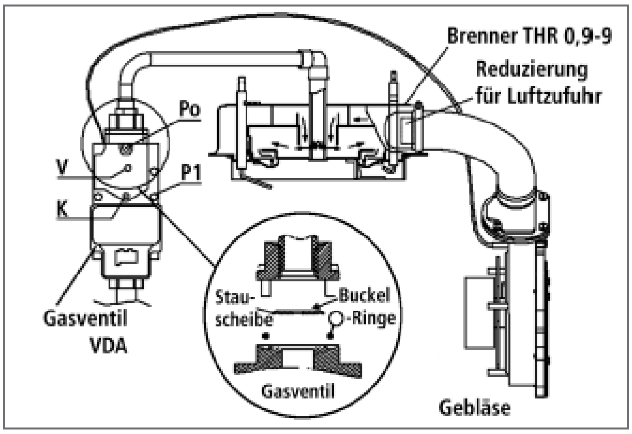


Figure 4-13.
Thision, condensing boiler from Elcotherm, modulation range 9,5 - 0,9kW.

One way of solving this is the use of an extra diaphragm which increases the available air pressure at the pneumatic ratio control unit. With a similar device that increases the pressure over the gas valve in the same proportion, the pneumatic ratio control unit can function again, but now at higher resolutions.

4.4.3 Integrated mixing & control valve

Another technique that is being developed is the IMS control, “Integriertes Misch- und Stellventil”. This development project (by Kromschröder, Ruhrgas and Remeha) also aims at improving the modulation range to 1 : 10. The IMS is a system is a combined mix- and control unit, using two valves that are both controlled by a motor. The motor adjusts the position of both valves. The position of the gas valve is based on the requested heat load, the position of the air valve is derived from that.

Figure 4-14.
Principle of the IMS-control

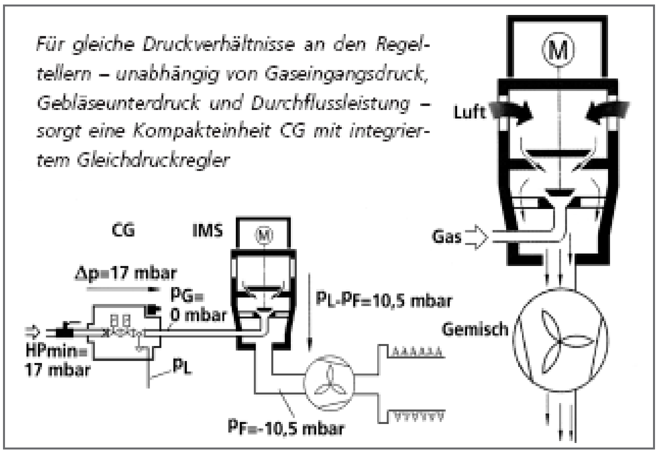
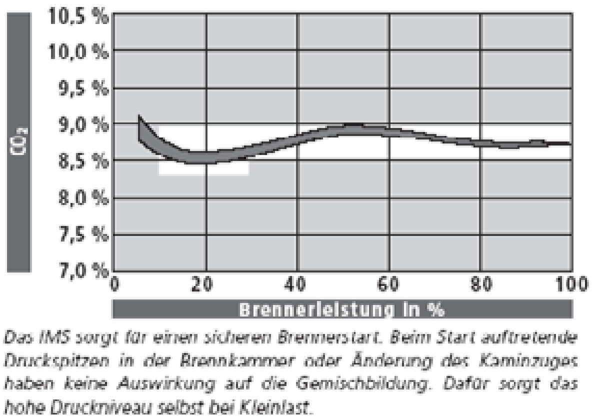


Figure 4-15.
CO_2-percentages at varying power inputs



A relatively high flow speed of the combustion air insures good system stability also in the lower regions of modulation. The fan is positioned between the IMS and the burner and if the burner is switched off, the IMS closes, which decreases convection losses over the burner in the off-mode.

Figure 4-16.
Pressure sensor switch

Pressure sensor switch

The pressure sensing switch is sensor/actuator –combination used in gas combustion appliances in which the combustion air is fully dependant on the fan (as in premix burners). Therefore, the air flow needs to be closely monitored.

More technologies are being developed for controlling the fuel/air-ratio. Main driver however is not the *burner modulation*, but the changing enthalpy of the fuels, due to the use of different gas-qualities.

Related techniques are discussed in the next paragraph.

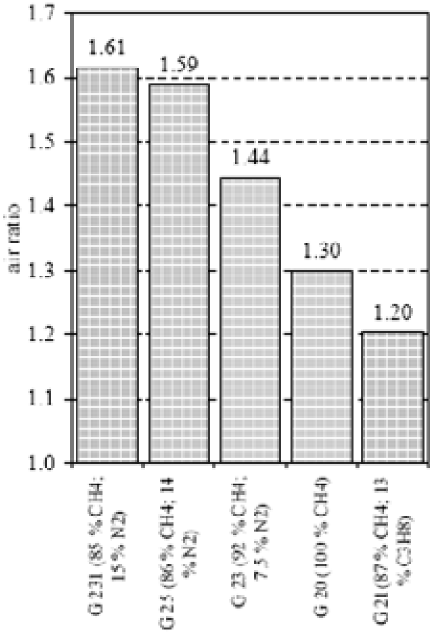
4.4.4 Fuel/air ratio control

The liberalization of the EU-gas markets forces distribution companies to allow gases from different suppliers into their networks. Already today gasses of different suppliers and qualities (including tests with bio-gas and hydrogen) are mixed and supplied into the network. As a result the enthalpy or Wobbe index of the supplied gas may change, causing a shift in the air factor λ (fuel/air-ratio). Varying gas qualities will cause *higher emissions* and a *lower boiler efficiency*, unless control systems are used that measure either the quality of the fuel or the quality of the combustion and adjust fuel/air-ratio likewise.

Figure 6-10 gives an impression of the magnitude of the air ratio shift due to gas quality variations.

A design point of air ratio λ = 1,3 for methane was taken as a reference and the resulting air ratios of some other gases used in Germany are compared. The figure shows air ratio shifts of 1,2 to 1,61 (adjusted for different gas densities).

Figure 4-17.
Air ratio shift duet to gas quality variations, adjusted for the also varying density of the supplied gas.



As a result of these shifts in air factor, emissions will show large variations, flames might blow off, thermo-acoustic resonance could occur and efficiencies may drop considerately. Especially for condensing boilers, the efficiency drop is important because not only the flue gas losses increase (higher exhaust flow volumes) but also the dew-point is lowered due to a shift of the partial pressure of the water vapour.

Figure 4-18.
Principles and parameters for fuel/air-ratio control

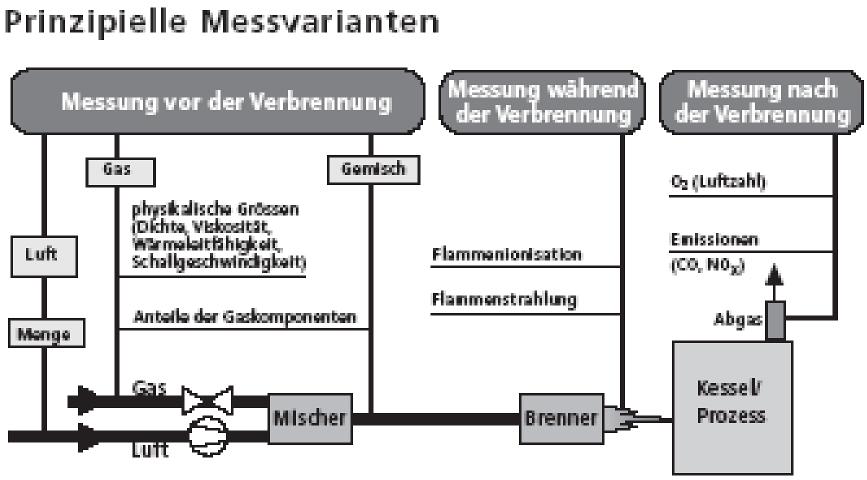


Figure 4-18 summarizes the parameters that can be used to measure and control the fuel/air-ratio.

Parameters that can be measured *before* combustion:

- specific mass;
- viscosity;
- thermal conductivity;
- sonic speed;
- substance.

Parameters that can be measured *during* combustion:

- flame ionization;
- flame radiation;
- temperature.

Parameters than can be measured *after* combustion:

- oxygen;
- CO;
- NO_x.

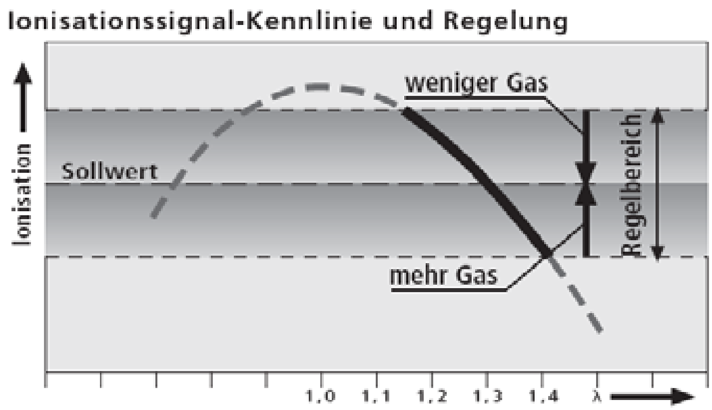
A lot of research has been done over the years to design, built and test the various options. Some of these R&D activities have actually evolved in solutions that are applied today in state of the art boilers/water heaters.

Measurement of flame ionization

This technology is based on the measurement of the ionization voltage over flame and gas mixture. This ionization is already used for flame-control reasons (in case no ionization signal is measured, there is no flame and the gas valve is closed). With additional electronic circuitry the intensity of the ionization signal can be measured. And because the flame temperature (ionization voltage) is directly related to the air factor, the ionization signal is a indication for the quality of combustion.

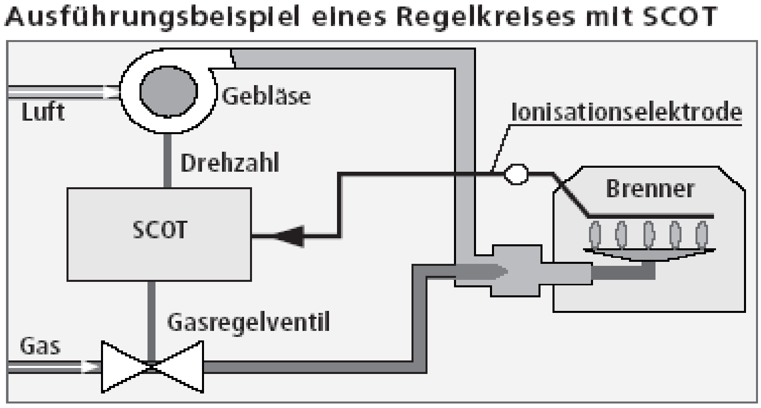
For surface burners with laminar flames the relation between ionization signal and air factor is unambiguous and similar to a parabolic curve (see Figure 4-19). The maximum ionization signal is always measured at air-factor λ = 1. This point is used for the automatic calibration of the combustion control system.

Figure 4-19.
Typical curve for the ionization signal. Source: VSG



Next step for a fully functional combustion control system is to use this ionization signal for an active control of the gas valve and the fan. Weishaupt uses this type of active combustion control in their wall hung gas condensing boilers called Weishaupt – Thermocondens.

Figure4-20.
Schematic representation of combustion control system using the ionization signal.(In Germany this technology is called SCOT, meaning System Control Technology).



Viessmann uses this technology in the VITODENS boilers, and they gave it the name “Lambda Pro Control”.

Buderus uses the ionization signal for controlling the gas supply in their atmospheric gas fired LT-boilers.

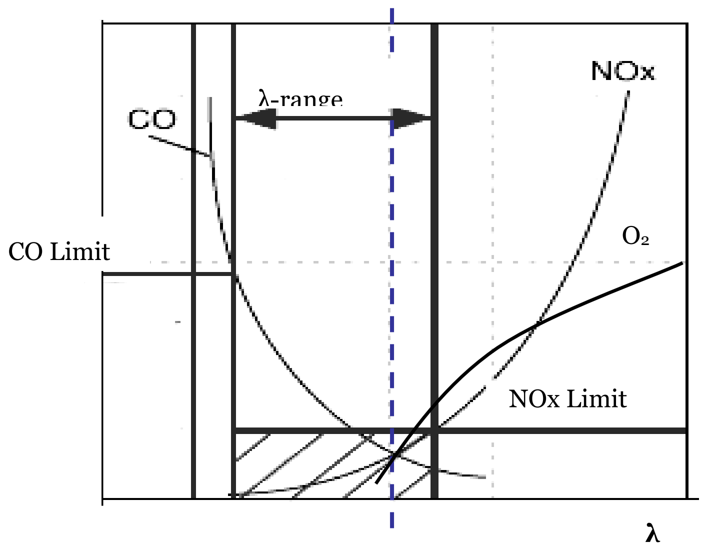
Many of these boilers are available as combi_storage boilers (central heating boiler with integrated DHW storage).

Measurement of O_2

Oxygen sensors are already in use for some time now in cars and gas motors. They control the air- factor within the limits set by the catalytic reformer. The amount of oxygen in flue gasses can directly be related to the combustion quality and the air factor and O2 analysis therefore could offer proper feed back related to combustion control. However there are certain drawbacks. Heat generators are usually operated at slightly negative pressure. Any leaks cause air to be drawn in and as a result the O_2 readings in the stack will be higher than those actually found in combustion zone. Also, stratification of stack gases can make O_2 sampling at a single point inaccurate.

Several companies have tried and are trying to apply these sensors for combustion control in residential boilers / heat generators as well, but so far didn’t succeed in getting the technology beyond prototype stage. Sensor stability and price remain as the prohibitive thresholds.

Figure 4-21.
Relation between air-factor λ and CO, excess O_2 and NO_x



For a car the sensor would need an operational lifetime expectancy of approximately 4.000 hours. For a boiler one would need 30 to 40.000 hours.

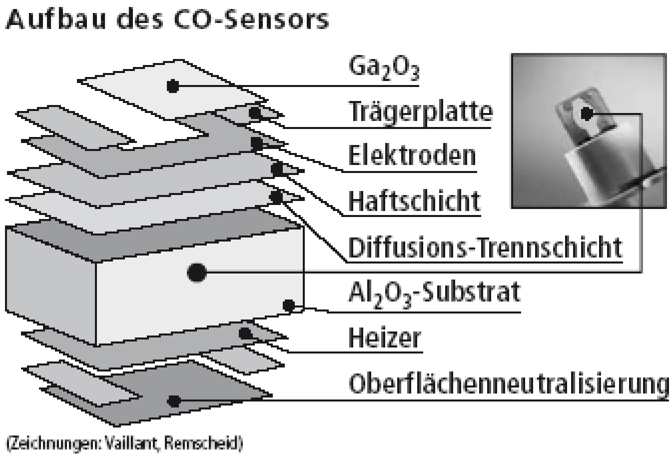
Measurement of CO

The other flue gas component than can be measured for combustion control purposes is CO.

CO is a product of incomplete combustion which will combine with oxygen to form CO_2 if sufficient O_2 is available. Ideally, if combustion is complete, the level off CO will drop to zero. Since complete air/fuel mixing is not possible, the practical level of CO for control purposes is usually < 160 ppm.

Using CO to trim combustion control systems offers an advantages over O_2/trim: the CO control point remains constant for all types of fuels.

Figure 4-22.
Construction of CO-sensor used by Vaillant.



Vaillant GmbH developed together with Steinel Solutions AG a CO-sensor based on a Ga_2O_3 sensor platform.

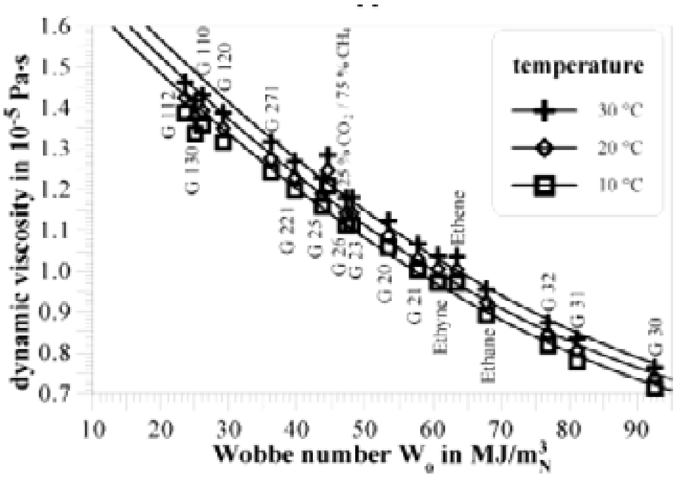
Based on the information from the CO-sensor the also new gas valve / safety valve assembly is operated with a step controller, which again influences the fan rotation speed.

The CO-sensor can also be used to detect wear to components like the fan or pollution of the burner, resulting in more efficient maintenance schemes.

Measurement of viscosity

Gas quality can be expressed by the Wobbe number. The Wobbe number correlates with the dynamic gas viscosity, according to the figures given in Figure 4-23.

Figure 4-23.



The correlation between the Wobbe number and the viscosity is well known since a long period of time but so far not used for combustion control purposes. Only due to developments in micro technology a compact sensor design became possible. The Institute of Fluid Mechanics of the University of Erlangen – Nuremberg, Germany, developed a prototype of a viscosity sensor a tested the principle on a test rig.

The principle could work but additional development on the sensor part (based on capillary viscosimetry) is needed.

5 HEAT EXCHANGERS

5.1 Introduction

This section focuses on the type of heat exchangers found in (combi-)boilers and dedicated gas- and oil-fired water heaters. In principle a heat exchanger is a thermal device in which heat is exchanged between media. The three basic principles for heat transfer are:

- *Direct*
  Direct contact between two media (e.g. steam or gas through water).
- *Regenerative*
  Heat is transferred through an intermediate material that cycles between receiving and transferring heat; (e.g. electric emitters with thermal store or warmtewiel)
- *Recuperative*
  In a recuperative he the media are always separated with a thin wall through which the heat is transferred, mainly through convection and conduction. The influencing parameters are A (= size of surface), the shape of the surface, thermal conductivity of the material used, speed and flow characteristics of the media, direction of the flow (counter, cross or parallel flow).

For boiler- and water heater-applications the recuperative heat exchanger is predominantly used. However, to illustrate that a direct contact heat exchanger technically also is feasible, the principle of a prototype that achieved a constant thermal efficiency of 96% is shown below.

Figure 5-1.
Schematic diagram of the direct contact heat exchanger system. Source: Caddet Energy Efficiency projects, Result 438.

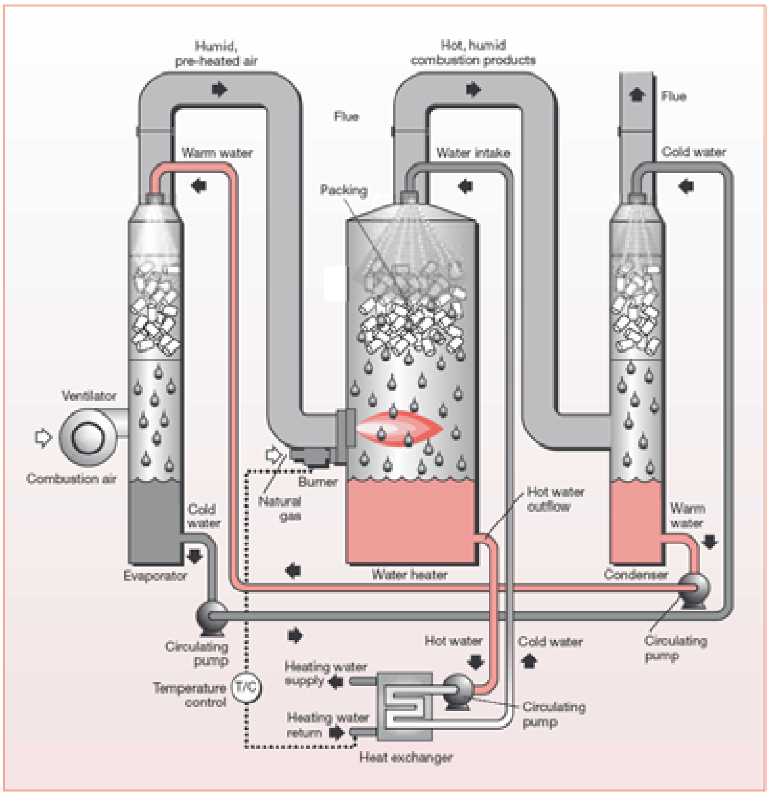


Figure 1: Schematic diagram of the direct contact heat exchanger system.

In the following paragraphs the recuperative heat exchanger will be further analysed in terms of its design aspects and application in boilers for primary, secondary and tertiary heat exchangers. In this type of heat exchanger, heat is transferred through a combination of the three mechanisms: conduction, convection and radiation. In heat exchangers for combiboilers/water heaters, convection is the most important part in total heat transfer (appr. 60 – 80%, see chapter..). Depending on the type of burner/heat exchanger configuration, the heat transfer through radiation may vary from 5 to approximately 25%.

To give some more detail on the energy transfer processes, the general formulas mentioned in the previous chapter (Basic energy and mass balance) are elaborated on (see box below).

The total heat transfer coefficient "U" of a heat exchanger through *convection* can be expressed with the following formula, (calculates to total heat transfer resistance).

$$1/U = 1/\alpha_h + d/\lambda + 1/\alpha_c + R_f$$

In which:

- α_g = heat transfer coefficient on the gas side of the HE [W/(m²K)]
- d = wall thickness [m]
- λ = thermal conductivity of HE material [W/(mK)]
- α_c = heat transfer coefficient on the cold side of the HE [W/(m²K)]
- R_f = heat transfer resistance caused by corrosion & pollution [W/(m²K)]

The total heat transferred through convection can be calculated with:

$$Q_{conv} = U * A * (T_g - T_c) \ [W]$$

The total heat transfer through radiation of the burner towards the HE can be expressed with the formula:

$$Q_{rad} = \psi_{b\text{-}he} * A * \varepsilon_{res} * \sigma_s * (T_g^4 - T_w^4)$$

In wich:

- Q_{rad} = the radiation heat energy [W]
- $\psi_{b\text{-}he}$ = exchange factor between burner surface and HE-surface [-]
- A = the surface of radiating part (burner in this case) [m²]
- ε_{res} = the resulting emission-factor [-]
- σ_s = the constant of Stefan-Bolzmann: **5,67**. 10^{-8} [W/ (m²K⁴)]
- $T_{g,}$- T_w = temperatures of the gas and the wall in [K]

Indications for the exchange factor $\psi_{b\text{-}he}$ can be calculated with the absorption factor method of Gebhart (not further explained here), and largely depends on whether both surfaces can "see" each other and on the emission factors of both materials.

The design parameters for optimising the heat-exchange process are:

- thermal conductivity (λ) of the material used [W/mK];
- wall thicknesses [m];
- surface area (the bigger the better) [m²];
- flow characteristics (on both sides of the heat exchanger) [turbulent, laminar, etc.];
- burner/HE – configuration [radiation / convection / conduction component].

For the overall boiler/water heater design however, other design aspects need to be integrated here, amongst which:

- HE- weight;
- HE- size;
- Reaction time HE on changing heat loads;

- Corrosion / foul-up / maintenance.

For boiler/water heater manufacturers the developments in heat exchangers over the last decades can be characterized firstly by the optimization of the standard cast iron (primary) heat exchangers for floor standing LT-boilers (e.g. with with separate storage cylinder), by improving the heat exchange performance (up until the dew point of flue gas) and by improving the material resistance for corrosion. Manufacturers however, not only improved upon the floor standing standard boiler – and by doing this they prolonged the life of the cast-iron HE—, most of them also developed new light weight heat exchangers and started to apply other materials than cast-iron (being not the best process/material-combination for light weight heat exchangers). Main reason for this was the clear market trend towards wall hung modulating (combi-)boilers with efficiencies up until dew point (< 90% GCV). This represented another reason for re-evaluating and redesigning the cast-iron heat exchanger. Light-weight materials and heat-exchangers became the preference, and the application of the cast-iron heat-exchanger (non corrosive alloys) remained in the segment of floor standing LT-boilers plus the shrinking market for standard boilers.

A second important trend that characterizes the last two decades is the integration (or combination) of the sanitary hot water heat exchanger with the CH- heat exchanger. A lot of different approaches were used, varying from instantaneous appliances with a sanitary HE within a CH-HE, to combinations of both were the sanitary HE is no more than a small plate HE or tube HE in a small storage tank, to solutions were large storage tanks are used, either for CH of sanitary hot water.

The third element that is typical for the HE- development trends, is the optimization op the primary heat exchanger beyond the dew point of the flue gasses (condensing boilers). Secondary heat exchangers were integrated (gas boilers) or added (floor standing oil boilers) to the primary heat exchangers, and again non corrosive light weight materials were preferred.

More companies started to outsource the development and production of these condensing heat exchangers, mainly because –coming from cast iron primary heat exchangers— the knowledge and hands-on experience needed for the design and manufacturing of these new type of integrated light-weight and condensing heat exchangers were not always available within the company.

Boiler manufacturers without the historical burden of a foundry obviously took the lead here, because they could fully concentrate on the condensing boiler only.

The last decade can be characterized by a further optimisation of the different he-solutions that were selected by the various boiler manufacturers, meaning:

- further optimisation of DHW production efficiency;
- reducing maintenance cost (by improving material specs);
- cost-price optimisation by a further integration of functions within the HE-assembly (integration with burner, air-vent, flue ducts, condensate collector and piping);
- cost-price optimisation through improvement of component commonality throughout the product range and through rationalisation of production.

5.1.1 Materials

Apart from cast-iron, the other materials that are predominantly used for *primary and secondary* heat exchangers in boilers and combis, are aluminium alloys, (stainless) steel and copper alloys.

The thermal conductivity λ varies quite a lot: stainless steel 27 [W/mK], cast iron 60 [W/mK], aluminium 237 [W/mK] and copper 390 [W/mK]. The advantage of stainless steel over cast iron is, that wall thickness can be reduced to far below 1 mm, while with cast-iron approximately 2,5 mm is the minimum. Since heat transfer also depends on the wall thickness and total surface, steel is the better material when size, weight and cost need to be optimized. For this reason steel can also compete with cast aluminium. Another advantage of (stainless) steel is its resistance to corrosion and thermal cycling. Copper has the best thermal conductivity and can be produced – like aluminium and steel – in thin plates or strips. Copper is also commonly used for sanitary (hot water) application (including heat-exchangers); main drawback is the price per kg (approximately 3 to 4 times higher than stainless steel).

For floor standing boilers (relevant for water heaters with storage tank) the materials are cast iron or steel or a combination of both, in most cases combined with jet-burners. For the smaller and lighter wall-hung boilers (relevant for instantaneous combis) aluminium, steel (finned tubes) and copper are mostly commonly used.

5.2 Typology

Apart from the material (λ) that is used, the shape and surface of the HE plays an important role in the optimization of the heat transfer through convection and radiation.

Shape and overall design however strongly depends on the basic (semi finished) material that is used. This can be tubes, plates or the raw material being casted in the requested shape.

An overview of types of heat exchangers in gas-/oil-fired water heaters, including combi-boilers can be structured according:

- heat transfer media (flue gas, CH water, DHW, combustion air),
- material/shape combination (cast iron, fin-tube, etc.)
- application (HEs for heating only boilers, instantaneous combis, etc.)

Please note this overview does not include heat exchangers found specifically in separate storage cylinders, although the same materials and shapes may apply (like for boilers with integrated storage).

The overview shows that multiple types of heat exchangers can be found in a single appliance (.i.e. a combi-boiler with primary fin-tube heat exchanger and a plate heat exchanger for DHW production). Also the same heat exchange principle can be found in various product groups (the shell-tube HE is applied in large heating only boilers as well as gas storage water heaters).

Table 5-1. Heat exchangers - an overview

Common description	*cast-iron*	*shell-tube*	*fin-tube*	*aluminium die-cast*	*submerged coil HE*	*plate HE*	*tertiary HE*
Material (for conventional DHW)	cast-iron	steel / copper	steel / copper/ aluminium	aluminium	stainless steel, copper	stainless steel, copper	various, incl. plastics
<u>Typical application</u>							
boilers with separate DHW storage	✓	✓	✓	✓	✓ (ext. cyl.)		(✓)
combi-boilers with DHW storage ≥ 15 l			✓	✓	✓	✓	(✓)
combi-boilers with DHW storage < 15 l			✓	✓	✓	✓	(✓)
combi-boilers without DHW storage			✓	✓		✓	(✓)
gas storage (no CH)		✓					
gas instantaneous (no CH)			✓				
<u>Heat transfer direction</u>							
flue gas to CH water	✓	✓	✓	✓			✓
CH water to DHW					✓	✓	
flue gas to DHW		✓		✓			...
flue gas to comb. air							✓

Primary heat exchangers are designed to transfer heat up to the dew point of the flue gases, secundary heat exchangers are designed to extract heat beyond the dew point and thus create the condensing mode of gas/oil combi-boilers and water heaters. The tertiary heat exchanger is purely intended as an efficiency booster, to extract even more heat from the flue gases. It can only be applied in conjunction with a primary and secundary heat exchanger.

It is of course very likely that there are heat exchangers applied in gas/oil water heaters or combis that are not described above. However to indicate ALL possible variations would not help to structure the main trends as intended in the table above. The table is not exhaustive.

The following sections describe aspects of heat exchangers as applied in DHW systems. Since the design of a (combi)boiler or water heater is usually centered around the heat exchanger as the main component the overview also functions as a first introduction into types of (combi)boilers / water heaters available.

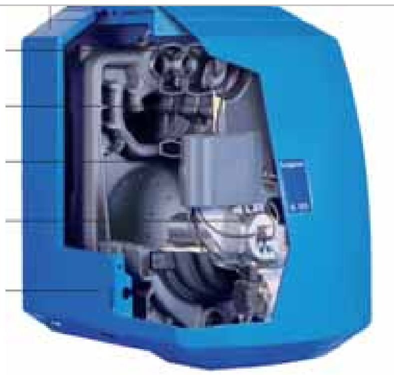
5.2.1 Cast iron heat exchanger

As described above the cast-iron heat excahnger is among the oldest principles/designs of heat exchangers. It is still applied in heating-only boilers with DHW supplied by an external cylinder equipped with a CH to DHW heat exchanger.

Boilers with cast-iron HE can be characterised as heavy, slow responding types of boilers with high primary water content (lots of water in the primary flue gas to CHW heat echanger) which also adds to its weight.

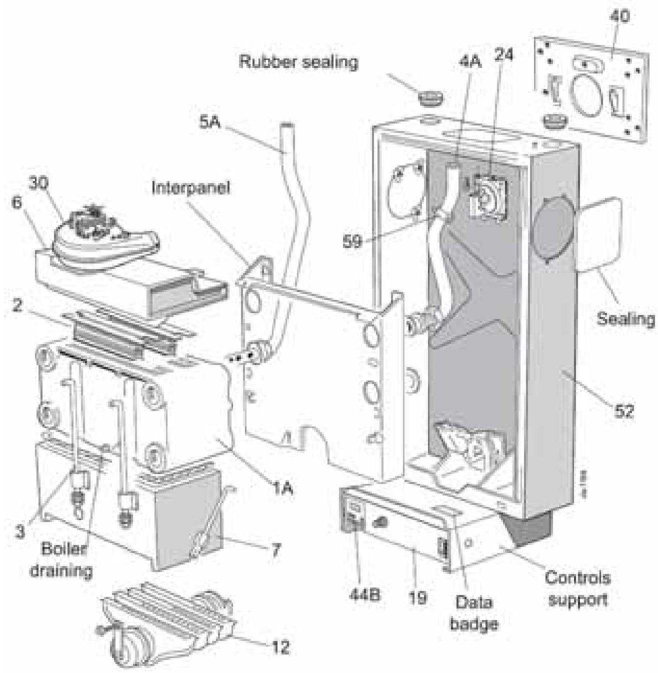
Figure 5-2
Vitogas 100 kW22. Floor standing atmospheric gas fired LT-boiler with cast-iron heat exchanger; Viessmann. Part load eff. 85% (GCV), Net weight: 119 kg. Water content: 9,7 l.

Figure 5-3
Buderus Logano G125 21kW. Floor standing oil fired LT boiler with cast iron heat exchanger. Part load eff.: 90% (GCV),
Net weight: 175 kg. Water content 33 l.



In the UK and Ireland there has been a market for cast-iron wall hung boilers. Nowadays these boilers often do not meet the demands of Part L of the Building Regulations.

Figure 5-4.
Ideal Boilers Classic SE (Sedbuk D), the cast-iron heat exchanger is indicated as part 1A).



5.2.2 Shell-tube heat exchanger

The "Shell & Tube" heat exchanger is based upon a tube- or pipe-arrangement placed within a shell that contains the connections for the two flows. Shell-tube HEs can function both as water-to-water HEs or as flue gas-to-water HE and are applied in many industrial applications. Here - for residential use - the main application is flue gas-to-water heat exchange.

Flue gasses are guided through the tubes, while boiler water circulates between the outer shell and the tubes. In the industry, this still is the most applied type of heat exchanger since it is very robust, especially towards flows containing particles. But also for small scale heat generators for residential applications, all kinds of variations on this type of HE are commonly used.

Figure 5-5
Viessmann Vitoplex 200 / 90kW.
Example of a shell & tube heat exchanger in a floor standing boiler gas fired LT-boiler.
Part load eff. 85% (GCV).
Net weight 345 kg. Water content 180 l.
[Source: Viessmann]

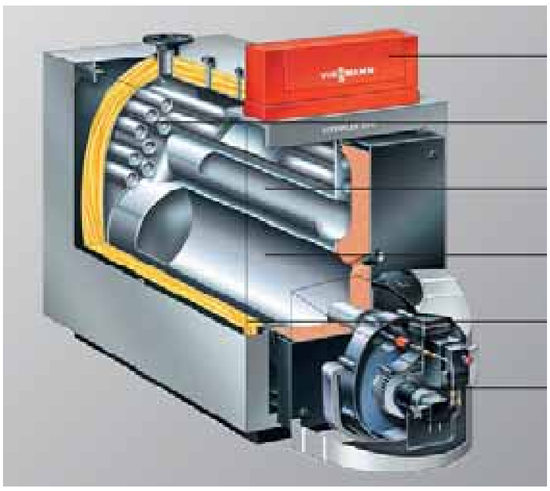


Figure 5-6.
Left: single pipe AO Smith NGT gas-fired storage water heater. Right: multi-pipe AO Smith ADMR gas-fired storage water heater

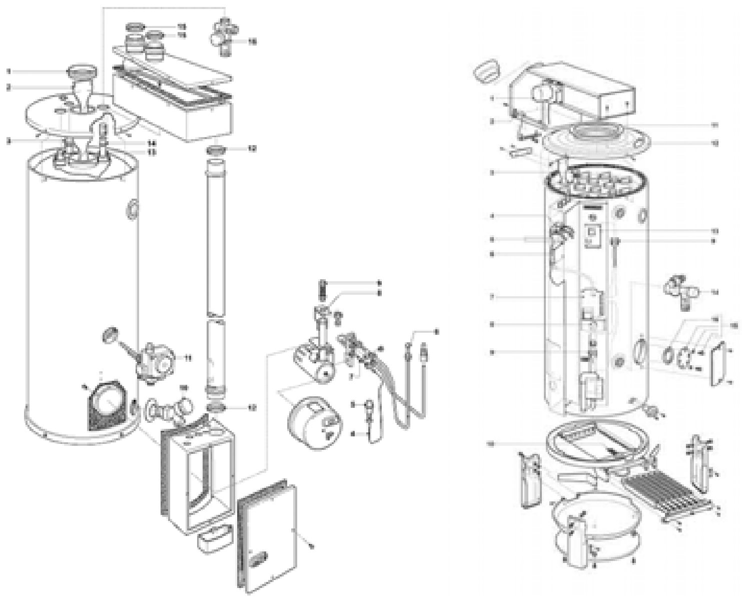


Figure 5-7.
Shell-tube heat exchanger by Frisquet, the coil supplies DHW

Heat exchangers based on plates

A variant of the shell-and-tube heat exchanger is the "shell-and-plate" heat-exchanger.Instead of tubes the flue gases are led to a construction with a (broadly speaking) flat plate surface (the plate can be circular or butted so that three-dimensional shapes are present).

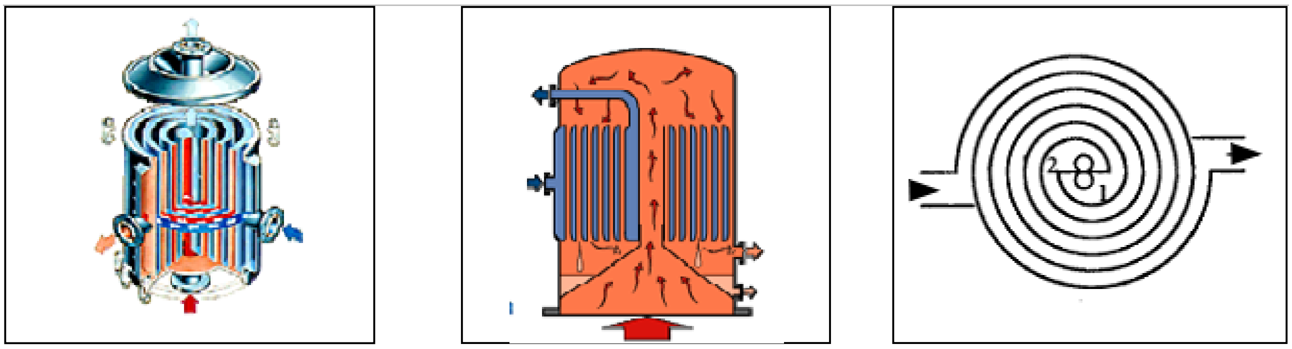


Figure 5-8.
Principle of spiral plate heat exchangers (source: ECN, Overzicht commercieel verkrijgbare warmtewisselaars, juli 2001).

Also for shell-and-plate heat exchangers it is possible to add fins to the surface and achieve higher heat transfer coefficients. Plates and corrugated fins (deformed plates) are then collated together in a sandwich construction.

Shell-tube heat exchangers are also redesigned to function as dual heat exchangers, for CH and DHW.

A special configuration of the “Shell & Tube” principle in the concentric tube-in-tube HE. In the boiler industry this type of HE is used for instantaneous combi appliances. This HE can both be used as a separate secondary HE for hot water production, or as a combined primary HE in the burning-chamber, heating both flows (CH- and sanitary water) at the same time (flue gases heating the outer tube which is used for CH operation. The inner tube is used as CH to DHW heat exchanger and is essentially a sort of submerged coil HE).

Figure 5-9
Tube-in-tube heat exchanger (as variant of shell-in-tube)

Another variation is the Daalderop Combifort which has a burner located at the top of a storage tank which directs flue gases through a shell-tube type heat exchanger to the bottom of the tank. The heat is first transferred to the CH circuit and from there to the DHW storage.

Figure 5-10: Daalderop Combifort

The figure above even shows a third coil-type heat exchanger that functions as a heat exchanger for a secundary CH circuit.

5.2.3 Fin-tube heat exchanger

Finned tube heat exchangers are probably the most commonly applied for light-weight wall-hung boilers and combis and probably represents the archtetypical heat exchanger applied for DHW. The fins are added to the tube/pipe to increase the heat transfer through convection on the gas-side (outside) of the tubes. To improve the heat transfer on the inside of the tube (water-side) groves can be applied.

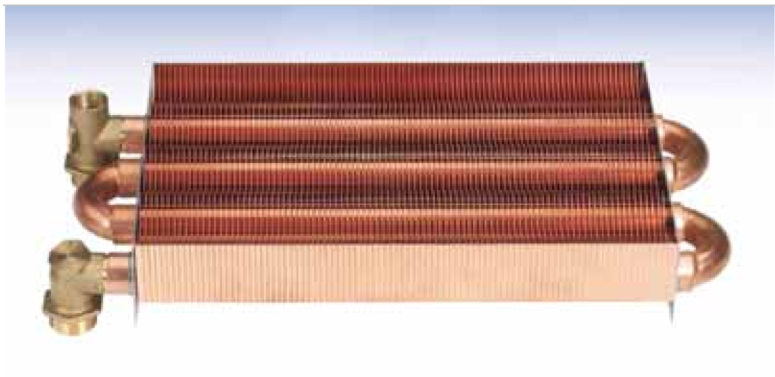


Figure 5-11.
Most commonly applied finned tube heat exchanger for wall-hung non condensing boilers, combis and water heaters. Fins or plates are brazed unto the copper pipes, the surface is hardened by shot blasting and painted with a silicone-aluminium mixture. This subassembly is placed within a casing (shell) on top of the burner (source: Fugas Italy).

Figure 5-12.
Heat generator of instantaneous dedicated gas-fired water heater exposed (Picture: eBay)

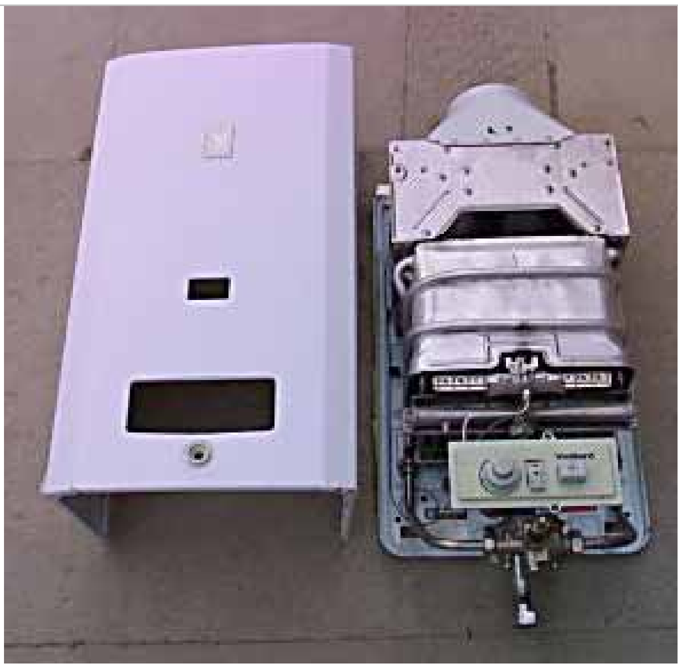
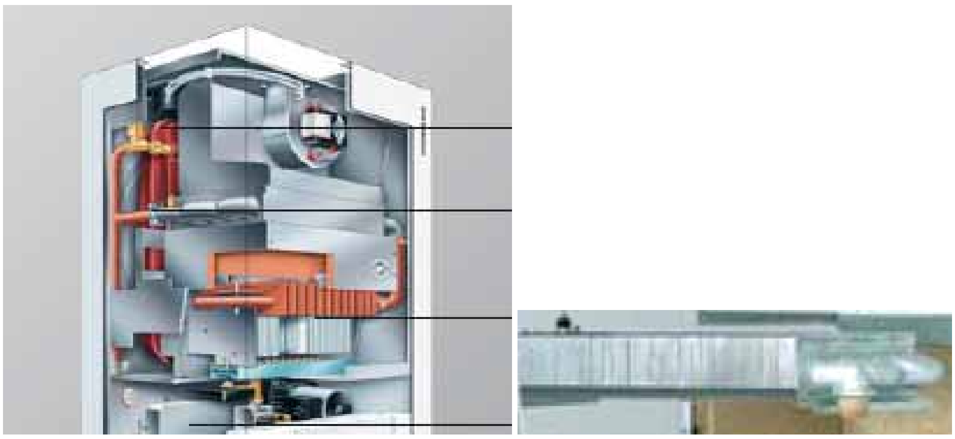


Figure 5-13.
Viessmann Vitopend 200 (24 kW). Wall-hung premix modulating fan assisted gas boiler, with light-weight finned tube heat exchanger. Part load eff.: 85% (GCV). Net weight: 48 kg. Water content: 0,55 l.



Several techniques are used to manufacture the finned pipes, like brazing, welding (high frequency /resistance), rotary extrusion (in case of aluminium) etc.

Other options to apply fins are illustrated below.

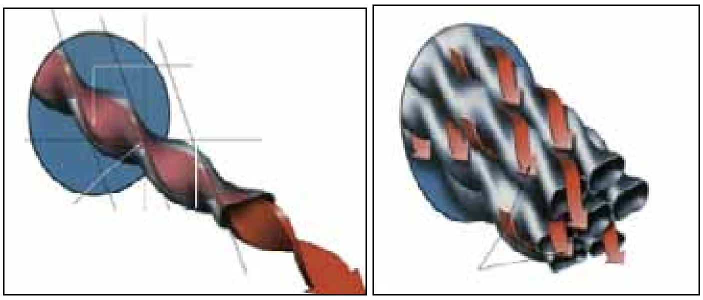
Figure 5-14.
Solid fin, in the form of a metal strip: The fin is helically wound around the specified pipe/tube and continuously fillet welded to the tube using the M.I.G. weld process (source: Tex-Fin, USA).

Figure 5-15.
Longitudinal fin: Fin in the form of a U-shaped fin channel, is resistance welded along the tube's longitudinal axis (source: Tex-Fin, USA).

Figure 5-16.
Serrated Fin: A metal strip that has been serrated or cut and then helically wound around the specified tube. The fin is welded to the tubular base using a high frequency weld process (source: Tex-Fin, USA).

Figure 5-17.
Extruded fin: This finned surface is formed as a thick walled aluminium tube is put through cold rotary extrusion, forming fins that are much longer in diameter than the original tube. This process hardens the aluminium so the fins are very strong, resulting in good heat transfer efficiency and high durability. It can be applied to single aluminium tubes (mono aluminium) or with the addition of a liner tube within the original aluminium tube (bi-metal) (source: UniFin, Canada)

Figure 5-18.
Twisted Tubes™: It is also possible to twist the whole tube, causing a turbulent flow both inside and outside the tube. According to the manufacturer heat transfer increases with roughly 40% (source: Brown Fintubes).



To improve the heat transfer coefficient on the inside of a tube the following options are available.

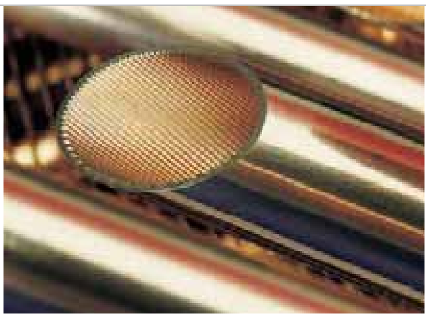


Figure 5-19.
Inner grooves: Inner grooved cooper tubes achieve a high energy transfer coefficient inside the tube at low pressure drop.

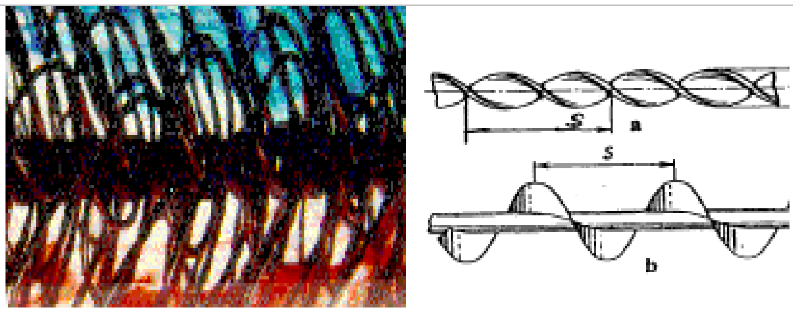


Figure 5-20.
Inserts: Another way to improve heat transfer on the inside of the tube is to add inserts into the tube that influence the flow characteristics of the boiler water. The left picture is an illustration of an internal wire matrix and the right picture is an example of a "twisted tape" insert.

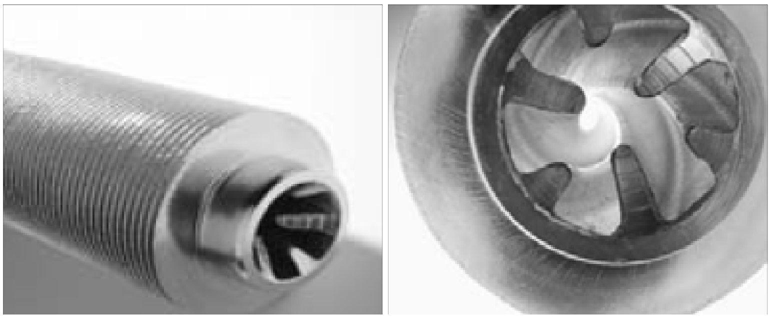


Figure 5-21.
Alu finned pipes: Nefit
Latest aluminium heat exchanger of Nefit with twisted flow technology (twisted ribs on the inside of the tubes).
In this version of the HE the aluminium ribs are coated to minimize oxidation and pollution of the HE (source: Nefit BV)

The fin-tube configuration is not only used in the traditional kitchen water heater (geiser), but also in the latest high efficient condensing boilers, however without the fins, but with a flattened tube to increase surface area.

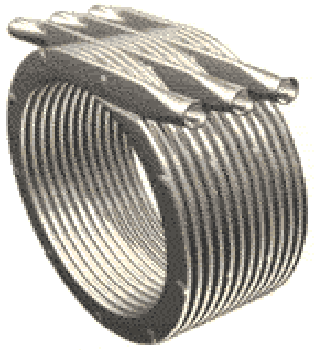


Figure 5-22.
Spiral flat-tube heat exchanger
Made of 0,8 mm stainless steel, consisting of 3 hydroformed coils of each appr. 8 kW
(source: Giannoni).

Figure 5-23.
The casing (or shell) of the spiral flat tube exchanger. Casing holds the 4 connections for the two media (flue gas and water) and mounting plate for the concentric burner
(source: Giannoni).

The condensing mode (at low temperature of primary water) is achieved by an extra coil which functions as the secondary heat exchanger. This coil is divided from the primary coil and burner by a well insulated deflector disc. The cold return primary water enters the HE in the last segment of this secondary coil and exits the HE at the first segment of the primary coils close to the burner. Because of its configuration and material, a relatively large part of the radiation heat is transferred to the boiler water, which can reduce the amount of material needed compared to a heat exchanger with mainly convective heat transfer.

This type of heat exchanger is being applied by several condensing boiler manufacturers, to name a few: Remeha (Avanta en Aquanta), Vaillant ecoTEC, Viessmann Vitodens.

Another variant of the fin-tube principle is the combination of fin-tube with an internal coil HE. This type of heat exchanger is able to simulatneously produce both CH and DHW.

Figure 5-24.
Ferroli Dual Heat Exchanger as found in the Domitop range.

5.2.4 Aluminium die-cast heat exchanger

Various boiler manufacturers use their own integrated casted heat exchanger. Some manufacturers still use cast iron as base material (floor standing boilers) but the many companies already changed to aluminium alloys. The advantage of this approach is that casing and heat-exchanger and all necessary connections can be integrated into the castings, reducing the number of components and assembly times.

Another advantage of this integrated approach is that heat exchanger design can be further optimised for radiative heat transfer, by creating a configuration where the burner surface is fully surrounded by the water containing heat exchanger- surface.

A few design- and engineering companies are specialised in this field.

Figure 5-25.
Integrated aluminium HE by Aluheat.
The company Aluheat (taken over by Bekaert may 2006) designed a new family of condensing heat exchangers. This new product line is available for all boiler manufacturers.
Characteristics
+ available in capacity of 28 kW, 36 kW and 46 kW
+ monobloc casting, so no internal weldings or couplings
+ low water content
+ low hydraulic resistance
+ small compact design
+ fire chamber water cooled, so no ceramic insulation required
+ water channels in full serial water flow
+ smoothened heat transfer through optimised flue and water geometry
+ aluminium; good anti corrosion properties, high heat conductivity, low weight
(source: Aluheat)

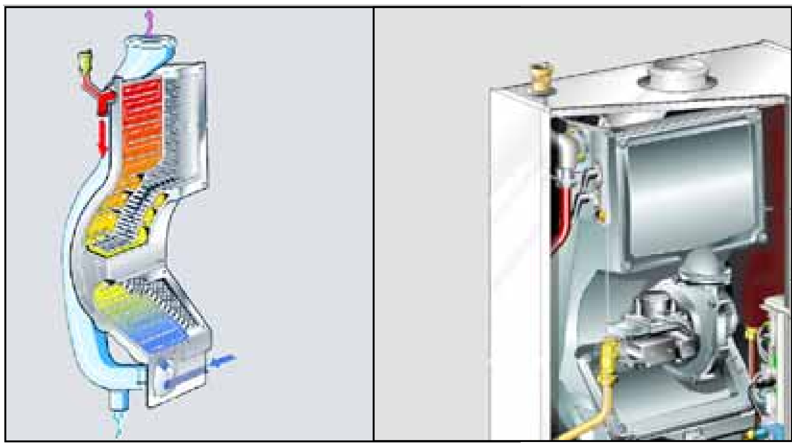
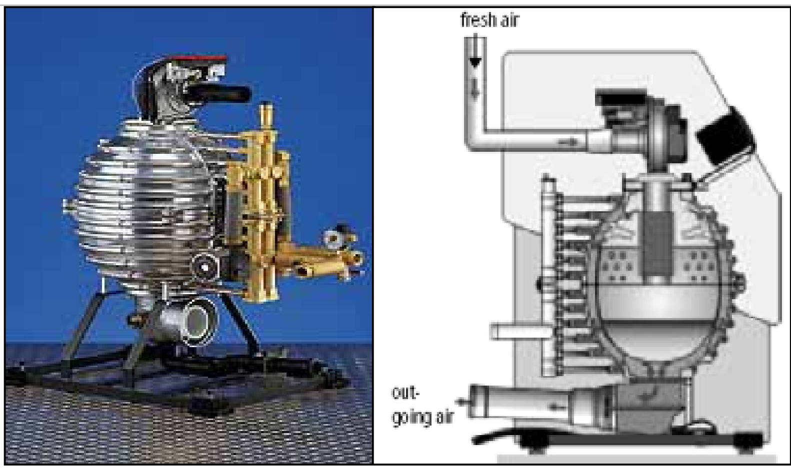


Figure 5-26.
Weishaupt Thermo Condens: Weishaupt uses an integrated al/si-casting as heat exchanger in their new Thermo Condens wallhung boilers. The heat transfer coefficient is optimised for each temperature zone through a dedicated surface design per zone. The half-moon shaped channel prolongs the surface and optimises the heat transfer from the condensate. Combined with the flat radiative burner part-load efficiencies (40/30°C) of 100% (GCV) are reported (EN303) (source: Weishaupt)

Figure 5-27.
Rotex A1 BG Gas condensing boiler: This floor standing boiler used a ball-shaped aluminium die-casted heat exchanger in combination with a premix burner. Part load eff. 99% (GCV) Net weight: 74 kg (incl. 49 kg for boiler chassis) (source: Rotex GmbH)



An innovation regarding die-cast aluminium heat exchangers was introduced by Dutch company Intergas in 1996. They combined the primary CH heat exchanger and the DHW heat exchanger in one integral component by inserting copper tubes in the die-cast mould and then pressure cast the aluminium around the tubes. The integral heat exchanger is capable of achieving condensing modes for both CH and DHW mode. Furthermore this solution could do without the 3-way valve or other components needed in traditional combis to transfer the heat from the primary CH heat exchanger to the DHW.

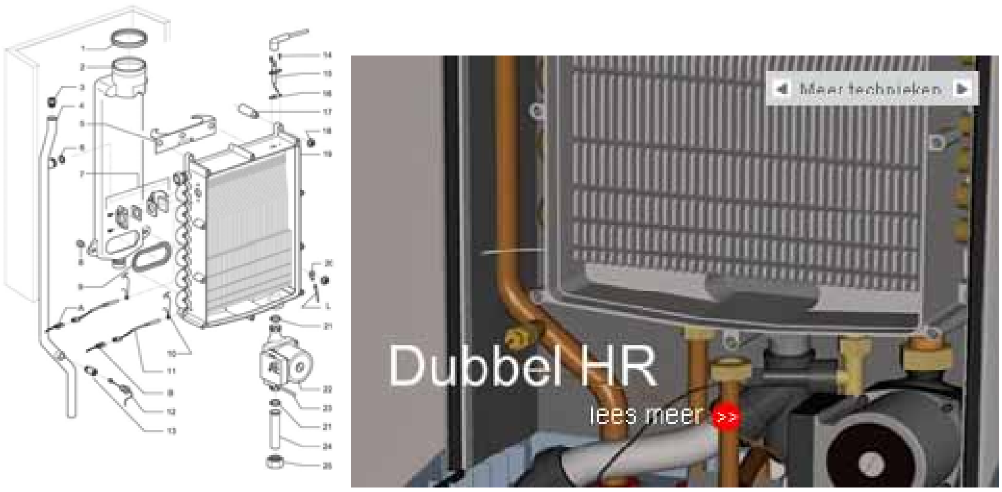


Figure 5-28.
Intergas Kombi Kompakt HR 28, introduced in 1996, boasts condensing DHW performance., due to its integral heat exchanger (#19 in figure). Annual DHW efficiency 89% (NL test standard), DHW performance 8 l/min @ 60ºC / 13 l/min @ 40ºC (28 kW). Space heating efficiency (part load) 109%. 15 Year guaranty on heat exchanger, 2 year on other parts. Minimum flow 2 l/min.

5.2.5 Tank-in-tank heat exchanger

In the case of a separate DHW cylinder the heat exchanger is not positioned in the heat generator, but in or onto the cylinder itself. One version is the tank-in-tank heat exchanger where a tanks is positioned inside (often only partially) another tank. The outside area of the inner tank forms the heat exchange area with the outer tank.

A major difference with conventional coil-shaped heat exchangers in a tank is that the primary water volume is much larger.

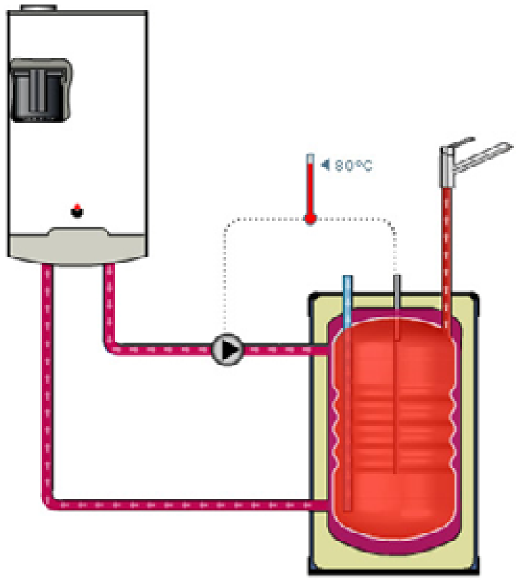


Figure 5-29.
ACV Tank-in-tank heat exchanger as applied in separate storage cylinder.

5.2.6 Coil heat exchanger

The coil heat exchanger is a typical water-to-water heat exchanger and is applied mostly as CH-to-DHW heat exchanger in DHW storage tanks.

Probably the best known application of a coil heat exchanger is in a storage tank filled with DHW in which the coil supplies heat from a CH circuit. The reversed configuration is also applied, where the tank is filled with CH water and for the coil extracts heat for DHW purposes (allowing a sort of instantaneous DHW production possible).

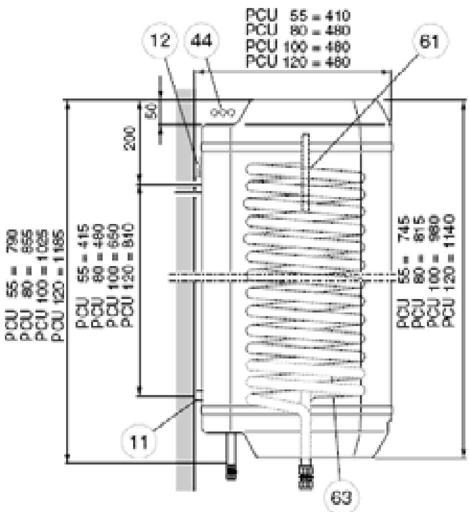
Both principles are applied throughout the market for combi-boiler (or similar set-ups based upon solo-boilers), in small to very large variants.

The application in DHW storage means that most coil heat exchangers operate at temperatures (well) above 60 °C in order to maintain a safe, legionella-free DHW system. The drawback is that it is difficult to use latent heat from combustion (condensing mode). The recent years have shown development of storage configurations which do allow the use of heat below 55-60°C. In this report they are referred to as "Schichtladenspeicher" - and are further described in the paragraph further down.

Performance

A 80 liter tank can be equipped with 8 meter coil heat exchanger of 22 mm outer diameter copper tube. The heat transfer surface is in that case 0,55 m² and with a feed temperature of 90 °C and a storage temperature of 10°C the power transferred is 29 kW. Such a boiler can produce 710 liters of water per hour or 11,8 l/min at 45°C continuously.

Figure 5.30.
Nibe boiler, type PCU



Type		PCU 80/8	PCU 100/10	PCU 120/12
Boilerinhoud	liter	80	100	120
Netto gewicht	kg	47	55	65
Hoogte/breedte/diepte	mm	816/475/480	978/475/480	1140/475/480
Diameter	Ø mm	-	-	-
Spiraallengte warmtewisselaar	m	8	10	12
VO warmtewisselaar	m2	0,55	0,7	0,9
Continu tapcapaciteit 90 /10-45°C	ltr/uur	710	810	960
Warmte overdracht90 /10-45°C	kW	29	33	39
Aanwarmtijd tot c.a 60°C	min	16	16	14
KW/WW knelkoppelingen	Ømm	15	15	22
Aansluiting CV A+R	Ømm	22	22	22
Artikelnummer		088354	088310	088311

Figure 5-31.
Increased surface area of heat exchanger by splitting a single tube into four smaller tubes [source: www.Albion-online.co.uk]

5.2.7 *Plate heat exchanger*

These types of compact plate heat exchangers are mainly used for liquid media or media with similar heat transfer coefficients (α). In the boiler industry this type is widely applied for sanitary hot water production, where heat from primary CH-water is transferred to sanitary water.

A plate heat exchanger consists of several rectangular plates (with a flow pattern pressed into them) that are mounted on top of each other. Between two plates a compartment is created through which the flows are guided. Each plate contains four openings (one in each corner) to allow the flows to enter and leave a compartment. Each medium only flows through half of the total number of compartments, each time skipping one compartment. As a result the two media always flow next to each other, with a heat-transferring plate in between. For this purpose, plate heat exchangers are considered the most compact and cost-efficient solution.

This type of compact plate HE is not suited for the heat-exchange of flue-gas to water.

Figure 5-32.
Pictures of soldered plate heat exchangers (source: ECN, Overzicht commercieel verkrijgbare warmtewisselaars, juli 2001).

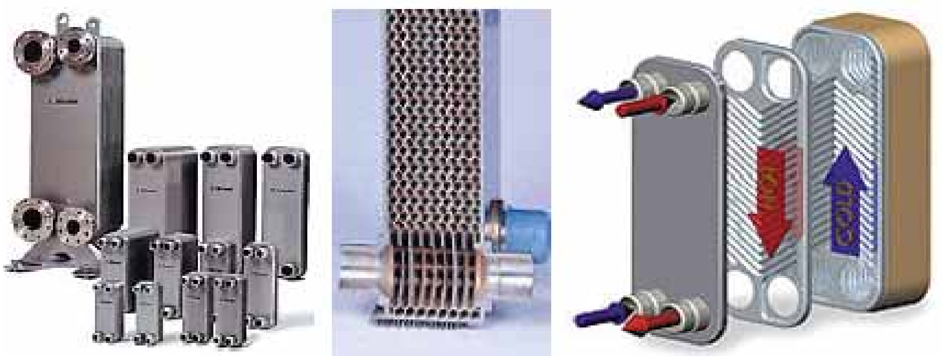


Figure 5-33.
Vaillant atmoTEC VC194 (22kW). Wall-hung atmospheric modulating gas boiler, with light-weight finned plate heat exchanger (positioned in the bottom half of the appliance, left to the pump).
Net weight: 37 kg

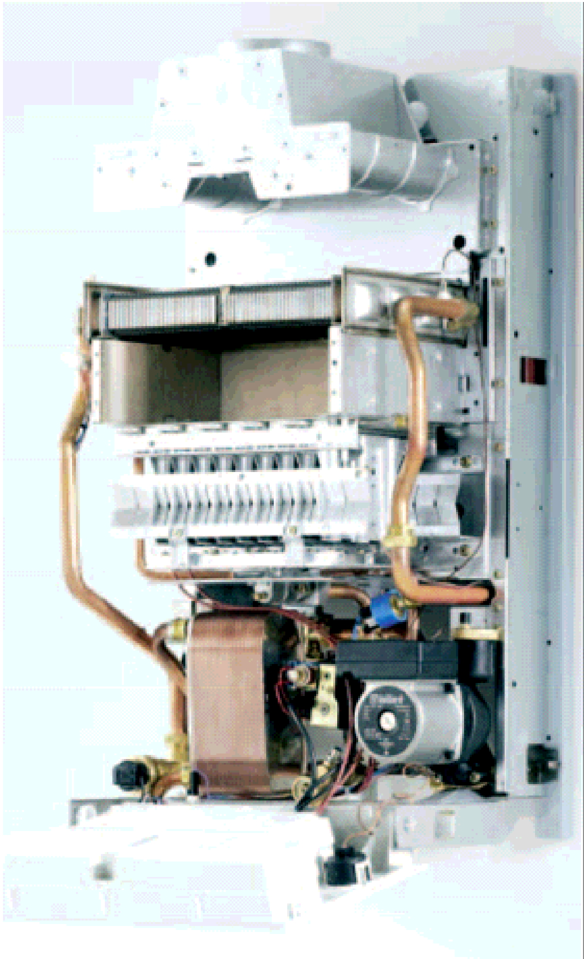
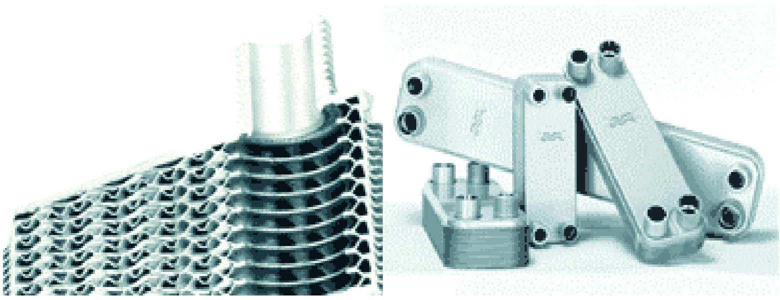


Plate heat exchangers are also the main component in substations for collective heating (and district heating)

The water-to-water heat exchanger is usually of the plate heat exchanger type. These are very compact and ideally suited for transferring heat from media with similar fluid characteristics.

Figure 5-3.
AlfaLaval Plate heat exchangers



The output of heat exchanger can range from a few kW up to 500 kW and should be dimensioned to satisfy the maximum hot water demand.

The output of a plate heat exchanger is primarily a function of heat transfer surface, which follows from the dimensions of the stack of plates. Other design issues are the pressure drop (pressure loss) over the component (or the whole system), the build up of lime and scale and materials used.

The build up of limescale is in some types of substations prevented by a fast responsive valve, shutting down the supply when the hot water demand stops - this way hot water is only allowed to enter the heat exchanger when there is a demand to transfer the heat to. In general plate heat exchangers are less susceptible to limescale because the flow is very turbulent when compared to tube-in-tank type of heat exchangers.

The materials used in the PHE determine its longevity and how it affects other components. Some larger plate heat exchangers (like the AlfaLaval TSN range) are gasketed (each plate is seperated from the other by a leak-proof gasket), the stack is compressed by a series of fasteners. Others are copper brazed or fusion bonded (like the all stainles steel AlfaNova plate heat exchangers by AlfaLaval). Each types comes with its specific pro's and con's [35]:

- Gasketed PHE: Has limited resistance to high temperature and certain fluids. Needs maintenance. Capacity can be modified on site, at will.
- Copper brazed PHE: High resistance, but limits due to copper ion exchange (can incurr corrosion in nickel plated steel);
- Nickelbrazed PHE: Limited mechanical strenght due to chemical changes in braze area;
- (Laser) Welded PHE: Fulfills most demands but is costly
- AlfaFusion PHE [36]: Patented technology by AlfaLaval, applied in AlfaNova PHE. providing high tensile strength and temperature resistance. Its 100% steel composition prevents copper ion leakage which may cause corrosion in galvanised piping networks. In some Ditrict Heating areas the use of copper brazed PHE is not allowed anymore.

Figure 5-35.
Copper brazed [Figure: Alfa Laval]

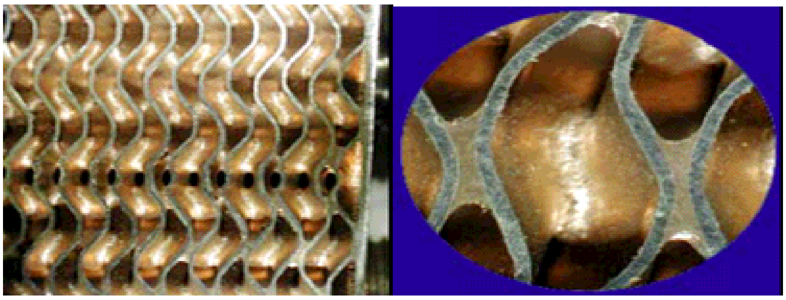
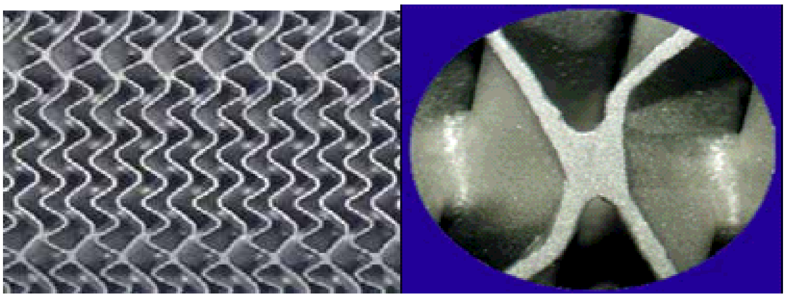


Figure 5-36.
AlfaFusion [Figure: Alfa Laval]



Most PHE can easily withstand temperatures of 120 °C and 16 bar pressure.

The heat transfer efficiency of plate heat exchangers is very high: The flow is counterflow and turbulent, the stacks are made from very thin steel sheet thus ensuring high thermal efficiency in the range 80 to over 90 %. Heat that is not transferred to the secundary circuit is not essentially "lost", it is only retained in the primary circuit. The effect however is a somewhat higher return temperature which in most cases reduces the efficiency of the primary heat generating process. Radiation losses of the plate heat exchanger are "real", non-recoverable losses. These losses depend on the siting of the heat exchanger (in or outside the heated area), the insulation and the number of cycles.

[35] http://svk.ch/Kalteforum/2006/Buendelrohraustauscher.pdf

[36] Stainless steel chemically bonded by thermically hardened paste, without changing the chemical properties of the base material.

5.2.8 Secundary and tertiary heat exchangers

Secundary and tertiary heat exchangers are applied to extract latent energy from flue gasses. Materials used are corrosion resistant: Stainless steel (forged, welded, brazed), Aluminium (die-cast), copper (forged, welded, brazed)

Figure 5-37.
Weishaupt Thermo Unit, WTU 25 GB (25 kW). Floor standing condensing oil boiler with external secondary (ceramic) heat exchanger. Part load eff.: 96% (GCV). Net weight: 268 kg. Water content: 40 l.

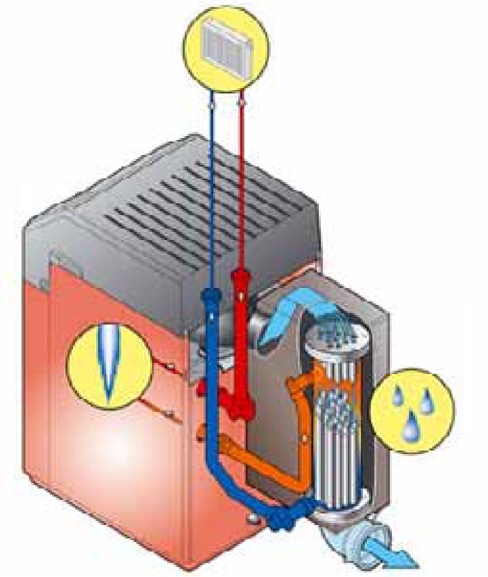
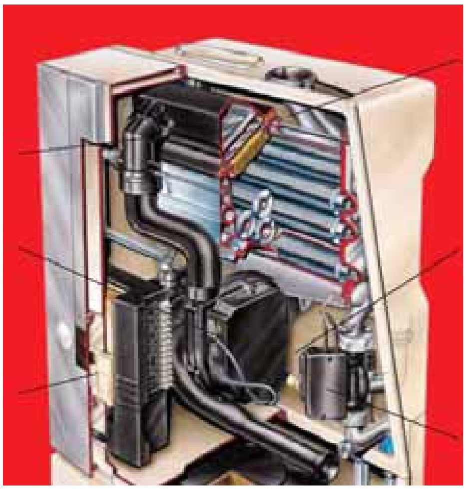


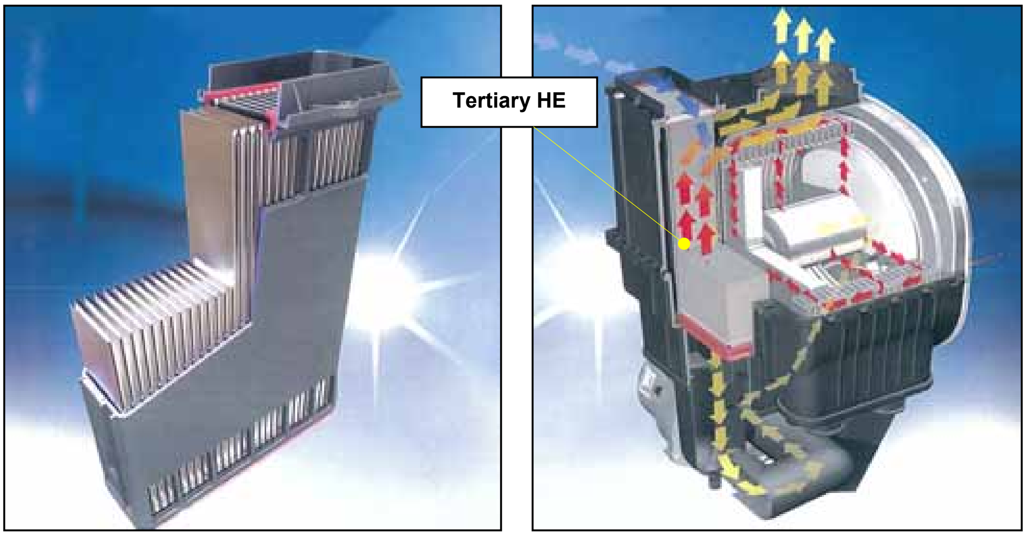
Figure 5-38.
Nefit Ecomline Excellent HR 30 (28 kW)
Wall-hung condensing premix gas boiler, with aluminium finned pipe heat exchanger. Part load. Eff. 97% (GCV). Net weight 59 kg. Water content: 2 l.



For *tertiary* heat exchangers (flue-gas/combustion-air he) plastics can be used because temperatures of flue gasses are below 90°C. Since with plastic the wall-thickness of the material between the two flows can be reduced to below 0,3 mm. the heat transfer between flows becomes less dependent on the thermal conductivity of the material itself. Plastics (e.g. PP) are then a good option, because they have a very good chemical resistance.

HE-manufacturer Giannoni SAS integrated a tertiary heat exchanger in it's condensing HE-design, and uses only plastic for the casing. The tertiary HE itself is made off metal strip.

Figure 5-39.
Heat Exchanger from Giannoni, with a stainless steel primary- and secondary heat exchanger and an integrated tertiary heat exchanger. Giannoni S.A.S. / Aeropole Centre, 29600 Morlaix France / www.giannoni.fr



The air to air heat exchanger is positioned between the combustion air intake and the flue gas outlet. It provides continuous condensing operation, regardless of the water temperature regime used. The company claims that fume temperatures are always lower than 55°C, and that it also reduces plume production at the outlet.

The German company Götz Heizsysteme GmbH, uses a thermoformed plastic heat exchanger for its floor standing oil or gas boiler, carrying the name "ProCondens".

With this plastic tertiary HE the combustion air is preheated to approximately 60°C and the flue gasses are cooled down to around 40 – 50°C. As a result flue gasses will condensate also with higher boiler water return temperatures.

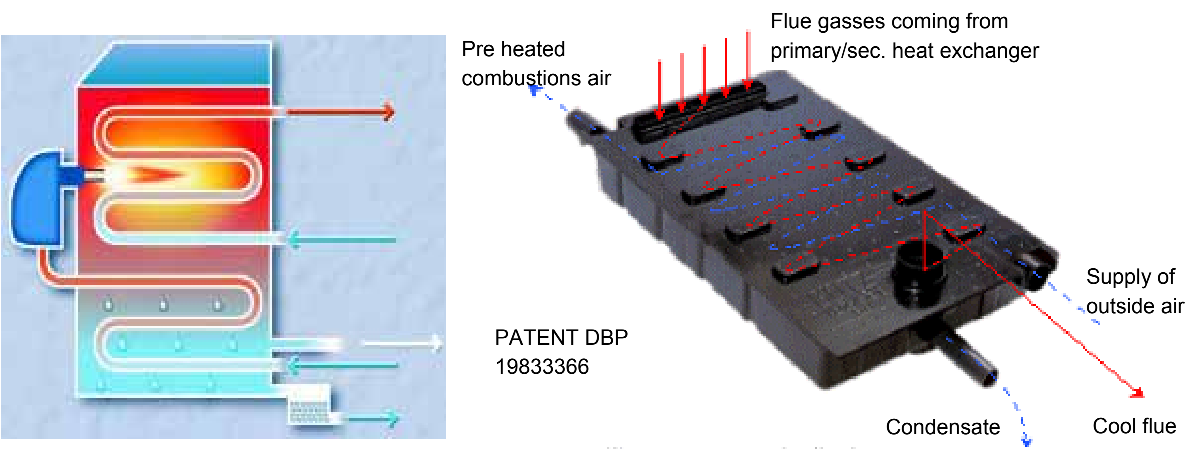


Figure 5-40. ProCondens, from Götz Heizsysteme GmbH, www.procondens.de

SECTION TWO - WATER HEATERS, GAS-/OIL-FIRED AND ELECTRIC

6 SUBSTATIONS

Note: District Heating networks rely on substations to distribute DHW to dwellings. District Heating is however outside the scope of the underlying study. This Section (and Task 2 Market Analysis) includes substation water heaters to complete the overview of water heating technologies, but substations will not be part of further investigation in the subsequent Tasks.

6.1 Product description

Substations transfer heat from a collective hot water circulation loop to a DHW circuit and/or the space heating circuit of a dwelling or building. The collective loop can be part of a district heating circuit or the central heating circulation loop from a collective boiler in a multi-family building.

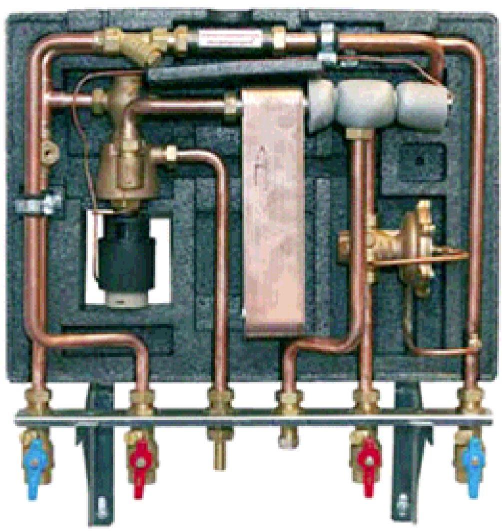
The *space heating* function of a substation can be directly fed (meaning the distributed hot water is fed directly to the radiators for space heating) or with mixing facility (hot water is injected / mixed into a circuit for space heating) or indirect (the space heating circuit is hydronically separated from primary hot water).

The *water heater* function is always indirect, producing DHW on demand from mains cold water. It is possible to connect the substation to a storage tank which is referred to as a semi-instantaneous system. In combi-substations the DHW overrules the space heating function.

As a result various types of substations exist, but the main components are more or less the same:

- heat exchanger (water-to-water);
- regulating valves (thermostatic, pressure regulated or motorised);

Figure 6-1.
Substation internal lay-out
(picture: AGH Centurion)



Certain types of substations include circulators for the space heating circuit or for thr DHW circuit (in case the substation feeds a DHW storage tank).

Larger substations, serving multiple dwellings, hospitals, hotels or service flats, etc. are available at least in sizes ranging from 75 up to 500 kW (example AlfaLaval TSN range).

Figure 6-2.
Large substation, available up to 500 kW (picture: Alfa Laval TSN)

Major manufacturers of substations are: Alfa Laval (Sweden), Danfoss (Denmark), AGH (Netherlands - using Danfoss components) and Agpo-Ferroli (Italy/Netherlands).

Materials

In most cases, copper and/or copper brazed heat exchangers are used in district heating substations. In some district heating areas copper brazed heat exchangers are not allowed because of potential copper ion leakage. Copper ions may introduce the risk of corrosion of galvanised pipework - the copper ions break down the galvanic surface thus exposing the steel. A stainless steel heat exchanger can be used to avoid the problem.

6.2 DHW performance

6.2.1 Flow rate

The DHW flow rate produced by substations depends on the size of the heat exchanger and feed temperature (assuming a constant flow rate and a predefined allowable temperature drop of the feed circuit).

Typically a substation is designed to produce DHW for an entire dwelling, e.g. function as a primary water heater. The flowrates are thus in the area of 8 l/min at 60ºC or higher. This corresponds to heat exchanger capacities of 24kW and higher.

Example: The maximum flow rate of the URS Elegance (two options) is 8 or 12 l/min at 60ºC indicating a heat output of 25 or 38 kW [37], which is comparable to standard sized combi-boilers (providing the heat supply is also large enough).

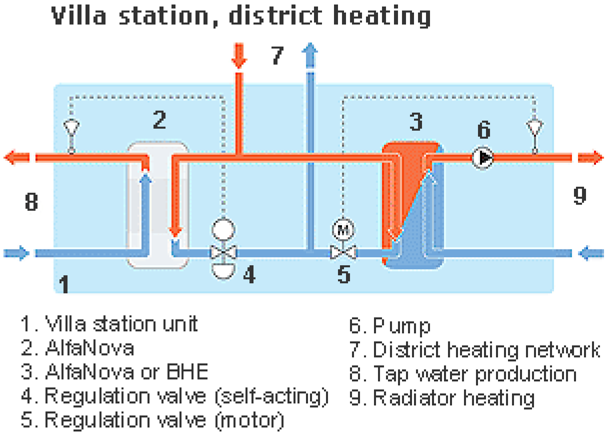
6.2.2 Temperature control

The substation keeps the DHW temperature at the outlet constant independent of flow rate fluctuations (draw-off valves opening/closing, pressure loss, etc.). through passive (hydraulic) or active (electronic) control components.

An example of 'passive' control (without auxiliairy energy use) is the Alfa Laval Villa Station pictured below, which uses a 'self-acting' thermostatic valve in the 'primary' supply side and a the temperature gauge placed in the DHW circuit. The gauge may be pre-set to (for example) 55ºC and allows the thermostatic valve to remain open until the DHW has reached the set temperature. When this temperature is reached the thermostatic valve closes. This way a fairly steady temperature of DHW can be attained, although there is some delay due to the response time of the thermostatic valve.

[37] The flow of 8 l/min equals 0.13 l/s and with a water inlet temperature of 15 degrees the temperature rise is 45 ºC. The specific heat capacity of water is 4.18 kJ/l*K. The output of the plate heat exchanger is 0.2*45*4.18 is 25 kW. 12 l/min results in 38 kW.

Figure 6-3.
Functional schematic of substation with thermostatic valve for DHW operation (picture: AlfaLaval)



An example of a substation with 'active' components is the AGPO URS Elegance which uses an electronic controller connected to a flow sensor to sense DHW draw-off, temperature sensors to sense DHW and feed temperature and a motorised valve to control DHW temperature. The temperature control is more accurate under varying circumstances. The responsiveness is still subject to the speed of the motor valve (may take 2-3 seconds to open).

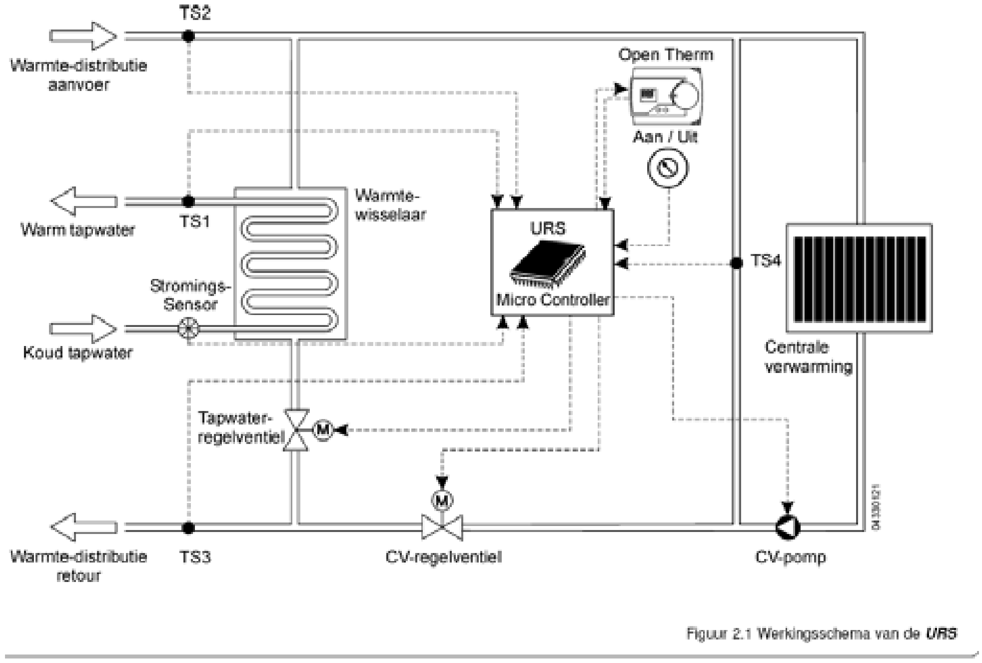
Figure 6-4.
Sensors Surface mount NTC

Temperature sensors
Sensors that measure the temperature of fluids, air or gasses. These sensor elements are usually thermistors (NTC) but other types are also possible. Sensors are available as surface mount sensor and as direct immersion sensor, in various shapes and with various NTC characteristics.
T-sensors are used in safety thermostat, and for measuring boiler feed- and return temperature, and in combis the sanitary water temperature.

Figure 6-5.
DHW Water flow sensor

Waterflow sensors
Flow sensors are primarily designed to measure the hot water flow rate in domestic water heater appliances. Most of them are mechanical and use a turbine that indicates the flow with its rotation speed. The turbine supports a magnet which rotates in front of a Hall effect sensor, which results in an electronic frequency that is directly proportional to the water flow through the sensor.

Figure 6-6.
Schematic of Agpo URS Elegance
(picture: www.agpoferroli.nl)



6.3 Energy

6.3.1 Steady-state efficiency

Substations do not have a heat generator. The efficiency of the primary heat generator (collective boiler or district heating station) and heat distribution should be considered in a system approach and should include an allocation of these losses to DHW heating and space heating functions when applicable.

When looking at the heat transfer efficiency of the plate heat exchanger only, one may assume this is very high, possibly over 95% (turbulent, counter flow). Heat not transferred to DHW is returned to the distribution loop. It can be argued that such 'un-used' energy raises the return temperature and reduces the efficiency of the primary heat generation process (at district heating plant or collective boiler) and reduces the overall efficiency of the system. This is however outside the scope of the study.

6.3.2 Standby energy consumption

Comfort switch

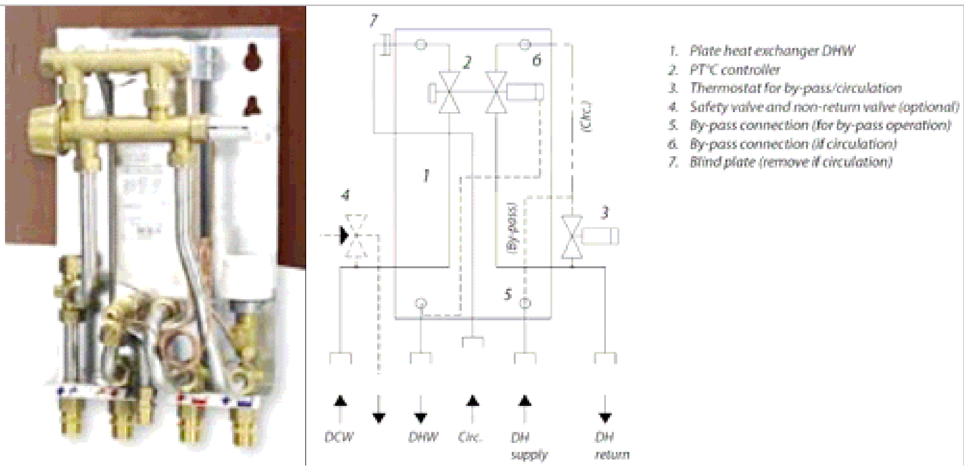
Most substations experience some delay in heating up DHW. Partly this is due to the thermal mass of components involved and to overcome this delay substations may be equipped with a "comfort switch" that offer faster DHW delivery times, especially during periods of low heat demand. It is during these periods (summer operation) that no heat is transported through the appliance for extendend periods and the heat exchanger stays relatively cool.

Substations with an active (electronic) control offer a 'comfort switch' that activates a setting to periodically open the 3-way valve and send some heat over the plate heat exchanger.

Other, 'passive', substations can use a thermostatic valve to continuously feed the supply side of the DHW heat exchanger with water of a certain pre-set temperature (often limited to max. 45ºC to avoid scaling). See #3 in the picture below (thermostat for by-pass/circulation).

The comfort switch thus adds to envelope losses or standing losses.

Figure 6-7.
Passive substation with comfort switch (thermostat by-pass circulation #3 in picture) (picture: www.danfoss.com - Akva Lux)



Modern substations may have an insulated casing, made of pre-moulded (EPS) parts that closely follow the outline of the components to reduce thermal losses.

Figure 6-8.
Insulated Westfa substation (picture: www.westfa.de)

6.3.3 *Start-stop losses*

Start-stop losses are mainly related to repeated heating up and cooling down of the thermal mass. The mass (product weight) of the URS Elegance is 25 kg. The AkvaLux pictured above weighs 15 kg, which gives and indication of the weight range for domestic use.

6.3.4 *Auxiliary energy*

Hydraulic controlled ('passive') substations using a thermostatic valve to regulate DHW temperature do not require auxiliary electric energy and are controlled by passive components only (example by Danfoss, AGH).

Electronic controlled ('active') substations need electrical power for electronic controls. In case the substation also provides space heating an 'active' 3-way valve or two 2-way valves (to open/close the DHW or CH circuit) are needed. The power consumption of the Agpo URS Elegance for example with two motorised valves is 5VA minimum and 30VA maximum (excluding circulator). The circulation pump may use some 50 to 65W to feed the space heating circuit (but is essentially not part of the DHW system). A benefit of the system with a central controller and motorised valves is that it can be connected to a standard room thermostat for easy control of room temperature (modulating). The control-unit itself may consume a few Watts continuously (the AGPOFerroli URS Elegance has a minimum power consumption of 5W, Rendamax units with a capacity of 15 to 500kW require 15W for the control unit).

Figure 6-9.
Features of the AgpoFerroliURS Elegance (picture: www.agpoferroli.nl)

The AgpoFerroli URS Elegance 12 l/m features options that are typical for combi-boilers:

- Can be combined with on/off and modulating room thermostats (Open Therm possible);
- Can be combined with solar water heater storage;
- Hot water production overrules space heating;
- There is an comfort-option that periodically heats up the heat exchanger in periods of low space heating demand - thus ensuring that the supply lines are filled with warm water.

6.3.5 Alternative energy sources

Certain manufacturers claim their substations to be ready for connection to solar storage (or heat pump) systems. This assumes the substation is capable of handling inlet of water at high temperatures (e.g. 90°C) which should not be a problem given the existence of space heating and district heating circuits with a feed temperature of 90°C. The thermostatic feedback-loop reduces the outlet temperature to 60°C (or other pre-set value).

6.4 Infrastructure

6.4.1 Combustion air / flues

Substations do not require combustion air nor flues.

6.4.2 Envelope / noise / position

Important factor in envelope losses is the ambient temperature, which depends on the position in the dwelling. Substations for single-family households are relatively modest in size and are placed within the insulated shell of the dwelling but out of sight in cupboards, metering closets or storage spaces. The presence of district heating pipework often raises ambient temperatures.

Figure 6-10.
Substation without cover, placed in metering cupboard (picture: www.aqua-tech.nl)

Larger substations (like the Alfa Laval TSN of 75-500 kW) that provide DHW for a whole building can be placed in the boiler rooms or equivalent spaces, that are probably but not necessarily within the insulated shell of the building.

The product size of normal domestic substations differs per model type but is approximately 0,03 to 0,06 m³.

Noise is not really an issue (below 30 dBA)

6.4.3 *Drains*

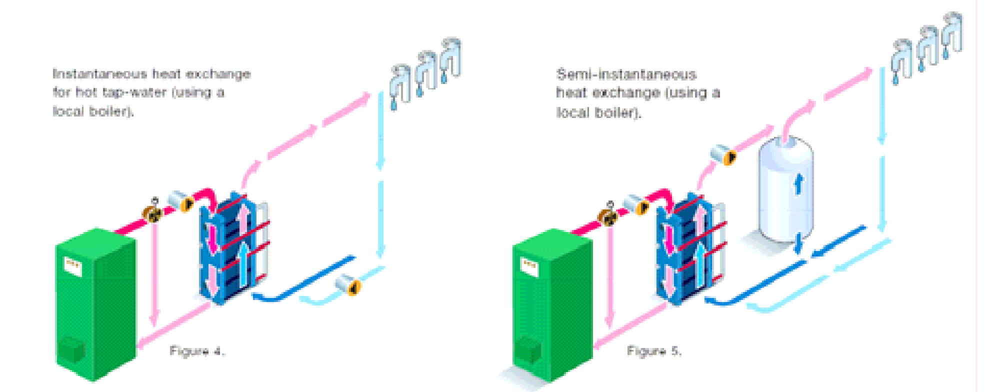
Some substations are equipped with a safety relief valve (blow off pipes) and require a connection to waste water drains. This is not a standard feature.

6.4.4 *DHW infrastructure*

Substations generally provide enough capacity to act as primary water heater, serving multiple draw-off points. Realisation of a DHW recirculation loop is possible.

It is possible to link substations to individual primary (space heating) boilers and/or storage tanks and produce (and store) DHW this way. In such cases the substation acts as an external DHW heat exchanger and from technical point-of-view the difference with a boiler plus internal heat exchanger is minimal (see chapters on combi-boilers - instantaneous and storage).

Figure 6-11.
Substations linked to DHW circualtion or storage boiler (here fed by a local boiler) (picture: www.alfalaval.com)



6.5 Prices

Substations streetprices are close to that of gas fired combi-boilers. Below are some street prices for substations found for the Netherlands and Austria:

The AGH Centurion costs € 1.130,00 (incl. VAT) in the Netherlands. To this has to be added some € 380,00 for standard installation costs and a monthly maintenance charge of € 4,03. This includes servicing and repair (excluding € 15,50 upfront costs for each visit). The unit can also be rented for € 20,34 / month, including installation, maintenance/repairs. (http://www.e-s-a.nl/producten.php?id=73)

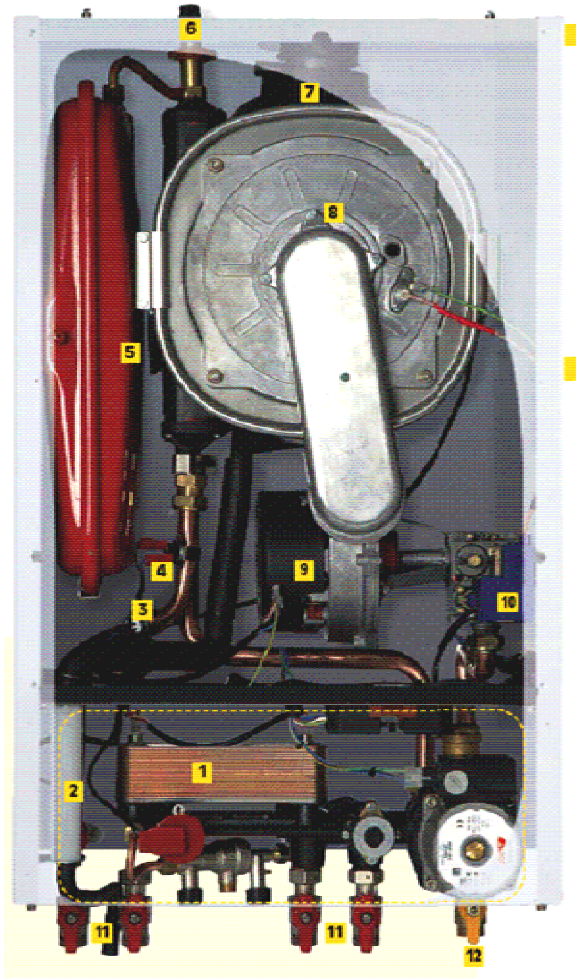
The Danfoss Akva Lux 26 substation costs € 1199,52 (incl. 20% VAT) in Austria and the Akva Lux 40 costs € 1578,78 (incl. 20% VAT) (http://shop.smuk.at).

7 GAS/OIL-FIRED INSTANTANEOUS COMBIS

7.1 Product description

The gas- or oil-fired instantaneous combi-boiler is one of the most successful water heater products in Europe today. It combines production of space heating and DHW in one, relatively small package. Gas-fired wall-hung models are the most popular (see also Task 2 Report - Market Analysis). Oil-fired instantaneous combis do exist but are rare.

Figure 7-1.
Typical combi internal lay-out (picture: www.AuerGianola.fr - model Lelia)



1 DHW plate heat exchanger
2 Modular design: this section can be replaced by other sections offering other functionality e.g. solo boiler
3 CH supply
4 CH return
5 CH Expansion vessel
6 Air vent
7 Flue exhaust
8 Burner chamber, with combustion air supply on front
9 Combustion air fan
10 Gas control unit
11 On/off valves for CH supply/return and DHW cold in/ warm out
12 Gas valve

In this study the instantaneous combi is defined as a boiler with an internal DHW storage of zero to maximum 15 L. The latter (micro-storage or micro-accumulation) was introduced primarily to boost instant hot water delivery (better comfort) and minimise burner cycling during small draw-offs. A large DHW draw-off however provokes a burner action and therefore these combis are considered to be 'instantaneous' water heaters.

Gas-fired combis are available in an immense variety of designs, shapes, features, specifications, and so on.

As regards the way the heat from the flames and flue gases are transferred to DHW there can be significant differences. There are two main principles:

- The burner heats a primary (CH) circuit which feeds a DHW circuit through a DHW heat exchanger (requires 3-way valve);
- The burner heats a combined CH / DHW heat exchanger, with separate circuits for CH and DHW.

Either of these principles can be combined with micro-DHW storage (< 15 l). The following figures are examples of the approaches sketched above.

Figure 7-2.
Typical wall-hung atmospheric modulating gas combi-boiler, with light-weight finned primary CH heat exchanger and DHW plate heat exchanger. (picture: www.vaillant.com atmoTEC VC194, 22kW, net weight: 37 kg)

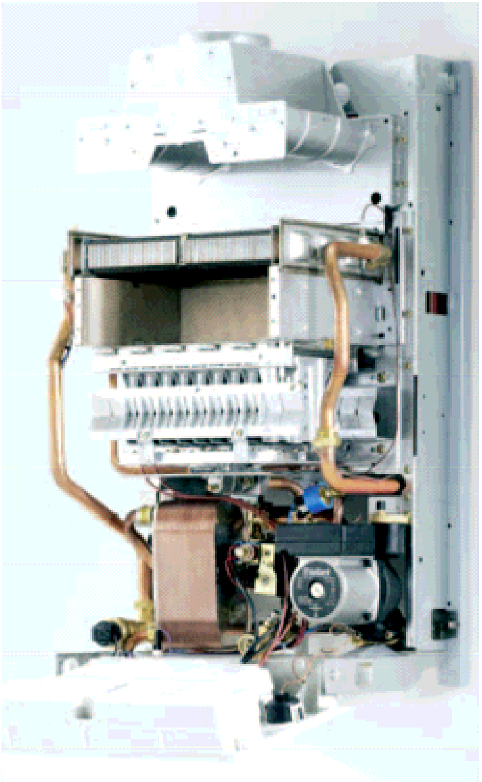


Figure 7-3.
Combi-boiler with 1 ltr integrated DHW storage (detail below) (picture: www.nefit.nl - Smartline)

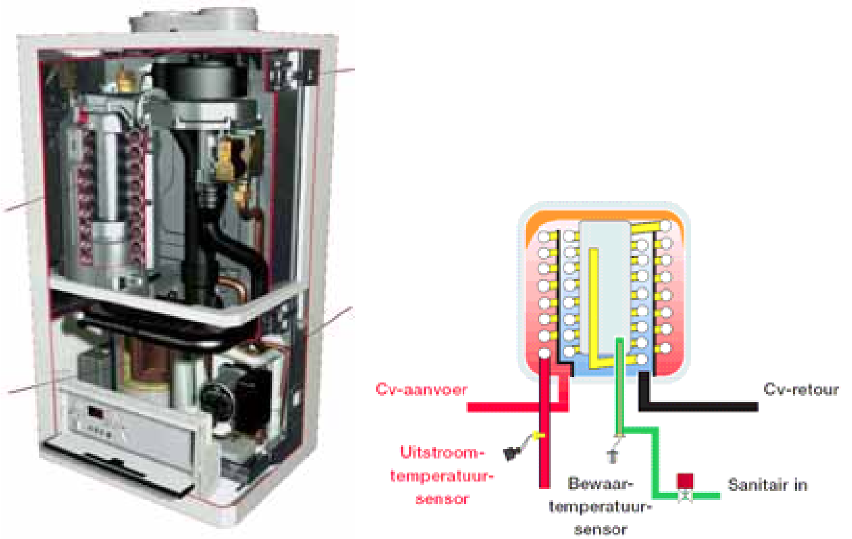
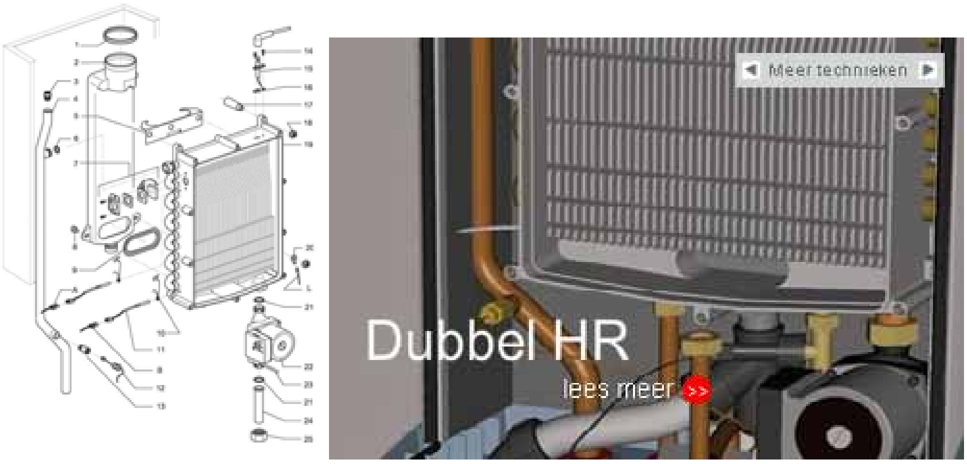


Figure 7-3.
Integral DHW/CH heat exchanger (#19 in figure) in Intergas Kombi Kompakt HR 28, introduced in 1996. Boasts condensing DHW performance. Annual DHW efficiency 89%, DHW performance 8 l/min @ 60ºC or 13 l/min @ 40ºC (28 kW). Space heating efficiency (part load) 109%. 15 Year guaranty on heat exchanger, 2 year on other parts. Minimum flow 2 l/min (picture: www.intergasverwarming.nl)



The gas burners are either free flame, radiation or flameless burners. Oil burners (not really applicable) are jet burners (atomising).

Primary CH heat exchangers applied in instantaneous combis are of the (improved) fin-tube type (e.g. Nefit), bare tube (no fins) (Auer Gianola) or aluminium die-cast (e.g. Weishaupt). Secondary circuit DHW heat exchangers are either of the plate heat exchanger type or submerged coil.

The number of manufacturers and brand names is numerous. The leading manufacturing groups are Vaillant, Baxi, MTS and BBT (in random order and many more to add - see also the Task 2 Report on water heaters market analysis).

7.2 DHW Performance

7.2.1 Flow rate

Most combis have a heat output of 18 to 30 kW in DHW mode with the typical combi hovering around 24 kW. The table below gives an overview of theoretical (100% efficiency) power output for various flow rates.

Table 7-1. Heating power and flow rate at fixed delta_T [38]

l/min	l/sec	T_in	T_out	delta_T	spec.heat	kW needed
2	0,03	15	60	45	4,18	6,3
4	0,07	15	60	45	4,18	12,5
6	0,10	15	60	45	4,18	18,8
8	0,13	15	60	45	4,18	25,1
10	0,17	15	60	45	4,18	31,4
12	0,20	15	60	45	4,18	37,6
14	0,23	15	60	45	4,18	43,9
16	0,27	15	60	45	4,18	50,2
18	0,30	15	60	45	4,18	56,4
20	0,33	15	60	45	4,18	62,7

The maximum flow rate at a given temperature lift is defined by the maximum power output in DHW operation. The values in the table above presume 100% heat exchange efficiency, which is usually not the case: In real life a typical 24 kW combi produces some 6 l/min at 60ºC which requires 19 kW (see above). Dividing output by input (19/24 LHV) gives an efficiency of around 80% (LHV).

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[38] The formula applied is : flow [l/sec] * temp.diff [K] * spec.heat water [4.18 kJ/kg*K] = power [kW] (density of water is kept constant at 1 kg/l)

7.2.2 Temperature control

Most combis are factory-set to a DHW outlet temperature of 60ºC (to avoid scalding and reduce legionella counts). In order to maintain a constant 60ºC at the outlet the combi has to be able to adjust the burner output in accordance with the flow rate (and temperature of incoming water).

The minimum flow rate is related to the modulation range of the burner and heat exchange characteristics. If the boiler operates below the minimum flow rate 'boiler cycling' will occur.The temperature control mechanisms are described in Section One - Chapter 4 Burners.

Lower flow rates are becoming a necessity with the advent of low flow water saving shower heads, thermostatic mixing valves and -recently- waste water heat recovery.

For example a water saving showerhead pinches the flow to approximately 5,5 l/min. If T_shower is 40ºC and T_cold is 15ºC then the boiler must deliver a flow of 3 l/min of 60ºC (9,6 kW). This is close to minimum flow rate of many boilers; the Vitodens 200 (25,7 kW) for example has a minimum flow rate of 3 l/min. Some combis offer even lower minimum flow rates such as the Intergas KombiKompakt HR 36/30 (32,7 kW LHV, 2 l/min) and the Vaillant HRV30C (23,1 kW LHV, <1,4 l/min). A solution to reduce minimum flow rates to 'zero' is the application of a (small) DHW storage tank (for as long as the DHW storage lasts).

7.2.3 Responsiveness

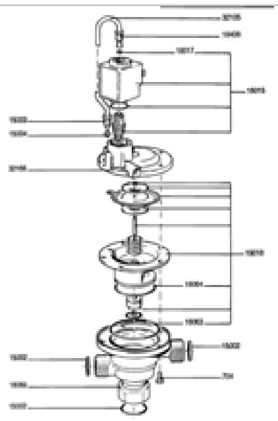
Most instantaneous combis are relatively *slow starters* because of their thermal mass. The speed with which a combi can produce hot water at the desired temperature (measured at the boiler DHW outlet) is determined to a large extent by:

- Whether or not the combi has a DHW storage;
- The control settings (pre-purge time, keep hot facility / comfort switch on/off);
- The thermal mass of the heat exchangers and components;
- The responsiveness of mechanical components directing DHW flow.

The *'keep-hot facility'* or *'comfort switch'* makes the boiler periodically send some heated CH water over the DHW heat exchanger. This adds some 50 to 100 kWh annually to the overall energy consumption.

Many combis employ three-way valves to direct primary (CH) water over the DHW heat exchanger. Solenoid valves allow a rapid response, motorised valves take a few seconds to change position. Another variant is a two-directional pump.

Figure 7-5.
Left:Solenoid 3-way valve from AWB Thermomaster (picture: www.getprice.de)
Right: Parts of solenoid 3-way valve from Nefit VR combi (picture: www.technischeunie.nl)

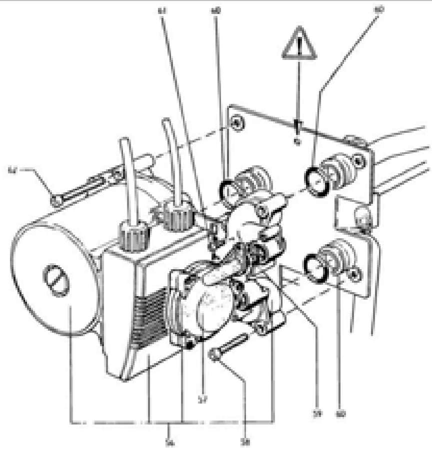


Soleboid valves use power when in "on" position.

Figure 7-6.
Motorised 3-way valve (picture: www.danfoss.com - model AMZ 113)

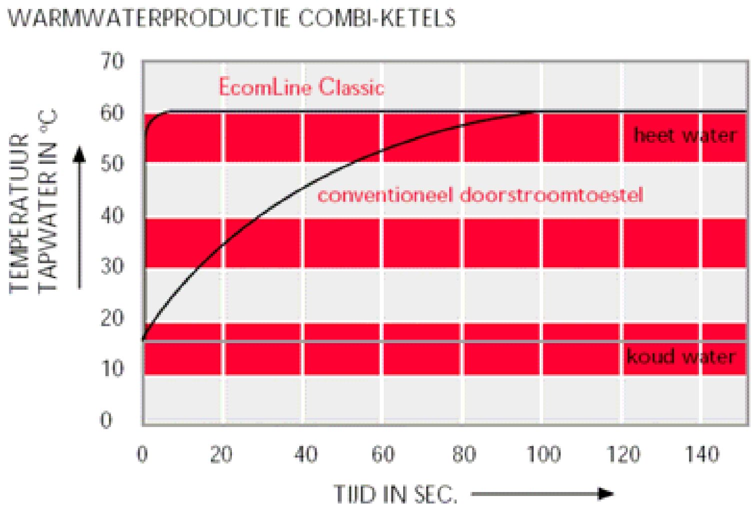
Motorised valves only use power when changing position.

Figure 7-7.
Three-way valve as applied in Nefit Economy HR.
(picture: www.technischeunie.nl)



The valve is integrated in the circulator housing. The circulator can operate in two directions. In direction 'A' the valve opens the space heating circuit, in direction 'B' the valve opens the DHW circuit (in the Nefit HR this is s small storage tank)

Figure 7-8.
Responsiveness of instantaneous combi-boilers ("*conventionleel doorstroom-toestel*") compared to a combi-boiler with 25 l storage ("*Ecomline Classic*").
(picture: www.nefit.nl - from product brochure Ecomline Classic)



7.3 Energy

7.3.1 *Energy efficiency*

The energy performance of combi-boilers for DHW production is assessed through test standard EN 13203 (limited to combis of max. 70kW and 300 l storage). The recent finalisation of this test standard (2006) means that little information based upon EN 1320 made its way to product brochures yet [39].

The energy assessment covers a period on 24 hrs per tapping cycle of which at least two must be executed. The result thus includes losses in on-mode, off-mode and start-stop.

Without going into too much detail (modelling is part of the next Task) some aspects that influence the energy efficiency in on-mode are:

[39] In the Netherlands a test standard exists for energy efficiency of gas water heaters / combi's. Water heaters exceeding certain minimum values can be awarded the "gaskeur HRww" label.

- The surface area of the primary heat exchanger and associated condensing operation;
- The outlet temperature. Many countries require an outlet temperature of minimum 60ºC;
- Minimum modulation / flow rate. At a given output temperature the power input is determined by the flow-rate at the draw-off point. If the flow rate drops below the minimum modulation cycling will occur.

Condensing combis with integrated DHW heat exchangers (exposed to burner) are able to (partly) operate in condensing mode since incoming water of 10 to 15ºC is well below the dew point (around 57ºC for natural gas). Total recovery of latent heat is not possible with outlet temperatures of minimum 60ºC. Most combis however avoid such thermal stress at the primary heat exchanger and use a secundary DHW heat exchanger.

The steady-state efficiency is an important parameter for larger tappings (shower, bath) and many national (building) standards use default values for 'on-mode' efficiency. Previous studies (SAVE study on water heating 2001) note the following steady-state efficiencies:

- > 90% hhv for condensing combi-boilers;
- 78 - 83% hhv for improved efficiency combi-boilers;
- < 78% hhv for combis with conventional efficiency.

7.3.2 Off-mode

Energy losses in off-mode (standing losses) are mainly envelope-losses and flue duct losses if no flue damper is used. Some combis still use pilot flames for ignition that also contribute to off-mode losses. These are covered in EN 13203.

The envelope losses depend on the placement of combis and the ambient temperature. Most combis are wall-hung and installed within the insulated perimeter of the dwelling. The preferred position is close to the main tapping point (the kitchen, as is customary in UK and Italy) but national Building Regulations regarding the position of flues do not always allow this and lead to combis being tucked away in corners of the dwelling (attic, basement, scullery, den, airing cupboard) or even outside the insulated / heated perimeter of the building (balcony, patio, conservatory, etc). Obviously the latter solution contributes to envelope losses (also depending the local climate).

Envelope losses are also increased when using the *keep-hot facility* or *comfort switch* offered by most (instantaneous) combis and if the combi has a micro-storage of DHW. A small DHW tank of say 5 l. has standing losses varying from 0,2 to 0,4 kWh/day (or 75-150 kWh_{pr}/year). The *'keep-hot facility'* or *'comfort switch'* makes the boiler periodically send some heated CH water over the DHW heat exchanger. This adds some 50 to 100 kWh annually to the overall energy consumption.

The pilot flame is believed to consume some 75 to 125 m³ natural gas per year (or 750 tot 1212 kWh_{pr}/year) (SAVE WH). However not all the heat from the pilot flame should be treated as a loss, since some of it pre-heats the appliance (reducing start-stop-losses)

7.3.3 Start-stop losses

Instantaneous production of DHW means many boiler cycles (start-stops) per day. Repeated heating and cooling down of the thermal mass of the boiler, plus pre- and after-purges introduce energy losses and is covered in EN 13203: Standby-losses are measured in a seperate 24hr cycle without draw-offs.

Instantaneous combis without micro-storage are heated up and cool down again at each draw-off. The SAVE WH study calculated that a 40 kg instantaneous combi loses some 0,53 kWh_{pr} per cool-down cycle. Depending on the number of cycles and the thermal characteristics of the appliance (level of insulation etc.) the annual loss could be 1865 kWh_{pr} (for 7 draw-offs per day, no benefit form CH operation included). In winter time the combi is often already heated up for central heating operation and the annual start-stop losses for DHW operation may be reduced by say 40 or 50%.

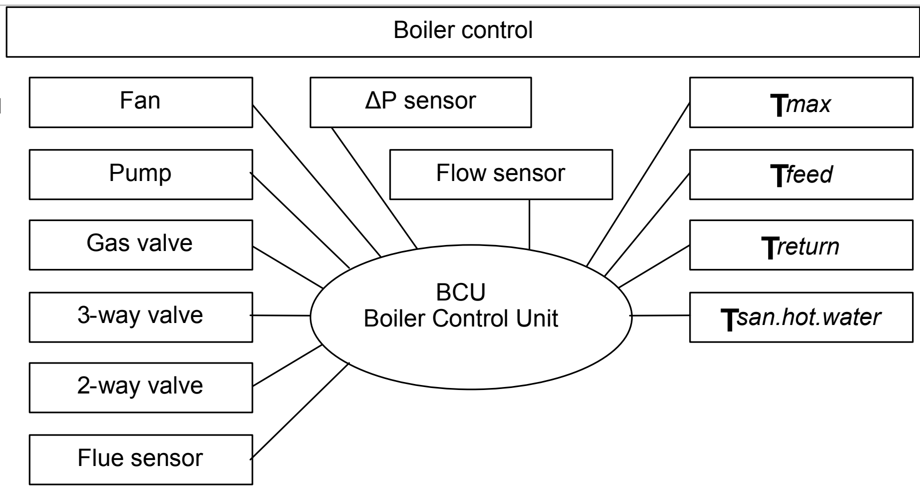
7.3.4 Auxiliary energy

Auxiliary energy is also taken into account in the EN 13203.

Modern combi-boiler control systems measure several parameters in order to operate and control combi-boiler functions such as automatic ignition, fuel/air-ratio control, power input control, inlet temperature sensors, 3-way valve control.

For these purposes a low voltage system is applied for the operation and communication of sensors, microprocessor and actuators.A schematic representation of components controlled by the BCU and input sensors is shown below.

Figure 7-9.
Schematic representation of (electric/-onic) components involved in (combi)boiler control



The power consumption in operation can range from 100 to 200 Watts, depending on size of pumps and fans (the main power consumers). In standby (only electronic controls active) power consumption is 5 to 15 Watts.

The 2005-2006 stude SAVELEC investigated the power consumption of combi-boiler components [40] .

[40] Schweitzer, J. et al, Technical Report Work Package 4: Impact analysis, Boiler SAVELEC - Characterisation and reduction of the electrical consumption of central heating systems and components, EU SAVE Project CONTRACT SAVE No 4.1031/Z/02-021/2002

Table 7-2. Power consumption of electric components in (combi)boilers

	Power (W)	Time (hours)	kWh/yr	Ownership (%)	Stock (millions)	GWh	%
Gas Boilers							
Circulation pumps	65	4248	276,1	100	80,2	19057	61,0
Fans	50	2288	114,4	60	48,1	4955	15,9
Gas valves	7	2288	16,0	100	80,2	1156	3,7
Igniters	2	76	0,2	100	80,2	11	0,0
Motorised valves	6	2288	13,7	70	56,2	694	2,2
2-port valve	5	286	14,3	15	12,0	155	0,5
Thermostat	0	2860	0,6	75	60,2	31	0,1
Programmers	2	8760	17,5	60	48,1	843	2,7
Wireless controls	3	8760	26,3	1	0,8	21	0,1
Electric heating elements in boiler storage	25	5256	131,4	1	0,8	105	0,3
Boiler standby power	8	6472	51,8	75	60,2	3226	10,3
Electronics for boiler on-time	8	2288	18,3	75	60,2	991	3,2
TOTAL GAS						31246	100
Oil Boilers							
Motor for oil pump and fan (same shaft)	145	2288	331,8	100	27,1	9195	55,8
Oil preheater	70	6	0,4	100	27,1	12	0,1
Solenoid valve	15	2288	34,3	100	27,1	951	5,8
Burner control box (mechanical)	3	2288	6,9	100	27,1	190	1,2
Burner control box (electronic)	10	2288	22,9	0	0,0	0	0,0
Ignition transformer	60	76	4,6	100	27,1	127	0,8
Circulation 3 speed pump 40 kPa	65	2288	148,7	90	24,4	3710	22,5
Circulation E pump 40 kPa, summerstop	65	4437	288,4	10	2,7	785	4,8
Electronic control of radiator/floor heating system	8	8760	70,1	5	1,4	95	0,6
Boiler standby power	8	6471	51,8	75	20,3	1043	6,3
Electronics for boiler on time	8	2288	18,3	75	20,3	380	2,3
TOTAL OIL						16488	100
GRAND TOTAL OIL + GAS						48	100

The columns regarding operating time, ownership/stock and GWh in the table above are related to space heating and are not relevant from DHW perspective - they are however part of the original table and shown here for informative purposes only. In general the electricity consumption of boilers (in space heating - not DHW- operation) is split up as follows: pump 57%, fan 34%, control 9% [41] .

7.3.5 *Alternative energy*

Many modern combis are able to cope with high inlet temperatures of 85-90°C and can be connected (retro-fitted) to solar storage cylinders. In the Netherlands these boilers carry the Label *"Gaskeur NZ"*. Such boilers must also have a facility to reduce the outlet DHW temperature to max. 60°C to prevent scalding.

[41] Schweitzer, Jean, Electricity consumption of central heating appliances, Joint workshop GERG-SAVE, Horsholm, 4 April 2001

In principle the *Gaskeur NZ* combis can be connected to (pre-heated water storage) from heat pumps as well, but this is rarely applied in practice.

There are heat pump applications that use a (gas)boiler as emergency / back-up heater but these heaters are usually not instantaneous combis.

7.4 Infrastructure

7.4.1 Chimney and supply air

Instantaneous combis are available in both B- and C-type flue/air configurations.

Combis that are designed to operate under condensing conditions require a suitable (gast-tight / condensate proof) flue duct, even in case the combi doesn't condense during DHW production. See the Task 3 Report (section on chimneys) for strategies and solutions available for applying condensing boilers in existing dwellings and buildings.

7.4.2 Drains

All combis are equipped with a pressure relief valve, for the CH part and/or for the connection to the drinking water mains, and are thus connected to a drain. In case the combi is condensing (even only in CH mode) the condensate can be discharged through this drain (provided discharge is allowed and the diameter is sufficient). For oil-fired combis a neutralisation box may be required.

7.4.3 DHW piping

Most instantaneous combis are primary water heaters, serving multiple draw-off points, and are thus connected to a potentially lengthy DHW circuit.

Such pipe lengths introduce energy and water losses due to waiting times. These losses will be calculated in the technical model that is constructed in the subsequent tasks. Relevant input parameters are: the length, diameter and R-value of the piping and the supply- plus ambient temperature. Also the response time of the water heater itself is a factor.

Especially the distance from the water heater to the most frequently used draw-off point (usually the kitchen) is an important factor in determining waiting time losses.

Connection of instantaneous combis to DHW recirculation systems is not a realistic option: The instantaneous combi lacks the DHW buffer to feed the recirculation loop.

7.5 Prices

For combi-boiler prices see the Task 2 Report.

8 GAS/OIL-FIRED INTEGRATED STORAGE COMBIS

8.1 Product description

This group comprises gas-/oil-fired combis with integrated DHW storage of more than 15 litres. "Integrated" in this context means that the heat generator and storage tank are sold as one unit. In practice the unit can be delivered in two parts (a boiler part and storage part) to ease transport and installation and to be assembled on site. The groups comprises wall-hung combi-boilers (with heat generator hung above or aside the DHW storage) as well as floor standing models (with the heat generator placed on top or beside the DHW storage).

Storage-combis offer high DHW performance by definition, although many variants exist in how the storage is charged.

The traditional combi with integrated storage is based upon a heating only boiler with a matched storage cylinder equipped with a DHW coil heat exchanger.

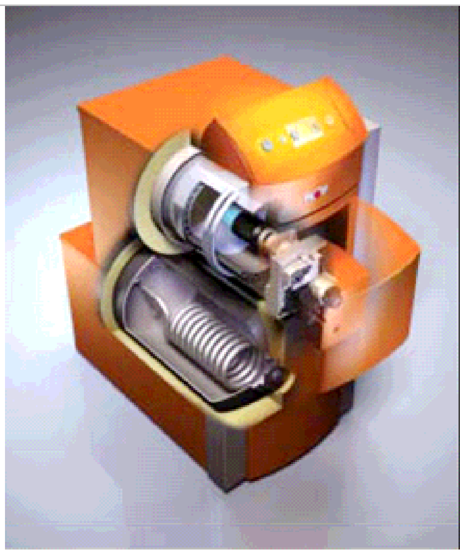
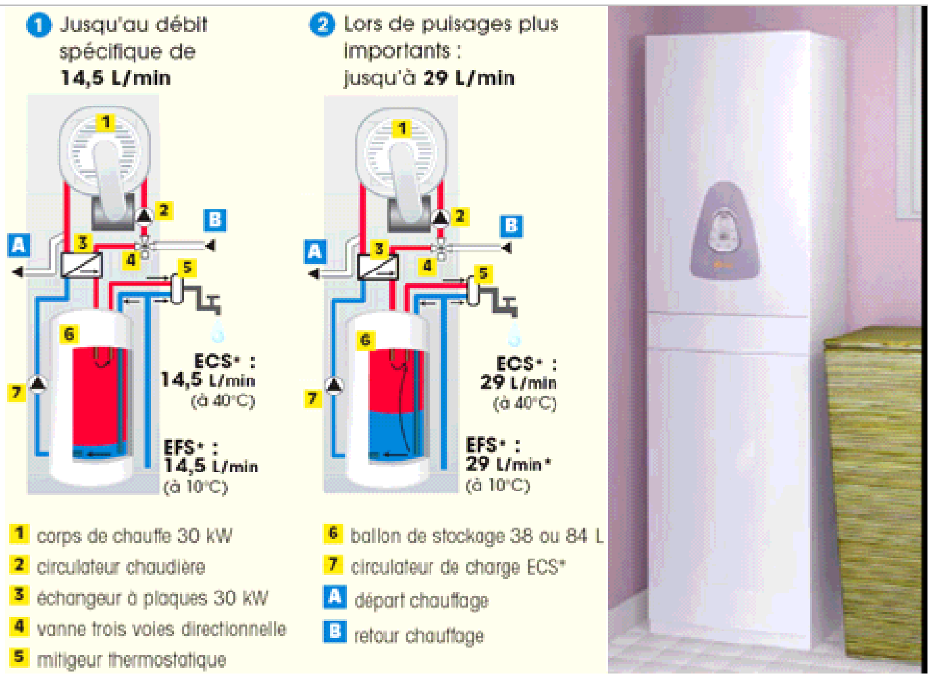


Figure 8-1.
Oil-fired storage combi (155 l) by Wolf Heiztechnik
(picture: www.wolfheiztechnik.de)

More recent storage combis use an external (plate) heat exchanger to produce DHW and inject this directly in the top half of the storage. This type of storage is called "Schichtenspeicher" (thermal layer storage) and offers faster reheat times and eliminates the *'empty-boiler'*-effect (DHW injected can be extracted immediately, giving instantaneous combi-like operation).

Figure 8-2.
Example of combi-boiler with thermal layer storage. (picture: Auer Gianola Lelia Profusion Sol 84 l (there is also a wall hung version of 38 l storage. www.auergianola.fr)



A third route to integrated storage combis is based upon gas storage heaters that are equipped with a heat exchanger for space heating operation. An example of this is the Daalderop CombiFort.

Figure 8-3.
Daalderop Combifort integrated storage combi.
(picture: www.daalderop.nl)

Major manufacturers (groups) are a.o. Vaillant, Baxi, BBT, MTS, Viessmann, etc. (overview incomplete - see also the Task 2 Report, Market Analysis).

8.2 DHW performance

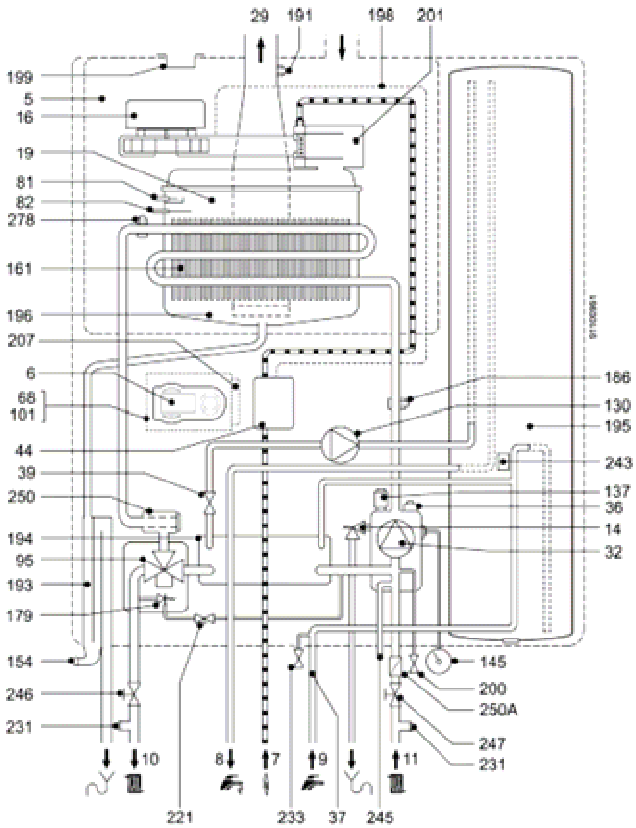
8.2.1 Flow rate and temperature stability

The storage component offers very high initial flow rates in the range of 12 to 30 l/min or more. The question is however how long the desired flow-rate can be maintained at a given temperature difference. In other words: what is the *recovery rate* (in l/hr at a given T_diff).

One way to increase recovery rates is to increase storage size. Another approach is introduced above, by creating a thermal layer storage, increasing the power input and make sure this power output is delivered at the DHW outlet. Such storage combis function like an instantaneous combis during large tappings, but offer fast response and high initial flow rates as well.

To indicate the performance of modern storage combis the following comparison is made: An *instantaneous combi* like the 26 kW Viessmann Vitodens 200 produces 803 l/hr (with T-diff. at 30K). The 24 kW *storage combi* by Auer Gianola Lelia with a 130 l storage tank produces a comparable 840 l/hr. Depending on the size of the storage, the capacity of the boiler and the design of CH to DHW heat transfer boilers can produce from 450 l/hr (100 l storage, 20 kW) to 1500 l/hr (300 l storage, 60 kW).

Figure 8-4.
Combi-boiler schematic, with 20 l storage (picture: www.agpoferroli.com - MegaLux6)



This boiler has a 20 l storage cylinder contained in its casing.

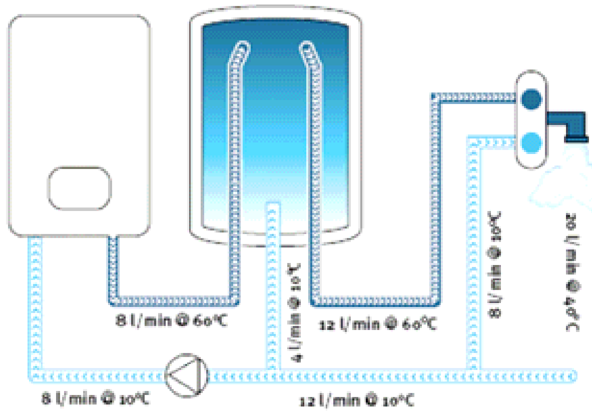
During small -low flow- draw-offs DHW is taken from the storage tank and as long the temperature doesn't drop below a certain set-point the burner will not ignite and the boiler functions as a boiler with external storage.

At large -high flow- draw-offs the setpoint will be reached within a short time period and the boiler will ignite.

Due to the proximity of the storage feed loop (follow 39) next to the storage outlet tube (follow 8) most of the feed water will directly flow to the outlet: the boiler acts as an instantaneous boiler.

After such draw-offs the burner will continue to operate to fill the storage tank with hot water, circulation provided through a DHW circulator (130).

Figure 8-5.
Saunier Duval F35E ISOTWIN 33kW (picture: SaunierDuval F35E product brochure)

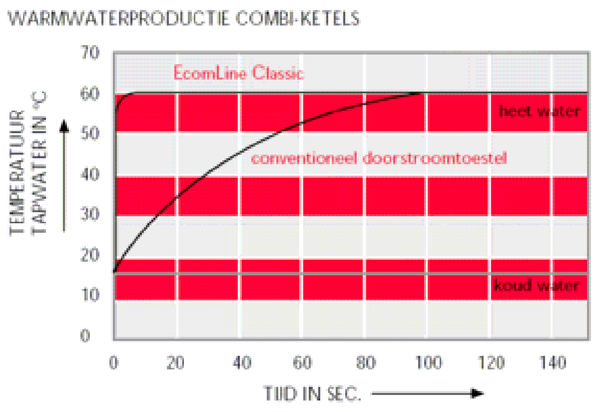


Once the 200l. tank is depleted the ISOTWIN continues to operate in normal combi mode producing 14 l/min of hot water @ 35ºC rise.

8.2.2 Responsiveness

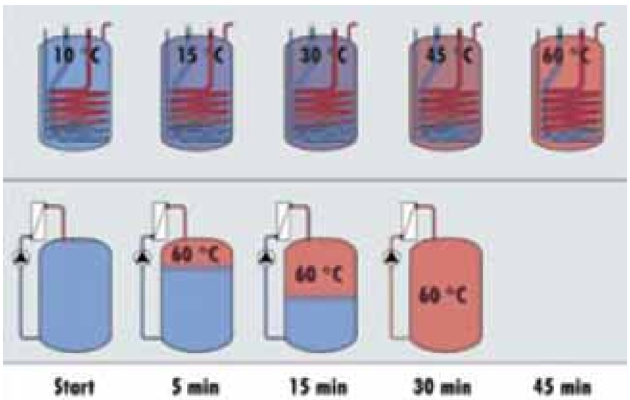
The availability of a (fully charged) DHW storage ensures instant DHW production at the appliance outlet. The figure below present an example of responsiveness of a storage combi compared to an instantaneous combi.

Figure 8-6.
Responsiveness of combi-boiler with 25 l storage ("*Ecomline Classic*") compared to traditional instantaneous combi-boilers ("*conventionleel doorstroom-toestel*"). (picture: www.nefit.nl - from product brochure Ecomline Classic)



In case of a 'cold-start' (the DHW tank is depleted) conventionally heated tanks with coil heat exchanger in bottom half of tank need more time to reach the required temperature than *thermal layer storage* tanks. The reheat time depends on the storage volume, the capacity of the burner and the heat exchanger efficiency.

Figure 8-7.
Reheat times of conventional and thermal layer DHW storage tanks.
(picture: Vaillant ecoCOMPACT brochure)



8.3 Energy

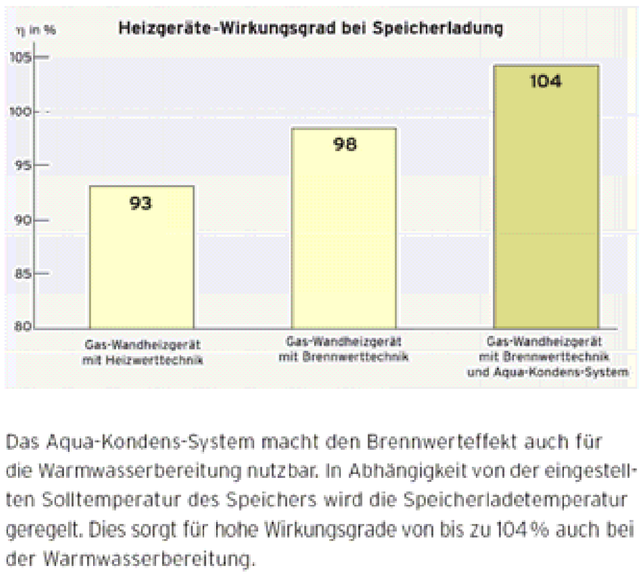
8.3.1 On-mode

Most storage combis are heated by conventional burners and heat exchangers (spiral in storage). The average efficiency lies in the range of that of instantaneous combis. Previous studies (SAVE study on water heating 2001) note the following steady-state efficiencies:

- >90% hhv for condensing combi-boilers;
- 78 - 83% hhv for improved efficiency combi-boilers;
- < 78% hhv for combis with conventional efficiency.

The availability of *thermal layered storage* opens up the possibility for increased efficiency of water heating: *Thermal layer* storage combis can create a loop in which the coldest water is send to the primary heat exchanger, which creates the highest heat exchange efficiency (condensing). Mixing of hot and cold water is postponed until the storage is almost completely full. Only to fully charge the storage tank the boilers switches to a higher supply temperature. This *two-stage* heating process makes the most use of the thermal stratification in the storage tank and the benefits of the coldest return temperatures that allow condensation. Part of the water heating thus may take place with an efficiency above 100% LHV (Vaillant calls this their *"AquaKondensSystem"*, a.o. applied in the ecoCOMPACT models).

Figure 8-8.
Vaillant Aqua-Kondens-System (picture: Vaillant brochure)



8.3.2 Off-mode

During off-mode the storage combi loses energy through the envelope (mainly the through the thermal DHW storage), flue duct and pilot flame (if present).

The standing losses of the storage tank are significant and may vary from 0,96 kWh_{pr}/day for a 30 l storage to 2,65 kWh_{pr}/day for a 300 l storage. For a 75 l storage combi this is approximately 471 kWh_{pr}/year. Combining this with an estimated average hot water consumption of 105 l/day at ΔT of 50°C (translates to 2222 kWh_{pr}/year) the standing losses are 21% of the total usable energy content of the DHW water (471/2222) (SAVE WH).

An important factor determining standing losses through the envelope is of course the ambient temperature of the appliance. Many boilers will be placed within the insulated perimeter of the dwelling or building, whereas others will be placed in unheated area's such as the attic, den, loft.

Also contributing to these standing losses are thermal bridges and thermosiphon effects. Insulation and careful design minimises the first and application of heat traps (a small riser in a pipe or a strainer - ball type - in horizontal streches of pipe) reduce the latter.

The pilot flame losses (if applicable) are in the range of 75 to 125 m³ natural gas per year (or 750 tot 1212 kWh_{pr}/year) (SAVE WH). However not all the heat from the pilot flame should be treated as a loss, since some of it pre-heats the appliance (reducing start-stop-losses).

8.3.3 Start-stop

The actual energy use per cool-down cycle is probably in the range of instantaneous combis. The big difference however is the number of start-ups: Storage combis will only start-up if the storage sensor senses a reduced capacity (say half full) and will then fire for a prolonged period to completely charge the storage again.

SAVE WH calculated annual cool-down losses of 1332 kWh_{pr}/year for a storage combi compared to 1865 kWh_{pr}/year for an instantaneous combi or 70% compared to 100%. (SAVE WH). These figures are indicative only.

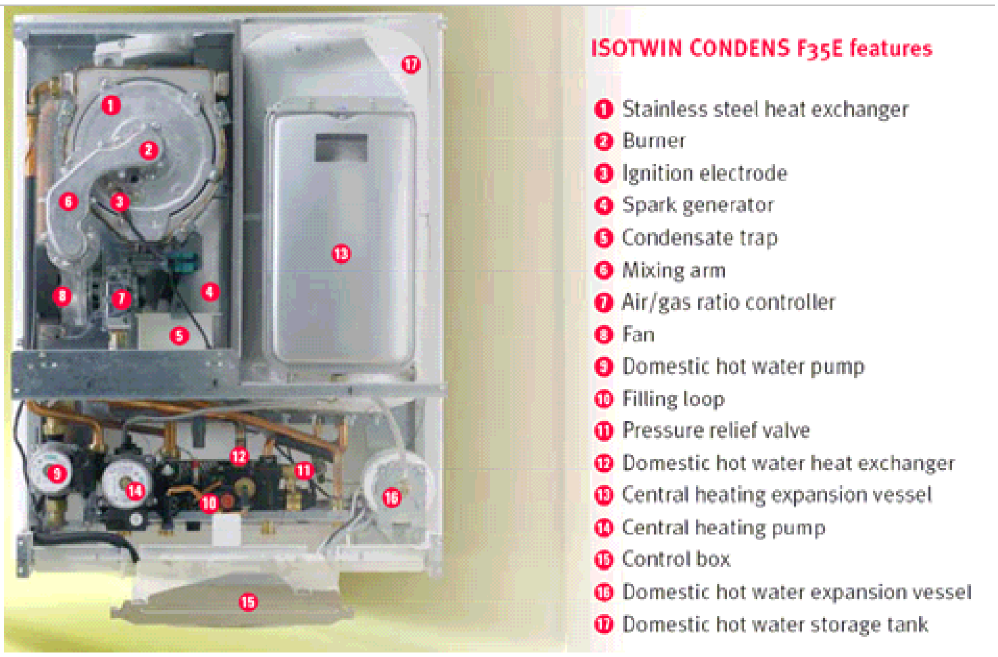
8.3.4 Auxiliary energy

The storage combi consumes electricity when in standby and in operation. The standby power consumption is often 10 Watts or less for normal sized boilers (below 35 kW).

The power consumption when in operation depends to a large extent of the power output of the burner (a more powerful boiler requires more powerful fans, circulators, controls, etc.) and ranges from 100 to 200 W.

Some models employ a dedicated DHW feed pump instead of a 3-way valve plus a double duty (CH plus DHW) circulator.

Figure 8-9.
This combi (Isotwin condens) has a seperate central heating and DHW circulator (picture: Saunier Duval F35E product brochure)



The 2005-2006 stude SAVELEC investigated the power consumption of combi-boiler components [42] .

[42] Schweitzer, J. et al, Technical Report Work Package 4: Impact analysis, Boiler SAVELEC - Characterisation and reduction of the electrical consumption of central heating systems and components, EU SAVE Project CONTRACT SAVE No 4.1031/Z/02-021/2002

Table 8-1: Power consumption by boiler components (source: SAVELEC study)

	Power (W)	Time (hours)	kWh/yr	Ownership (%)	Stock (millions)	GWh	%
Gas Boilers							
Circulation pumps	65	4248	276,1	100	80,2	19057	61,0
Fans	50	2288	114,4	60	48,1	4955	15,9
Gas valves	7	2288	16,0	100	80,2	1156	3,7
Igniters	2	76	0,2	100	80,2	11	0,0
Motorised valves	6	2288	13,7	70	56,2	694	2,2
2-port valve	5	286	14,3	15	12,0	155	0,5
Thermostat	0	2860	0,6	75	60,2	31	0,1
Programmers	2	8760	17,5	60	48,1	843	2,7
Wireless controls	3	8760	26,3	1	0,8	21	0,1
Electric heating elements in boiler storage	25	5256	131,4	1	0,8	105	0,3
Boiler standby power	8	6472	51,8	75	60,2	3226	10,3
Electronics for boiler on-time	8	2288	18,3	75	60,2	991	3,2
TOTAL GAS						31246	100
Oil Boilers							
Motor for oil pump and fan (same shaft)	145	2288	331,8	100	27,1	9195	55,8
Oil preheater	70	6	0,4	100	27,1	12	0,1
Solenoid valve	15	2288	34,3	100	27,1	951	5,8
Burner control box (mechanical)	3	2288	6,9	100	27,1	190	1,2
Burner control box (electronic)	10	2288	22,9	0	0,0	0	0,0
Ignition transformer	60	76	4,6	100	27,1	127	0,8
Circulation 3 speed pump 40 kPa	65	2288	148,7	90	24,4	3710	22,5
Circulation E pump 40 kPa, summerstop	65	4437	288,4	10	2,7	785	4,8
Electronic control of radiator/floor heating system	8	8760	70,1	5	1,4	95	0,6
Boiler standby power	8	6471	51,8	75	20,3	1043	6,3
Electronics for boiler on time	8	2288	18,3	75	20,3	380	2,3
TOTAL OIL						16488	100
GRAND TOTAL OIL + GAS						48	100

The columns regarding operating time, ownership/stock and GWh in the table above are related to space heating and are not relevant from DHW perspective - they are however part of the original table and shown here for informative purposes only. In general the electricity consumption of boilers (in space heating - not DHW- operation) is split up as follows: pump 57%, fan 34%, control 9% [43] .

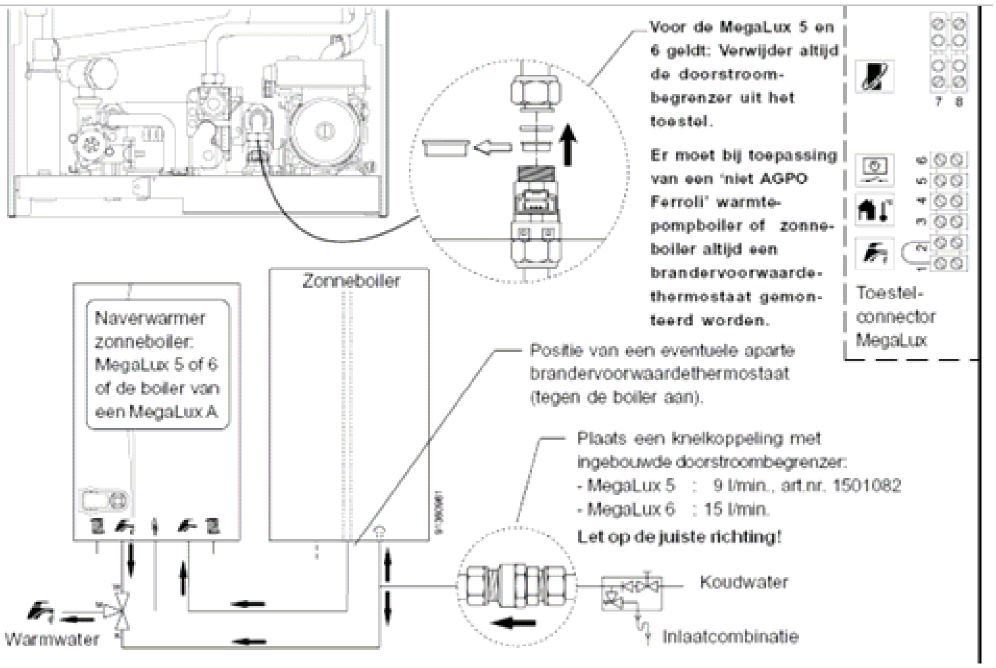
8.3.5 Alternative energy sources

Whether a (combi-)boiler is able to cope with solar (or heat pump) pre-heated water is mainly determined by its components at the DHW water inlet side. The Dutch Gaskeur NZ prescribes a maximum inlet temperature of 85°C.

[43] Schweitzer, Jean, Electricity consumption of central heating appliances, Joint workshop GERG-SAVE, Horsholm, 4 April 2001

Most (storage) combi-boilers produced after 1999 are able to use pre-heated water. In fact, many manufacturers that also market solar systems make sure their combi-boilers can be connected to their solar systems.

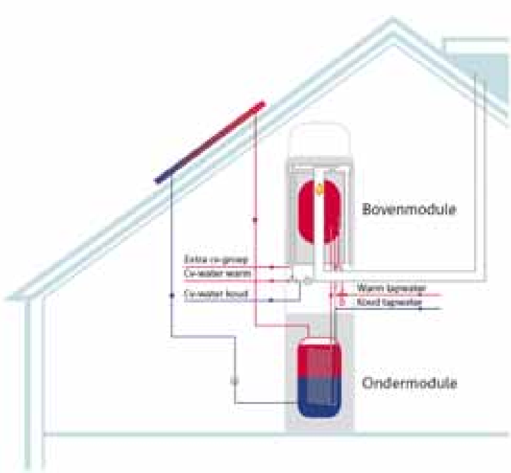
Figure 8-10.
Connection to a solar system
(picture: www.agpoferroli.nl - Megalux brochure)



The text above explains that (for this model):
- the flow restrictor needs to be removed from the boiler inlet and installed before the solar storage;
- the installer has to make sure the boiler has a thermostat switch - to prevent the boiler from firing if water is already hot enough;
- installation of a thermostatic mixing valve to limit the DHW temperature to max. 60ºC to prevent scalding.

Systems that integrate solar storage and (combi)boilers in one casing are also available, but these fall outside the intended scope of this chapter.

Figure 8-11.
Schematic of Daalderop Multisolar combined solar system and combi-boiler.
(picture-left: www.daalderop.nl - Multisolar brochure)
(picture-right: www.zonne-energie-fryslan.nl)



8.4 Infrastructure

8.4.1 Chimney / drains

The storage combi requires a chimney/flue gas system and a combustion air supply. If the boiler is able to operate in condensing mode the chimney needs to be airtight and moisture proof - see also Task 3.

Another requirement is a waste water drain to be used by the pressure relief valve. The same drain can be used for condensate if applicable.

8.4.2 Draw-off point

Most storage combis are the primary water heater in the dwelling and serve multiple draw-off points and are thus connected to a lengthy DHW circuit.

It is very well possible to use the storage combi in a DHW recirculation system thereby reducing waiting times at the point-of-use. This price comes at a loss: There are heat losses of the piping system and energy consumption for circulation.

8.5 Prices

For combi-boiler prices see the Task 2 Report.

9 SEPARATE CYLINDERS

9.1 Product description

Although separate cylinders aka external storage tanks, like substations, lack an internal heat generator and thus cannot function as an independent water heater they are included in the scope of the study.

The heat source of external DHW storage tanks or cylinders (also referred to as calorifiers) is CH system water. The heat input is via a heat exchanger (coil or tank-in-tank), sometimes in combination with an electric heater. Features characterising external storage tanks are: heat exchanger, tank material, insulation (plus jacket/casing).

Most cylinders in mainland Europe are pressurised (under water pressure). In the UK many external cylinders are 'unpressurised' but fed by a feed tank located above the cylinder. Unpressurised storage cylinders can also be applied as a primary store with the DHW heat exchanger under mains pressure.

Coil heat exchanger

The heat exchanger generally applied in external storage tanks is a coil heat exchanger (spiralled tube), usually of the same material as the cylinder itself. The diameter, length and surface-features of the coil determine the heat transfer surface and are designed for the desired performance.

A 22 mm diameter coil heat exchanger (no fins) offers a heat transfer surface of approximately 0,07 m²/m length. With a feed temperature of 90ºC and a hot water production of 45 ºC (cold water in at 10ºC) the coil transfers 3 to 3,6 kW_{heat}/m_{coil}.

Figure 9-1.
Example typical external storage cylinder (picture: www.nibe.com - Nibe PCU)

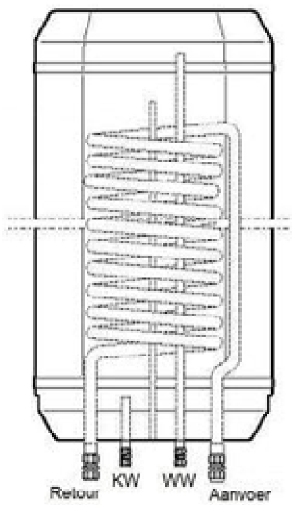


Table 9-1. Specifications of range of external storage cylinders

Nibe PCU/DDS		single-wall		double-wall
volume (l)	80	100	120	120
Coil length (m)	8	10	13	13
Heat transfer surface (m²)	0,55	0,7	0,9	0,9
Heat transfer 90/10-45ºC (kW)	29	33	39	16,5
kW/m	3,6	3,3	3,0	1,3

Some countries require cylinders with a certain heating capacity (Netherlands: over 45 kW, see BRL K656) to be fitted with double-walled heat exchangers. Double-walled heat exchangers are also applied in case cross-contamination has to be avoided (f.i. if the heat exchanger is placed in a toxic environment, like in certain solar systems where the collector fluid contains toxic anti-freeze fluids). The space between the walls is vented to the outside so that leakages can be noticed. Disadvantage is that the double-wall heat exchanger performance is much less compared to single-walled versions.

Example: Nibe PCU 120 with double-wall HE performance is 42% of single-wall version (39 kW for single-wall version vs. 16,5 kW for double-wall version).

The price of the double-wall HE is 143% of the single-wall (list price: 615 versus 880 euro).

Double-coil/bi-valent

Double-coil cylinders are applied in bi-valent systems or in systems that apply feeding with low- and high-temperatures, possibly from different energy sources. The coils are vertically oriented to use the effect of thermal stratification. The 'colder' bottom HE is used for low-temperature heat sources (e.g. solar collector, heat pump or boiler in condensing mode). The 'hotter' upper HE can be used for DHW production (in case the boiler is filled with CH water and the bottom coil is for solar), or CH heat input (in case the tank is filled with DHW and the bottom coil serves a solar collector). With ratings of 39 kW per coil continuous tapping is possible when the top coil is fed by a boiler with such capacity.

Figure 9-2.
Example bivalent external storage cylinder (picture: www.nibe.com - Nibe PUB)

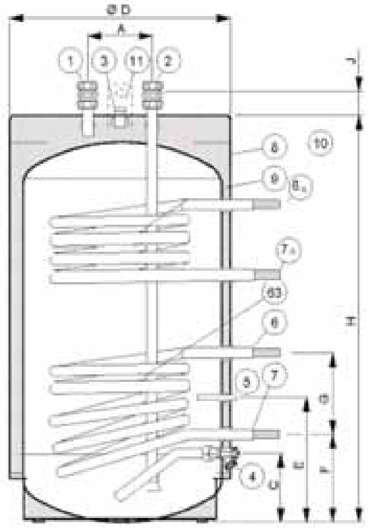


Figure 9-3.
Vaillant uniSTOR

Tank-in-tank

The tank-in-tank HE is characterised by its low pressure drop and relatively large water content of the heat exchanger. Extra-large heat exchanger versions are available to minimise cycling of boilers and are recommended for heat pumps. The water content of the enlarged version is triple the amount of a standard version: 66 l versus 22 l for a 200 l storage tank).

Figure 9-4.
Nibe VPA

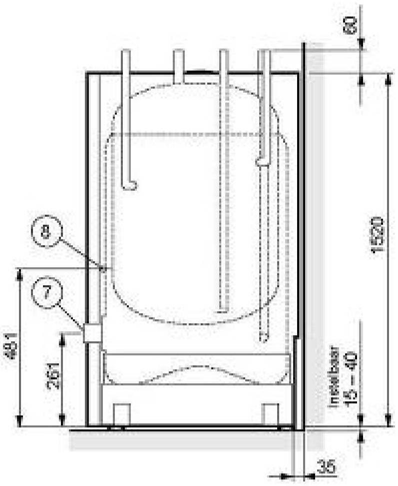


Figure 9-4.
www.dzd.cz

Table 9-2. Sp[ecifications of tank-in-tank cylinders

Example NIbe tanks	SP standard				VPA tank-in-tank		
DHW storage volume (l)	110	150	200	300	200	300	450
HE volume (l)	12	18	22	22	66	190	145
Heat transfer 90/10-45°C (kW)	13	14	22	25			
Heat transfer 55-45/10-45°C (kW)					8.2	10	14.1

Pressure loss coil HE vs. tank-in-tank HE

At 1000 l/h the coil HE has a pressure loss of 10-17 kPa, the tank-in-tank (double mantle) has a pressure loss of around 0,2-0,3 kPa.

Figure 9-6.
pressure loss singe coil
(picture: NibePUB)

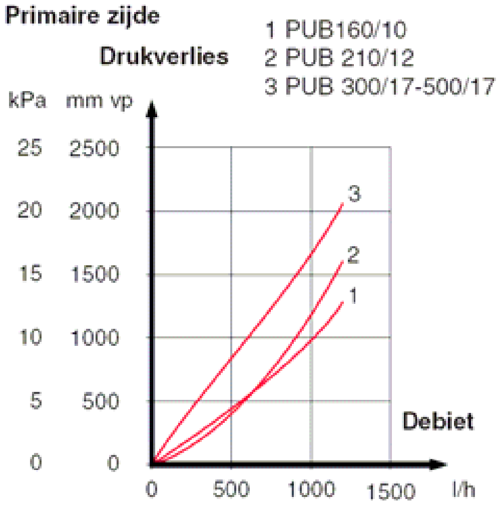
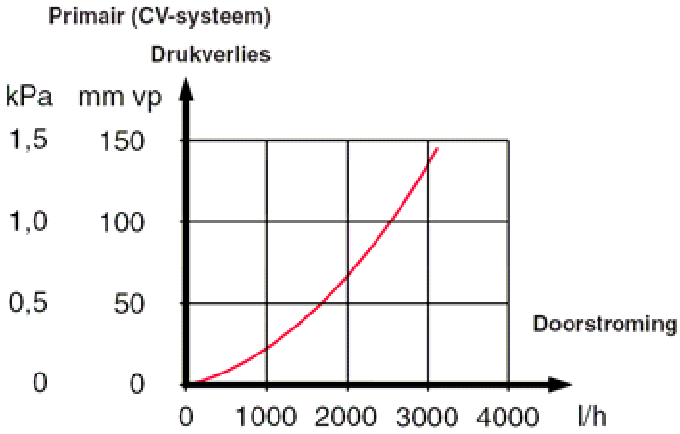


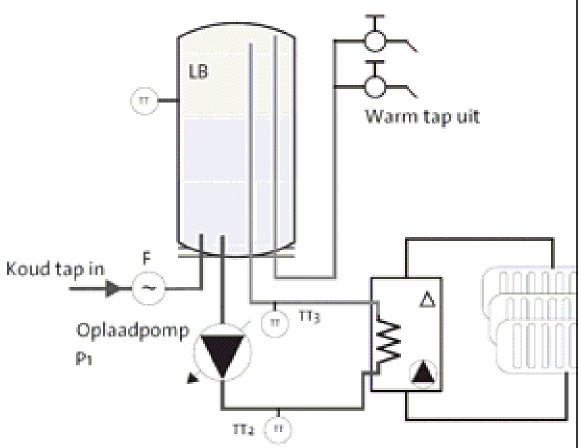
Figure 9-7.
pressure loss tank in tank
(picture: Nibe SP)



External storage cylinders without HE

In some applications external storage cylinders are fed directly with heated DHW (possibly by instantaneous combi-boilers) and thus do not require a heat exchanger for CH/solar/other to DHW heat transfer. In such cases they are practically no more than a thermal DHW store. An example is the "boost-boiler" introduced by Itho in 2006 and designed to operate in combination with a medium performance combi-boiler in order to 'boost' the hot water performance. The tank stores hot water produced by the combi-boiler and, when emptied, activates a dedicated feed circuit connected to this boiler, to refill the store. For that purpose the boost boiler comes equipped with a feed-pump, sensors and control circuit.

Figure 8-8.
External storage tank direct fed - without heat exchanger
(picture: www.itho.nl - Itho 'boost boiler' LB90)

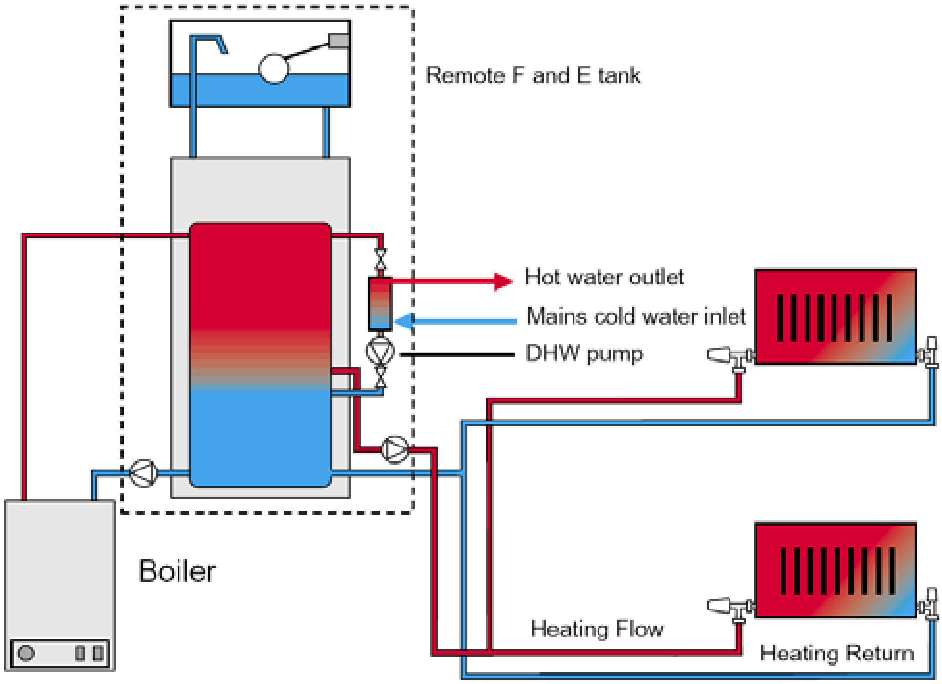


Unpressurised primary stores

In the UK and Ireland one can also find unpressurised primary stores: the storage tank is filled with unpressurised CH water system (tank is connected to feed and expansion cistern on top of the primary store). Such tanks can be equipped with a coil or (external) plate heat exchanger for DHW production.

Claimed advantages are reduced start-stop losses and smaller boilers possible.

Figure 9-9.
Thermal store principle (picture: http://www.gledhill.net > water-storage)



Materials

Materials used for DHW external storage tanks and heat exchangers are:

- copper

- stainless steel

- enamelled (glass lined) steel

Copper cylinders (i.e. by Nibe) and coils are not recommended for areas with high chloride or calcium content in water or prolonged feeding with high temperatures. In such cases a tank-in-tank cylinder is recommended (less susceptible to calcium deposits or scaling and corrosion pitting). In aggressive waters an aluminium rod can be specified to provide corrosion protection. Sometimes copper is avoided in the circuit since copper ions can attack metals further downstream.

Stainless steel tanks (i.e. by Nibe, Viessmann) are gaining popularity. Provided the stainless steel grade is sufficiently high (AISI 316L, Duplex 2304) the tanks are virtually maintenance free and have very long life.

Enamelled tanks (glass lined) (i.e. by Buderus) have also high corrosion resistance, but do need protection against corrosion since the base material is steel-sheet and minute cracks in the enamel layer may induce corrosion. Two methods are applied generally: The first is insertion of a magnesium anode which is a less precious metal than steel and sacrifices itself. The dissolved products are not dangerous for one's health but the sacrificial rods need to be replaced periodically. Traditionally the anode needs to be removed in order to inspect it (requiring removal of mains pressure). Nowadays there are anodes that provide a (colour) signal when it's time to replace them. Street prices per anode range from 10-50 euro (incl. VAT) depending on brand, fitting and size.

Figure 9-10.
Magnesium-oxide anode. Right: a used anode showing large magnesium-crystal growth (picture: www.eurojauge.fr)

A second method is applying a tiny current that prevents discharge of ions that contribute to corrosion (DE: "*Fremdstromanode*"). Such elements can cost up to 130 euro for cylinders up to 300 l and 180 euro for cylinders larger than 300 l (street price, incl. VAT). The anodes can be supplied by 230 V and consume some 2,5 kWh/year. In normal working conditions they do not need replacement.

Figure 9-11.
Correx UP Fremdstromanode (picture: www.Haustechnik-express.de)

Insulation materials

A very common method of insulation of (external) DHW storage cylinders is by placing the cylinder in sheet metal casing and filling the space with PUR foam. The method is simple, reliable and cheap but hinders easy separation of the materials after product life. Another method is to cover the tank in an insulating sleeve (can be flexible PUR, expanded PE or PS foam), with or without a external liner, and cover the top and bottom with a rigid plastic lid.

Common insulation materials applied are:

- Polyurethane foam (PUR);

- Expanded polyethylene (EPE) or polypropylene (EPP);

- Expanded polystyrene (EPS) - open cell foam, expanded beads;

- Extruded polystyrene (XPS) - closed cell foam;

- Mineral wool (only used for large > 500 l cylinders)

Common thickness of insulating PUR jackets is 30 mm or higher. See some examples on the next page.

Figure 9-12.
EPS moulded parts with metal cladding (picture: www.vanderbeyl.nl)

Figure 9-13.
PUR insulation without cover (picture: Megaflo)

Figure 9-14.
Boost boiler with uncovered EPS foam (picture: www.Itho.nl)

Overview of characteristics of several insulation materials (VIPs are treated in a separate chapter as well):

Table 9-3. Characteristics of insulation

Material	Density (kg/m³)	Thermal Conductivity (W/m*K)	Foaming agents	Prices (eur/m³)
Mineral wool	28 - 55	0,041* - 0,045	n.a.	45-52
Glass wool	15 - 28	0,041* - 0,045	n.a.	43-48
EPS	25	0,040* - 0,045	pentane, water or CO_2	35-60
XPS	27	0,034* - 0,040	may be HFC	220
PUR/PIR	30-40	0,028* - 0,035	pentane, water or CO_2	170-185
VIP	162 - 192 (silica)	0,002 - 0,009	depends on core material	5000 - 10000

1) Values indicated with * have been certified by ATG-BUTGb. Source: Bewust Duurzaam Bouwen, text Vibe for Vlaamse Provincies

2) Prices are street prices indicative for building applications, excluding VAT and depend on geometry, quantity, etc. Prices have been recalculated to euro/m³. Source: Richtprijzen, Cobouw.nl.

9.2 Performance

The hot water performance of external storage tanks is essentially identical to that of integrated storage tanks. See section 11.2.

9.3 Energy

9.3.1 *On-mode*

The heat generator is by definition an external (heating only) boiler and does not form part of the product. On-mode efficiency is defined by the external boiler.

Part of the efficiency is however influenced by the external storage tank design and especially the heat exchanger.

9.3.2 *Off-mode*

Energy losses in off-mode (standing losses) are the main loss factor for external storage tanks. A few examples of standing losses:

- 150 litre (120mm insulation): 65-70W, 600 kWh/year;
- 350 litre solar (110mm insulation): 100 W, 870 kWh/year.

Please note that these values are already much lower (ca. factor 3) than the maximum values suggested by e.g. EN 303-6. Actual standing losses naturally depend on insulation level, storage temperature, stratification effects, etc. but the general calculation of standing losses (verage tank) is "45*0,16*volume ^{0,5} ".

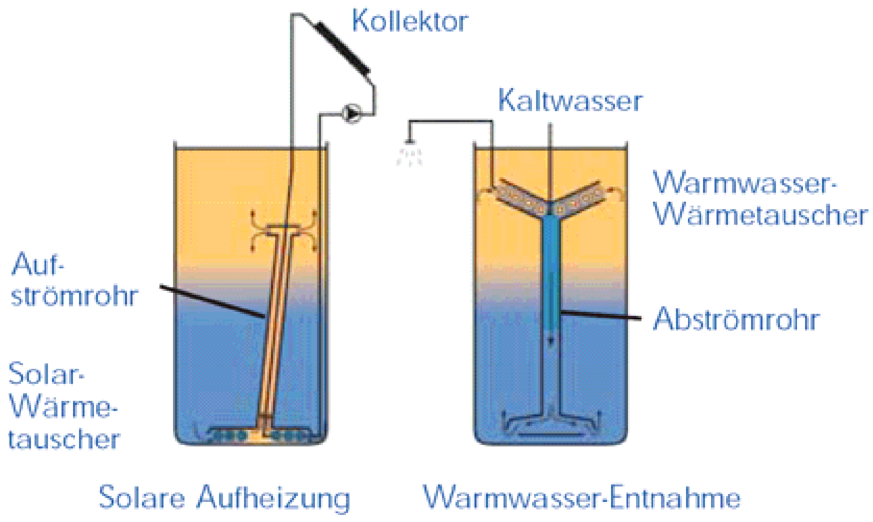
9.3.3 *Auxiliary energy*

Although most if not all separate cylinders are delivered without a power chord there is some auxiliairy energy consumption - this however occurs in the boiler itself which needs to operate at least a circulator and a three-way valve (to send primary CH water over the coil), fans and gas-valves for the combustion process and some electronic controls (that monitor the need for burner action). This energy consumption depends on the type and make of the boiler that supplies the heat and cannot be influenced by the manufacturer of the cylinder itself.

9.3.4 *Alternative energy*

"Thermal layer tanks" (DE: *Schichtenspeicher*) can use heat produced in condensing mode but also low-temperature heat from sources like solar collectors or heat pumps. By maintaining a relatively "cold" spot in the bottom half of the tank even the low temperature solar heat can be transferred to the contents of the tank.

Figure 9-15.
Solus II (www.consolar.de)



An example of the use of solar heat is shown above (by Consolar, Germany): The left side shows the transfer of heat from solar collectors through a coil heat exchanger positioned at the bottom of the storage tank. The surrounding storage water is heated, expands and rises to the top half of the tank through a dedicated riser. Thus the tank is filled from the top down, while still achieving maximum heat transfer between the relatively warm solar collector fluid and relatively cold storage water at the lower part of the tank.

The right side shows the extraction of heat for DHW purposes. In the top half a coil heat exchanger (shape: inverted umbrella) is positioned which extracts heat from the storage for DHW. The cooled down storage water sinks to the bottom half of the tank through a dedicated shunt.

The principle shows that the aim is to prevent mixing of thermal layers and to keep the heat at the top half of the tank for better DHW performance and keep the bottom half relatively cold (for optimum solar heat transfer).

9.4 Infrastructure

9.4.1 Chimney / drains

Pressurised storage cylinders require a pressure relief valve discharging into a waste water drain.

Chimneys, flues and combustion air supply are not applicable to external storage cylinders.

9.4.2 Draw-off point

Most storages are the primary water DHW source in the dwelling and serve multiple draw-off points and are connected to a lengthy DHW circuit. Some unpressurised systems however cannot meet the desired flow rates and multiple points and are sometimes only servicing a bathroom (or even bathtub only).

Connection of external storage cylinders to DHW circulation systems is very well possible. Such systems greatly reduce waiting times at the point-of-use and minimise wastage of heated water. At the downside there are heat losses of the piping system and energy consumption for circulation.

9.4.3 Distribution losses

Separate cylinders are typically used as primary water heaters, serving DHW for the whole dwelling. THe distribution of this DHW water throughout the dwelling causes energy losses that can be calculated using different approaches, described in the relevant standards (see also the Task 1 Report on Standards & Legislation).

9.5 Prices

The figure below presents list prices from Nibe of several types of external storage tanks: Copper tanks with a coil (single or double-walled), tank-in-tank or no heat exchanger, Copper tanks with an electric heater (3 or 6 kW rods) and Steel tanks without heat exchanger [source: Nibe list prices].

Figure 9-16.

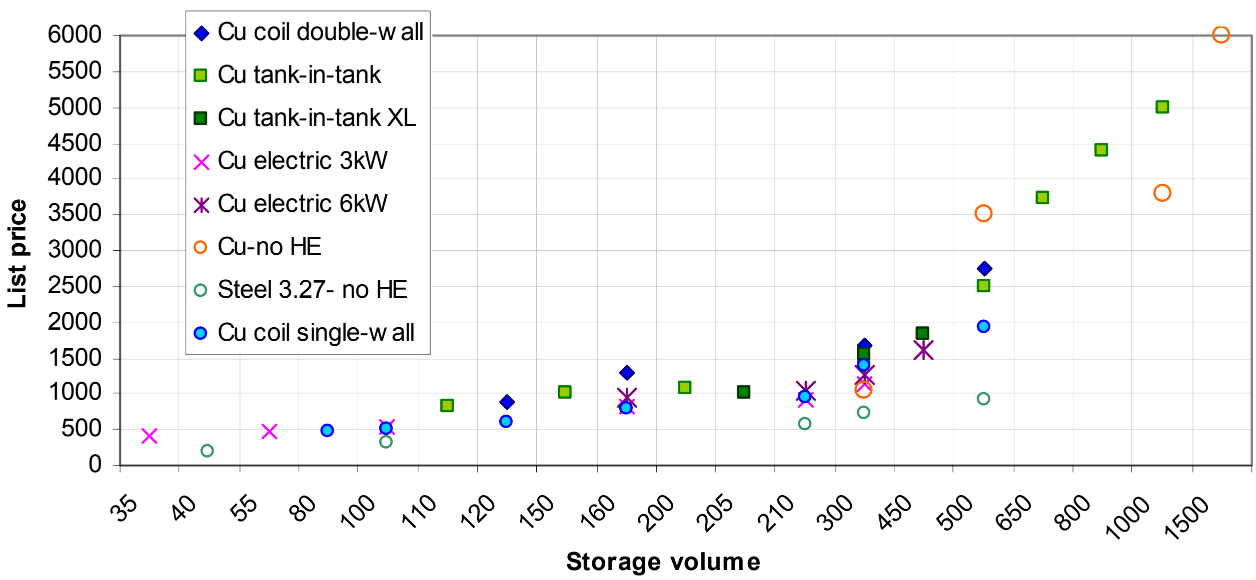


Table 9-4. List price vs. street price, examples

	List price	Street price
Nibe PCU External cylinder, Copper tank, 20 kW Copper HE (single wall) 100 L	€495,-	€510,59 (103% of list price)
Nibe PCU External cylinder, Copper tank, 28 kW Copper HE (single wall) 120 L	€615,-	€634,37 (103% of list price)

10 GAS/OIL STORAGE WATER HEATER

10.1 Product description

This group comprises gas-/oil-fired water heaters with integrated DHW storage. The difference with storage combis being that these are dedicated water heaters - not designed to supply heat for space heating although in practice some construction similarities may exist.

Storage-water heaters offer high DHW performance (l/min) and recovery rates (l/hr at given temp. difference). Most storage water heaters are essentially storage cylinders with a burner / heat exchanger built into the appliance. The basic principle is fairly simple and robust and the product may last for decades with adequate maintenance (ie. corrosion protection for storage tank).

Gas- and oil-fired storage water heaters are produced with atmospheric or fan-assisted burners, in open or closed configurations and a wide range of burner output power (from < 5 kW to > 180kW) and storage volumes. Some examples are listed below.

Figure 10-1.
Left: single pipe AO Smith NGT gas-fired storage water heater. Right: multi-pipe AO Smith ADMR gas-fired storage water heater (picture: www.aosmith international.com)

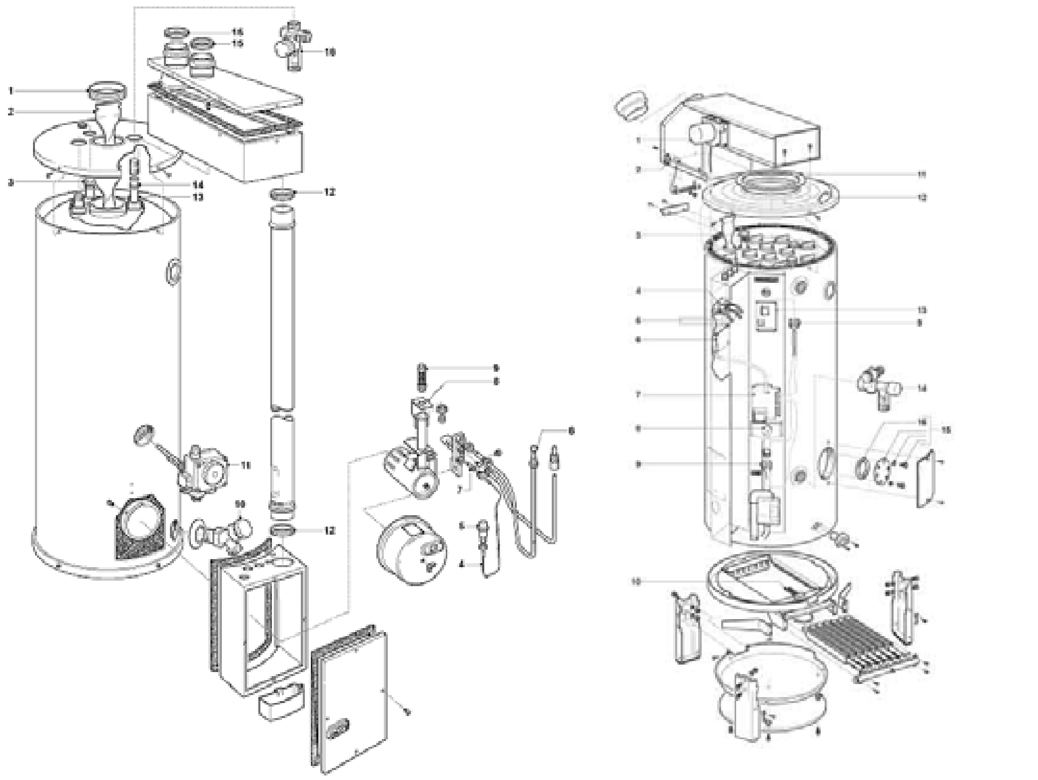


Figure 10-2.
Merloni-Ariston "Micro". 42 l volume, 4.4 kW power
(picture: www.mtsgroup.com)

Figure 10-3.
Gas fired water heater, available in 90, 125 and 250 gallons (340, 475 and 950 l)
(picture: www.pvi.com)

Figure 10-4.
"Platinum" Gas fired condensing water heater, available in 70 gallons (277 l)
(picture: www.pvi.com)

PLATINUM Condensing Water Heater

A. Completely submerged, vertical, 2-pass firetube heat exchanger with solid copper firetubes and steel combustion chamber with copper /PTFE composite for corrosion protection on waterside

B. Flange connection allows complete removal of heat exchanger

C. 316L stainless steel condensate and flue collector. Vents as a category IV appliance through PVC or CPVC when water temperatures are at sanitizing levels

D. Fan-assisted, pre-mix surface burner with electronic sequencer and flame safeguard (capable of connection to direct inlet air)

E. ASME pressure vessel for hot water storage lined with POLYSHIELD or fabricated of 439 stainless steel

Figure 10-5.

Maxxflo condensing gas water heater.

This type of water heater can operate at 109% efficiency until the tank is charged for 80%.

(picture: www.andrews waterheaters.co.uk)

The maxxflo series is a direct fired condensing storage water heater which has a stainless steel tank that is heated by up to four burner modules placed outside the tank, providing 30 to 120 kW.

The burner module has a stainless steel heat exchanger in which the burner is placed. The water heater works according to the loading principle: The water in the bottom of the tank is led directly through the heat exchanger, heated up and carried back to the top of the tank. The temperature of the water at the bottom of the tank (return temperature) is representative of the input heat; the burner modulates on the basis of this return temperature. The temperature at which the water is supplied to the tank from the heat exchanger (supply temperature) is kept at the set water heater temperature using pump modulation.

An important advantage of bringing the heat transfer from outside the tank is that the output is not influenced by the temperatures that prevail in the tank. As long as draw off occurs the water from the bottom of the tank to the heat exchanger is almost the same as the supply cold water temperature. This means the maximum output is maintained during the heating up period. On the final heating period, when the tank is almost completely heated up, the return temperature will increase and the burner modulates. Because the water is pumped round from the lowest point in the tank, the whole tank is heated up and there are no cold spots.

Figure 10-6.

This Itho / vanderbeyl GGBB is technically a gas-fired water heater - the main components (boiler, external storage) clearly visible.

(picture: www.itho.nl)

The GGBB is 54 kW, 300 or 500 l storage, auxiliary energy 180W

Figure 10-7.
ACV HM70 gas- or oil-fired storage water heater.

The ACV range extends

For safety reasons some storage water heater are equipped with a thermally operated valve in the flue. This valve shuts down the gas supply in case the flue gases do not leave the appliance in the correct way.

Manufacturers are among others Andrews Water Heaters (UK, part of the Baxi Group), Vaillant (atmoSTOR range), Junkers (StoraFlam range), ACV (HM models) and MTS Group (under the Ariston / Radi / Simat brand). Many North-American brands are also active in Europe such as A.O. Smith and Lochinvar.

10.2 DHW performance

10.2.1 Storage capcity

The performance of storage water heaters is primarily determined by the storage capacity and the research indicates this capcity ranges from approximately 40 l to over 500 l.

Another performance parameter for gas storage water heaters is the recovery rate which links storage capacity and the power of the heat generator. The recovery rate is defined as the amount of hot water the device can produce in a specified period and a specified temperature raise. A large storage capacity with a relatively modest burner may achieve similar recovery rates (for a specific time period - not continously) as a smaller storage with larger capacity burner. The efficiency of the heat transfer is also a factor in this.

The table below gives an indication of recovery rates for some gas fired storage water heaters: from 140 to almost 1800 l/hr (temp. difference 50°C). Oil fired storage water heaters produce even up to almost 2800 l/hr (also temp. difference 50°C).

Table 10-1. Recovery rates of gas/oil fired water heaters (Andrews Water Heaters)

Gas fired	Heat input (kW)	Recovery rate (l/hr)
		at delta_T 44/56ºC
Standard series	12	178 / 142
	19	278 / 222
	26	397 / 316
HiFlo series	42,8	649 / 517
	50	786 / 829
	80	1199 / 959
	102	1549 / 1239
	128	1899 / 1520
	139	1988 / 1598

		l/hr at delta_T 50ºC
Maxxflo series	30	510 l/hr
	60	1020 l/hr
	90	1530 l/hr
	120 kW	2040 l/hr
Oil-fired		l/hr at delta_T 44/56ºC
OF series	30,8	491 / 390
	34,4	577 / 443
	71,8	1227 / 975
	102,6	1759 / 1398
	123,1	2110 / 1677
	184,6	3166 / 2516

The average recommended storage temperature is 60ºC, although higher temperatures can be supported. Generally manufacturers advise not to keep temperatures higher than 80ºC for risk of scalding.

10.2.2 Temperature control

A typical low-cost gas storage water heater uses an aquastat as temperature control - at a preset temperature the aquastat switches the burner on and off. The simplest form requires a pilot flame so the burner ignites automatically as the gas valve is opened. The burners are atmosferic burners with 'open' (type B) combustion air supply.

More sophisticated gas storage water heaters are equipped with an ionisation control module and self-ignition and those equipped with fans usually employ a boiler-like gas control unit (also ionisation). These gas storage water heaters can be type C ('room sealed') although non-fan assisted (balanced flue) heaters are also available.

Furthermore several safety thermostats apply (to limit max. temperature etc.).

10.2.3 Responsiveness

Storage water heaters produce hot water with virtually no time delay.

10.3 Energy

10.3.1 On-mode

Historically the heat generator is placed inside the storage tank, with the burner chamber and flue gas duct surfaces functioning as heat exchangers (see figures in section 13.1). Burners range in capacity from 5 kW to over 180kW.

The trend towards condensing operation also reached the gas storage water heaters and several models are available nowadays. Condensing heat transfer is achieved by enlarging the heat exchange surface, preferably combined with burner modulation (see figure 13. 3 and below as example).

Figure 10-8.
Condensing gas storage water heaters

Left:BFC Cyclone by A.O.Smith. Note the large spiralling extended flue duct. (picture: www.AOSmith international.com)

Right: Ecoflo by Andrews Water Heaters. This WH has a three stage flue duct/heat exchanger. (picture: www.andrews waterheaters.com)

Another strategy to achieve condensing mode is pursued by Andrews' Maxxflo that features a heat generator placed outside the storage tank, creating a dedicated filling loop. The external burner extracts the coldest water from the bottom of the tank and inserts this at the top. Condensing modes can be maintained until the tank is approximately 80% full. This set-up is very much alike combi-boilers with storage, except for the space heating functionality of those.

By the way, even non-condensing storage water heaters can produce condensate during "cold" starts (tank is filled with cold water). Instruction manuals prepare users for *'hissing sounds'* of water condensate droplets falling onto the burner - and that these should dissapper once the water is heated up further.

The efficiency (lhv) for conventional heaters is 85% and may reach 95-96% for condensing models.

10.3.2 Off-mode

Standby losses are the thermal losses from the storage tank. In fact these losses occur continuously and not only when the water heater is in standby (burner not ignited) - therefore "standing losses" are a better description.

The losses depend on the storage temperature, the insulation applied and edge losses like standing feet or connections to rest of DHW system. Gas- and oil-fired water heaters also have a flue gas system and air supply that may contribute to standing losses.

Common measures applied to reduce standing losses are: improved insulation (inlcuding the standing feet / bottom part / connections), flue dampers (reduce draught when not ignited), non-return valves in system connections (reduce heat transfer through internal flow), connections aimed downwards (also reduce heat transfer through internal flow) and lower system temperatures (this strategy should be aligned with anti-legionella measures).

10.3.3 Auxiliary energy

Simple gas storage water heaters equipped with a pilot flame (ignited manually) and a gas valve operated by the thermostat require no electrical power. The burner is atmospheric and the construction is open (B...) (example: A.O.Smith BT range).

Electric / electronic components typical for fan-assisted, sealed gas fired storage water heater are:

- Burner control, including connection to ionisation electrode (to detect ignition);
- Gas valve (operates gas supply, works with solenoid valve);
- Pressure differential sensor (checks airflow);
- Fan (controlled by burner control);
- Thermostat (temperature thermostat and safety thermostat).
- Switches, control lights, etc.

The power consumption of this set-up (5 kW heat input for 75 or 110 l storage) is 26 W of which 10 W by the gas valve and 16 W by the fan [44].

Fan-assisted gas water heaters of a different brand, with more capacity (190 l), may use ten times as much energy: the Andrews RFF 190 (190 l storage) consumes 236 W. The extra consumption can partly be explained by a more powerful fan (the RFF range is a 19.5 or 23kW heater with open configuration intended for longer/difficult flues). More advanced models (the sealed CSC range of 44 to 104kW by Andrews) also consume up to 236W. Apparantly the fan and controls are designed for the maximum power model and are throttled to fit less powerful models.

Highest electricity consumption is recorded for condensing boilers. The A.O.Smith BFC Cyclone condensing gas water heater consumes 275W (30 to 60kW models), 625W (80kW) or 710W (100kW). The Andrews Maxxflo consumes 170W (30kW model), 340W (60kW), 510W (90kW) and 680W (120kW).

Models equipped with a timer may consume 10 to 15 W for this option (example Baxi/Sentry EBW: 14W) .

Oil-fired storage water heaters require auxilairy electricity for feed and dosage pumps and other controls (no data).

10.3.4 Alternative energy sources

Since most storage water heaters can be connected to DHW circulation loops there should no real problems with handling incoming pre-heated DHW water from a solar system (if needed a thermostatic valve may be used to limit inlet temperatures). The gas-/oil-fired storage water heater acts as a re-heater.

Total integration of the solar storage into the DHW storage is problematic the DHW storage temperature of minimum 55 to 60ºC reduces the solar contribution (solar heat of less than 55ºC cannot be transferred).

10.4 Infrastructure

10.4.1 Drains

All UNVENTED - ie mains pressure - storage water heaters have to have a facility that handles the pressure build-up by the expanding heated water. A pressure relief valve (usually combined with a non-return valve and stop-cock in one component) is a mandatory item and sometimes is combined with an expansion vessel (as indicated in some UK installation manuals)[45]. The pressure relief valve must be connected to a waste water drain. Vented storage water heaters can expand through the cistern located in the loft.

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[44] The appliance described here is the WFF 80 / 120 by A.O.Smith. This boiler produces 164 l/hr at a delta_T of 25ºC. The efficiency is 94% (calorific value and test standard not indicated, most likely EN89).

[45] ACV also recommends expansion vessels to prevent extreme pressure build-up due to water hammer effects (induced by rapid closing of valves).

Condensing gas-/oil-fired storage water heaters also need a drain for condensate. This drain can be combined with the waste water drain provided it is allowed to dispose of the condensate in the general sewage system and includes an air-break. For gas-fired water heaters this is usually allowed, for oil-fired systems a neutralisation box may be required.

10.4.2 Chimney

Gas-/oil-fired storage water heaters require a chimney/flue gas system and a combustion air supply. If the boiler is able to operate in condensing mode the chimney needs to be airtight and moisture proof - See also Task 3.

Many dedicated gas-fired storage water heater are equipped with a thermally operated valve in the flue. This valve shuts down the gas supply in case the flue gases do not leave the appliance in the correct way.

10.4.3 DHW piping

Most storage WH's are the primary water heater in the dwelling and serve multiple draw-off points and are thus connected to a lengthy DHW circuit. It is obvious that frequent small tappings and large pipe lengths contribute to waiting time losses. These losses will be modelled in other Chapters of this Task.

It is also not uncommon for large storage water heaters to be applied in circulation loops. This requires extra circulation energy and compensation of heat losses of the circulation pipes.

10.5 Prices

In general gas storage water heater product price increases with storage volume and output power of the burner. However (the combination of) features like open or sealed configuration, automatic flue diverters, storage tank materials, temperature control features and special precautions for 'agressive' water quality may cause sharp price increases over the standard product price.

The table below gives an indication of list- and street prices for several storage volume / kW combinations for four countries.

Table 10-2. Product price of gas storage heaters (first column: volume/kw, second column: price)

UK 1)	GBP/euro (street)	FR 2)	euro (street)	IT 3)	euro (list)	NL (list) 4)	
120 / 6.9	652 / 978	115 / 7.5	537	80 / ...	895	75 / 4.7	740
150 / 7.2	679 / 1018	155 / 8.4	580	100 / 5.5	968	115 / 4.7	893
200 / 8.0	693 / 1040	195 / 10.1	852	120 / 5.6	1066	109 / 7.5	500
200 / 28.5	1890 / 2835	115 / 4.3	716	80 / 2.9	605	144 / 9.1	600
300 / 31	2090 / 3135	155 / 4.7	799	100 / 2.9	624	181 / 10	986
		195 / 5.2	1085	50 / 3	320 - 340	265 / 18	1669
		80 / 5.4	739	80 / 4.4	320 - 380	355 /18.5	2284
		100 / 5.4	817	100 / 4.4	360 - 380	217 / 30.1	5430
		111 / ...	980	120 / 4.4	412	368 / 32.8	5715
		142 / ...	1076	120 / 3.6	740	368 / 48.6	6407
		185 / ...	1722	150 / 4	834	368 / 59.6	6935
				200 / 4.5	928		

1) www.discountedheating.co.uk (streetprices)

2) www.brosette.fr (listprices)

3) Ariston list prices for Italy (listprices)

4) www.technishceunie.nl (wholesaleprices)

11 GAS/OIL INSTANTANEOUS WATER HEATER

11.1 Product description

Gas- and oil-fired instantaneous water heaters are available in a wide capacity range, ranging from small 'geysers' of a less than 10 kW, to bath water heaters of 40kW, to very large industrial type water heaters of over 1000 kW. The lower end of the range is intended for "kitchen-sink only" whereas the higher end is found in washdown and process use in the food industry, hotels, sports and leisure centres, universities, colleges and hospitals, etc.

Figure 11-1.
Nefit kitchen-sink geyser 4.7 - 9.4 kW (picture: www.nefit.nl)

Figure 11-2.
Merloni Fast 14 FIMET 9-24.3kW (Picture: http://www.mtsgroup.com)

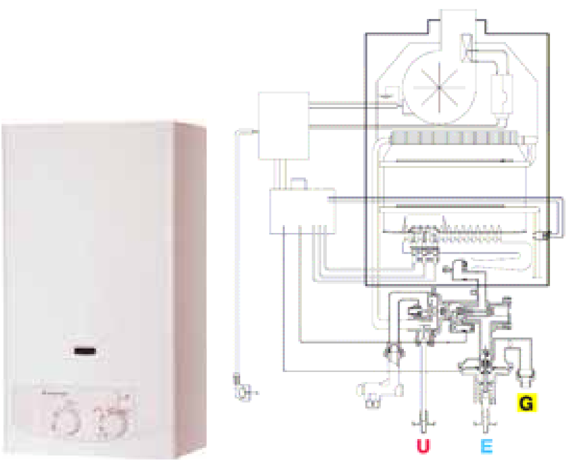


Figure 11-3.
Andrews SupaFlo R18 range 481-1002kW (picture: www. andrewswaterheaters.co.uk)

Most instantaneous water heaters on the market today are gas-fired. Oil-fired instantaneous water heaters do exist but are rare in Europe (the Toyotomi TO 148 is mainly aimed at the Canadian and US market).

Figure 11-4.
OM-148 Instantaneous Domestic Hot Water Heater (picture: http://www.tanklesswaterheaters.ca)

Most gas-fired instantaneous water heaters are wall hung, with fin-tube type heat exchangers. (Small gas-fired) Instantaneous water heaters are still available in type A configuration (open flue - emits flue gases in installed space), although type B or C are recommended by legislators and installers for health, safety and efficiency reasons.

Some brand names of manufacturers of (gas-fired) instantaneous water heaters are Vaillant, Bosch, Nefit, Chaffoteaux, Ariston, Main, Andrews Water Heaters, Vokera, Rinnai, etc.

11.2 DHW performance

11.2.1 Flow rate

The maximum flow rate of DHW by instantaneous water heaters depends foremost on the capacity (and efficiency) of the burner. The amount of power to produce 1 litre per minute however remains fairly constant over the range (some 3.4 to 3.5 kW per l/min). Some examples are listed below.

Table 11-1. Examples of flow rate and power

	Max. power output	Max. flow (ΔT 50ºC)	constant	Brand, model series
Kitchen sink	9,4 kW	2,4 l/min	3,9 kW per l/min	Nefit F1400
Shower + sink	17,5 kW	5 l/min	3,5 kW per l/min	Nefit F2555
Bath, shower + sink	27,1 kW	8 l/min	3,4 kW per l/min	Nefit F4055HE
Bath, shower + sink	42 kW	11,9 l/min (1)	3,5 kW per l/min	Andrews WH(X)42
Bath, shower + sink	55,8 kW	16,5 l/min (1)	3,4 kW per l/min	Andrews WH(X)56
Collective/commercial	70 kW	20,25 l/min (1)	3,5 kW per l/min	Andrews R300 series
Collective/commercial	274 kW	79,6 l/min (1)	3,4 kW per l/min	Andrews R300 series
Collective/commercial	481 kW	139,7 l/min (1)	3,4 kW per l/min	Andrews R18 series
Collective/commercial	1002 kW	291 l/min (1)	3,4 kW per l/min	Andrews R18 series

(1) Original data interpolated for ΔT 50ºC

Temperature stability partly depends on the minimum flow rate. Below the minimu flow rate the appliance will start to 'cycle' (DE: *Takten*). The minimum flow rate for the smaller water heaters (up to 30 kW or so) is in the range of 2,4-2,5 l/min (at ΔT 50°C). For the larger models (40-60 kW) it can be 3.5 l/min. The Andrews Supaflo range (70 to 1000 kw) is stated to be able to modulate down to 20% of burner output, all within a 1% temperature accuracy. The Lochinvar IntelliFin featuring extended electronic controls is said to be accurate within 0,5°C.

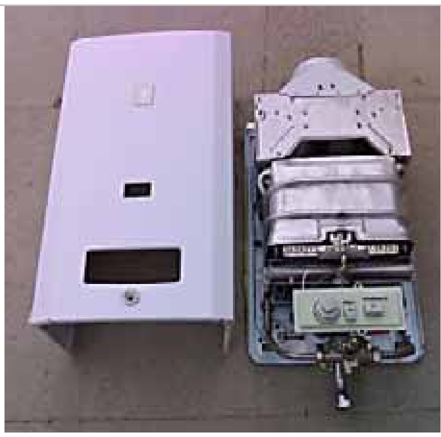
Responsiveness of gas- (and oil-) fired instantaneous water heaters is generally quite fast due to low thermal mass (mainly fin-tube heat exchangers with little thermal mass) and simple controls. The room sealed appliances (mainly type C configuration) apply pre-purging of the burner chamber. Water heaters with a pilot flame have a little advantage in terms of waiting time.

11.3 Energy

11.3.1 On-mode

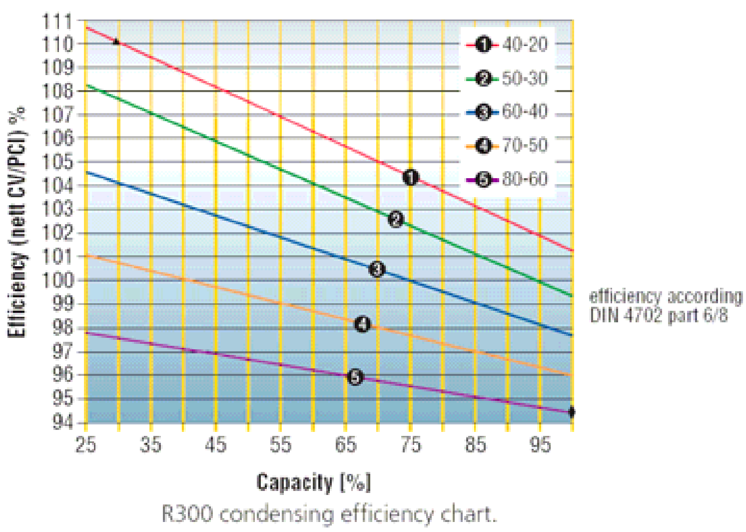
The heat generator is in most cases a burner with a fin-tube heat exchanger arrangement.

Figure 11-5.
Stereotypical domestic instantaneous water heater, apparantly type B (not room sealed, with flue) (picture: eBay)



Net efficiency is in the range of 85-90%, although condensing water heaters are available (at least from Andrews and Lochinvar) with net efficiencies up to 110% (depending on temperatures and flow). The figures below present efficiency data from the Andrews and Lochinvar condensing water heaters, also indicating the dependance of efficiency from supply-send temperatures. Other energy losses in on-mode are due to envelope losses.

Figure 11-6.
Graph representing the efficiency of the Andrews R300 series over a range of supply-send temperatures. (picture: Brochure Andrews Water heaters SupaFlo)



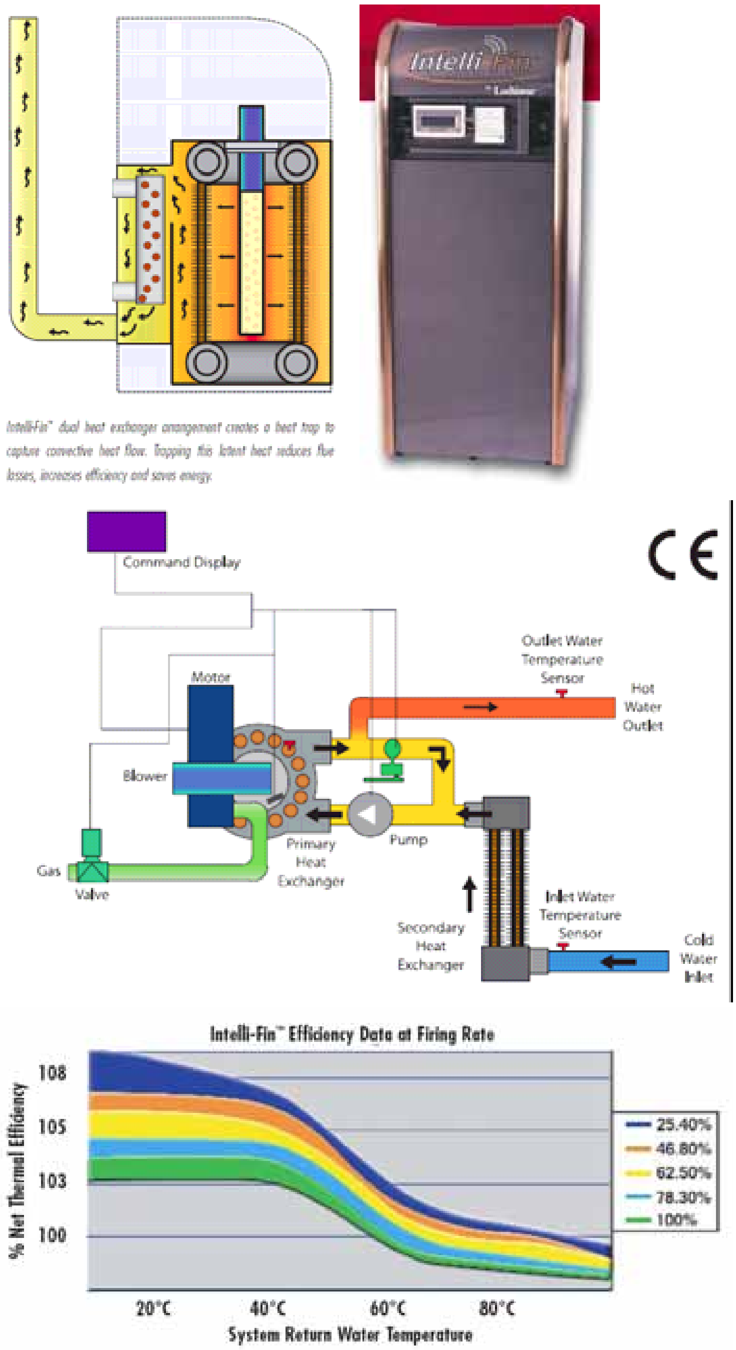


Figure 11-7.
Intelli-Fin condensing water heater by Lochinvar (UK). Output of 397 to 428 kW produces 7084 to 9440 l/hr (118 - 157 l/min).
(picture: Lochinvar Intelli-Fin brochure)

(continued)
The dual heat exchanger arrangement preheats return water to control condensate formation. Using a pumped bypass, a portion of the heated supply water is recirculated to raise inlet temperature to a point where condensation on the primary heat exchanger is avoided.. The secundary heat exchanger allows condensing operation (103% ncv) even if the supply temperature is over 70°C.

11.3.2 Off-mode

In off-mode envelope losses also occur, especially if a pilot flame is present. Another factor is the placement of the appliance (several manufacturers offer models in both indoor and outdoor versions). Appliances without a pilot flame may be equipped with a flue damper to prohibit downdraughts of cold outside air.

In case the appliance is connected to a DHW circulation loop extra system losses are introduced (heat losses and power needed for circulation).

11.3.3 Start-stop

Start-stop losses are mainly due to pre- and post purging (heating/cooling of thermal mass, unburnt fuel losses).

In case the flow is below the minium flow rate frequent start-stops occur (even within a tapping cycle).

11.3.4 Auxiliary

The simplest gas-fired water heaters (open configuration: Type A or B, with pilot flame and hydraulic control) do not use auxiliairy energy (pilot flame left aside). More advanced (closed: type C) water heaters use electronic (piezo) ignition and require electric mains connection or batteries to ignite.

Fan-assisted water heaters are always connected to the electric mains: by example the Ariston Fast 14 FFI (27 kW) consumes 55W at maximum.

An Austrialan-led study [46] gives the following values, based upon a survey of 20 mains powered gas water heaters:

- On-mode: 40-120W;
- Cool down-mode: 10-40W;
- Passive standby mode (off-mode): 4,5-12W, average 10W and newer models between 6-8W;
- Frost protection-mode: Either zero (drain down type) or 50-120W.

Some types of gas_instantaneous water heaters can operate without being connected to an energy source: AquaStart water heaters by Nefit are powered by a small water turbine, driven by the flow of the water. The principle is applied by Vaillant and some other brandnames too. The technology however is not suited to power flue fans or electronic controls requiring constant power and as such limited to atmosferic, type B heaters.

11.3.5 Alternative sources

No gas- or oil-fired instantaneous water heaters have been found to use pre-heated DHW from alternative energy sources (solar of heat pump).

11.4 Infrastructure

11.4.1 Drains

Condensing models are equipped with condensate drains. Depending on local requirements a neutralisation kit may be needed.

11.4.2 Chimney/ air supply

As stated earlier instantaneous water heaters are available in all flue/supply air configurations: Type A, B and C.

Some models are equipped with safety provisons that monitor correct flue functioning, eg. Ondea with S.P.O.T.T. (Système Permanent d'Observation du Tirage Thermique).

11.4.3 Single, multiple or circulation draw-off points

Smaller kitchen-sink models can be equipped with a faucet and can be hung directly over the sink - these are typical single-point appliances. Larger models can be connected to conventional DHW piping and can facilitate multiple draw-off points.

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[46] Instantaneous gas water heaters - standby product profile 2004/04, Australian Greenhouse Office, March 2004

Figure 11-8.
Nefit Aquastart

Appliances producing up to 5 l/min (at ΔT 50ºC) are often indicated for kitchen use only, up to 8 l/min could facilitate a shower and more than 8 l/min could facilitate a bath.

Connection to a storage tank is a possibility, just as connection to a DHW circulation loop - even in cascade configuration if required.

Figure 11-9.
Andrews FastFlo water heater connected to a storage tank (picture: Andrews FastFlo brochure)

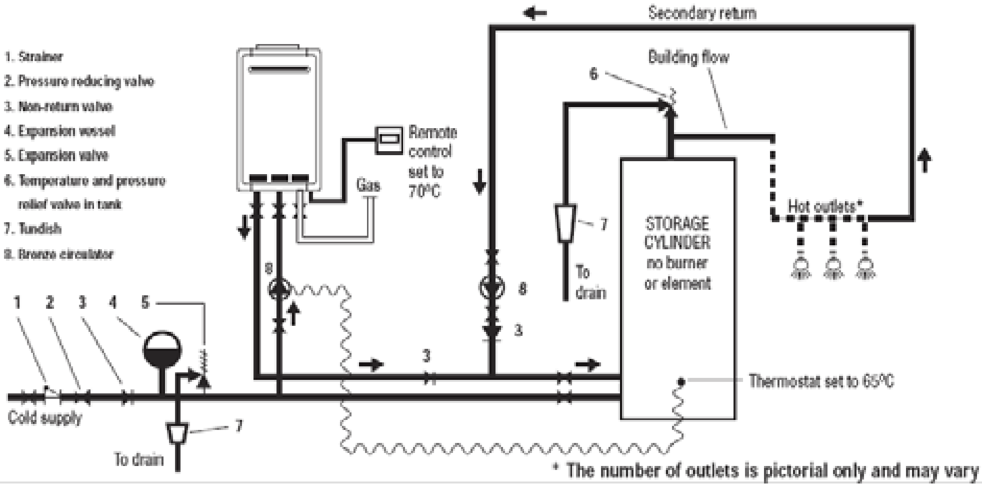
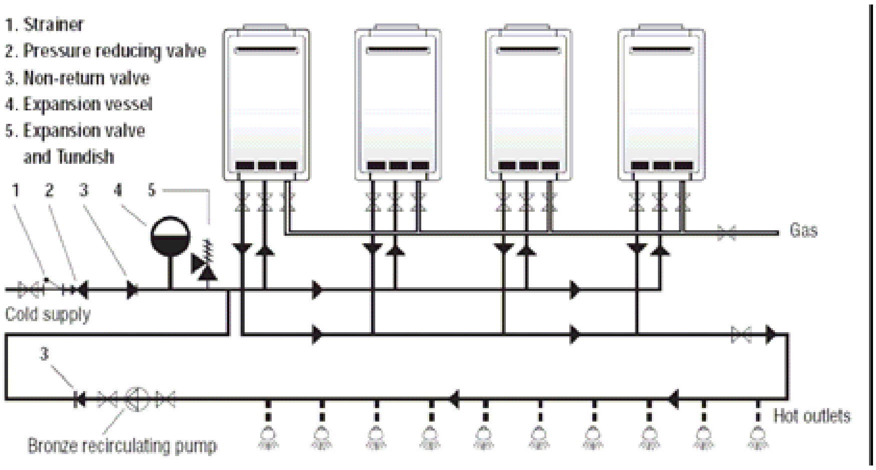


Figure 11-10.
Andrews FastFlo water heater in cascade, connected to DHW circulation loop (picture: Andrews FastFlo brochure)



11.5 Prices

Street and list prices of some small to medium sized appliances were retrieved:

Table 11-2. Street and list prices of small to medium sized instantaneous gas-fired water heaters

1) List price excl. VAT *2) Street price incl. VAT*	l/min at ΔT 50ºC	DE *2)* getprice.de	IT Ariston list prices (excl. VAT)	FR e.l.m. leblanc list prices (excl. VAT)	UK *2)* Discounteheating.co.uk bhl.co.uk	NL *2)* www.tempus.nl
Bosch W135-TZ1	2					287
Nefit F1400	2,4					284
Chaffoteaux Celt Star	2,5				242	
e.l.m. leblanc LM5	2,5			(243)		
Vaillant atmoMAG 9	2,7	340-345				
Nefit F2555HE	5					400
Bosch 250-1AM	5					737
e.l.m. leblanc LM10	5			(359-426)		
Vaillant atmoMAG 9	5,5	449-516				
Ariston Fast 11 pilot/electronic /modulation	5,5		(244/330/ 544)			
Chaffoteaux Britony IIT	6				505	
Bosch 325-1AM	6,5					844
Nefit F3255HE	6,5					649
Vaillant atmoMAG 9	7	551-625				
Ariston Fast 14 pilot/electronic /modulation	7		(320/396/ 594)			
e.l.m. leblanc LC17	8,5			(510-586)		
Andrews FastFlo 42	12				819	
Andrews FastFlo 56	16,5				1087	

12 ELECTRIC STORAGE WATER HEATER

12.1 Product description

Electric storage water heaters are relatively easy installed (no flues, combustion air or fuel supply needed, just electricity and hot/cold water piping, possibly a drain) and offer relatively high water comfort (depending on recovery rate).

The principle design is a storage tank with one (or more) electric immersion heater(s). The size of the storage tank may vary from just a few liters (for single point use) to several hundreds of liters (for multi-point use). The power of the electric immersion heater increases as the size of the storage increases but electric power exceeding 6 kW is rare, given the average maximum size of a household fusebox (20 A). Larger tanks (over 200 l.) are often floor standing.

Electric storage heaters may be pressurised (with the storage at mains pressure) or unpressurised. The latter is either an open vented storage or cistern (more common in the UK) or a vented tap (more common in Germany, in small storage heaters (max 5 l.) placed above a washbasin). Such unpressurised heaters can be equipped with plastic tanks, whereas pressurised heaters are made of metal (enamelled steel, copper or stainless steel). And there are versions with an electrically heated primary store, producing DHW through a (plate) heat exchanger (like the Gledhill PulsaCoil).

A special group of electric storage water heaters is the boiling water heater, intended to supply (almost) boiling hot water for consumption (tea, soup, etc.). Again here we have pressurised and unpressurised systems.

The table below tries to group electric storage water heaters by application and volume.

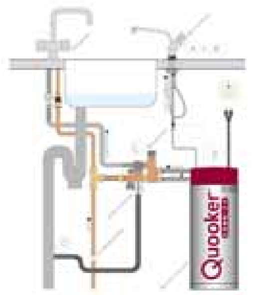
Table 12-1. Electric storage water heaters - products by application

Application	Storage volume	pressurised	unpressurised
boiling water (point-of-use by definition)	1,5 to 40 liter	up to 7 l.	up to 40 l.
small DHW storage	5 - 30 l.	whole range	whole range
medium sized DHW storage	30-200	whole range	up to 125 l (cistern)
large DHW storage	>200	whole range	not found (for primary stores see External Storage cylinders)

The figures below give a (not comprehensive) overview of the product group electric storage water heaters.

Figure 12-1.
Boiling water heaters.
(pictures left: ZIP hydrotap (1.5 to 4 l boiling water)
(picture mid: Clage KA range, 1.5 to 40 l.)
(picture right: HeatraeSadia Supreme range 10-40 l)

Figure 12-2.
Combined boiling and/or hot water heater



The Quooker combi combines a boiling water heater with a hot water heater in one package (volume 7 l, 2.2 or 3kW), pressurised.
price range 1200 euro

The Vaillant VEK can manually be set to produce water from 30ºC to boiling point (unpressurised). The pipe on the left is the overflow pipe.

Figure 12-3.
Small storage water heaters (< 30 l), available in pressurised and unpressurised versions for either above or under-sink installation.
(picture left: Stiebel Eltron 10-15 l)
(picture right: Ariston - unpressurised, 10 to 30 l)

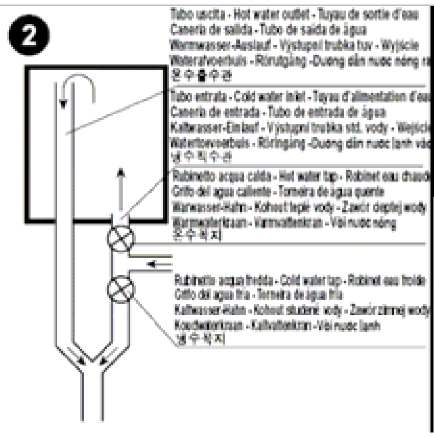


Figure 12-4.
medium sized storage (30 to 200 l), pressurised.
(picture left: Vaillant VEH, 50, 80 and 100 l)
(picture right: Ariston TI TRONIC BEST 80 VR/5)

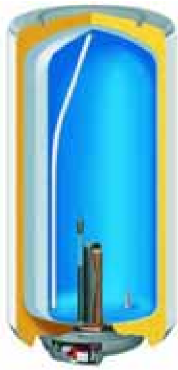


Figure 12-5.
large sized, pressurised (> 200 l).
(picture: Vaillant VEH)
(picture: Stiebel Eltron SHO, 1000 l, up to 18 kW element)

200 to 400 l floor standing

1000 l floor standing

Figure 12-6.
Unpressurised 25 to 125 l. storage
(picture: HeatraeSadia Cistern, direct fed)
(picture right: Gledhill PulsaCoil, indirect storage)

Figure 12-7.
Horizontal storage tanks are also available
(picture: Ariston)

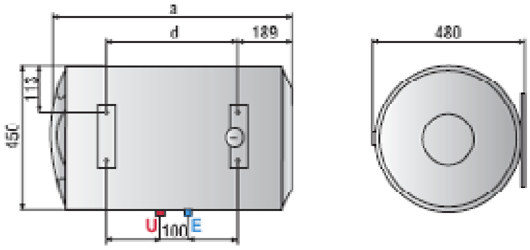
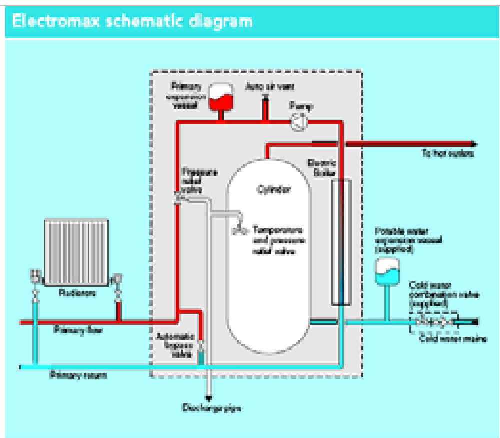


Figure 12-8.
This electric storage water heater is combined with an electric boiler in one package - although judged from outside to be a combi-boiler the DHW storage is not heated by the space heating boiler.

(picture: HeatraeSadia Electromax)



There are numerous manufacturers of electric storage water heaters. Brandnames are Stiebel Eltron, Heatrea Sadia, Clage, Vaillant, Ariston, Inventum, Daalderop, Bosch, Junkers, Blomberg, A.O.Smith, etc.

Heat generator

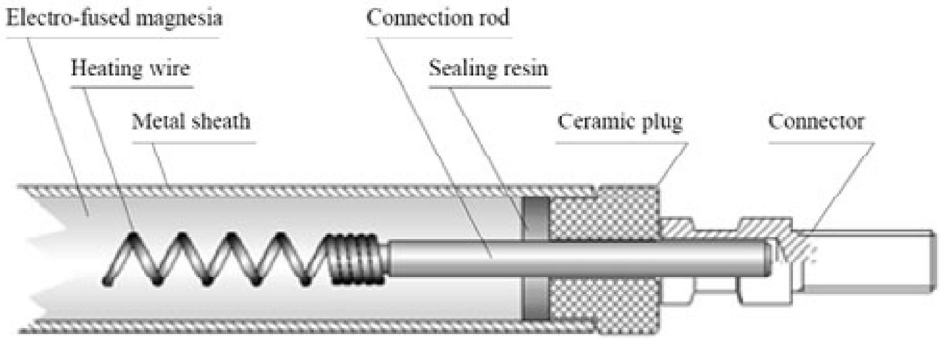
The electric heater applied in electric storage water heaters is a tubular heater which consists of a spiral-wound resistive wire perfectly centred in a tubular metal sheath filled with a powdery insulator (electro-fused magnesium-oxide MgO). The type of metal sheath (or its surface finishing) is optimised for the working conditions (susceptibility against scaling, water conditions, temperature range, etc.).

The magnesium powder is compacted by a laminate, also necessary to obtain good thermal conductivity and good mechanical and dielectric strength.

The extremities are sealed with a resin (silicone, epoxy, polyurethane, etc., according to the application) and terminated by a ceramic plug. The electric connections and the mechanical attachment accessories required can be specified by the manufacturer. Several types of flanges or other fastening methods can be applied.

Manufacturers of electric heater elements: Cetal (France), Caloritech (US), Cotherm (France), Electrowatt (France), RICA (Italy), Thermowatt (Italy), NIBE (Sweden, several trademarks), etc.

Figure 12-9.
Cut-out tubular heater (Electrowatt)



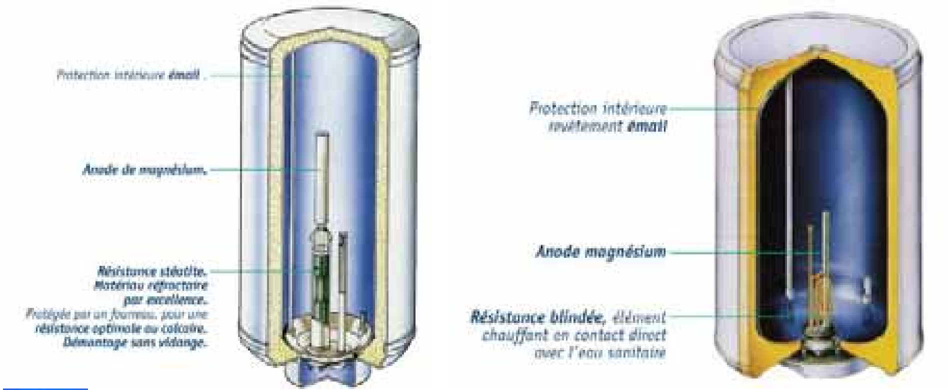
Screw-plug (Electrowatt)

Flanged heater (Electrowatt)

Specialty flange (Electrowatt)

Figure 12-10.
Stéatite (FR) heaters are not immersed in the water but contained in cylindrical shaped hollow rods enable heating element replacement without emptying the boiler. The immersion type is called *Blindée* (FR).

(picture: www.brossette.fr)



Anti-corrosion

Like all external storage cylinders (Chapter 12) the electric storage water heater has to be protected from corrosion. Copper and stainless steel cylinders are corrosion resistant by themselves (although there are differences in type of quality of stainless steel) and enamelled steel tanks have to be equipped with self-sacrificing (magnesium) anodes that dissolve over time. Small unpressurised vessels may also use a plastic (polyolefine) tank.

Temperature settings and safety

Most electric storage water electric heaters allow setting of the storage temperature in the range from approximately 40 - 50°C to 80 - 90°C (some models support operating temperatures in the range of 7°C to 85°C). User manuals warn against the risk of scalding when using higher temperatures. Higher temperatures (above 60°C) also contribute to scaling of the electric element and sediment formation.

In case of thermostat failure the heaters have a thermal sensor/switch to prevent overheating. Usually at temperatures of 95°C or above the sensor switches off the electric supply, which can only be turned on again through manual intervention (after a check for correct operation and repair if needed).

Some heaters have frost-protection ie. they switch on if the storage temperature drops below 7°C. Please note that fittings and piping leading to and from the heater need frost protection too.

Boiling water heaters are designed to produce water up to the boiling point.

12.2 DHW performance

12.2.1 Flow/recovery rate and temperature stability

The performance of electric storage water heaters is best expressed through their recovery rates: the amount of hot water the device can produce in a specified period and with specified temperature raise. The main determinant for the (continuous) recovery rate is the capacity of the electric heaters. The recovery rate starting with a fully charged storage is of course higher than the continuous recovery rate.

The table below presents some data for typical electric storage water heaters over 25 ltiter (AO Smith EES range).

Table 12-2.Technical specifications electric storage water heaters

AO Smith EES range		6	15	20	30	40	52	66	80	120
Volume	l	25	55	75	115	155	190	250	300	450
Electric power	kW	1,8	1,8	1,8	2,7	2,7	2,7	2,7	2,7	2,7
Current	A	8	8	8	11-13	11-13	11-13	11-13	11-13	11-13
# Elements	-	1	1	1	2	2	2	2	2	2
Electrical supply	VAC/Hz	230 (-15/+10%) /50 Hz								
Max. set temperature	°C	77	77	77	77	77	77	77	77	77
30 min. ΔT=28°C	l	63	108	138	211	271	323	413	488	713
60 min. ΔT=28°C	l	91	136	166	253	313	366	456	531	756
90 min. ΔT=28°C	l	119	164	194	295	355	408	498	573	798
120 min. ΔT=28°C	l	148	193	223	338	398	450	540	615	840
Continu ΔT=28°C	l/h	56	56	56	85	85	85	85	85	85
Full ΔT=28°C	min.	27	58	80	81	110	135	177	212	319
30 min. ΔT=50°C	l	35	60	77	118	152	181	231	273	399

60 min. ΔT=50°C	l	51	76	93	142	175	205	255	297	423
90 min. ΔT=50°C	l	67	92	109	165	199	228	279	321	447
120 min. ΔT=50°C	l	83	108	125	189	223	252	303	345	471
Continu ΔT=50°C	l/h	32	32	32	47	47	47	47	47	47
Full ΔT=50°C	min.	47	104	142	145	196	240	316	379	569
# Anodes	-	1								
Max. pressure	bar	8								
Weight empty	kg	13	21	27	36	43	48	64	80	125
Weight filled	kg	35	76	102	151	198	238	314	380	575

For electric water heaters of less than 25-30 liters the recovery rate is often not indicated in product brochures, only the reheat time. The example below gives reheat times (and standing losses) for some smaller electric storage water heaters.

Table 12-3. Reheat times of electric storage water heaters

Example Junkers EHU range					
Volume (l)	10	10	15	15	30
Reheat time (from 10ºC to 60ºC with 2 kW element)	20	20	30	30	60
Standing losses (kWh per 24 hr at 65ºC)	0,57	0,43	0,69	0,53	0,69

Another aspect defining the performance of a storage water heater is its *useful volume*, which is indicated by the *mixing efficiency* factor V40 and a.o. depends on the placement and shape of sensor and heater in the storage tank.

For example:

a hot water need of 150 l at 40ºC can be covered by:

- a 100 l storage at 65ºC (V40 = 1,5N);
- or 86 l at 65ºC (V40 = 1,75)
- or 100 l at 56ºC (V40 = 1,75)

A better mixing efficiency thus increases the nominal capacity with the same storage volume, or enables the same nominal capacity with a smaller storage at the same temperature or a similar sized storage with a lower temperature. The table below gives the mixing efficiency for several base case storage volumes.

Table 12-4: V40 mixing efficiency [47]

30 l	1.60 * nominal capacity
80 l	1.60 * nominal capacity
100 l	1.65 * nominal capacity
200 l	1.70 * nominal capacity

12.3 Energy

12.3.1 On-mode

The immersed electric heater element transfers virtually all energy to the storage content: the transfer efficiency therefore reaches 100%. The primary efficiency (and CO_2 emissions) depends on grid characteristics.

More important for overall energetic performance are the standing (off-mode) losses.

[47] CECED presentation, 14.02.2007

12.3.2 *Off-mode*

The off-mode describes the status of the electric storage water heater with the electric element turned off, also referred to as standing losses (heat losses through envelope and connections).

Standing losses are an important energetic loss of electric storage water heaters and are determined by the temperature difference between the water and the surroundings and the insulation level (radiation, convection and conduction losses).

In a presentation by CECED on 14.02.2007 regarding electric storage water heaters the standing losses of a basecase 200 l storage heater were calculated as 37% of the total energy consumption. Increasing insulation thickness would improve standing losses to 31% of total.

Table 12-5: Standing losses of basecases

CECED basecase	CECED basecase standing losses (65°C)	standing losses of total (useful energy 1246 kWh/year, 400 kWh for 30 l model))
30 l storage volume	244 kWh/year	244 / (400+244) = 38%
80 l storage volume	487 kWh/year	487 / (1246+487) = 28%
100 l storage volume	500 kWh/year	500 / (1246+500) = 29%
200 l storage volume	743 kWh/year	743 / (1246+743) = 37%

Even small details like insulated standing feet help to reduce standing losses. Also the surface/volume ratio is a factor in this (the 5 l model loses 0,05 kWh/24hr*ltr and the largest 400 l model 0,0065 kWh/24hr*ltr: roughly 1/8th).

Table 12-6: Standing losses of modern electric storage water heaters

Storage volume (l)	Standing losses		Remarks
	(kWh/24 hr at 60ºC)	(kWh/year)	
5	0,25	91	0.05 kWh/24hr*ltr or 10 Watt continuously
10	0,35	128	
15	0,40	146	
30	0,49	179	
50	0,54	197	at 65ºC
80	0,66	241	at 65ºC
100	0,79	288	at 65ºC
120	0,92	336	at 65ºC
150	1,07	391	at 65ºC
200	1,8	657	
300	2,2	803	
400	2,6	949	0,0065 kWh/24hr*ltr or 108 Watt continuously

These examples are from the Vaillant electric storage water heater line and concern basic models ("classic") if applicable.

As the storage temperature is an important factor in determining standing losses, optimisation of storage temperatures can further reduce these losses. An intelligent management of storage temperature would take into account peak demands, night-time tariffs, legionella risks, seasonal impact on needs, etc. to achieve the least standing losses (nigt-time operation is already standard in a.o. France and Belgium).

12.3.3 *Start-stop*

Start-stop losses of the electric storage water heater are not a significant loss factor: The thermal mass of the electric element is minimal and pre-heated by the volume of DHW in which it is immersed.

Start-stops are regulated by a aquastat sensor-switch. The hysteris of the sensor-switch determines the deviation form the set temperatures (overshoot, responsiveness). The better this control the less energy is consumed unnecessary.

12.3.4 Auxiliary energy

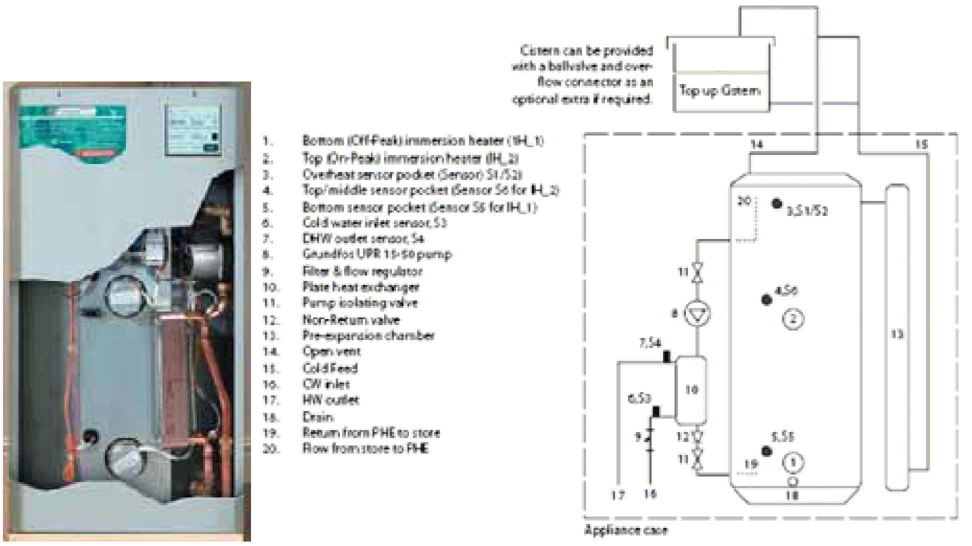
The simplest electric storage water heaters (whether they are 5 or 400 liters) do not use auxiliairy electrical energy: The temperature sensors (aquatstats) are capillary tubes operating the on/off switches of the heating element.

However, more sophisticated models may be equipped with a control panel with signal lights or an electronic (LCD) display indicating the settings and temperature. These added functions require some power (generally < 1 watt).

Electric storage water heaters equipped with a electric anode for corrosion protection (DE: *Fremdstromanode*) may require less than 0,5 Watt electric power (some 2,5 kWh/year).

And there are electric storage water heaters that heat and store primary (non potable) water. DHW is produced via a plate heat exchanger which is fed by a circulation pump circulating the stored primary water. The pump of the Gledhill PulsaCoil (Grundfos UPR 15-50) consumes some 50 W max.

Figure 12-11.
Indirect, primary, storage
(picture: Gledhill PulsaCoil)

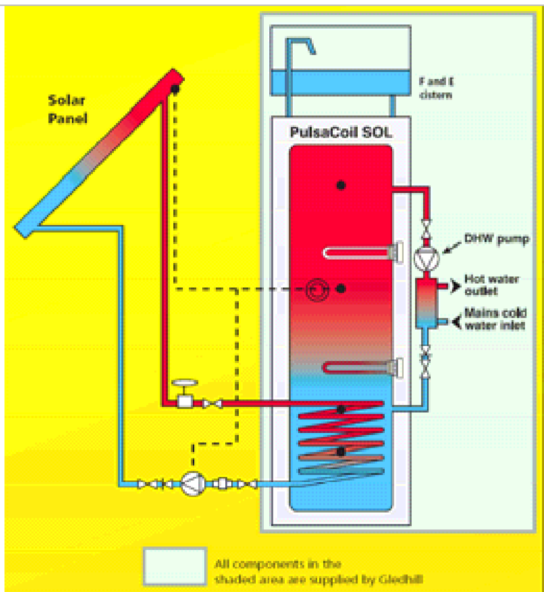


12.3.5 Alternative energy

Combination of solar heat with electric storage water heaters is quite often applied in solar storage tanks where the electric element is used to charge the system during periods of low solar energy. Such systems are primarily solar water heaters and the electric elements are only used for back up e.g. during the winter months or to boost DHW if solar irradiation is low.

Systems where the electric element is the main heater and solar heat functions as an extra energy source are less common. A few products on the market do combine the two heat sources. In such systems great care is taken to avoid conflicts between heating in electric or solar mode. The electric heater is only turned on when there is no chance of solar contributions (night-time) and then only heats the upper part of the tank. The bottom part remains 'cold' (stratification) and this is where the solar heat exchanger is placed. Mixing of solar pre-heated water occurs through natural convection. Conflicts between the two sources cannot be avoided in all circumstances since the electrically heated part of the tank reduces the available capacity for storing solar heat. Legionella is not a problem in the PulsaCoil-Sol solution since DHW is produced via a plate heat exchanger.

Figure 12-12.
Electric storage water heater with heat exchanger for solar system (picture: PulsaCoil-Sol brochure from www.gledhill.net)

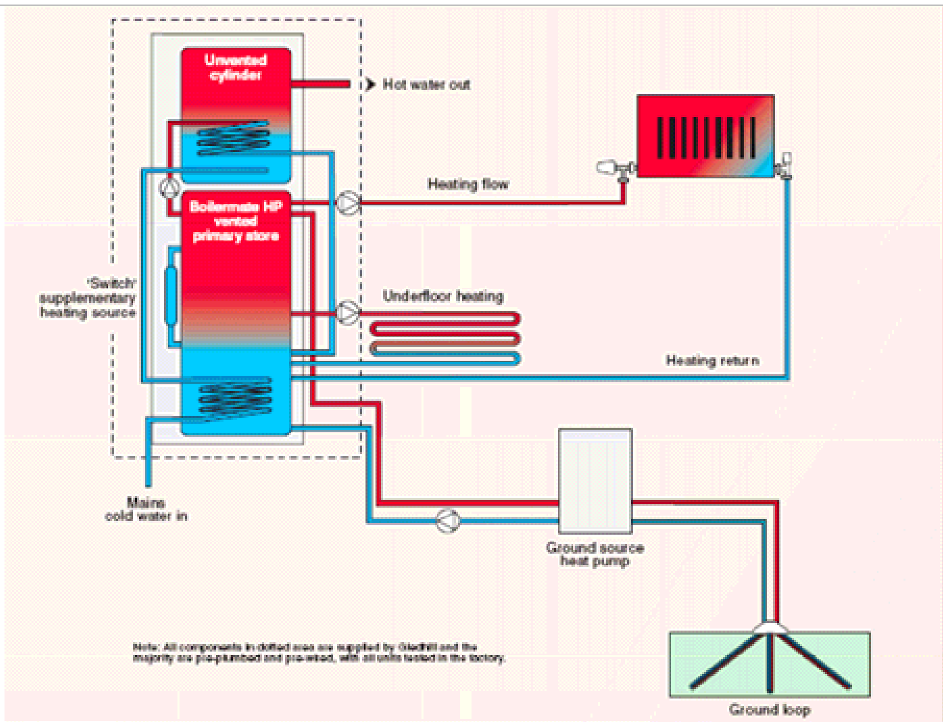


The combination of an electric heater with intermittent solar heating only makes sense if the electric heater uses off-peak electricity / night-tariff, charging the system overnight when no solar contribution is expected.
Another feature of this product is the mains pressure DHW delivery through the plate heat exchanger, eliminating the need for pressure relief valves and reducing risk of legionella.
The store itself has a feed/expansion cistern. An advantage is that scaling is less of a problem, since the storage water is not renewed.

Heat pumps and electric heating are often combined a similar fashion as solar and electric heating: Many heat pumps storage systems employ an electric heater as back-up or to periodically raise the temperatures to 60°C and above. However one cannot categorise these appliances as electric heaters since the heat pump is always the dominant heat generator - .

The combination depicted below of a (vented primary storage) electric water heater with a heat pump could also be regarded as a (heat pump) boiler with an external cylinder, equipped with an electric heating element as booster / back-up during off-peak hours.

Figure 12-13.
vented primary storage water heater combined with heat pump (picture: BoilerMate HE OPE brochure from www.gledhill.net)



12.4 Infrastructure

12.4.1 Water pressure

Pressurised boilers are usually tested to 8 to 12 bar maximum pressure. The minimum pressure is often not stated but should be enough to fill the boiler, regardless its placement in the house.

Small (max 30 l) unpressurised cistern-fed storage heaters may require a minimum pressure of 0,4 bar (so the feed tank, if applicable, should be located over 4 m above the appliance). Most of the unpressurised storage heaters without cistern (using vented taps) are not rated at all as they are designed to relieve any excess pressure through the tap or an overflow pipe.

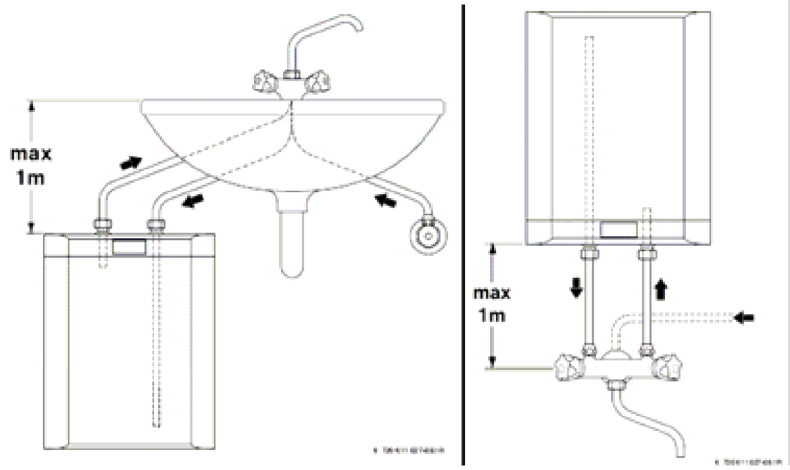


Figure 12-14.
Vented tap systems (picture: Junkers EHU Untertisch / Obentisch)

Large unpressurised cistern-type vented storage tanks are equipped with float valves, capable of withstanding 7 bar. The cistern itself is under atmospheric pressure only.

The open vented indirect storage water heater with a plate heat exchanger accepts water pressure from 1 bar minimum to 5 bar maximum. The cistern (open vented feed tank) should not be placed over 10 m above the storage tank (1 bar).

12.4.2 Electrical supply

The power of a single electric heater element is usually in the range of 2 to 3 kW. Some small heaters operating on night-time tariff may use a 0,4 kW heater (longer heat-up times allowed). Large heaters may use up to 6kW or more for faster heat-up times. High power heaters exceeding 6 kW are often supplied by a 3-phase 400V electric supply.

Many electric water heaters, especially the larger ones, offer the possibility to connect the heating elements to a night-time tariff electrical supply (DE: *Zweikreisbetrieb*) to reduce running costs.

12.4.3 Chimney / drains

Chimney

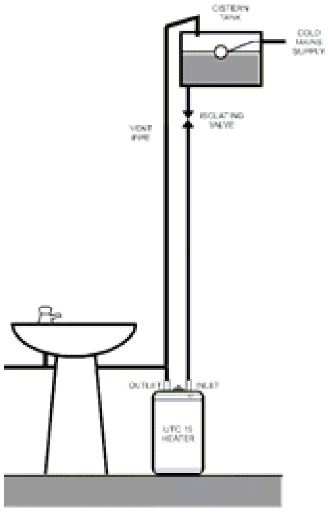
Chimneys, flues and supply air are not applicable to electric storage water heaters.

Drains

Pressurised systems always need a relief valve to let off pressure from expanding water. The valve is usually set a 3 bar and should be allowed to feed into a waste water drain.

Unpressurised systems can either be open vented or connected to a vented tap.

Picture 12-15.
HeatraeSadia, UTC point-of-use water heater, max pressure 20 m



12.4.4 Single- or multi-point

Depending on the storage volume the electric storage water heater is connected to either a single-point or multi-point DHW system.

Since every electric storage water heater is connected to some sort of pipework, extra heating losses are introduced if the hot water is allowed to circulate in this pipework (by convection). These losses can be reduced/prevented by measures like heat traps in attached pipework (U-shaped or angular fittings that prohibit convention) and ball valves that prevent circulation.

Unpressurised, cistern-fed storage boilers may need a venting pipe rising from the appliance to the cistern located in the loft of the dwelling. This may introduce considerable piping losses since the vent-pipe may act as a large heat-emitter: Heated water rises to the top of the vent pipe, introducing extra piping losses in often unheated areas. (see figure 12.14)

Other piping losses are introduced by the repeated heating up and cooling down of pipe contents. of course this factor is smaller for single-point water heaters (over- or under-sink position). For multi-point systems with 8 meter pipework of 22mm, filled by 65ºC hot water with 10 tappings/person/day the losses are around 140 kWh/year [48].

At the final section of the system, the draw-off point, losses are introduced by in-efficient tapping. A contributor to this are single-lever taps with a middle position producing 50/50 hot and cold water. The easthetically pleasing neutral position may induce unnecessary hot water tappings. Assuming 5 unintentional tappings/day at 1 min each at 6 l/min with 30% DHW "content" supplied at 65ºC (cold water is 15ºC) the energy loss is 450 kWh/year. For single-point storage water heaters the effect is likely to be less [49].

[48] CECED Presentation, 14.02.2007, Brussels

[49] CECED Presentation, 14.02.2007, Brussels

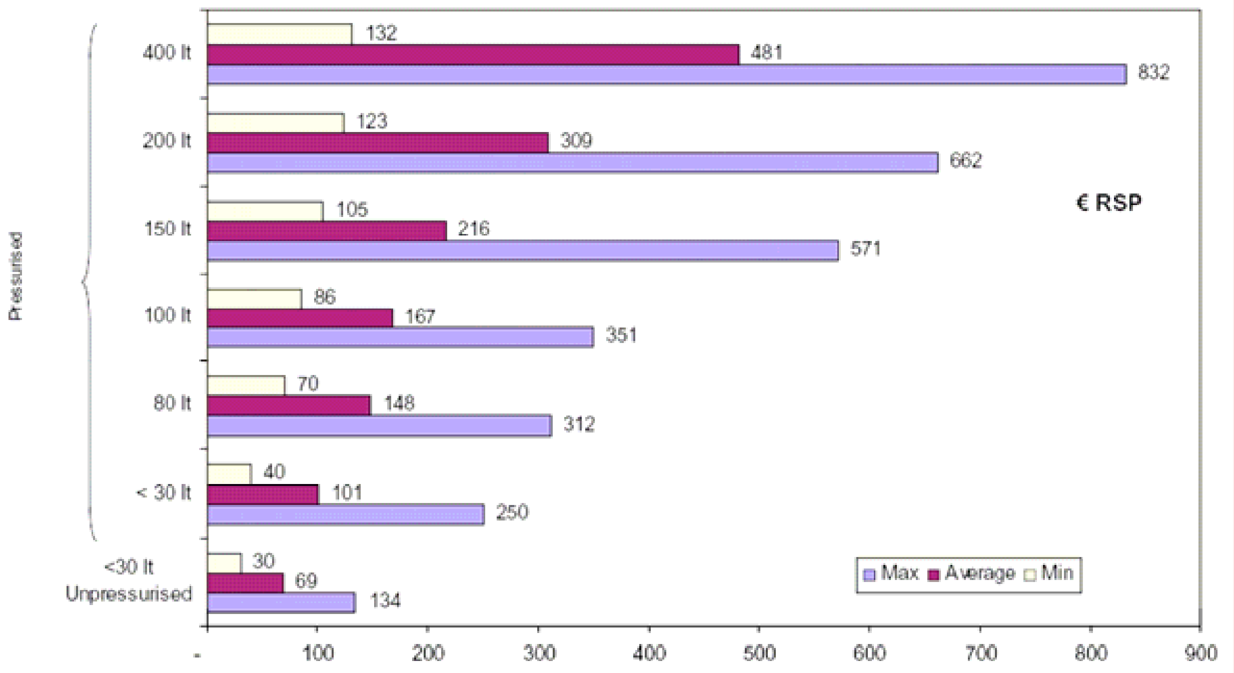
12.5 Prices

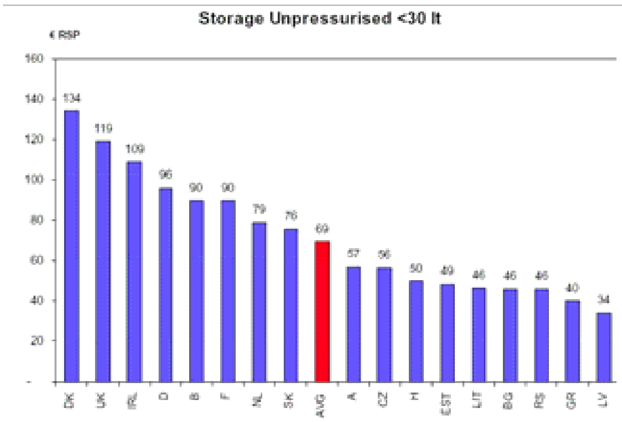
In general electric storage water heater product price increases with storage volume. However (the combination of) features like day- and/or night-tariff heating elements, 400V/3-phase elements, pressurised/unpressurised, storage tank materials, temperature control features and special precautions for 'agressive' water quality may cause a price increase over the standard product of 100% or more.

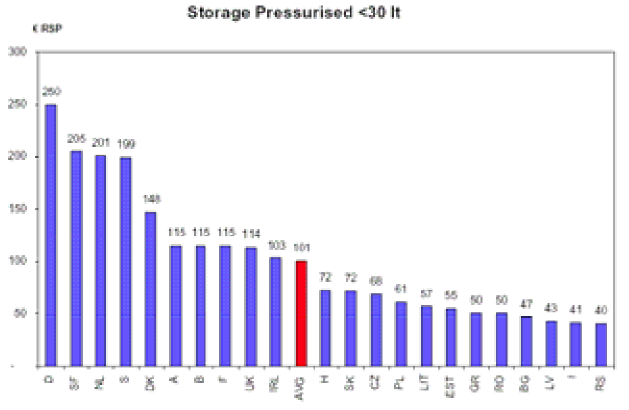
Table 12-7: Overview of list- and street-prices electric storage water heaters

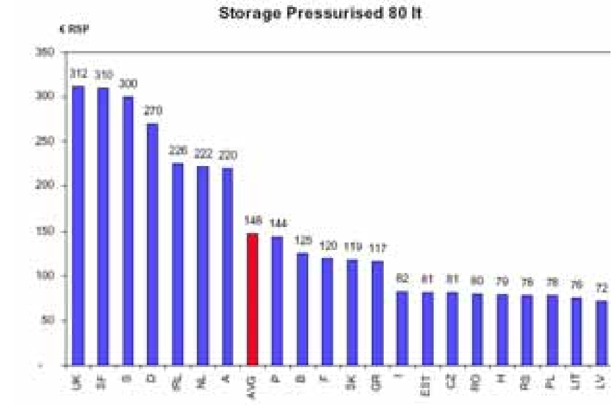
Type of electric storage water heater	UK streetprices www.plumbworld.nl GBP:euro = 1.5:1	DE streetprices www.getprice.de	FR streetprices www.brosette.fr	IT listprices Ariston	NL listprices Techn.Unie
5 - 10 - 15 l pressurised or vented tap	7: 150 - 400 10/15: 120 - 500	5: 50 - 150 10: 170-240 15: 150 - 290	10: 180 - 220 15: 200 - 220	10: 75 - 130 13: 180 15: 88 - 120	10: 170 - 190 15/20: 190 - 250
30-50 l pressurised	>800	30: 170-410 50:190	30: 230 - 250 50: 240 - 370	30: 100 - 170 50: 140 - 200	30: 430 - 570 50: >500
80-300 pressurised	n.a.	80: 200-520 100: 230 > 600 150: >500 200: >700 400: >1000	80-300: 300 - 900	80: 140 - 240 100: 170 - 270 120 / 150: > 400 200: >500 300: > 700	80: >500 120: >650 150: >950 200: >950 300: >1000 1000: >2600
unpressurised cistern 25 - 125 l	1000 - 1800	n.a.	n.a.	n.a.	n.a.
boiling water	>150 to >1500 (multi-tap)	5:129 - 217	n.a.	n.a.	5: 170 - 190

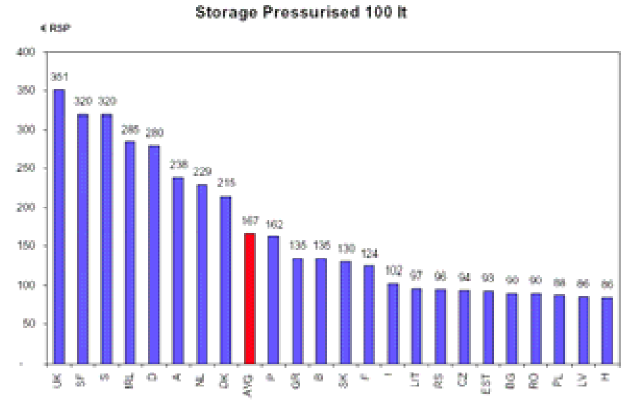
Figure 12-16. Electric storage EU prices [BRGConsult, 2007]

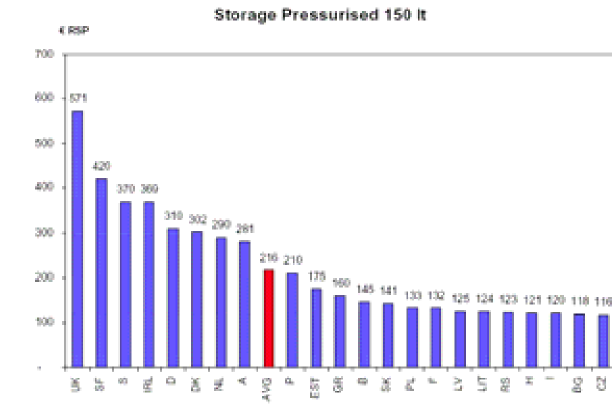


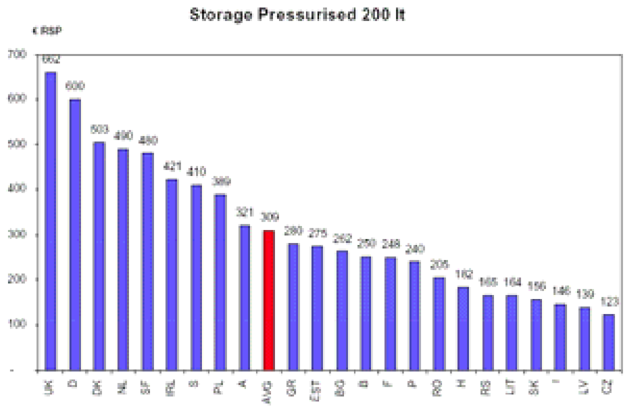

Storage Unpressurised <30 lt
€ RSP
134 119 109 96 90 90 79 76 69 57 56 50 49 46 46 46 40 34
DK UK IRL D B F NL SK AVG A CZ H EST LIT BG RS GR LV

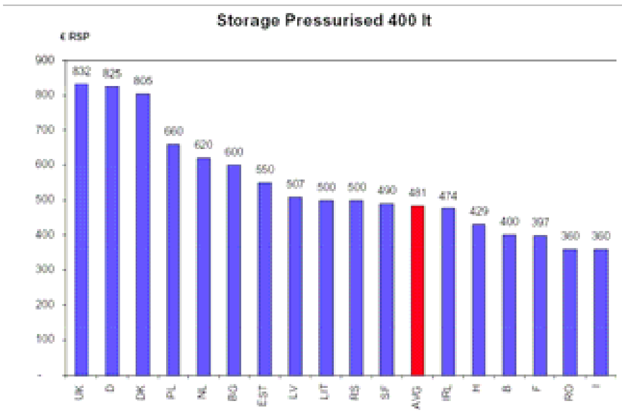

Storage Pressurised <30 lt
€ RSP
250 205 201 199 148 115 115 115 114 103 101 72 72 68 61 57 55 50 50 47 43 41 40
D SF NL S DK A B F UK IRL AVG H SK CZ PL LIT EST GR RO BG LV I RS


Storage Pressurised 80 lt
€ RSP
312 310 300 270 226 222 220 148 144 125 120 119 117 82 81 81 80 79 78 78 76 72
UK SF S D IRL NL A AVG P B F SK GR I EST CZ RO H RS PL LIT LV


Storage Pressurised 100 lt
€ RSP
351 320 320 285 280 238 229 215 167 162 135 135 130 124 102 97 96 94 93 90 90 88 86 86
UK SF S IRL D A NL DK AVG P GR B SK F I LIT RS CZ EST BG RO PL LV H


Storage Pressurised 150 lt
€ RSP
571 420 370 369 310 302 290 281 216 210 175 160 145 141 133 132 125 124 123 121 120 118 116
UK SF S IRL D DK NL A AVG P EST GR B SK PL F LV LIT RS H I BG CZ


Storage Pressurised 200 lt
€ RSP
662 600 503 490 480 421 410 389 321 309 280 275 262 250 248 240 205 182 165 164 156 146 139 123
UK D DK NL SF IRL S PL A AVG GR EST BG B F P RO H RS LIT SK I LV CZ


Storage Pressurised 400 lt
€ RSP
832 825 805 660 620 600 550 507 500 500 490 481 474 429 400 397 360 360
UK D DK PL NL BG EST LV LIT RS SF AVG IRL H B F RO I

13 ELECTRIC INSTANTANEOUS WATER HEATERS

13.1 Product description

Electric instantaneous water heaters (or "inline" water heaters, DE: *Durchlauferhitzer*) are very versatile in installation (requires no flue) and mostly used as point-of-use water heaters. The main determinant for their application is the flow rate at a certain outlet temperature: For wash basin use 2 liters per minute of max 40ºC is satisfactory, for shower use one would prefer minimum 6 l/min of 40ºC and for kitchen use (eg. dishwashing) a temperature up to 60ºC is preferred.

The flow rate that can be achieved at a certain temperature lift is determined by the electric power of the electric heating element. The table below presents the range available.

Table 13-1. Electric instantaneous water heaters - products by application

Application	Electric power (kW)	Flow rate	
		ΔT 25K	ΔT 45K
hand-wash sink	3 - 6,5 kW	1,7 - 4 l/min	
kitchen sink (small shower)	6 - 12 kW	3,4 - 6,9 l/min	1,9 - 3,8 l/min
kitchen / normal shower	12 - 27 kW	7 - 15,5 l/min	3,8 - 8,6 l/min

Besides electric power there are also differences in type of electric heating element (coil immersion or bar-wire), temperature/flow rate control (hydraulically or electronically) and whether the heat exchanger is 'pressurised' or 'unpressurised'. *'Unpressurised'* can mean that either the product is connected to a low-pressure feed (e.g. less than 0,8 bar) or that the heat exchanger is protected from mains pressure by a stop-valve located before the heat echanger.

Versions that are designed for use as electric showers often include a matching shower head and hose.

Figure13-1.
2.8 to 3 kW instantaneous hand washer
(picture: www.heatraesadia.com)

"Concept" hand washer (Heatrea Sadia)
- 2,8kW, 230V
- flow rate: 1,7 l/min @ ΔT25K (estimate by VHK)
- inlet pressure: min. 1 bar, max. 7 bar
- vented tap

Figure13-2.
Pressurised water heater
(picture: Clage website)

Electronic intantaneous water heater (Clage MDX-range)				
kW	3,5	4,4	5,7	6,5
flow l/min. (ΔT25K)	2	2,5	3,3	3,7
on/off flow l/min.	1,2/1,0	1,5/1,3	1,5/1,3	1,5/1,3
A/V	15/230	19/230	25/230	2*16/400

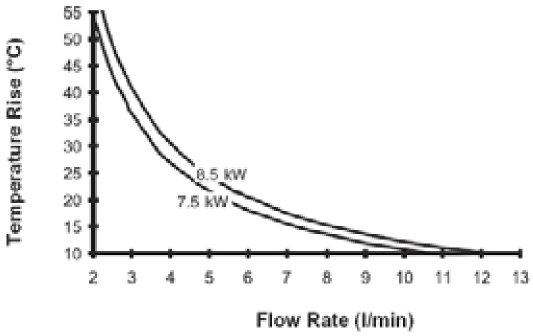
max. inlet temp: 60ºC

Figure13-3.
Electric instantaneous water heater
(picture: Vaillant website)

Vaillant VEDe, power up to 27kW				
power (kW)	13	18	21	24
flow (ΔT 28K)	6,7	9,2	10,7	12,3
on/off (l/min.)	3,6/6,5	4,0/7,0	4,6/8,0	5,0/9,0
current (400V)	3*19 A	3*26 A	3*30 A	3*35 A

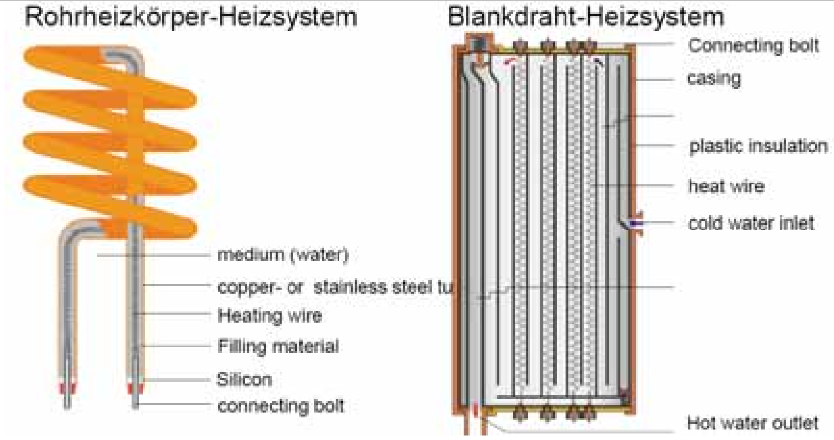
Figure13-4.
Mira Zest electric shower
(picture: www.plumbworld.co.uk)

Mira Zest electric shower
Produces 4 l/min at 38ºC at 8.5 kW (240V) and inlet temp. of 10ºC.



An important technical feature is whether the heater is controlled hydraulically or electronically. Newer electronically controlled water heaters all use a "bar wire" (*DE: Blankdraht*) heating element which allows very fast response times. The conventional hydraulically controlled models (including most electric showers) may use a coil-shaped element, immersed in a small quantity of water.

Figure 13-5.
Conventional coil imeersion and improved bar-wire heating element
(picture: CECED presentation 14.02.2007)



A third type of eletric instantaneous water heater is the *Verbundheizkörper* (DE), a special version of a tubular heating system with an outside lying heating element. The heating element is not immersed in water, but is soldered laterally to a water pipe and all together is wound up to a spiral. This is probably the most simple and robust heating system for an electric instantaneous water heater: The enlarged heat transfer surface allows a lower heating surface temperature and is as such better suited for sections of the water grid with agressive water quality (above average level of chlorine and/or acids present, like in certain areas in Spain). It is however not as responsive as other types due to its high thermal mass (higher start-stop losses).

Figure 13-6.
Verbundheizkurper. The spiral wounded coil clearly visible.
(pictures: Siemens

Table 13-2. Comparison of three heating element types for instantaneous DHW production (VHK 2007)

	bar wire	tubular immersed	tubular laterally
robustness	good	good	best
start/stop-losses	lowest	medium	worst
dynamic temp. control	best	medium	worst
calcination	lowest	worst	medium
costs	lowest	medium	medium
water quality	standard	standard	not important
min. water pressure	medium	low	low
preferred used in	Germany and Poland (China is coming up)	England and worldwide	special environments

Brand names (mainly UK and Germany) are among others: Stiebel Eltron, Vaillant, Junkers, Clage, Siemens, Zanker, Ariston, Hyco, Redring, Santon and Heatrea Sadia. For electric showers some brand names typical for the UK can be added: Mira, Triton, Aqualisa.

13.2 DHW performance

13.2.1 Flow rate and temperature stability

The temperature lift is linked to the flow rate and the electric power of the heater. The table below gives the maximum flow rate produced at a certain electrical power and two temperature lifts (assuming 100% efficient heat transfer at all flow rates).

Table 13-3. Flow rate at kW and temp. lift

kW	l/min at delta_T 45°C	l/min at delta_T 25°C
1,5	0,5	0,9
2	0,6	1,1
3	1,0	1,7
4	1,3	2,3
6	1,9	3,4
8	2,6	4,6
10	3,2	5,7
12	3,8	6,9
16	5,1	9,2
18	5,7	10,3
21	6,7	12,1
24	7,7	13,8
27	8,6	15,5
30	9,6	17,2

Two temperature control mechanisms are applied in electric instantaneous water heaters: hydraulical and electronical. Both are described below.

Hydraulic control

The conventional hydraulically controlled water heater simply turns on/off heating elements depending the flow rate (or: the water *pressure* to be more exact, hence *hydraulic* control). Below a certain pressure the device does not actuate the heating elements and the water stays cold.

Above this pressure point the heating element will be activated and the water is heated. The outlet temperature then depends on the flow rate. In figure 13-7 the appliance is equipped with two stage power control. This option is often marketed as 'summer/winter' switch to accomodate the drop in temperature of the incoming water during winter times.

Figure 13-7.
Functional depiction of hydraulic control mechanism. (picture: CECED presentation 14.02.2007)

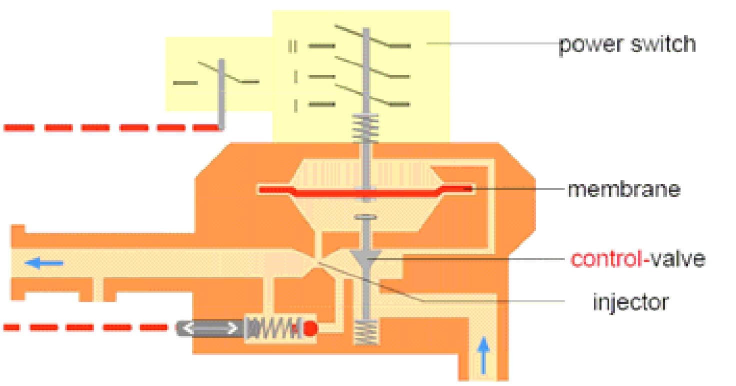


Figure 13-8.
Components of hydraulically controlled water heater. (picture: www.heatershop.com)

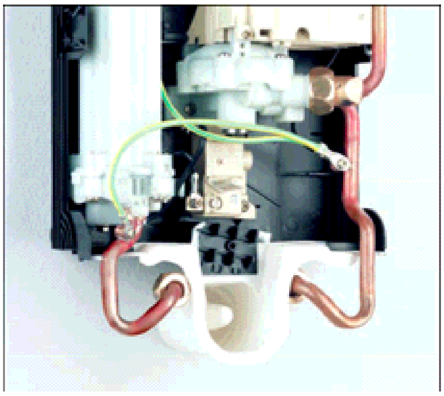


Figure 13-9.
Components of hydraulically controlled water heater. (picture: CECED presentation 14.02.2007)

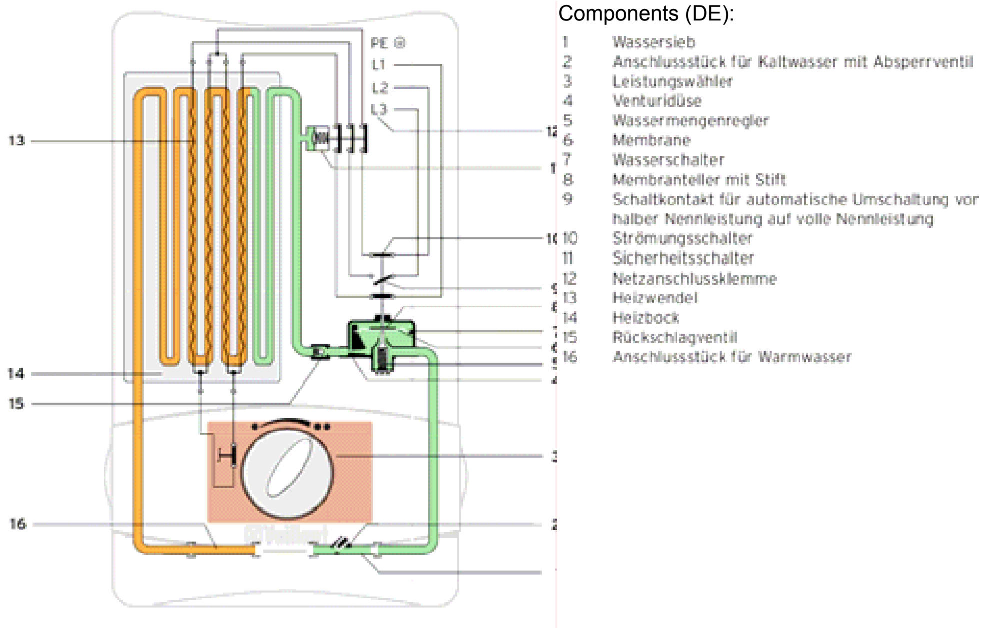
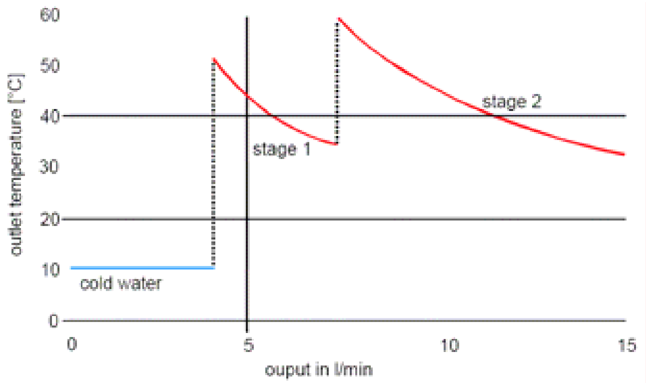


Figure 13-10.
Temperature and flow rate by a hydraulically controlled water heater. (picture: CECED presentation 14.02.2007)



The dependence of outlet temperature on flow rate / water pressure also means that if elsewhere in the house a tap is opened (a toilet is flushed) the available pressure and flow rate drops, leading to an increase in outlet temperature (and vice versa if a running tap is closed).

Electronic control

The electronically controlled electric instantaneous water heater is able to maintain a set temperature throughout a certain range in flow rate, and in addition to this, offers the possibility of temperature pre-sets and flow rate presets (depending on the actual model).

The picture belows shows the main components of an electronical water heater and the outlet temperature in accordance with flow rate (output volume). It shows the minimum flow rate needed before the appliance switches on. The vertical line indicates the possibility of restricting the flow rate to a maximum 6 l/min (example).

Figure 13-11.
Components of electronically controlled water heater. (picture: CECED presentation 14.02.2007)

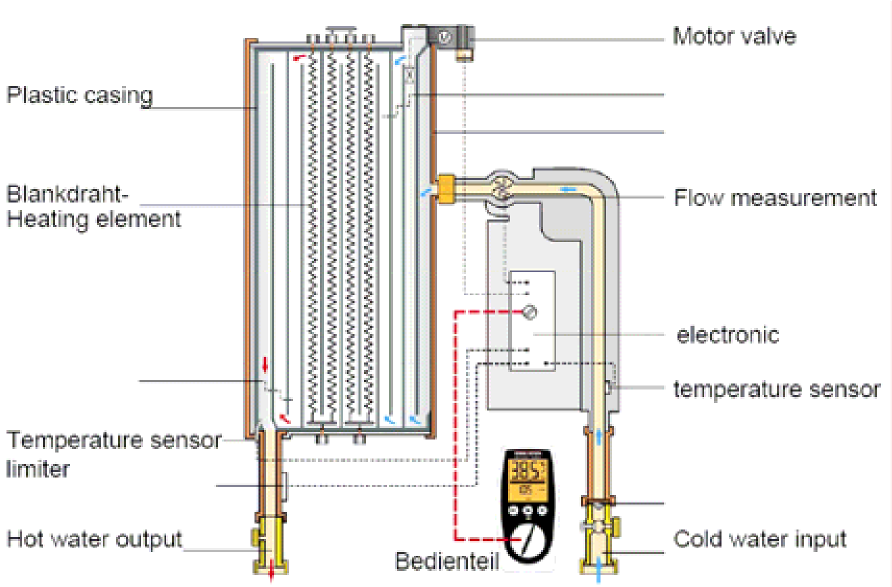
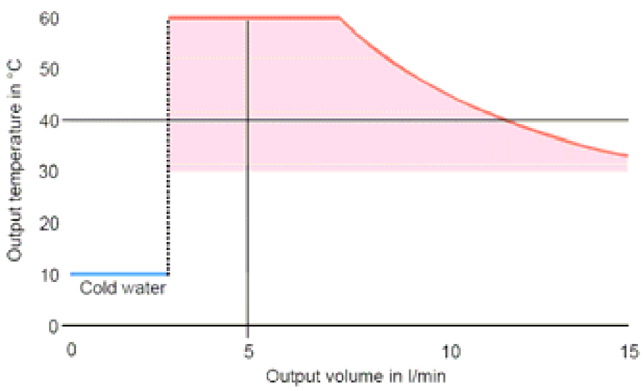


Figure 13-12.
Temperature and flow rate by a electronically controlled water heater. (picture: CECED presentation 14.02.2007)



The temperature is maintained constant by powering the electric heating elements (bar-wire type) in steps of approximately 100 Watts. If the flow rate increases to beyond the point where the water heaters is using its maximum power the outlet temperature will drop just like for hydraulically controlled water heaters.

Minimum flow rates

Both hydraulic and electronic controlled appliances need a minimum flow rate before the heating elements are activiated. This helps to protect the heating elements (ensures that enough heat is transferred for safe operation). The electronic controlled water heater with bar-wire heating elements is a much faster responding device and can thus operate from lower minimum flow rates.

As an example: The Vaillant VED range needs a minimum flow rate of 3 l/min before the appliance switches 'on'. The minimum flow rate below which the appliance switches off is 2,5 l/min.

Accurate temperature setting

In hydraulic controlled water heaters in case the water becomes too hot, the desired outlet temperature is realised by mixing in cold water (reducing the flow of warm water has counterproductive effects). In electronically controlled water heaters the temperature can be set with 1 to 0,5K accuracy, displayed on the appliance user interface.

Advanced electronic models offer preset buttons for specific temperatures. Remote control of temperature setting (from multiple draw-off points) is also a possibility.

Figure 13-13.
Development in temperature control: from simple, hydraulic (upper left) to simple electronic (mid left), more advanced electronic (lower left) and fully controlled (right) - with optional remote control.

(pictures left: Vaillant VED brochures)

(picture right: Clage website)

13.2.2 Responsiveness

The response speed of electric instantaneous water heaters is seldom documented in brochures. However, some delay in reaching operating temperatures can be expected during heat up of the heat exchanger (heating elements and water contents).

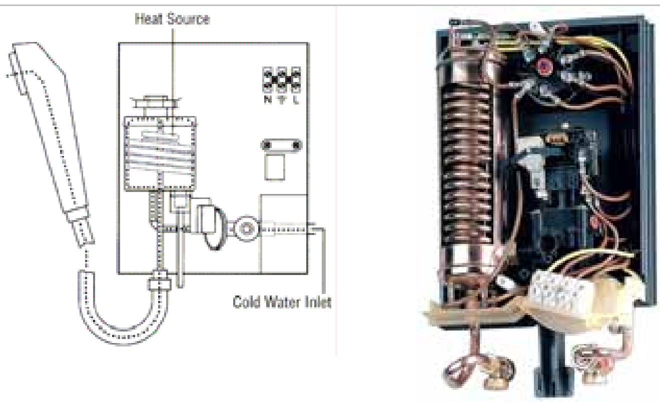
Important determinants here are the type of heater elements: conventional coil immersion heaters are submerged in a tank of approximately 0,6 l, whereas a water heater with a bar-wire heating element may have a water content of 0,3 l.

Due to the lower thermal mass and less water content the bar-wire heating elements reach their operating temperature must faster than the powder and metal encapsulated coil immersion heaters: A 'waiting time" of 20 seconds is deemed indicative for coil-immersion / hydraulically operted water heaters. 5 Seconds is indicative for bar-wire, electronic heaters.

Figure 13-14.
Hydraulic control and (coil) immersion heater elements as applied in a electric shower and water heater.

(picture left: from HeatraeSadia Accolade installation manual)

(picture right: Heizkorper Vaillant VED 18/3)



13.3 Energy

13.3.1 On-mode

The immersed electric heater element transfers virtually all energy to the water: the on-mode heat transfer efficiency therefore reaches 99-100%. The primary efficiency (and CO_2 emissions) depends on grid characteristics.

13.3.2 Off-mode

Most if not all electric instantaneous water heaters are installed close to or are integrated with the draw-off points, within the heated area of the dwelling / building.

There is no DHW storage kept at temperature, nor a pilot flame. Residual heat in the heat exchanger is part of 'start-stop losses'.

During off-mode electronic heaters may use some power to operate the circuit board and display, which is covered at 'Auxiliairy energy'.

13.3.3 Start-stop losses

At 'start-up' from cold start the thermal mass of the electric heating element and the water contained in the heat exchanger chamber have to reach operating temperatures. The typical water content of the heat exchanger chamber varies from 0, 1 l (2 kW system) to 0,4 or 0,6 l (27 or 24 kW).

Assuming a flow rate of 3 l/min the water content of a conventional hydraulic / coil immersion heater (0,6 l.) is replaced in 12 seconds during which the heater also heats up. The electronic / bar-wire heat exchanger has its contents replaced in 6 seconds (0,3 l.) during which the heating elements reaches its operating temperature.

At 'stop' the residual heat is lost to the environment (also depending on the tapping pattern). A temperature drop of 25K (from 40ºC to 15ºC) causes losses of some 31 kJ/8Wh (0,3 l) to 63 kJ/17Wh (0,6 l).

13.3.4 Auxiliairy energy

Hydraulically operated electric instantaneous water heaters can operate without auxiliary power.

Electronically controlled heaters use auxiliary power for the controller (PCB) and the user interface display (if applicable). The power consumption is rarely documented in product literature/brochures but experience learns this is probably in the range of 1 Watt or less.

13.3.5 Alternative enery sources

Many instantaneous electric water heaters can be combined with solar pre-heating (certain models by Clage for instance allow inlet temperatures of up to 70ºC).

For the installation of solar pre-heated water a mixing valve is often prescribed to limit the maximum outlet temperature and prevent scalding accidents (solar pre-heated water may reach very high temperatures, 80 to 90ºC is not uncommon. The electric water heater itself is not designed by default to reduce outlet temperatures).

For water pre-heated by heat pumps the same principle applies (although in most cases the heat pump will also be a primary water heater, supplying the whole house with DHW).

13.4 Infrastructure

13.4.1 Water pressure

For both hydraulic and electronic instantaneous water heaters designed for connection to mains water pressure ('pressurised') the minimum / maximum water pressure is 0.8 / 10 bar (with small deviations depending on model and manufacturers). This ensures enough flow over the heat exchanger (minimum flow rate).

Products connected to a vented tap (like the Clage MH range) are called unpressurised (DE: *Drucklos*) and a min/max pressure is not indicated, but the minimum flow rate of 1.6 l/min also assumes a minimum pressure.

Figure 13-15.
3.5 to 6.5 kW unpressurised water heater
(picture: www.clage.de)

Unpressurised inline water heater from Clage - to be connected to a tap with pressure relief. Note the cold water line running from the wall outlet first to the tap then to the water heater and back (hot water line) to the tap again. The stop valve is located in the tap.

In case of very low (like DHW storage cisterns in the UK) or no water pressure, specialised products need to be applied: An example is the HeatraeSadia *SureFlowPlus* electric shower with an integrated booster pump.

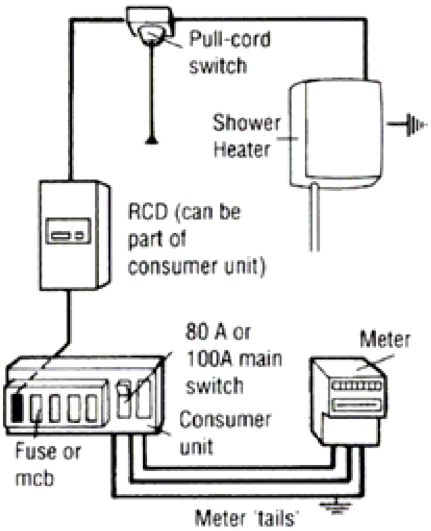
13.4.2 Electrical supply

The type of electrical supply needed, depends on the electric power of the appliance and the (local/national) regulations applicable to electrical installations. Almost all electric instantaneous water heaters are connected by a fixed terminal (no plug socket).

In many countries exceeding 4,5kW (20 Ampere @ 230 V) electric power requires a dedicated three-phase, 400 V supply (like applied for electric hobs).

In other countries (the UK for instance) higher currents are allowed (up to 45 A) provided the cabling and routing support this. With 45A@240V 10,8 kW can be realised, which is the maximum rating for most electrical showers. In such cases the cable diameter (4, 6 to 10 mm²) is chosen depending on power, cable lenght and other aspects (ambient temperature, bunched with others or not, behind insulation, etc.).

Figure 13-16.
Typical installation of an electric shower - via on/off switch and fuse terminal
(picture: HeatraeSadia Sapphire product brochure)



13.4.3 Chimney / drains

Chimney

Chimneys, flues and supply air are not applicable to electric instantaneous water heaters.

Drains

A pressure relief valve is not a must for these water heaters. The heat exchanger of pressurised systems can widthstand mains water pressure (plus a safety margin). After closing the tap no heat build up takes place, in fact the water cools down thereby reducing internal pressure.

Some models (e.g. witnessed on electric showers and/or equipped with slower responding coil immersion heating elements) do have a pressure relief valve to cope with abnormal pressures. Electric showers may also allow the handset to drip for 7 seconds or so to cool down the heating elements before the next user uses the shower.

Unpressurised models can be connected to a vented tap.

13.4.4 Single- or multi-point

Electric instantaneous water heaters that produce maximum 6 l/min at ΔT 25K (corresponding with 12kW electric power) are in general considered single point water heaters. Examples are the electric showers in the UK and 'above' or 'under the sink' water heaters in the rest of Europe, Germany in particular. Although 12kW in principle suffices for hot water to a kitchen sink or a small shower, such multi-point use (and simultaneous use in particular) is not advised.

Water heaters above 12 kW are more often used for multiple draw-off points. In Germany the 24kW water heater is a popular product, providing hot water for the whole bathroom (shower, washbasin) and sometimes the kitchen as well (proximity provided).

Most electric instantaneous water heaters are used as secundary water heaters, parallel to primary systems: Over 32% of the EU22 households own a secundary water heater, 7,9% of which are electric instantaneous. The main markets where electric instantaneous water heaters are used as primary heaters are Germany, UK, Ireland, Poland and Slovakia (where 5% of households have electric instantaneous as primary water heaters).

One particular advantage of electric instantaneous water heaters is the reduction (and quite often eliminiation) of pipeline losses. When compared to circulation systems that also promise instant hot water the pipeline losses of circulation systems become relevant and may amount to 60 kWh/m*year [50]. This comes down to 34 to 50% of total energy consumption for hot water at 10 to 20m lenght of circulation pipes (15 mm Cu with insulation). Positioning the appliance close to the point-of-use also reduces waiting time (water and energy losses). This is further investigated in the modelling Task.

13.5 Prices

At the expert meeting of 15 March 2007 BRGConsult presented retail selling prices of electric instantaneous water heaters. The figures below present the average prices for hydraulic and electronic heaters per power category, and the average prices per country for electronic and electronic instantaneous water heaters in two categories (<12kW and 24 kW).

[50] CECED Presentation on Electric Instantaneous Water Heaters, Brussels, 14.02.2007

Figure 13-17.
Instantaneous - hydraulic

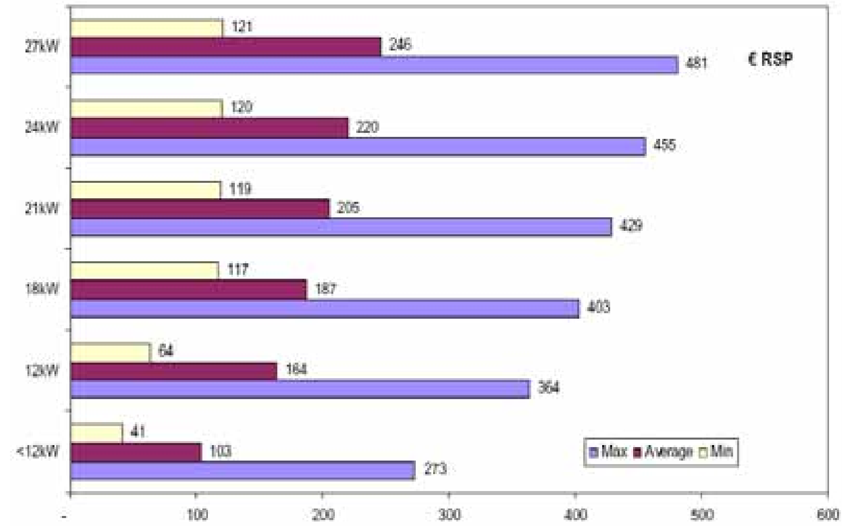
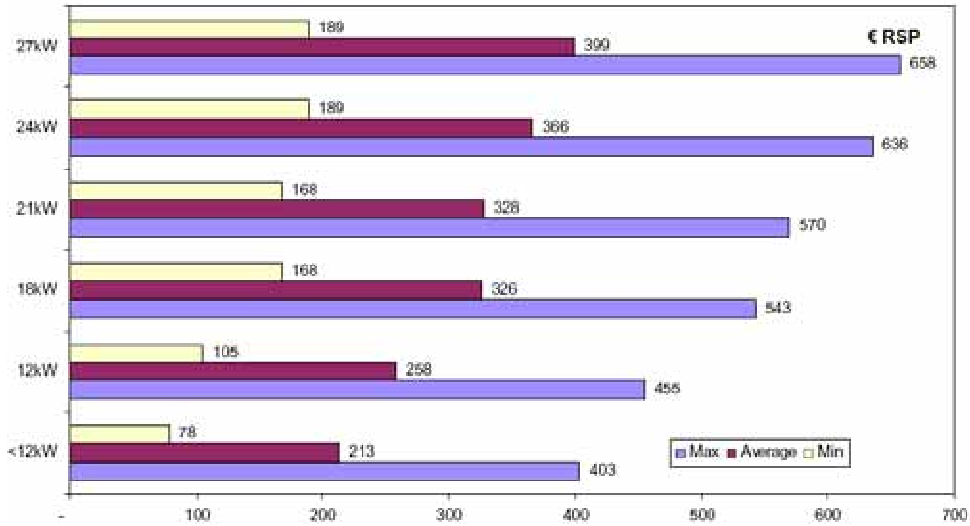
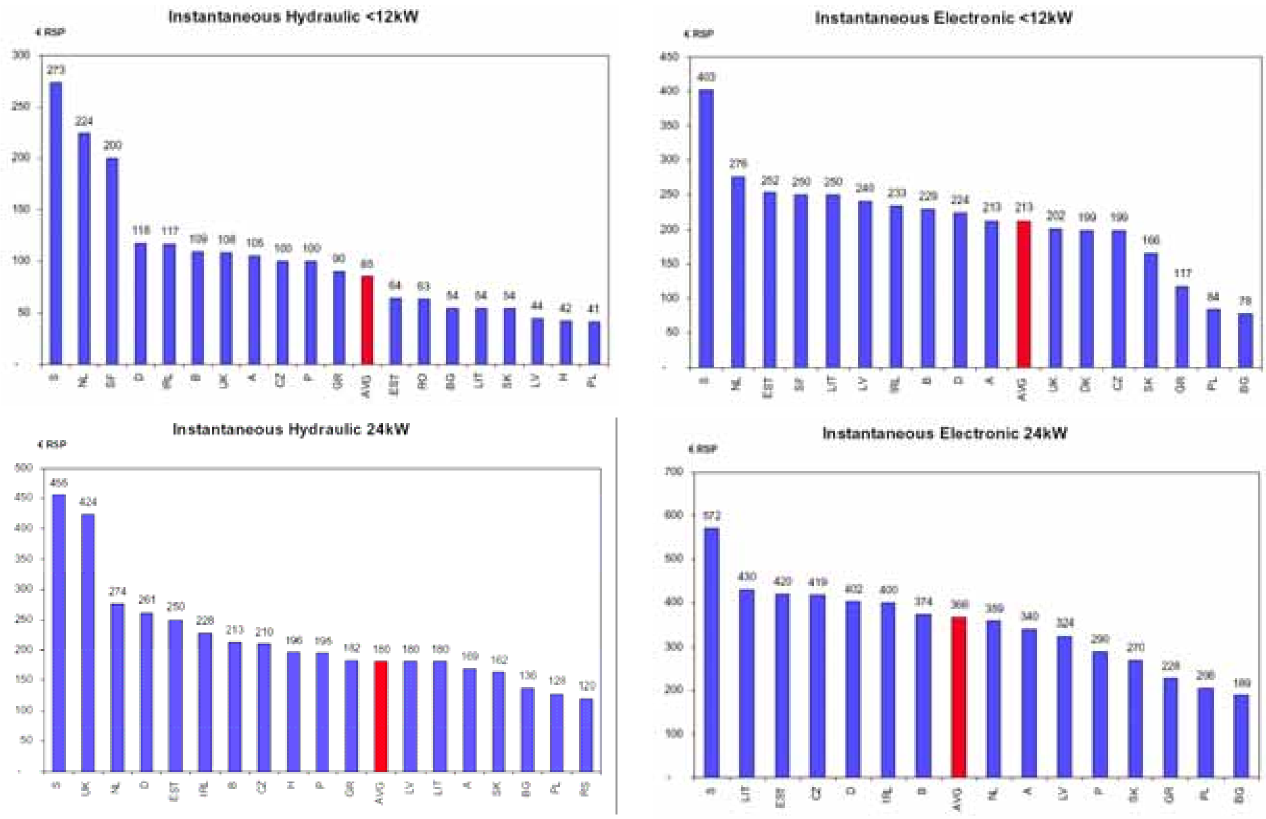


Figure 13-18.
Instantaneous - electronic



The purchase price of electric instantaneous water heaters depends on the electric power, type of control and extra features of the product and ranges from some 41 euro (bottom price range, hydraulic heater < 12 kW) to over 650 euro (top end price range 27 kW heater, electronic). Electronic heater pricing is 150 to 200% as much as hydraulic versions (prices are sales weighted).

Figure 13-19. Prices for electric instantaneous water heaters [BRGConsult, 2007]



In addition VHK looked at (street)prices of other types of instantaneous water heaters like electric showers (in the UK) and hand washers (unpressurised, vented through tap).

Table 13-4. Prices for electric instantaneous water heaters (streetprice)

Product	UK (www.plumbworld.co.uk)	DE (www.getprice.de)
Electric shower	55 GBP / 83 euro to 280 GBP / 420 euro, depending on features	n.a.
unpressurised / vented tap		3,5 to 6,5 kW = 110 to 130 euro
pressurised / hydraulic	Average hydraulic (max. 12kW): 80-100 euro,	13 to 24 kW is 230 to 250 euro
pressurised / electronic	Average electronic (max. 12 kW): 150-200 euro, 9,5 / 10,8 / 12kW = 162 / 184 / 189 GBP	3,5 to 6,5 kW = 150-200 euro 11 to 27 kW = 250 to 550 euro

The overall picture is that in Germany (large EU market for instantaneus water heaters) electronically controlled water heaters are almost double the price of hydraulically controlled heaters. An investment most consumers are willing to make since it saves them some 60 [51] to 120 [52] euros per year, resulting in a payback time of approximately 2

[51] http://www.durchlauferhitzer.info

[52] From http://www.heisswasser.de/, citing a calculation by Clage:

Comparing DSX oder DEX electronic water heaters with a flow rate 8l/min at exact 38 °C to a hydraulic water heater of 21 kW with a flow rate of 11,6l/min (to achieve 38 °C mixed water temperature) in a 3-person household with following parameters: Shower duration: 4 min/person, inlet temperature: 12 °C, showers: 330 days/year, electricity price: 0,15 €/kWh, water-/sewage rate: 4,– €/m^3 .

to 4 years. In 2006 the sales of electronic water heaters surpassed the sales of hydraulic water heaters [53].

The installation costs can be a significant part of the total price for an installed product. Connection of high electric power devices to the electrical mains most often requires trained personnel, especially if a 3-phase/400V connection is to be made. In certain EU countries DIY (do-it-yourself) is illegal, although enforcement of such laws is difficult. In the UK installation costs (for an electric shower) are in the range of 150 to 200 euro[54], which is probably also the price range for the remainder of Europe. This means that the installation costs are in the same order of magnitude as the product costs.

[53] personal information from CECED spokesperson, 14.2.2007.

[54] personal information from CECED spokesperson, 14.2.2007

SECTION THREE - ALTERNATIVE TECHNOLOGIES

14 SOLAR SYSTEMS

14.1 Product description

In many parts of Europe solar thermal systems are applied as DHW pre-heater or as stand-alone DHW system. Literature regarding solar DHW systems often makes the distinction between split (pumped) systems and thermosiphon systems. The Integrated Collector Storage (ICS) is presented as third technology.

Another categorisation can be made by the application: DHW only or combined with heating systems. A third categorisation could be on basis of components of which a vast array has been developed that differ in techniques applied to collect, transport, store and heat the collected solar energy (components like glazed/unglazed, flat-plate or evacuated tube collectors, pressurised or unpressurised storage vessels, low-flow or high-flow pumps, etc.).

When looking at components only, a solar DHW system basically consists of three main parts: The collector that collects solar thermal energy, a thermal storage unit that transfers solar heat to DHW and stores this and a heat generator that heats up the DHW to required outlet temperatures. In some parts of Europe the heat generator is omitted and DHW outlet temperatures of 60ºC can not be guaranteed / less than 60ºC is accepted.

Table 14-1. Typology of solar systems

	Collect	Store	Heat generator
Thermospihon	Flat plate - glazed Evacuated tube	On roof	None Electric element on storage Combined with boiler
Pumped	Flat plate - glazed Evacuated tube	Indoors	Combined with boiler
ICS	Storage tank is collector		None Combined with boiler

14.1.1 Collectors

Sales of collectors by type seem to indicate a regional or national preference: In Germany evacuated tubes are popular, in neighbouring country the Netherlands the glazed flat plate is most sold, in Greece the unglazed flat plate collector is wide-spread - mainly in the form of thermosiphon systems. There is of course a link between collector type and outdoor temperatures: The lower this temperature the more benefit from well-insulated solar collectors and/or collectors that work well even under overcast sky conditions (read: evacuated tubes).

Two main types of collectors can be considered. The integrated collector storage is treated in a separate paragraph:

- Flat plate (glazed, unglazed)'
- Evacuated tubes.

Within these two types many variants are possible, each with slightly different principles or designs. Common for all is the application of a spectral selective layer which enhances absorption of infrared and visible solar radiation and reduces emissivity of infrared radiation - the heat is retained in the material.

Flat plate collectors

Flat plate collectors vary in type of glazing (non-, single- or double-glazed), fin-tube arrangements (serpentine fin-tube, register type, cushion type). A few collectors are designed to operate using potable DHW water (which requires reliable controls to prevent overheating and freezing). Furthermore there are endless variations in size and design of the box and insulation, etc.

Heart of the collector is the absorber which connects the part that collects the solar heat with the part that transports this heat to some form of storage. Many techniques are applied.

Figure 14-1.
Fin-tube absorbers
A: Ultrasonic weld
B: Cold formed
C: laser welded (Sun Laser)
D: Point weld

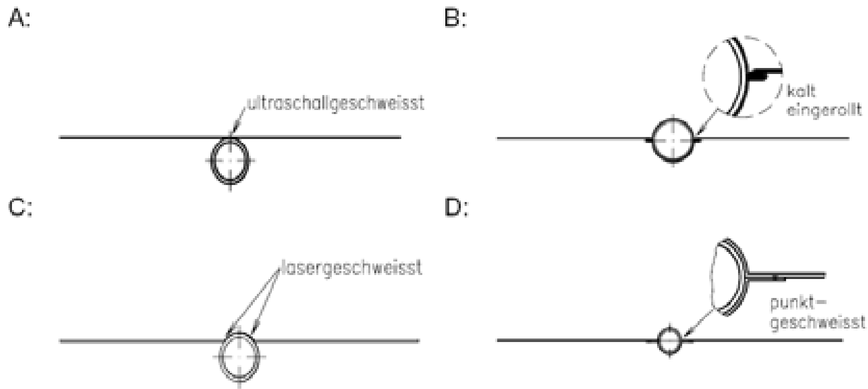


Figure 14-2.
"Cushion" or "sandwich" type absorber
E: (Energie Solaire)
F: (Solahart)

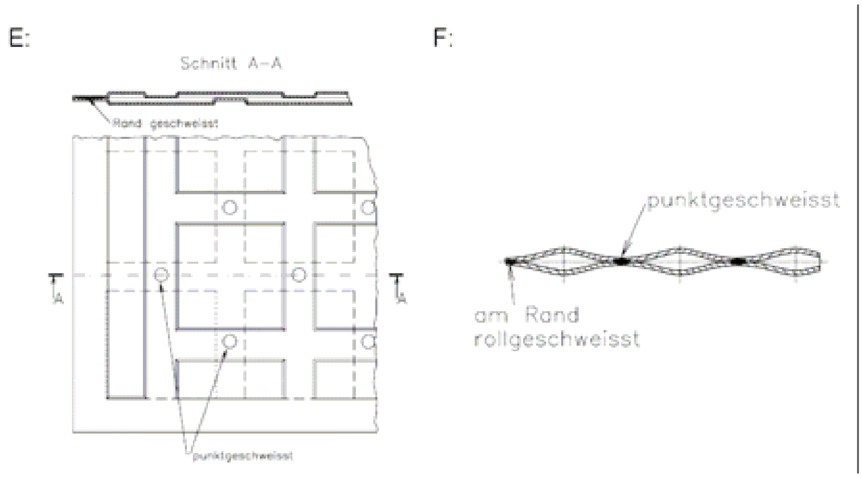
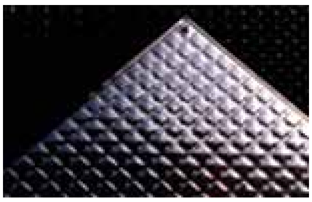


Figure 14-3.
The cushion-type absorber is fully irrigated Source: www.energie-solaire.ch



G: VDM-Evidal
H: Solar-Graubunden

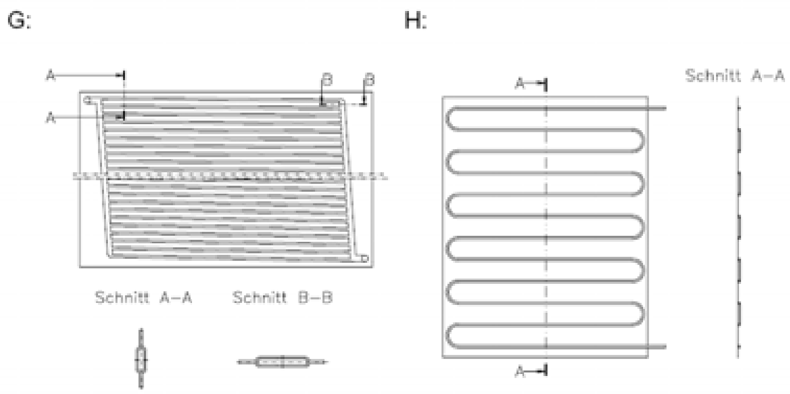
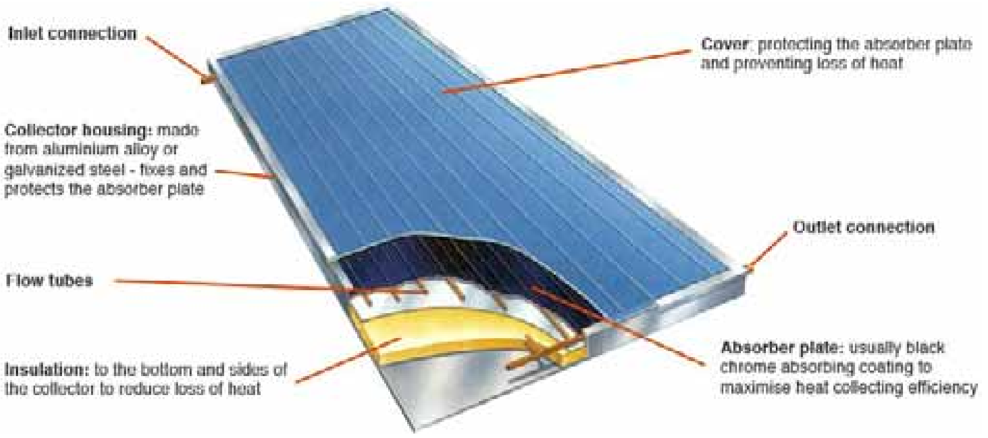


Figure 14-4.
Archetypical register type flat plate collector with single glazing [Source: wwwgreenspec.co.uk]



Evacuated tubes

Evacuated tubes also come in variety of designs. Each is briefly discussed below.

Fin-tube arrangement

Fin-tube collector uses a pipe-in-pipe arrangement with the inner pipe transporting the fluid to the outer end of the tube and an outer pipe transporting it back to the manifold thereby absorbing heat from the fin attached to it. This type of collector needs to be oriented towards the sun to use the optimal aperture.

Figure 14-5.
"Suntube" Source: www.sunutility.com

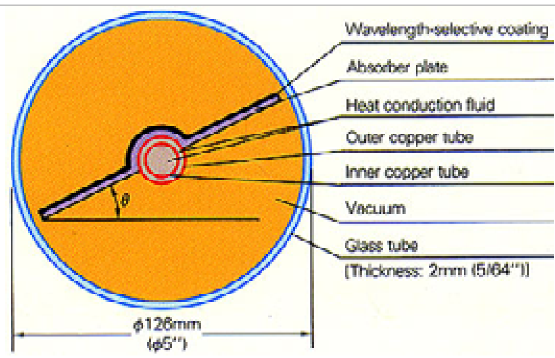
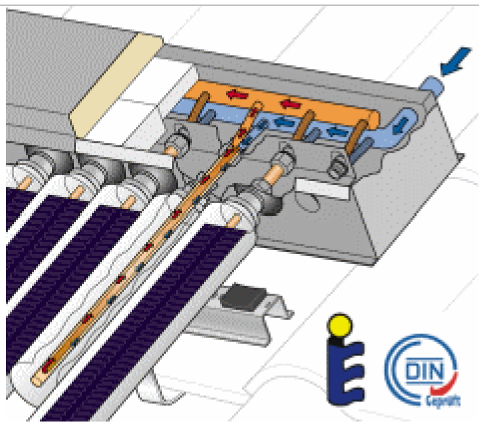
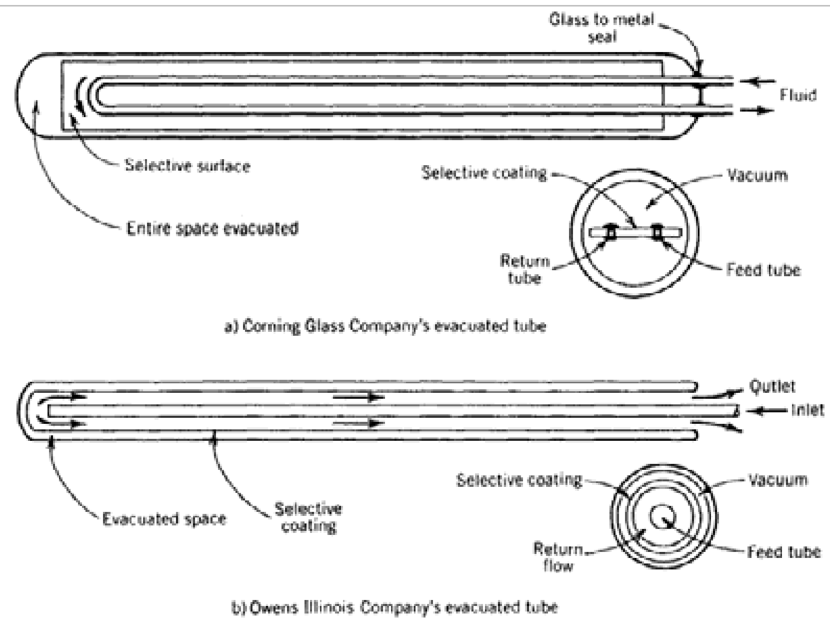


Figure 14-6.
Source: "Solamax" by Thermomax



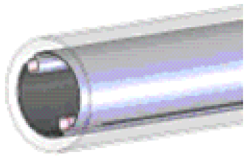
The second version employs a U-shaped tube, attached to a flat fin. The tubes can be rotated within their structure for optimal aperture exposure.

Figure 14-7.
Evacuated tube with U-shaped riser attached to fin



A third version uses a curved fin which results in maximal aperture throughout the day.

Figure 14-8.
Curved fin-tube. Source: Gaia Solar Co. Ltd.



The table below gives some general data for evacuated fin-tube collectors.

Table 14-2. Evacuated Fin tube data

Solamax	Fin tube	
	Solamax 20 Manifold	Solamax 30 Manifold
Net Absorber Area	2m²	3m²
Overall Dimensions	1417 x 2060 mm	2126 x 2060 mm
Manifold Capacity	4 litres	6 litres
Weight	55 kg	80 kg
Absorption	Better than 96%	
Efficiency	n0 = 0,82, k1 = 1,5, k2 = 0,005 w/m²K	
Vacuum	Better than 10 -5 mbar	

Tube-in-tube

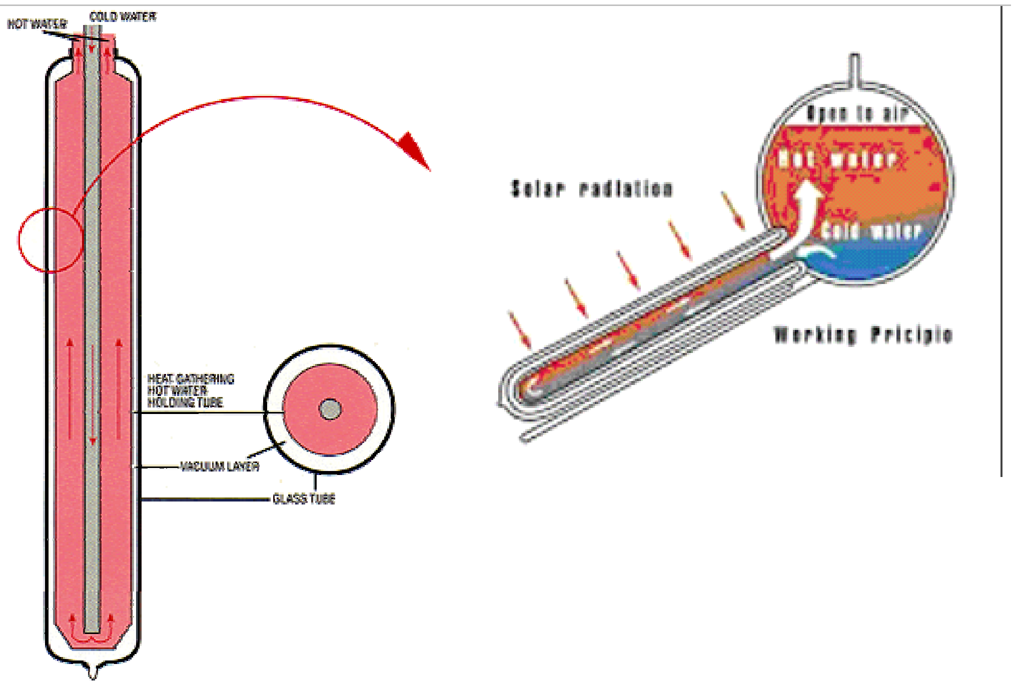
Here the absorber is formed by the outer tube of (again) a tube-in-tube arrangement, coated with a spectral selective layer. The working fluid is injected at the bottom end of the outer tube and absorbs the solar heat on its way up to the manifold at the top.

An even simpler design is applied in low-cost asian collectors where the transportation of the working fluid is wholly based on the thermosiphon principle. This is a **un**pressurised systems sold mainly in China. This principle is not (or rarely) applied in Europe, probably because of the risk of freezing and lesser comfort (unpressurised).

Figure 14-9.
Tube-in-tube

Left: glass outer tube, metal inner tube, evacuated space (picture: www.sunutility.com)

Right: Chinese low-cost thermosiphon system with vase-shaped evacuated wall tube.
(picture: Gaia Solare Co. Ltd)



Heat-pipe

A third principle applied in evacuated tubes is the heat-pipe. This collector combines high performance with high reliability. The heat-pipe functions as a sort of heat diode - it only transports heat from the aperture area to the manifold, not the other way around. Risk of freezing is low, since the amount of fluid in the heat pipe is very small and characterised by a very low boiling point (and very low freezing point as well).

The heat-pipe absorbs the solar heat either through a flat fin-tube absorber or a curved absorber design. The flat fin-tube design needs to be oriented towards the sun, the curved version already exposes maximum aperture.

Figure 14-10.
Evacuated tube with heatpipe, curved absorber version
(picture: wwwgreenspec.co.uk)

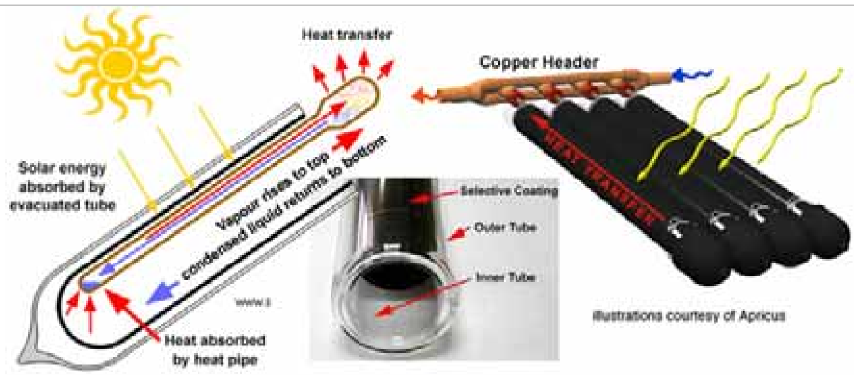


Figure 14-11.
Evacuated tube with heat-pipe, fin-tube absorber (picture: "Thermomax" by Thermomax)

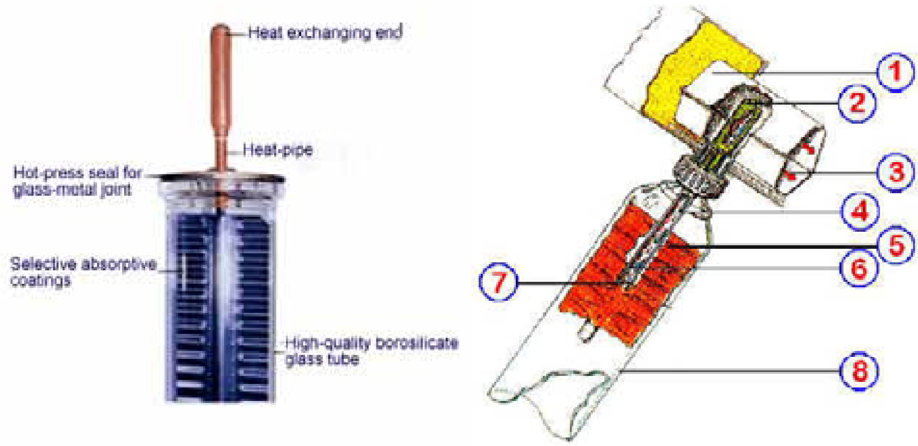
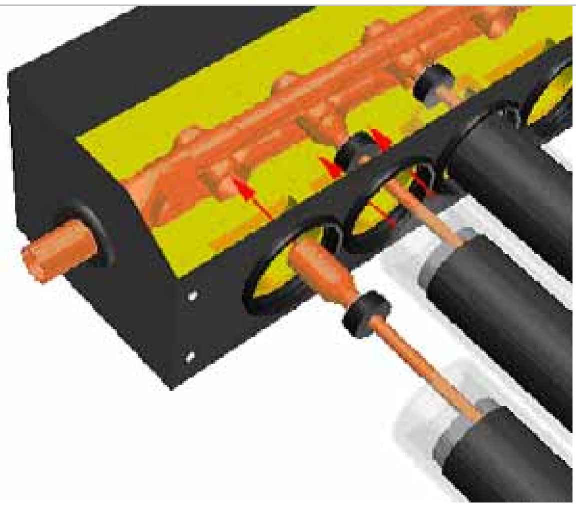


Figure 14-12.
heat-pipe in curved fin-tube



The table below gives some general data for evacuated heat pipe collectors.

Table 14-3: Evacuated tube data

Thermomax	Heat pipe with fins	
	MS20 Manifold	MS30 Manifold
Net Absorber Area	2m²	3m²
Overall Dimensions	1960 x 1420 mm	1960 x 2120 mm
Manifold Capacity	3,4 litres	5.1 litres
Weight	45 Kg	68 Kg
Absorption	Better than 96%	
Efficiency	n0 = 0,81, k1 = 1,2, k2 = 0,007 W/m²K	
Vacuum	Better than 10 -5 mbar	

Integrated collector storage

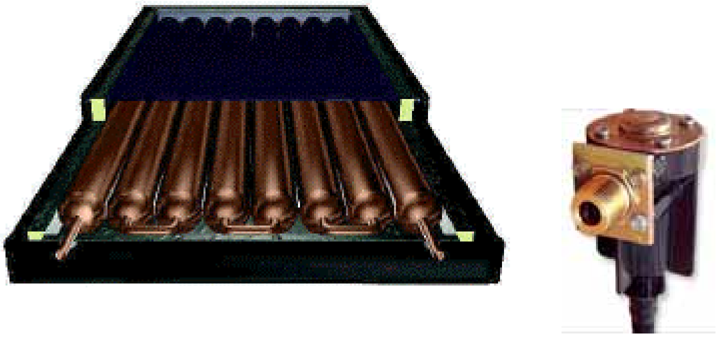
The third main type of solar collectors intergrates the storage tank in one housing. The definition of Integrated Collector Storage (ICS) is rather diffuse in the sense that some consider all products that combine a collector (absorber) surface and a storage tank in one housing and is put on top of the roof are ICS. In this sense the popular thermosiphon systems in Greece with a storage tank placed above a flat plate collector are also ICS.

Figure 14-13.
ICS systems installed on roofs in Greece
[picture: www.swt-technologie.de - NEGST demonstration programme]

Other people restrict the definition of ICS to products where the storage is completey integrated (or wrapped up inside) the collector. This interpretation includes the simple batch collectors (US term) - simple drums with black paint on them, placed on top of the roof .

ICS systems are simple, reliable solar water heaters. However, they should be installed only in climates with mild freezing because the collector itself or the outdoor pipes could freeze in severely cold weather. Furthermore the heat loss (also during cold clear nightskies) is significant and measuresshould be taken to prevent this (e.g. through transparant insulation, heat pipes).

Figure 14-14.
Copperheart batch heater with (on the right) the freeze-protection valve which utilizes a temperature activated element. The valve opens at 3-6°C allowing the discharge of near freezing water which is replaced by warmer water. When this warmer water reaches the valve, the port closes.
[picture: www.thesolar.bizz]

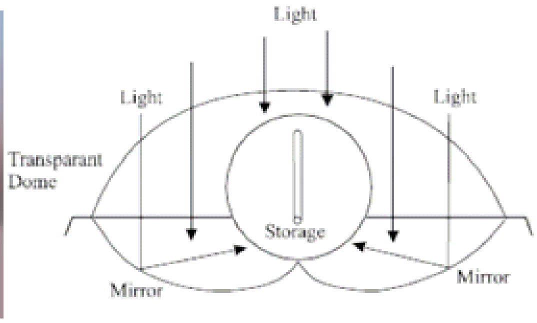


More sophisticated ICS systems are often heralded as offering the best price-performance ratio, mainly due to ease of installation and simple, rugged construction (no moving parts) and improvements in this price/performance ration are still being made.

Examples are the Dutch Econok and the ICS developed by Ecofys.

Figure 14-15.
Econok ICS system
[picture: www.dakweb.nl]

Figure 14-16.
Ecofys ICS
[picture: www.swt-technologie.de -NEGST demonstration programme]



Collector fluids

Most flat plate systems on sale today use a water-glycol mixture to prevent freezing. A drawback is that the mixture is toxic.

Figure 14-17.
Typical collector storage combi using anti-freeze glycol mixture as heating medium.

Other systems use pure (drinking) water as working fluid. Most of these systems are designed as a drain-back system where the collector is emptied in case of risk of freezing. Naturally these systems rely on pumps for circulation.

Freezing of the water-filled collector of the "AquaSystem" by Paradigma is prevented by linking the collector circuit to the DHW or CH heat exchanger of a boiler and, in case of risk of freezing, supply some of the DHW or CH heat to the collector (thereby in fact cooling the storage contents).

Integrated Collector Storage systems may also use drinking water as collector fluid. In the design of these systems particular attention is paid to preventing damage by freezing and overheating (boiling).

14.2 DHW performance

Assessing the DHW performance of solar water heaters is hindered by the fact that most solar systems are not designed to deliver DHW at a constant temperature. Most systems sold and in use in Europe are DHW pre-heaters, ie. the final heating up to required temperatures is done by some other water heating device.

There are however lots of solar water heaters, mainly thermosiphon systems, that include an electric element in the storage tank. This heater is used to boost the DHW performance and consequently these heaters may be able to achieve

14.3 Energy

14.3.1 Performance of collectors

The thermal performance of unglazed, glazed and evacuated tube collectors does not differ that much. The typical collector produces some 0,7 kW_{th}/m^2 .

The performance of solar collectors depends on a many variables and should ideally not be seen separate from the system it forms part of. However collectors can be tested as separate items and the main aspects determining performance are: How much solar energy is absorbed and retained in the absorber? How well does the absorber transfers its energy to the working fluid? What thermal losses occur in the collector?

These properties are described in the test method for thermal solar systems and components (EN 12975-2:2006 - Solar collectors - Part 2: Test methods).

The Swiss institute for Solartechnik-Prüfung-Forschung (SPF) publishes on its website a database of performance of flat plate and evacuated tube collectors, tested according EN12975 [55].

The collector efficiency is calculated as:

$$\eta = F'(\alpha\tau)_e - a_1 * (T_m - T_a) / G_k - a_2 * (T_m - T_a)^2 / G_k$$

and $\eta_o = F'(\alpha\tau)_e$

and $x = (T_m - T_a) / G_k$ (where x = reduced temperature coefficient)

$$\eta = \eta_o - a_1 * x - a_2 G_k x^2$$

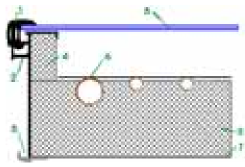
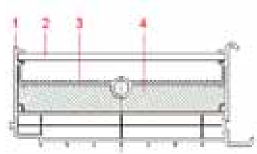
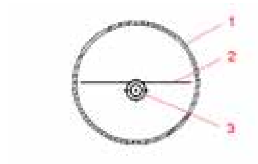
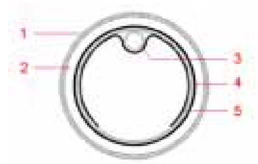
With:

F'	[-]	Kollektorwirkungsgradfaktor:
G_K	[W/m²]	Globale Bestrahlungsstärke in die Kollektorebene
T_a	[K]	Umgebungstemperatur
T_m	[K]	Mittlere Kollektortemperatur $T_m = (T_i + T_o) / 2$
T_i	[K]	Kollektor Eintrittstemperatur
T_o	[K]	Kollektor Austrittstemperatur
$(\alpha\tau)_e$	[-]	Effektives Absorption-Transmissionsprodukt
α	[-]	Absorptionskoeffizient
τ	[-]	Transmissionskoeffizient
η	[-]	Kollektorwirkungsgrad
η_o	[-]	Optischer Wirkungsgrad, Kollektorkennwert
a_1	[W/m²K]	Kollektorkennwert
a_2	[W/m^2K_2]	Kollektorkennwert

These SPF test reports for solar collectors include an indication of annual solar contribution (in kWh) to 1) DHW, 2) DHW pre-heating and 3) space heating alone. The overview below presents the values for of the best and worst collectors in the SPF database of which information was available (some models did not indicate the performance), assessed on basis of their annual contribution to DHW production.

[55] http://www.solarenergy.ch/spf.php?lang=de&fam=1&tab=1

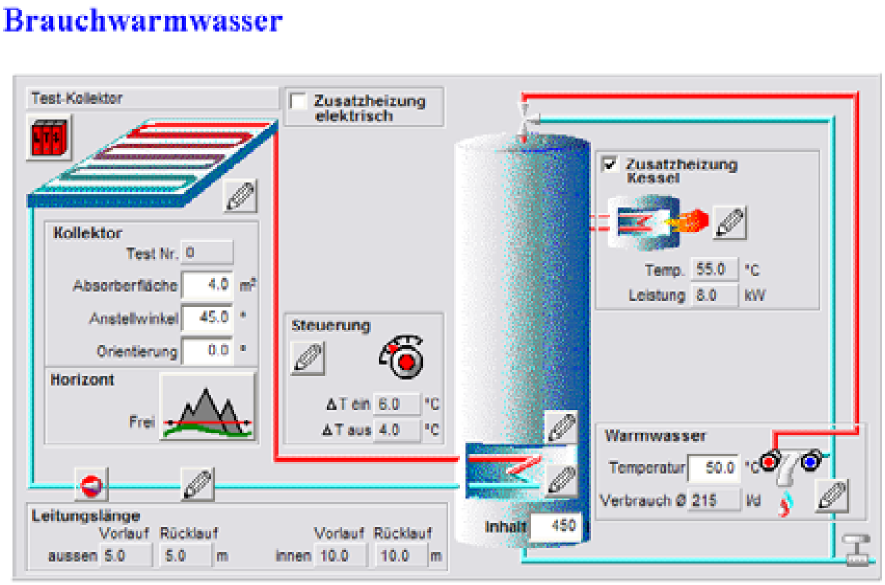
Table 14-4. Performance of solar collectors [Source: SPF, Switzerland]

	kWh DHW	η_0	a_1	a_2	
Flat plate					
Best	570	0,823	3,02	0,0125	
Worst	244	0,765	7,31	0,051	
(difference)	43%	93%	242%	408%	
Evacuated tube					
Best	669	0,813	1,32	0,0035	
Worst	455	0,571	2,1	0,0067	
(difference)	68%	70%	159%	191%	

The best/worse ratio for η_0, a_1 and a_2 of individual collectors can be even larger than indicated above.

The table shows that large variations exist, both in solar absorption/transmission properties as thermal losses. The differences for evacuated tubes however appear less prominent than for flat plate collectors. Also noteworthy and consistent with general rule of thought is that evacuated tubes have better performance (the worst evacuated tube is still 186% better than the worst flat plate in the database). Please note that these values relate to standardised test conditions (according SPF corresponding to European averages - see figure below).

Figure 14-18.
SPF standardised test-conditions



Kurzbeschreibung der Anlage	
Solare Einsparungen (Fss)	60%
Klima	Schweizer Mittelland
Anstellwinkel (Kollektorausrichtung Süd)	45°
Einstrahlung in die Kollektorebene	1'196 kWh/m²/Jahr
Kombi-Speicher	450 Liter
Brauchwarmwasser	215 Liter/Tag
Tagesenergiebedarf	10 kWh/Tag
Kaltwasser	10°C
Warmwasser	50°C
Energiebedarf Referenzsystem	4'200 kWh/Jahr

Storage systems can either positioned on the roof (thermosiphon or ICS) or indoor. The following types are identified:

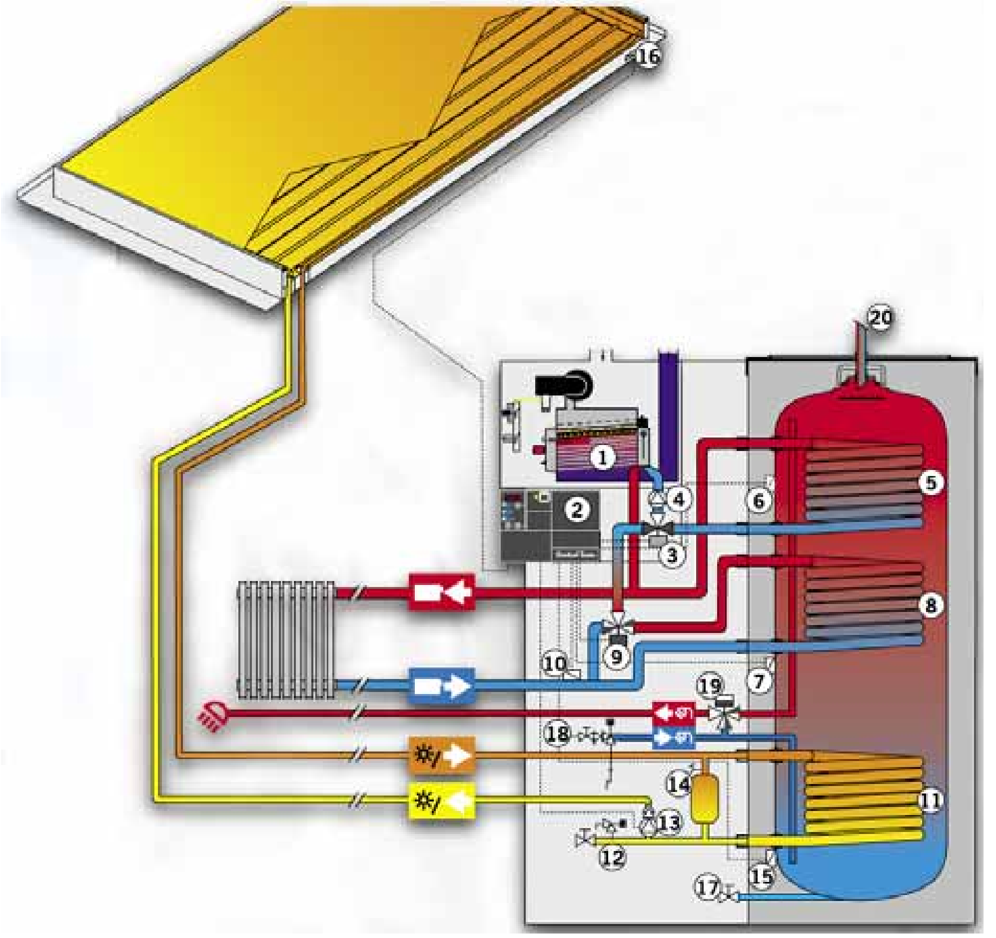
- On roof as in Integrated collector storage (see also above);
- On roof, storage only;
- Indoor, sttorage only;
- Indoor, ccmbined with heat generator.

As far as heat generators for solar DHW go they can be either integrated in the storage cylinder or be external (either separate or combined in a single casing):

- Internal - combined with storage
- External - feeds storage with heat supplied by non-integrated boiler (this includes storage and heat generator in one casing and storage with electrical element)

Storage

Figure 14-19.
Atag Q-Solar:
1. CH heat exchanger stainless steel
2. Control management
3. Three-way valve
4. CH circulator
5. Load storage (by CH) heat exchanger
6. DHW sensor
7. Solar circuit sensor
8. DH heat exchanger
9. Modulating three-way valve (solar circuit)
10. DH return temperature sensor
11. Solar heat exchanger
12. Fill/draw-off valve solar circuit
13. Solar collector circulator and flow control
14. Solar collector storage
15. Solar activating sensor
16. Solar feed temperature sensor
17. Storage draw-off valve
18. DHW safety valves
19. Thermostatic mixing valve
20. Connections for DHW circulation



14.3.2 (Auxiliary) Heaters

Circulation

Considering the pumped systems there are two options: A system which drains itself if the pumps stops - this is to prevent freezing or boiling of the working fluid. Another option is to use a working fluid which does not need to be drained (often filled with glycol anti-freeze). The non-drain system can do with a less powerful circulator.

The popular thermosiphon systems employ a electrical (emergency) heater in the horizontal tank placed upon the roof. There is some discussion that the use of such electric elements brings down the efficiency of the system, since it heats up the whole tank thereby frustrating heat transfer from the collector. In systems that use a vertical storage tank and position the heater in the top part the heat transfer of the collector in the bottom part is not hindered by what happens in the top half.

Most split systems (collector on roof, storage tank inside) use a drain-back system

Some solar systems are equipped with a form of frost-protection that uses electric heaters. Econok says 20W, PER is 0,03 GJ which converts to 0,012GJ$_{el}$ (40% eff. assumed) or 3,3 kWh$_{el}$.

Figure 14-20.
367 dollar solar collector plus storage (Tianjin)
Collector features:
1) Outer tube diameter: 47 / 58mm
2) Inner tube diameter: 37 / 47mm
3) Glass thickness: 1,6mm
4) Length: 1,5 / 1,8m
5) Material: borosilicate glass 3,3
6) Absorptive coating: graded Al-N / Al
7) Vacuum: <5 x 10 - 3Pa
8) Absorptance: >92% (AM1.5)
9) Emittance: <8% (80°C)
10) Thermal expansion: 3,3 x 10 - 6°C
11) Stagnation temperature: > 200°C
12) Heat loss: <0,8W/m²
13) Maximum strength: 0,8MPa
14) Hailstone resistance: up to 25mm in diameter

14.4 Infrastructure

The installation and operation of solar systems can be limited or influenced by several infrastructural and system constraints. Solar exposed areas, azimuth and orientation of collectors as well as structural integrity and weatherproofing of the roof are obvious aspects of the installation. The vertical distance between collector and storage of pumped systems depends on the head of the circulation pump. Thermospihon systems are critical as regards position of storage tank.

Aesthetic considerations can limit the feasibility of solar systems, as well as the legal infrastructure (tenant in practice experiences great great difficulties

Figure 14-21.
Large collective system in Samsø (photo: www.duurzaamtexel.nl)

In case of integrated or ICS systems the storage is also positioned on the roof, near the collector. In case of pumped systems (or thermosiphon systems with storage positioned above the collector) the collector is positioned indoors.

14.5 Prices

The German Stiftung Warentest published a solar system test in 2003, which included prices with and without installation. These solar systems were sized to assist in space heating as well and are therefore much higher priced than dedicated solar water heater systems.

Table 14-5. Solar systems in Stiftung Warentest 4/2003 [56]

	Price w.o. installation	Price with installation	savings on ann. heat demand (%)	aperture (m²)	collector (type / quantity)	Storage volume: sanitary / system (l)	Electricity cons. (kWh/yr)
seperate boiler required							
Wagner Solarpaket SH1440AR	8890	11430	29	14,22	Flatplate/6	200/977	84
Paradigma Kombipaket CPC Optima	12510	15190	24	10,47	Vacuumtube/3	250/794	74
Buderus Logasol Diamant Classic H750/6Ü-B+FM443	11010	13550	25	13,03	Flatplate/6	250/750	80
Consolar TUBO-SOLUS 6/560L Komplettpaket	10390	13050	18	5,74	Vacuumtube/6	100/530	100
Nau Variolux Vakuun-Röhrenkollektro mit Schichtspeicher BS800	22660	25160	21	8,80	Vacuumtube/8	300/788	149
Viessmann Solarsystem mit 4 Vitosol 100 Aufdachmontage	8380	10920	22	9,98	Flatplate/4	150/723	143
Ikarus Powerröhre mit Schichtspeicher HSK	8750	11410	21	8,04	Vacuumtube/12	100/795	72
UFE Solar Solarpaket Ecoplus Gold K4/518 Aufdach	7310	9850	17	7,90	Flatplate/4	125/546	73
internal gas burner - condensing							
Solvis max-Paket SX 6:Max 950 und Fera Flachkollektor	18040	19690	28	12,81	Flatplate/2	225/923	55
Rotex Solaris	10330	11980	11	7,00	Flatplate/3	150/447	78
internal gas burner - non-condensing							
Solatherm Solamax + Multibag 500 RW	not available anymore	not available anymore	15	6,45	Vacuumtube/2	275/517	116

The overview above is therefore expanded by an inventory of streetprices of solar water heaters (different designs and sizes, indicative prices only).

[56] From Stiftung Warentest 4/2003.

Figure 14-21.
Several streetprices of solar systems throughout Europe

Complete set: evacuated tube collctor, indoor storage, pump + control. Street price Spain: 2319 euro

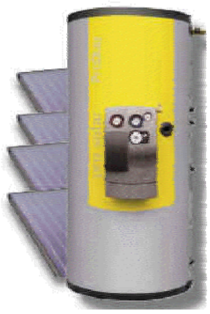
Schuco system with 2 collectors, 300L storage etc. costs 4200 euro (excluded installation)

ProSun H 403 HighLine (Artikel-Nr. 65010006)bestehend aus:

2 x Kollektor PS2400 HighLine 2 (Kollektorfläche: 4,6 qm) 1 x MP 2 HighLine SDZ HN (2N) 1 x Ausdehnungsgefäß Solar AG18S 1 x Haltebügel AGHB 1 x Frostschutzkonzentrat FS10 1 x Solarspeicher 300L Integrale 1 x Montageanleitung ProSun Integrale

Streetprice: from 4.023,00 to 2.599,00 Euro

[www.oeko-energie.de/Sonderangebote.htm#SOLARWÄRME]



ProDuo 7/540 HighLine (Artikel-Nr. 65030004)bestehend aus:

3 x Kollektor PS2400 HighLine 2 (Kollektorfläche: 6,9 qm) 1 x MP 3 HighLine SDZ HN (3N) 1 x Pumpstation PS10 Duospeicher 1 x Ausdehnungsgefäß Solar AG25S 1 x Haltebügel AGHB 1 x Frostschutz L 16KG 1 x 1-Kreissteuerung PS C104 1 x Duospeicher 540/150 ISO+BW-SET 1 x Montageanleitung ProDuo 06/04. Streetprice: from 5.908,00 to 3.999,00 Euro

[www.oeko-energie.de/Sonderangebote.htm#SOLARWÄRME]

Streetprices systems:

2,4 m², 200L: 2573 euro (incl.)

4,8 m², 300L: 3330 euro

7,2 m², 500L: 4269 euro

[www.okuonline.de]

Solar system, Greek system, double collector, 180Lstorage (ICS) costs 2000 euro (streetprice). A pumped system would cost up to 2500 euro. www.elitherm.com

Integrated evacuated tube system: Street price Spain: 1319 euro

Copper collector 144 to 230 euro (1.8 m²) and 198 to 300 euro (2.45 m²) difference in coating, insulation, glass.

[www.isteksolar.com.tr]

Solar storage cyclinder only: Street price Spain: 885 euro

ICS collector / batch collector: 895 EUR (min. order 27) http://www.alphasolar.com

ICS collector / batch collector (US dollar)

PT-20-CN, 20 Gallon, 84 x 20 x 7. 65 $998.97

PT-30-CN, 30Gallon, 97.4 x 35.4 x 7.75 $1279.97

PT-40-CN, 40 Gallon, 97.4 x 47.4 x 7.75 $1579.97

PT-50-CN, 50 Gallon, 97.4 x 47.4 x 7.75 $1729.97

http://www.thesolar.biz/Progressive%20Tube%20Water%20Heaters.htm

15 HEAT PUMP SYSTEMS

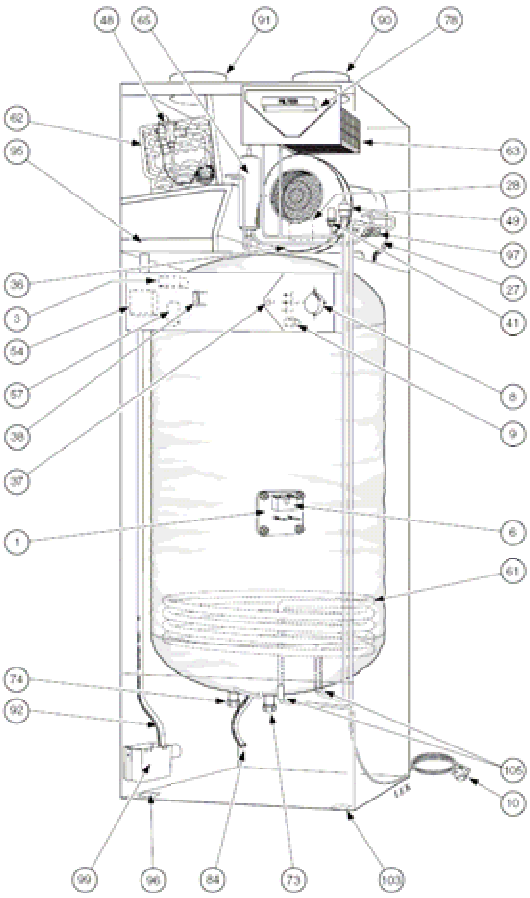
15.1 Product description

This section is limited to heat pumps for water heating that extract heat from either plain outside air or air extracted from the house (usually ventilation air). Heat pumps using other heat sources (soil, rock or ground-/surface water) and heat pumps providing space heating as well (sometimes combined in one appliance, but mostly a solo boiler with indirect storage) are not covered in this section. A typical air source DHW heat pump is pictured below.

Figure 15-1.
Techneco / Blomberg WPB closed

Compressor 385 W (230 V)
Electric back-up 1,5 kW
Refrigerant R134A, 0.9 kg
Tem. 58ºC
COP 2.34
Standing losses 45,2 W
Insulation 50mm PUR
Fan max. 350 m³/hr, 73W
Noise: Type E 59dbA (at Tair 15ºC and Twater 45ºC)
Reheat time 10-55ºC: 160 l 10 hr, 300 l 16 hr (w.o. el.back-up, at Tair 20ºC and 150 m³/hr)

Figure 15-2.
(picture: Nibe Fighter 100 installation manual)



1 - electric heater 1.5 kW
3 - thermostat 51ºC
4 - thermostat 60ºC
6 - temperature cut-out switch
8 - switch, position 0-1-2-3
10 - power chord
22 - connections controlling fan speed
27 - compressor
28 - start capacitor
29 - starting relais
30 - relais
36 - fan
37 - control light
38 - temp.switch
41 - low pressure pressostat
48 - expansion valve
49 - high pressure pressostat
54 - power supply fan
57 - operating capacitor
61 - condensor
62 - evaporator
63 - air filter
65 - fliter dryer
73 - cold water in
74 - hot water out
78 - filter hatch
84 - ventilation hose
90 - air in
91 - air out
92 - condensate hose
95 - condensate container
96 - type / model plate
97 - sump heater
99 - drain container
103 -serial number
105 - overflow outlet condensor

Heat pumps are considered very efficient electric storage water heaters: one unit of electrical energy is "lifted" to 3 or 4 units of useable heat.

The storage volume is in the range of 150 to 300 l. The average heat pump is electric compressor driven.

Manufacturers are Stiebel Eltron, Blomberg / Techneco, Nibe, Siemens, etc. (incomplete).

15.2 DHW performance

15.2.1 Flow rate and temperature stability

Heat pumps are storage DHW systems hence the flow rate and temperature stability of the heat pump are identical to any DHW storage system.

A major difference however can be the re-heat time since the heating power is often limited, especially at lower source temperatures and dependent on heat sink conditions. To boost charging times most electric heat pumps have an electric back-up heating element on board, usually in the range of 1,5 to 3 kW.

15.2.2 Responsiveness

Starting with a fully charged storage the response (measured at the appliance outlet) is very fast.

15.3 Energy

15.3.1 On-mode

The efficiency of a heat pump (in steady state conditions) is indicated by its Coefficient of Performance (COP), which indicates the ratio of electric power input and thermal output. For most DHW heat pumps the COP is in the range of 2,5 to 4. A heat pump with a 350 W compressor and a COP of 3,5 thus produces 1.2 kW of heat.

To date the only official test method for DHW heat pumps is EN255-3:1997 which measures (a.o.):

- heating up time and energy input;
- standby power input (includes energy for fans/pumps);
- COP (procedure includes tapping 50% of contents twice and measuring energy input;
- maximum quantity of usuable hot water in a single tapping;
- reference hot water temperature.

The COP not always includes all auxiliary energy, e.g. the energy to power the fans for transport of air and the electronic controls. In EN 255 some of the auxiliary energy is included through corrections for fan and pump operation: For fans corrections are applied to even out differences between appliances designed to operate without an air pressure difference or with an air pressure difference but with or without a fan. The corrections for pumps concern the circulation of heat transfer media to outdoor heat exchangers.

The heat pump with a 350 W compressor indicated in the pages before uses a 73 W fan, although more efficient (direct current) fans use less than 50% of that (31 W). This is still some 2,6 to 6% of heat output (1,2kW) or 10 to 20% of compressor power consumption.

The COP is also highly dependent on heat source and heat sink conditions. Since both change in time (the DHW storage -heat sink- is emptied and refilled throughout the day, outside air conditions change throughout the day and seasonally, indoor/ventilation may be limited in supply since every m³ extracted is replaced by un-pre-heated cold outside air) a measurement method was developed to take into account these variations: The seasonal perfomance factor.

The IEA Annex 28 workgroup undertook the task to come up with a test method to develop a standard that includes a seasonal performance factor. They did so for space heating and combi-appliances and on this the current prEN15316-4-2:2005 has been developed. The SAVE WH study also mentions the effect of the tapping pattern on appliance efficiency: A pattern with very small draws reduces seasonal performance to 145% whereas a pattern with some large draws achieves 225%.

The efficiency on primary fuels is also influenced by the type of electricity generation and the grid characteristics (in short: "grid efficiency").

15.3.2 Off-mode

Off-mode or standby / standing losses are a significant loss factor for all storage systems, including DHW heat pumps. The heat pump presented as example on the first pages of this chapter has standing losses of 45,2W (probably the 160 l. version at 55°C).

EN 255 describes a measurement of standby power consumption, which includes a few on-off cycles of the compressor to compensate for storage losses. prEN15316-4-2:2005 Annex B4 contains references to DHW heat pumps and provides some default values for COP and storage losses. It shows that storage losses are a significant part of the heat input (55W of 1200W is 4,6%).

Table 15-1. Default value for the electricity input to cover storage losses (for a 300 l. storage)

Testing point	Storage temperature	P_{es} [W]
B0/*	55	55
B0/*	50	49
B0/*	45	42

15.3.3 Start-stop

Start-stop losses for (electric compressor driven) heat pumps are relevant since frequent on-off switching reduces the overall energy efficiency (during every cycle a equilibrium of optimal energy transfer has to be reached which takes time). This is the reason that a DHW storage is applied - this allows for long(er) run times.

Start-up losses are included in the EN255-3 test for COP and standby [57] and are through this also considered in the prEN15316-4-2:2005 test standard on efficiency of heating systems. The prEN15316-4-2 contains a host of equations to calculate efficiencies of heat pumps for space heating and/or DHW production and refers to values from EN255 tests.

The dutch test directive for DHW heat pumps (R 98/463 November 1998) includes a tapping pattern over a 24 hr period, but it depends on the appliance whether any or frequent start-stops are included.

15.3.4 Auxiliary energy

In this section *auxiliary energy* is defined as all energy consumed by the heat pump except the energy required to drive the vapor compression cycle. EN 255 doesn't define auxiliary energy, but does make corrections for fan and pump energy (see above). Controls are also included in measurement of COP and standby energy consumption.

Some heat pumps use an electric heater for defrosting the evaporator, which may be necessary during very cold inlet temperatures. This energy is not considered in EN 255. And then an unknown number of (outside placed) heat pumps use a sump heater to

[57] The appliance is forced to charge the storage completely by making two draw-offs of 50% of the content - One can assume that the heat pump runs continuously during charging.

pre-heat the compressor sump (oil carter of compressor) in cold conditions. This reduces wear and tear on the compressor during start-up. Both forms of energy consumption are not included in the EN 255 test method and little is known about their actual energy consumption.

15.3.5 Alternative energy

Heat pumps are an application of alternative energy. Combination with the other main alternative energy source, solar heat, is possible but rarely applied since it would introduce two heat sources fighting to transfer their low temperature heat to a storage.

15.4 Infrastructure

15.4.1 Chimney / drains

The electric compressor heat pump requires no flues nor chimneys to operate. Condensate may occur at the evaporator-side, since this element is colder than ambient air. Depending on the model the condensate may be pumped away to a drain or is collected in a small container where it is allowed to evaporate.

A water drain is also needed to relieve pressure build up from the boiler and to facilitate filling and draining.

15.4.2 Air ducts

In case extraction air from the dwelling is used as heat source an air duct system is used to guide air towards the heat pump. These ducts can be quite voluminous (for a domestic heat pump Ø 125mm) and usually lead from extraction points in the kitchen and bath-room to where the heat pump is situated (air from the cooker hood is usually not used as heat source).

No ducts are required in case outdoor air is used and the heat pump is positioned outside as well. In case an outside-air heat pump is placed indoors it is usually placed next to an outdoor wall and only a short duct is required.

The flow rate of air is usually between 75 to 400 m^3/hr and thus may exceed the ventilation requirements of the dwelling at times. Persons commissioning the installation need to be aware that if the extraction rate increases more cold supply air is drawn into the dwelling. The heating system must be designed to cope with this. The minimum flow rate should be maintained while in operation.

An important aspect in heat pump operation is cleaning and maintenance of the air duct system and the filters in it. Blocked or seriously hindered airflow could damage the heat pump. Therefore the supply air filters should be checked and cleaned preferably 4 times per year. Vents or grilles that extract the air should be checked and cleaned annually. Finally, if an outside-unit is used, the evaporator should be checked and cleaned periodically as well.

15.4.3 Draw-off point

Heat pump water heaters are the primary water heater in the dwelling, serving multiple draw-off points. The lenght of DHW piping introduces extra waiting time and loss of energy and water.

Recirculation of DHW by the heat pump storage tank is possible but not often applied since the continuous supply of cooled down water (water is cooled in the recirculation pipes) may cause the heat pump to switch on-off frequently. Much depends on the settings of the DHW storage sensor/control.

15.5 Prices

Average costs for a completely installed exhaust air heat pump with a 225 l. storage tank (sanitary hot water only and excluding costs for the ventilation ducting system in the house) varies from 2000 to 3500 euro.

More recent prices (wholesale or street-price excl. installation costs, excl. VAT) are given below:

Table 15-2. Prices of heat pump water heaters (and some combis)

Manufacturer 'A'	
Ventilation air heat pump, COP 3 (heat up to 65ºC), Compressor 300W, fan 150W, electric element 1500W, timer control 5 W, 100 - 225 m³/hr Without electric element: 75 euro reduction	80 L: 1911 euro [1] (streetprice 2454 euro [2]) 120 L: 1982 euro [1] (streetprice 2538 euro [2])
Manufacturer 'B' [1]	
Ventilation air heat pump, compressor 300W, fan 150W, electric element 1500W, timer control 5 W, 72 - 350 m³/hr	225 L: 2427 euro
Manufacturer 'C' [1]	
Ventilation air heat pump, COP 3.45 (heat up to 65ºC), nom.power 400W, electric element 1500W, Air: 75 - 350 m³/hr	300L: 2336 euro (2493 for "solar ready")
Combi's [1]	
Ventilation air-to-water, 303L storage, nominal power 375W, 6.6kW electric element, 50-280 m³/hr	4276 euro
Ventilation air-to-water, 303L storage, nominal power 575W, 6.6kW electric element, 100-280 m³/hr	4286 euro
Water/brine-to-water, (source/system 0ºC /35ºC)	5.8kW: 4600 euro 7.7kW: 4650 euro 10.1kW: 5095 euro 13.4kW: 5495 euro
Water/brine-to-water (modular - cascade of max. 6)	13.4kW: 4300 euro 17.4kW: 4950 euro
Seperate storage tanks	100L: 354 euro 200L: 452 euro 700L: 905 euro
Manufacturer 'D' [3]	
heat pump 'model X' - 6 kW 3-phase 400 V	streetprice 5303 euro
separate storage cylinder 250 L	streetprice 1791.34 (excl. heat pump adaptation 470 euro)

[1] wholesale price: www.technischeunie.nl, [2] streetprice: www.tmgnederland.nl, [3] streetprice: www.suntechnics.be

The installation costs depend very much according the local situation. For ventilation air heat pumps these costs are comparable to installation of an electric boiler plus the connection to the (exhaust air) ventilation system. An (anecdotal) indication of product plus installation costs is 2600 euro all in [58]. If one allows 2000 euro for the heat pump itself some 600 euro can be attributed to the installation (in standard circumstances).

Important aspects to consider during installation are:

- vibration free installation: flexible connections to existing pipework/ductwork;
- reduce sound pressure to environment;

[58] From www.actieenergiezuinigwonen.nl, at 19-3-2007, for a 300L storage, COP 4-4.4 and nominal power 410W ventilation air heat pump water heater in standard situation.

- for ventilation air heat pumps: balacing of ventilation components, check airtightness of connections;
- for combi-heat pumps: balancing of heat flow from source/to sink (check circulator speed).

Re-occurring costs besides maintenance/servicing are filter replacement (indicative costs 10-20 euro per filter) and costs for cleaning the evaporator, condensate drain and fan (blades).

SECTION FOUR - WATER HEATER SYSTEM COMPONENTS

16 ANTI-LEGIONELLA SYSTEMS

16.1 Introduction

An important aspect of water heating systems is the prevention of infection with Legionella bacteria. In Task 1 Legislation & Standards, Chapter 4, several methods for preventing or combating growth of Legionella bacteria in water heating systems have been listed:

- Thermal prevention;
- Thermal disinfection;
- Physical or chemical-physical disinfection:
  - UV disinfection;
  - Micro- / Ultra membrane filtration;
  - Anodic oxidation;
  - Copper/silver ionisation;
  - Electrical pulses;
- Chemical disinfection.

In those situations where thermal techniques cannot properly be applied physical and chemical techniques are applied. Physical techniques are techniques that do not introduce foreign elements or substances into the water, examples are UV and filtration techniques. Chemical, physical and thermal techniques can be combined and sometimes have to be combined since some techniques only have a local or temporarily effect.

This Chapter will discuss those methods applied in water heating systems other than thermal prevention and disinfection in the water heater / storage tank itself.

16.2 Thermal prevention

Thermal prevention of legionella growth in hot or cold water systems is most of all a matter of good design. Prevention measures focus on aspects such as [59]:

- Avoid dead ends: in older systems certain pipe segments may have been disconnected due to changes in the system lay-out - these should be corrected. Pipe segments leading to fire hoses are equipped with stop valves - these should be located at the beginning of the segment. If the valves are at the end of the pipe, close to the fire hose, a large dead end segment is created in the supply piping.
- Avoid hot/cold spots: known problems are central heating pipes heating up cold water pipes (in shafts, under floor and even in crawlspaces where heat may be transferred by condensation). Cold spots can cool down hot water pipes (or storage) to temperatures that promote legionella growth.
- Ensure circulation: especially in circulation systems with pressure boosters (pumps that maintain desired water pressure, often applied in high-rise buildings) dead ends may be created in the expansion vessels. This can be overcome by special valves that maintain the flow through the expansion vessels. Another measure is applying modulating booster pumps. Traditional pumps are on/off type which may

[59] Driessen, S., Volcontinu circularen ter voorkoming van legionella, Installatiemagazine #4, September 2006.

cause stagnant pipe segments and un-even temperature distribution. Modulating pump control maintains circulation and temperature. Another effect is that expansion vessels may be smaller since the variations in pressure are much smaller.

- Not really a thermal prevention measure but nonetheless relevant are the materials used in the system. Some materials (like gaskets from organic materials) have been known to promote bacteria growth. Materials also differ in their effects on the formation of biofilms: e.g. plastic pipes are more susceptible than e.g. stainless steel. Last but not least sediment (usually formed at the bottom of storage tanks) also functions as a breeding ground for legionella bacteria.

Thermal prevention measures are now considered 'good design practice' for new buildings. Owners of existing buildings in which legionella is more likely or more risky to occur (e.g. buildings for elderly, health care) can be ordered to make changes to their system if on-site samples indicate legionella risks [60].

In many cases thermal prevention measures are combined with other prevention or disinfection measures, especially if these other measures are 'gatekeeper'-type methods.

16.3 Thermal disinfection

Thermal disinfection of DHW pipes is aimed at eradicating legionella bacteria in systems through a combination of high temperatures and residence time.

Disinfection measures ideally not only aim to disinfect the water in the pipes but also the biofilm on the inside of the pipes. Standard procedures are weekly pipe flushing with water of 60°C (20 minutes), 65°C (10 minutes) or 70°C (5 minutes) or water reheating at 60°C (10 minutes), 65°C (1 minutes) or 70°C (10 seconds). Also steam cleaning of spas and aqua centres is used (60 - 70°C at longer times).

Special care should be taken that during flushing with hot water (and immediately after, when there is still hot water in the pipes) the water system is not used. In shower areas for instance the flushing takes place outside visiting hours and after flushing the showers are (electronically) 'blocked' to avoid scalding.

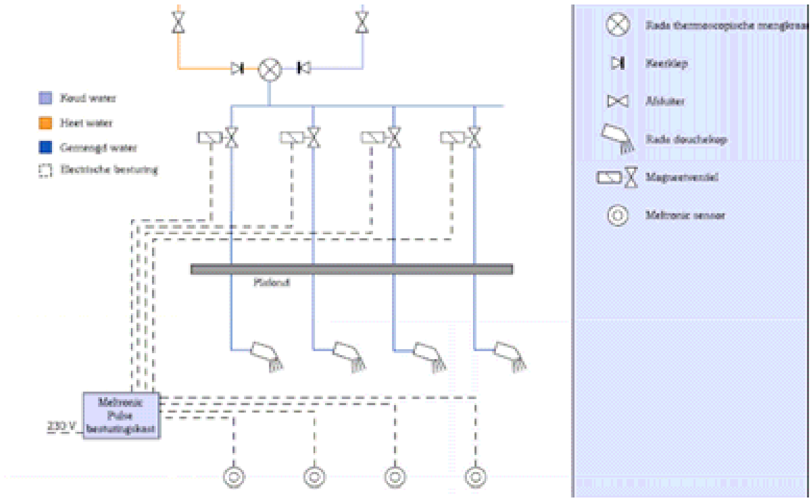
16.3.1 (Automated) Flushing

Flushing of pipes with hot water from the water heater(s) can be done manually but this is cumbersome and requires adequate management. Installation of automated valves makes operation and control a lot easier.

For systems with less than 1 ltr mixed water content (typically < 5m) behind the thermostatic mixing valve a solenoid operated valve in combination with a central control unit ensures periodic (daily) flushing. The system is combined with electronic controls for the showers that prevent use of the showers during flushing.

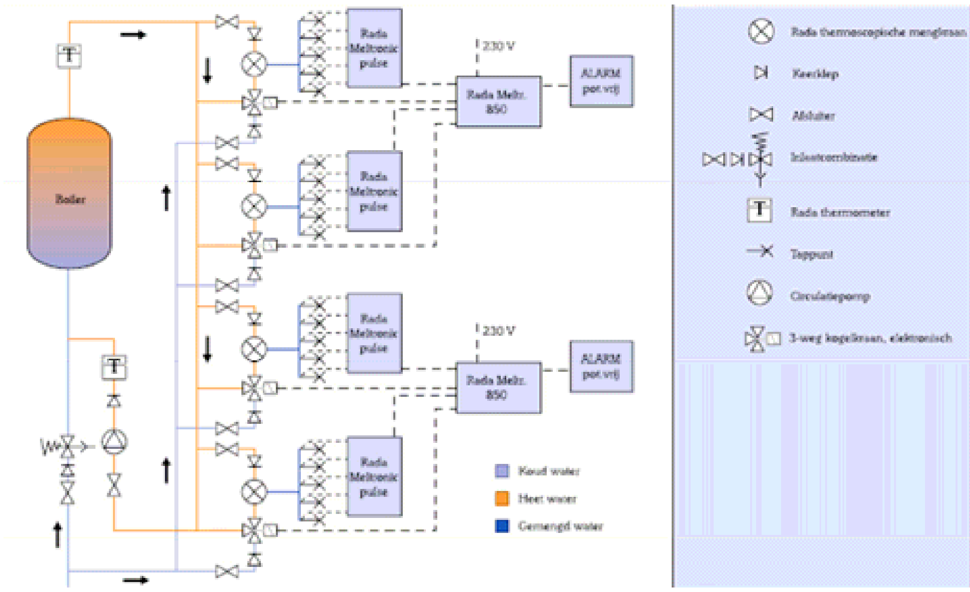
[60] In the Netherlands this is regulated in "Waterleidingbesluit Art. 4.1" and ISSO publication 55.1 and 55.2.

Figure 16-1.
Small water content system (picture: www.sanitair.melker.nl)



Systems with more water content (longer distances) behind the thermostatic mixing valve are flushed regularly with hot water by having a motorised three-way valve shut off the cold water inlet of the thermostatic valve and connect this to the DHW circulation. The system is also combined with electronic controls for the showers.

Figure 16-2.
Larger water content system (picture: www.sanitair.melker.nl)



16.3.2 Reaction chamber

A second option involves the use of a reaction chamber in which the cold incoming water is heated and stored in a reaction chamber. The temperature (> 60°C) and residence time (> 6 minutes) in this chamber ensure that the cold water is disinfected. A unique feature of this application is that during draw-offs the hot water is cooled down to useable temperatures. The extracted heat is transferred to the cold incoming water and is not lost - and no cold water (possibly with bacteria) reaches the mixed pipes. The application shown below is patented by AlfaLaval.

Figure 16-3.
The Aquaprotect / Ceteprotect system by AlfaLaval (picture: www.alfalaval.com)

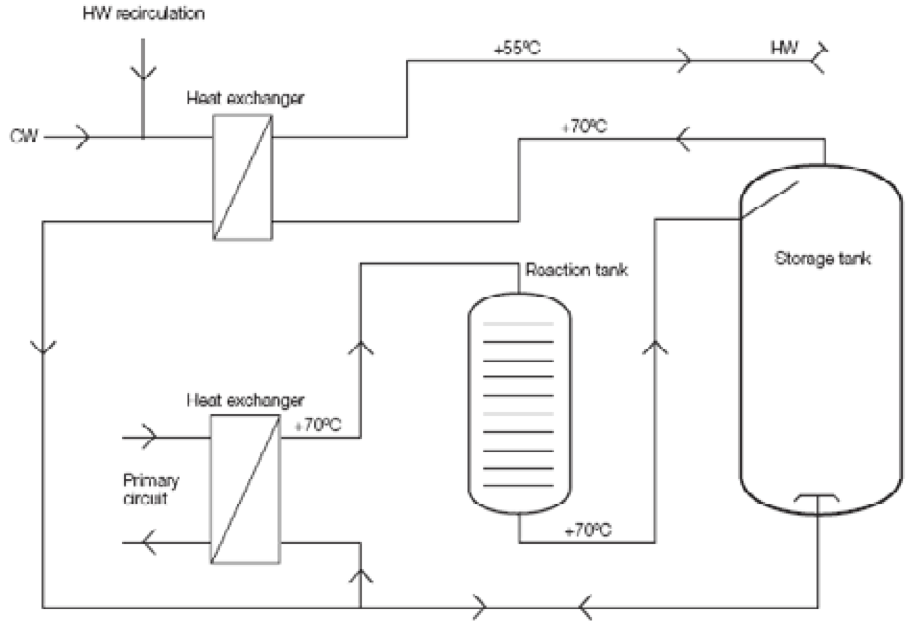


Figure 16-4.
Aquaprotect (picture: www.alfalaval.com)

16.3.3 Local heating

A third option is the local heating of water in the pipes followed by flushing the pipes with clean cold water. The pipe contents are heated by a heating wire (stainless steel chord) that has been inserted into the pipes and heats up the water to up to 70ºC. The pipes are then flushed with clean water by opening of automated valves [61].

The system promises minimum energy costs and minimum water costs and is patented by Legiofreewater systems. Legiofreewater claims an energy saving (compared to flushing with hot water for 20 minutes) of 98% [62].

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[61] Manufacturers information on the website www.legiofreewater.nl

[62] Source: http://www.senternovem.nl/energietransitie/over_energietransitie/koplopersloket/legio_free_water.asp

Figure 16-5.
Local heating (picture: www.legiofreewater.nl)

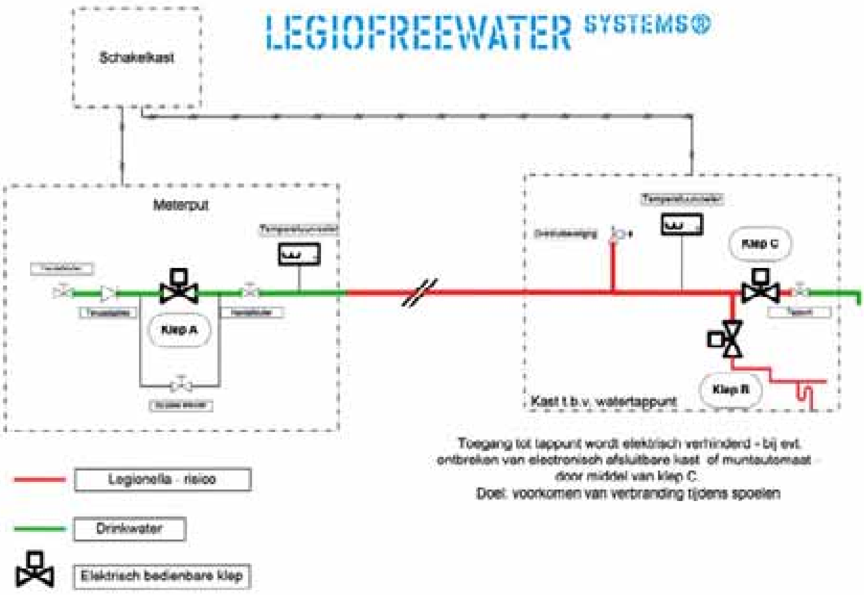


Figure 16-6.
Local heating (picture: www.legiofreewater.nl)

16.4 UV lamp

UV radiation, or more particular UV-C radiation of wavelength between 200-280 nm, breaks down the DNA structure of the Legionella bacteria. The effectiveness depends on the radiation intensity and the exposure time. The product of *intensity* * *exposure* is the *dosage* which is expressed in MJ/cm².

Figure 16-7.
Dosage needed to inactivate 99.9% of bacteria (picture: www.melker.nl)

Cholera	6.5 mJ/cm²
E. coli	6.6 mJ/cm²
Legionella pneumophila	3.8 mJ/cm²
Salmonella	10.0 mJ/cm²

Figure 16-8.
Higher dosage inactivates a higher percentage of bacteria (here Legionella) (picture: www.melker.nl)

3 log (= 99,9%)	inactivering	3.8 mJ/cm²
4 log (= 99,99%)	inactivering	5.1 mJ/cm²
5 log (= 99,999%)	inactivering	6.4 mJ/cm²

The heart of a UV disinfection system is the UV lamp, mounted in a quartz tube. This lamp produces UV-C of 254 nm wavelength which is very effective for disinfection. The tube is placed in the direction of the water flow, the chamber is called the reactor chamber. Depending on the features of the system a UV-sensor, time counter, alarm and temperature sensor are included.

The lamp has a life span of approximately 9000 hours after which efficacy reduces to below 80% of the specified value. The bulb is a low-pressure sodium discharge type, that emits some 30% of its power in the UV-C range where it is effective as disinfectant.

Most manufacturer advise replacement of filter and lamp of twice a year. The lamp operates on 12 V implying use of a power supply to enable connection to the 230 V mains.

The overall water quality must meet certain minimum standards in order for the unit to function properly. The recommended water quality is:

• Iron < 0,3 mg/l

• Manganese < 0,05 mg/l

• Turbidity < 1 NTU

• Tannin < 0,1 mg/l

• Hardness < 120 mg/l

• UV transmission > 75%

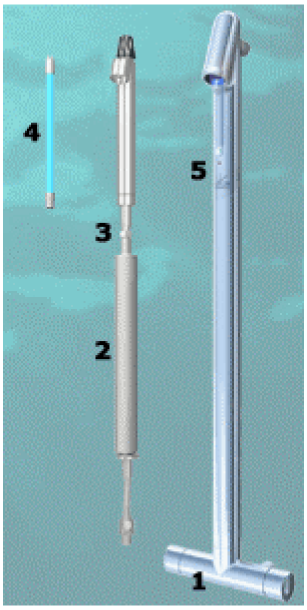
Very important when using UV light disinfection is the combination with filtration. Substances in the water (legionella may 'hide' in amoebae or floating biofilm) may block the UV light from reaching the legionella bacteria. Filtration of at least 1 micron is recommended.

The operating range of most UV units is 2-40°C. In case the water may be stagnant for longer periods the lamp will heat up the water. In such cases an automated vent can be applied, letting off water in case the temperature gets too high.

16.4.1 Point-of-use

In this application the UV light (and filter) is placed less than 5 meters from the outlet. The products can be relatively simple in-line lamps and filters or more elaborate, completed products like the "life shower". Examples:

Figure 16-9.
Lifeshower
(picture: www.uvlifeshower.nl)



1; thermostatic mixing valve,
2; 1 micron pass Dupont Microfree filter
3; physical anti-scaling device
4; UV-C lamp
5; electronic control device with LED signal light.

Figure 16-10.
single faucet UV unit
(picture: www.thewaterexchange.net)

Model PUV-6Watt, maximum flow rate 1 gallon/min (3,8 l/min). Power supply included. Filters are recommended but not included in the shipment.

(Street)Prices

The Lifeshower costs 1140,- euro in the Netherlands [63] (consumer price, excl. VAT / transport).

The single faucet purifier has a suggested sales price of 149 dollar / 113 euro including shipping within the USA [64] (1 USD = 0,76 EUR). A replacement bulb (6W) costs 85 dollar / 65 euro and, depending on use, may need annual replacement.

16.4.2 Gatekeeper

In larger water systems often a central gatekeeper or point-of-entry' disinfection system is applied, situated after the main water meter and before the rest of the installation. As with other central point measures the rest of the water system needs to be disinfected and properly designed and serviced to avoid legionella growth behind the central UV disinfection unit.

The range in capacity of the UV units from a specific supplier:

Table 16-1: Range in UV units

	Flow (l/min)	Power consumption (W, at 30 MJ/cm²)	Dimensions (mm)	Filter cartridges (#, 7.5l/min per cartridge)
smallest	4	12 (1 * 10W lamp)	310*52*52	1
medium	90	95 W (2 * 39W lamp)	940*178*241	12 (3 rows of 4 pcs)
largest	375	375 (8 * 39W lamp)	970*250*330	48 (4 rows of 12 pcs)

The overview shows that the electricity consumption varies from 3 W per l/min (small system) to 1 W per l/min (larger systems). The difference lies in that lamps are available in a restricted number of Wattages (10, 14, 17, 24, 36, 39 W) which also influences the dosage in the reactor chamber. Furthermore, there are differences in number of features incorporated in the electronic controls which cause extra electricity consumption.

Table 16-2: Features of UV units

	simple	elaborate
power on	yes	yes
lamp failure	yes	yes
9000 hr signal	yes	yes
elapsed time (days)	yes	yes
remaining time (days)	yes	yes
UV monitor signal		yes
contact for aux.eq.		yes
alarm at distance		yes
temp. of control unit		yes
temp. of reactor		yes

[63] Source: www.nieuwsbank.nl/inp/2004/09/28/R031.htm

[64] Source: www.thewaterexchange.net

Figure 16-11.
Purex all-in-one solution for systems up to 18 l/min (picture: www.uvnl.nl)

Specifications:
Max. 1100 ltr/hour = 18 l/min
HxLxB = 66x50x18cm
230V - 50Hz - 26W
Life time filters: 6 months
Life time UV lamp: 12 months
UV reaction chamber RVS 304
Max. 5 bar working pressure
Pressure loss max. 0,5 bar
Water temp. 2 - 40ºC
1x active carbon filter
Micron filters: 2 pcs., choice 10, 5 of 1 micron
Connections 3/4" (inlet/outlet)

Figure 16-12.
Elektrospekt Point of entry system (picture: www.elektrospekt.nl)

Shown is a filter (upright), UV unit (horizontal) and control units (wall). This unit serves a school and sports facility (picture: www.elektrospekt.nl)

Figure 16-13.
Point-of-entry system (picture: www.uvidis.nl)

(Street)Prices

The complete Purex UV system is 775,- euro, excl. VAT / shipping. For maintenance (replacement filters 6 months, lamp 12 months) 180,- euro (excl. VAT/ shipping) has to be added every 6 month.

Prices of UV units for swimming pools (mainly intended to break down ammonium to avoid typical chlorine smell) are [65]:

- 10m³/hr, 630,- euro (excl. VAT/shipping)
- 15m³/hr, 998,- euro (excl. VAT/shipping)
- 20m³/hr, 1398,- euro (excl. VAT/shipping)

It is not known whether these units offer the required performance (mJ/cm²) to eradicate legionella.

16.5 Micro-/Ultra Filtration

Micro-filtration is filtration with a pore size of approximately 0,1 µm to 1 µm. The required pressure is in the range of 0,1 to 4 bar. Ultra-filtration requires a pore size of approximately 0,01 µm to 0,1 µm and a pressure of 0,2 to 5 bar. The figure below indicates the types of organisms and particles retained by several filtration techniques.

Figure 16-14.
Range in filtration techniques (picture: Intech, may 2003) [66]

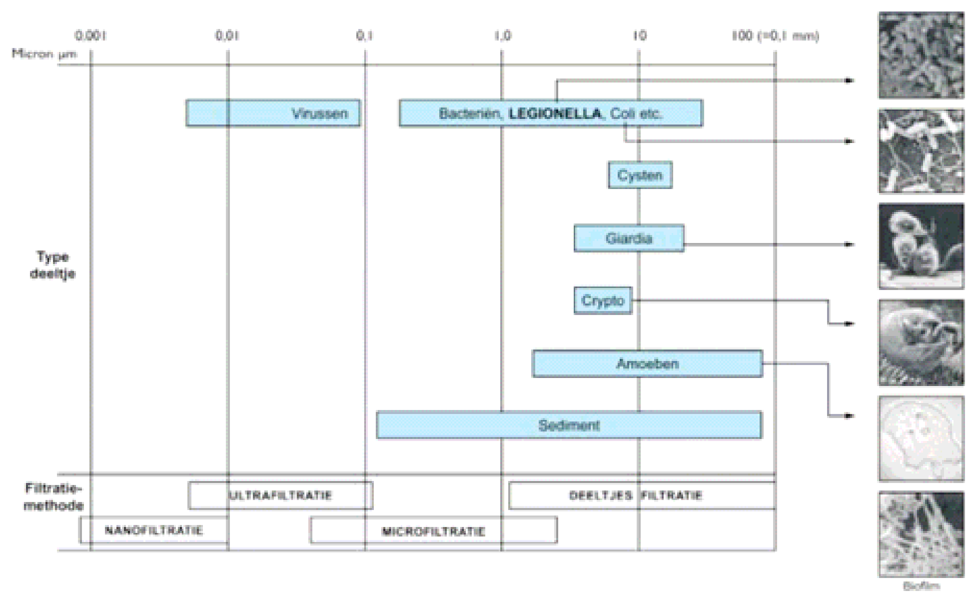
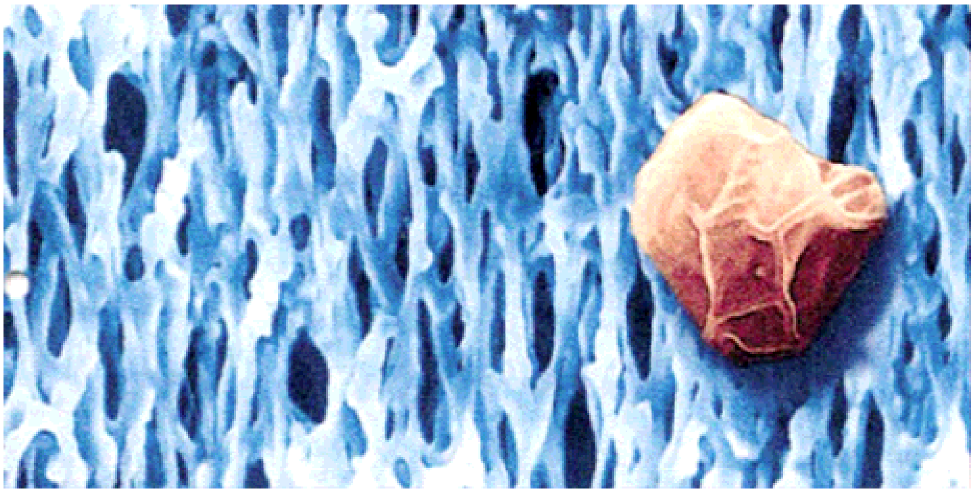


Figure 16-15.
Picture showing bacteria stopped by filter (picture: Intech, may 2003) [67]



The mains water pressure (3-5 bar) is often enough to drive the water through the membranes.

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[65] Source: www.pomaz.nl

[66] Source: Scheffer, W., Membraanfiltratie voor bestrijding van legionella, intech K&S, May 2003

[67] Source: Scheffer, W., Membraanfiltratie voor bestrijding van legionella, intech K&S, May 2003

Often two-stage filtration is applied in which a first membrane stops the largest particles that may damage the expensive micro- or ultra-filtration membrane.

Gatekeeper or Point-of-entry filtration does not prevent (re)contamination with Legionella further 'downstream'. When point-of-entry filtration is applied this should always be combined with legionella control and prevention techniques for the rest of the system.

Over time the surface of the filtration membrane is clotted / covered with sediments and bacteria etc. There are techniques that prolong the life of membranes. The first is called cross-flow where water circulates violently just before the membrane. Part of the water then enters the membrane. The violent water motion prevents deposition of bacteria and other sediments. Another method is the semi-dead end in which all the water is led through the membrane. After a while the membrane is clotted and a back-flush is performed freeing most of the sediments. Sometimes this can also be achieved by a forward-flush - a short violent forward motion of the water.

Other types of contamination of the membrane, like biofilm and scaling deposits, can be removed by chemical treatment. If chemicals are applied great care has to be taken that these cannot contaminate the municipal water supply nor that end-users come into contact with these sometimes toxic substances.

16.5.1 Point-of-use

Filtration at point-of-use is made possible through the introduction of in-line filters, shower sets with filters and filters for faucets.

Advantages are easy application (especially in retrofit situations) and little to no changes to the existing system. Disadvantages are the need for periodic replacement (re-occurring costs), aesthetics and reduced flow rates.

Figure 16-16.
Pall Aquasafe showerhead (picture: www.pall.com)

Figure 16-17.
Inline and faucet filter (picture: www.pall.com)

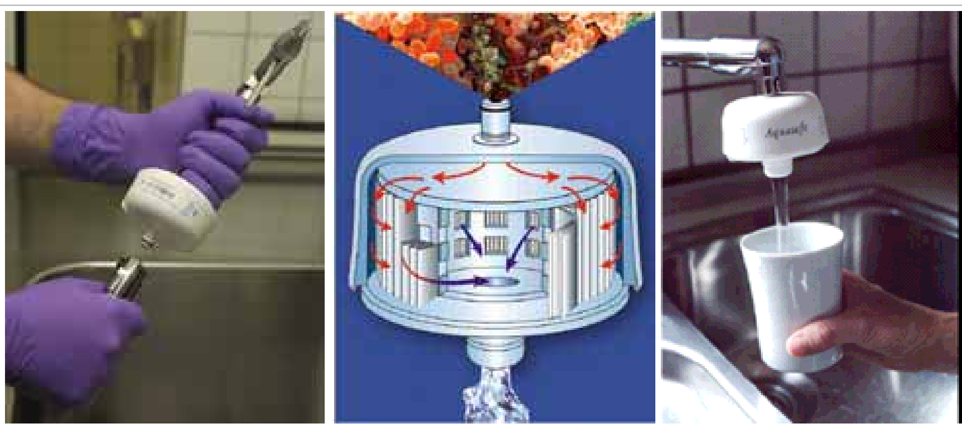
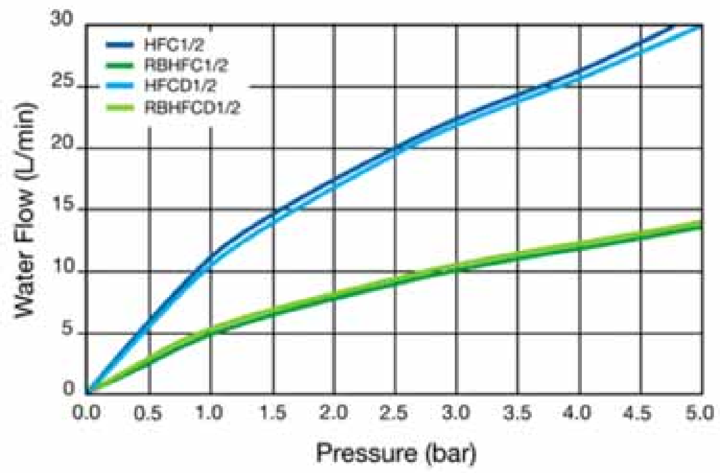


Table 16-3: Specifications AQL3 (source: www.pall.com)

Membrane area	1100 cm²
Membrane rating	0,2 µm Supor incorporating pre-filtration layer
Flow rate at 3 bar	See graph
Maximum operating pressure	5 bar
Normal operating pressure	2 - 4 bar
Maximum temperature exposure	70°C for 30 min.
Maximum operating temperature	60°C
Length (excluding connector)	Approx. 240 mm
Maximum duration of use	One calendar month

Figure 16-18.
Flow rate by pressure (HFC1/2 is showerhead)
(picture: www.pall.com)



The filter reduces the flow rate by approximately 50% and limits it to effectively 14 l/min at 5 bar maximum (the unfiltered version achieves over 30 l/min at 5 bar). At 2 tot 3 bar the filtered showerhead produces some 8-10 l/min, which is somewhat higher than water saving low flow showerheads.

(Street)Prices

The Ster-O-Tap inline filter is claimed to cost less than 0,02 dollar/l for 3000 ltr which converts to less than 60 dollar per cartridge (some 45 euro) [68].

Figure 16-19.
in-line Ster-O-Tap filter (picture: www.primewater.com)

16.5.2 Gatekeeper

Larger capacity membrane filters can be used in the gatekeeper concept, where all incoming water is filtered before entering the sanitary water system. The filters in such systems are flushed regularly (3 to 6 times a day) and the residue is directed to the waste water drain.

[68] Source: http://www.primefilters.com/faq.php?cat=5#ques14

Figure 16-20.
(picture: www.
http://www.aquaassistance.nl)

Manufacturers / suppliers

One of the largest manufacturers/suppliers of filter materials is Pall (www.pall.com), also supplier of point-of-use filter cartridges. In Belgium there is Prime Water (www.primewater.com) producing filters.

16.6 Copper-/silver ionisation

This technique involves the formation of charged copper (100-400 mg/l) and silver ions (10-40 mg/l) by way of ionisation (electrolysis of copper and silver electrodes). The positively copper-ions attack the negatively charged membrane of the bacteria and the silver-ions stops the reproduction of the bacteria. The system is electronically controlled to ensure a correct dosage of ions.

The introduction of substances (like ions) in (drinking) water is heavily regulated. When copper/silver ionisation is applied the relevant authorities must have approved the application and the status of the electrodes and the level of ions in the water must be carefully monitored.

Advantages of copper/silver ionisation is that the ions spread throughout the whole water system, even the dead ends. Also the biofilm is attacked by the ions. Disadvantages are the purchase costs of the system and the costs associated with control of dosage and maintenance.

Figure 16-21.
Copper-/Silver ionisation system by WTN, Netherlands (Picture: www.waterforum.net)

Manufacturers

Holland Milieutechniek (Netherlands) Bifipro, http://www.hollandmilieu.nl)

Ateca (Netherlands) (www.ateca.nl)

(Street)Prices

Prices of copper-/silver ionisation equipment for swimming pools are [69]:

- pool capacity 75m³, 2 electrodes, 620,- euro (excl. VAT/shipping);
- pool capacity 150m³, four electrodes, 731,- euro (excl. VAT/shipping);
- replacement electrode Cu/Ag, 43.50 (excl. VAT/shipping).

It is not known whether these swimming pool applications offer the same performance (i.e. adjustment of current depending the flow rate) as those for sanitary water systems.

16.7 Anodic oxidation

This technique involves the production of oxidising and disinfecting substances from minerals and salts already present in the water by means of anodic oxidation. No new substances are introduced to the water. Low voltage is applied to electrodes in the water which converts minerals to 'free chlorine' and salts to hypochlorite. Chlorine and hypochlorite attack the bacteria and are reconverted to harmless salts after treatment. Also some ozone and hydrogen peroxide is produced.

In order to work properly there must be a minimum chloride-content of 20 mg/l. Also the temperature of the water must be lower than 60°C to prevent damage to the electrodes. Other process parameters are the residence time in the reaction chamber (where the electrodes are positioned) and the voltage and current applied to the electrodes.

Frequent checks and maintenance is important for correct operation of the installation. An important consideration is that the free chlorine can promote corrosion of metals that form part of the water system itself. This very much depends on the chlorine content of the water.

According the manufacturer the hypochlorite is active throughout the whole water system. The hypochlorite also attacks the biofilm, preventing growth and —if the chlorite level is raised temporarily— helps to remove the biofilm.

[69] Source: www.vanremmen.nl

Belgian manufacturer Ecodis claims an energy consumption of 20 to 50 Watt per m³ treated water [70]


Figure 16-22.
(left): Anodic oxidation system (picture: www.brightspark.nl). Figure 16.23 (right): The electrodes in close-up, placed in a plastic tube segment (picture: www.brightspark.nl)

Manufacturers

- Bright spark (Netherlands) (www.brightspark.nl)
- Ecodis (Belgium) www.ecodis.nl

(Street)Prices

Bright spark developed the system originally for disinfection of drinking water storage tanks on ships. The current applied in these systems is 100 mA. The prices listed below are for such applications (incl. VAT, excl. shipping).

Table 16-4. Streetprice of anodic oxidation system for fresh water storage tanks (at ships)

Capacity fresh water storage	2B Sure Standard	2B Sure Luxe (with control panel)
10 - 100 litre	€ 385,-	€ 475,-
101 - 120 litre	€ 435,-	€ 525,-
121 - 150 litre	€ 435,-	€ 525,-
151 - 250 litre	€ 550,-	€ 640,-
251 - 500 litre	€ 675,-	€ 765,-
501 - 2000 litre	ask for price	ask for price

Application of anodic oxidation in water systems (in the supply pipe, with bypass option) will require much more installation work and will result in higher prices.

16.8 Electric pulse

Electric pulse is reported as effective for bacterial inactivation, with UV and plasma effects responsible for disinfection [71]. Inadequate information was available to assess this technology as it appears to be in experimental stage still.

70 Source: www.ecodis.be

71 Oemcke, D., The Treatment of Ships' Ballast Water, EcoPorts Monograph Series No. 18, March 1999 (citing Blatchley & Isaac, 1992)

16.9 Chemical disinfection

Legionella bacteria are killed by a certain dosage of ozone or chlorine. These chemical treatment methods are heavily regulated since (normally) it is not allowed to add substances to sanitary water.

Legionella is killed at a ozone concentration of 1-2 mg/l. Ozone however decomposes in hot water so that maintaining the correct level of ozone is difficult. Furthermore high concentrations of ozone may damage the piping [72].

Addition of chlorine to sanitary water reduces the Legionella count, but low dosages do not kill all the bacteria present since some may have developed some resistance towards chlorine. A chlorine treatment starts with high dosage (2-6 ppm) of chlorine and the system is flushed until a chlorine smell is detected at all draw-off points. The system is kept in this state for 2 hours and then taken into use with water with a low dosage of chlorine (1-2 ppm) - fit for human consumption. Disadvantage of chlorine treatment is the risk of corrosion and resulting leakage and the taste/ smell of the water. Continued monitoring of chlorine levels is necessary. Discontinuation of the chlorine treatment of water would lead to recolonisation with legionella [73].

Chemical treatment methods are typically applied in (public) swimming pools and not in residential installations.

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[72] Source: Vos, M.A., Troelstra, A., Legionella, diagnose en preventie, Infectieziekten Bulletin, year 12, nr. 12

[73] Source: Vos, M.A., Troelstra, A., Legionella, diagnose en preventie, Infectieziekten Bulletin, year 12, nr. 12

17 SCALDING

17.1 Introduction

To complete the overview of water heater products and systems this chapter focuses on techniques to prevent scalding.

17.2 Scalding

Scalding is a specific type of burning that is caused by hot fluids or gases. The burning can lead to first, second or third (full thickness) degree burns on the skin (or internal organs if ingested) also depending on the temperature of the fluid, skin area exposed and exposure time.

Table 17-1. Exposure time to scalding injury by temperature (source: Wikipedia - scalding)

Temperature	Max duration until injury
155F (68.3C)	1 second
145F (62.9C)	3 seconds
135F (57.2C)	10 seconds
130F (54.4C)	30 seconds
125F (51.6C)	2 minutes
120F (48.8C)	5 minutes

Tap water scald injuries can be very severe, even fatal, if they cover a large part of the body and are especially likely to occur in certain populations, particularly children and elderly. Both children and elderly have a thinner skin, leading to faster and/or deeper burns. Elderly also have a slower reaction time and together with persons with handicaps such as sensory neuropathies may be less sensitive to heat.

In the UK alone some six hundred people a year suffer severe bath water scalds, three quarters of whom are children. This means that every day a child under five is admitted to hospital with serious injuries resulting from scalding hot bath water. Many of such accidents lead to lengthy and painful treatments and permanent scarring. In the UK alone fifteen pensioners a year die from burns from bath water [74].

17.3 Prevention

Water temperature may be kept high for a number of reasons a.o. prevention of Legionellosis, increase hot water capacity, for cleaning purposes (washing up). Therefore most actions to prevent scalding are aimed at the bathroom only and focus on the temperature of the water at the outlet.

In Germany the maximum temperature at the draw-off point is limited to 45°C and similar legislation was introduced in Scotland on 1 May 2006, where new building regulations require that the temperature of all bath water in new build and extensively refurbished domestic properties be controlled to a maximum of 48°C. Similar legislation is under review in England and Wales (see also the task 1 report for Water Heaters, Chapter 4.3).

[74] http://www.marycreagh.co.uk/index.php?id=411 "hot water burns like fire" campaign, tabled a bill (ten minute rule) at 29 March 2006

In the UK a certification scheme for TMVs exists (based upon EN1111 and EN 1287) which prescribes valves certified to Buildcert TMV3[75] must be fitted in healthcare institutions. For most other premises valves to the domestic TMV2 standard are deemed acceptable but a risk assessment should be carried out to determine if the facilities are used by vulnerable people, such as the elderly, young children or the mentally or physically disabled. If so, manufacturers and installers recommend to install TMV3 valves to provide the maximum safety level.

The BuildCert Thermostatic mixing valve Scheme offers two approval Schemes, these being:

a. Type 2 approval (TMV2) certifying Thermostatic Mixing Valves against the requirements of BS EN 1111 and or BS EN 1287 and the additional requirements of the Scheme (details required in the information and maintenance document (I&M), marking and audit).
b. Type 3 approval (TMV3) certifying Thermostatic Mixing Valves against the requirements of the NHS Estates Model specification D 08.

Table 17-2. Type approval requirements for thermostatic mixing valves (British Standards)

	Low Pressure TMV2 BS EN 1287	High Pressure TMV2 BS EN 1111	Low Pressure TMV3 NHS Spec D 08	High Pressure TMV3 NHS Spec D 08
Maximum Static Pressure (Bar)	10	10	10	10
Flow Pressure, Hot & Cold (Bar)	0.1 to 1	0.5 to 5	0.2 to 1	1 to 5
Hot Supply Temperature (°C)	55 to 65	55 to 65	52 to 65	52 to 65
Cold Supply Temperature (°C)	£ 25o	£ 25 o	5 to 20	5 to 20

The TMVs do not necessarily need to be fitted at the draw-off point. In general 'mixer taps' and 'in-line mixing' is distinguished

Extra safety is added by TMV's that cut off the hot water inlet automatically if the cold supply fails. A lockable safety cap displays the temperature set point and prevents unauthorised adjustment.

Some manufacturers of TMVs are Rada, Honeywell, Grohe (to name a few).

[75] The TMV Scheme is an independent third party approval scheme administered by Buildcert. The TMV Scheme certifies Type 3 thermostatic mixing valves manufactured to meet the highest specifications required by the NHS Estates D08 standard for mixing valves for use within health care premises in the United Kingdom. The TMV Scheme also certifies Type 2 thermostatic mixing valves for the domestic market and is working with the Child Accident Prevention Trust to promote the safe use of hot water in domestic premises. (www.buildcert.com)

Table 17-3. Example list prices mixing valves (source: Reliance controls, www.rwc.co.uk)

in-line mixer		Heatguard LS2 55.50 GBP excl.
in-line mixer valve		Promix 22-2 497 GBP excl. VAT
valve mixer - surface mount		Thermomix bar shower 105 GBP, excl
valve mixer - concealed		Heatguard CS 274.30 GBP excl.

Table 17-4: Examples retrofit installation costs (source: http://www.reactfast.co.uk/htm/thermostatic_mixing_valve.htm)

bath (22mm pipe)	From £130 / 188 EUR
basin (15 mm pipe)	From £90 / 130 EUR

18 WASTE WATER HEAT RECOVERY

Drain water (or waste water cq. greywater) Heat Recovery (DHR) devices are able to recover (part of) the heat contained in used DHW water that is flushed down the drain into the sewer. The DHR is a very simple device, requiring little or no maintenance and can be used in retrofit situations provided there is enough space (either as vertical tube or as shower floor).

18.1 Drain water heat recovery

The first commercial product to recover heat from shower water is probably the GFX Drain Heat Recovery System, developed in the USA in 1993. The GFX uses a copper pipe of 2 to 4 inch diameter for the drain which is tightly wrapped with a pipe carrying the incoming cold water. Graywater flows through the drain pipe, forming a thin film of water on the walls. This thin film is essential in cleaning the walls from grease, detergents and other graywater contaminants. The system is in fact a double walled heat exchanger with a counter-flow aspect to it.

Figure 18-1.
GFX Drain Heat Recovery System
(picture: gfxtechnology.com)

In the Netherlands several companies have come up with a variant based upon a tube-in-tube principle. The cold incoming water flows through the space between an inner tube (which carries the waste water on the inside) and an outer tube. The space can withstand mains pressure. Again the thin film of flowing water keeps the inner surface clean and helps to maintain the performance over extended time periods. The use of calcium-containing detergents may reduce this self-cleaning ability and is discouraged.

The first versions were single-walled and (according to Dutch Regulations) needed an air-breaker before connecting it to the drain (to prevent sewage ever reaching the DHR part carrying cold water). More recent models are double-walled and feature a small air gap over the length of the pipe that will flood if the cold incoming water side is leaking. These can be connected to drains without use of an air-breaker.

Figure 18-2.
left: Cross-cut shower water heat recovery tube (picture: www.hei-tech.nl, edited by VHK)
Figure right: Bottom part showing cold water inlet of double-wall heat exchanger and a tiny liquid crystal thermometer decal (picture: www.bries.nl)

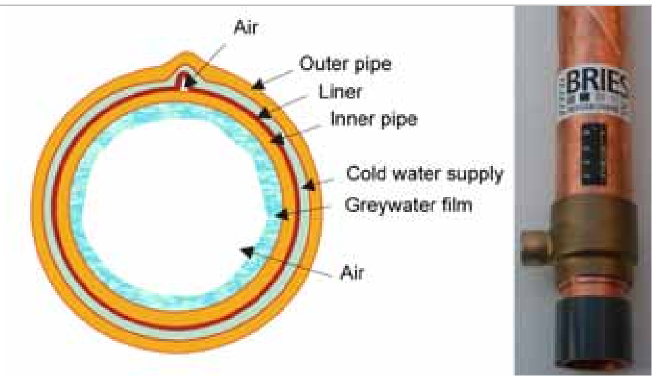
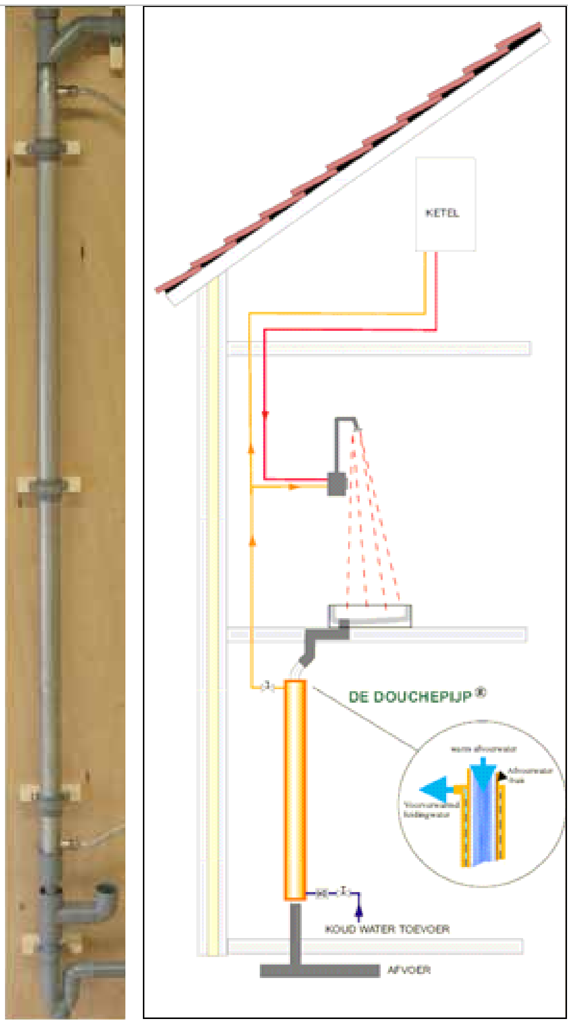


Figure 18-3.
left: Full length picture of Stainless steel Bries DoucheBooster. This installation features the "air-breaker" - an open vented connection to the drain. Length 1.8 m, diameter 48 mm (picture: www.bries.nl)

right: Typical installation of DHR in home (picture: www.hei-tech.nl)



A third type of DHR is integrated into the shower floor. This type simply directs the drain water over a pipe-heat exchanger carrying the incoming cold water. The efficiency of this system is somewhat lower than the vertical pipe systems. Furthermore it is likely a bit more susceptible to fouling because the speed of the water flow is lower. For cleaning the user can easily lift up the top floor and clean the heat exchanger. This type of DHR is especially fit for renovations an retrofitting.

Figure 18-4.
Bries shower floor version of the DHR (picture: www.bries.nl). This is a single-wall heat exchanger and incorporates an air-breaker.

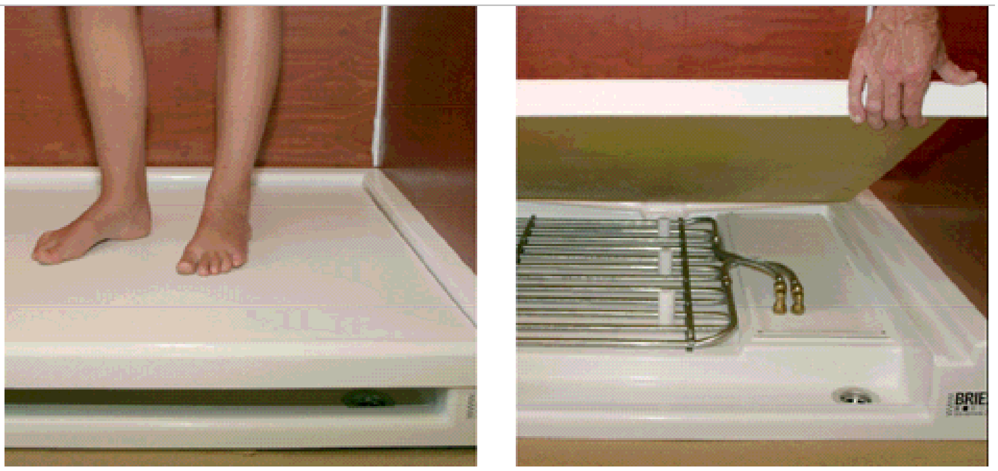
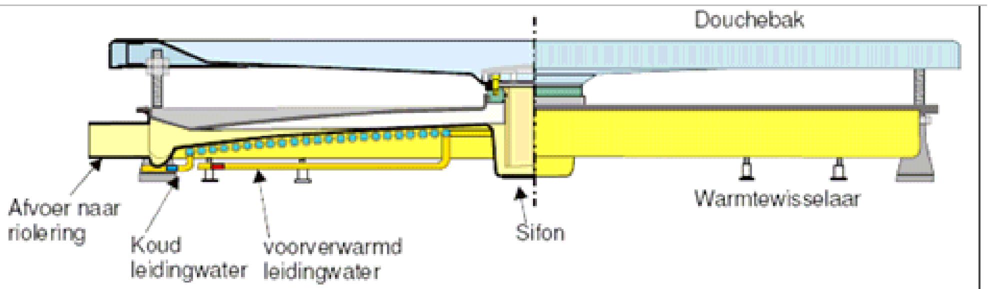


Figure 18-5.
Hei-tech shower floor version of the DHR (picture: www.hei-tech.nl). This is a double-wall heat exchanger so that the drain can be connected to the waste water pipes directly.



18.2 Application

18.2.1 Installation

There are essentially three different ways to connect a DHR to the water heater:

- The heated water is directed to both shower valve and water heater (A);
- The heated water is directed to shower valve only (B);
- The heated water is directed to the water heater only (C).

Studies have shown that installation according A results in the highest recovery rates. (see "performance/savings" further on). The water heater can either be an instantaneous water heater, but storage systems are also possible. In the latter case the preheated water enters the storage cylinder.

A fourth installation option is the combination of a DHR with a dedicated storage system to overcome the time disparity between availability of hot drain water and the need for DHW (like happens when emptying a bathtub). Such a storage system has been introduced by GFX Technology for the US market, called the GFX-Star system (Figure 18-7). Sensors register the availability of hot drain water and activate a circulation pump to recover this heat and store it in a storage tank. Of course the maximum temperature in this storage tank will seldom reach over 30°C (considering the average temperature of the return line is around 25-26°C). The pre-heated water is led to 'any type of water heater' for further heating.

Figure 18-6.
Installation scheme of DHR

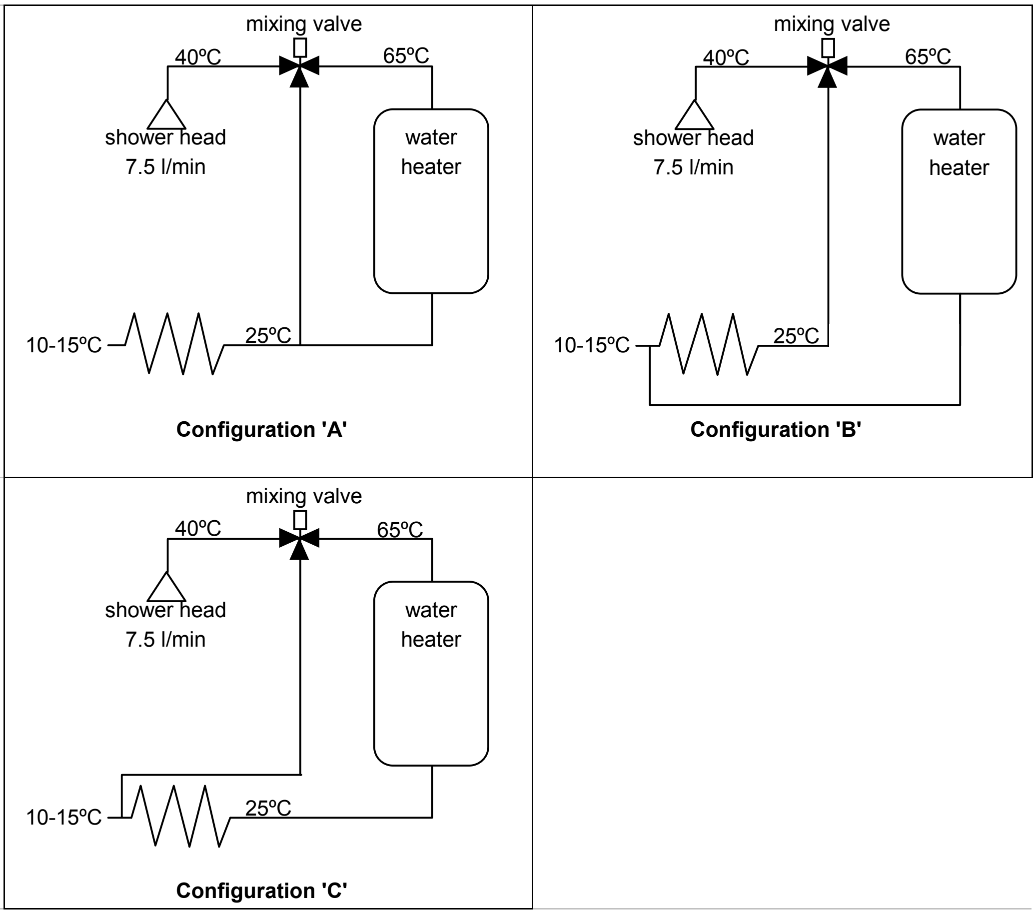
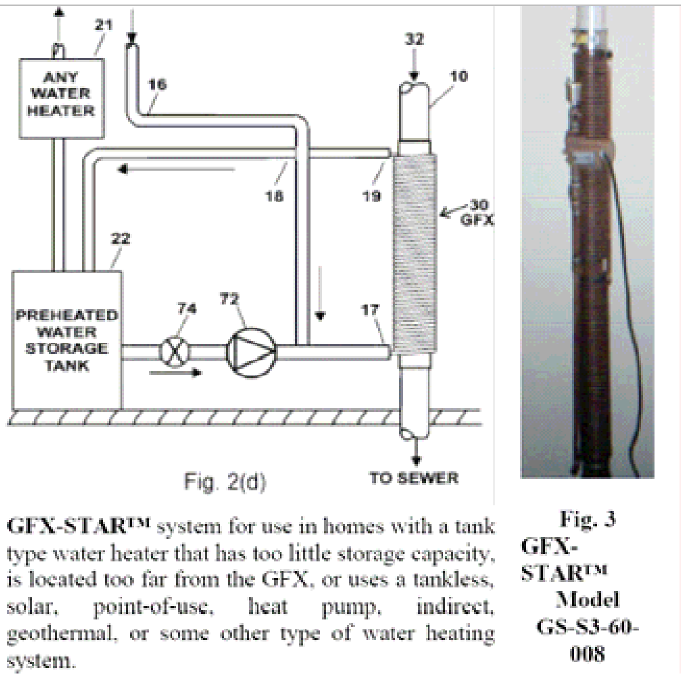


Figure 18-7.
GFX-Star (picture: www.gfxtechnology.com)



Larger systems

Although the single-family household appears to be the primary target group of DHR sellers the same principle can be applied in large DHW consuming environments as well, with often very short pay-back times. Such installations are applied in for instance health spa's, hotels, swimming pools, etc. Care should be taken to avoid legionella growth in pipes carrying pre-heated water, especially if the water in the pipes is stagnant for longer periods.

Figure 18-8.
Large scale solution by Hei-tech (picture: www.hei-tech.nl)

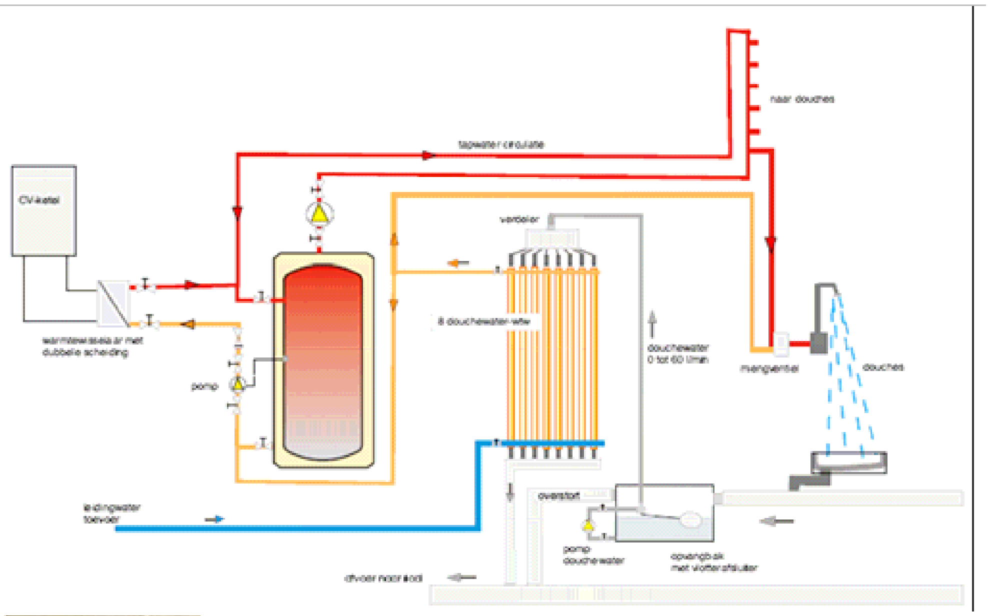


Figure 18-9.
Installation of 16 GFX DHRs in a fitness club in Toronto, Canada (picture: gfxtechnology.com)

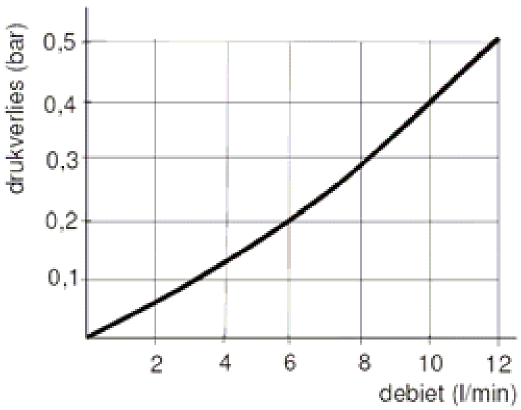
18.2.2 Other installation issues

The vertical DHR water systems have a length of 76 cm (small GFX) to 2,1 m (Hei-tech DoucheBooster). The larger vertical pipe-type DHR will not always fit in the crawlspace or basement which leaves only shower drains located at least one floor above ground floor suited for these DHRs. The shower-floor version and larger versions with a feed pump can be applied on the same level as the shower itself.

Bries recommends installation of the DHR parallel to (existing) vertical drains (DHR exclusively for shower, other-existing- drain for the rest). The DHR does not necessarily need to be directly under the shower drain - displacement is allowed but larger displacements will introduce more thermal loss. Some manufacturers discourage connecting the DHR to especially washbasin drains since deposits from toothpaste or shaving crème can cling to the inner surface and reduce the efficiency.

The use of a DHR is associated with a pressure loss in the cold water piping. This could lead to problems when showering at high flow (double shower heads). The pressure loss is dependent on the water flow and differs per type and dimension of the DHR.

Figure 18-10.
Pressure loss in pipe-DHR - horizontal: flow (l/min), vertical: pressure loss (bar) (picture: www. hei-tech.nl)



18.2.3 Regulations

The installation of DHR must follow local/national Regulations concerning drain water and domestic (cold) water systems.

In the Netherlands this means that installation of cold water pipe-segments that contain more than 1 ltr. in environments that heat up the cold water to over 25°C is prohibited[76]. Placement of the DHR in a metering cupboard that also holds a substation of a collective or district heating system is therefore not allowed (Dutch standard NEN 2768) and connection to a bath drain could also heat up the cold water.

However if the water content is less than 1 ltr. the requirements are less strict. Most DHR systems contain 0,3 to 0,5 ltr and can legally be fitted to a bath drain[77]. It is however necessary to refrain from insulating the DHR and allow the pipe to cool down rapidly. Still, connection of a DHR to a bath drain is discouraged. Connection of a DHR with air-breaker to a bath drain is also discouraged because of the risk of overflow when draining of a bath.

In order to avoid the possibility of contamination of the cold water supply with greywater the Dutch government required either an "air-breaker" (an open vented connection to the drain to avoid internal spills and contamination) for single-walled DHRs or a double-walled heat exchanger (relevant standard NEN 1717).

If the DHR is single-walled and contains an air-breaker this breaker must be situated at least 150mm above street level (to avoid overflow/ spills of sewage in case of blockades in the general sewage system) (Dutch standard NEN3215).

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[76] ISSO/UNETO-VNI-Richtlijn 30.4

[77] Modelbeheersplan Legionella-preventie inleidingwater, Ministerie van VROM

It is essential that the drain water enters the DHR-pipe correctly, e.g. forms a film over the total surface of the inner pipe. To ensure this Hei-tech recommends installation of a 'rotator': A small pipe-segment with a curve, that forces the water to swirl along the sides of the inner pipes for better efficiency.

The cold water inlet of the DHR must be equipped with a non-return valve an a stop-cock. The DHR (and air-breaker if applicable) should be accessible at all times.

Usually it takes a while, some 2 minutes or so, before the thermal inertia of the DHR is overcome and the DHR returns the maximum of heat to the cold incoming water. This means that (assuming installation according 'A' or 'B') the cold incoming water increases in temperature in a two-minute period. The use of an thermostatic mixing valve is advised for optimum comfort and highest savings.

18.3 Performance / Savings

According Dutch sources an average shower consumes some 60 litres of water of 38 to 40°C. Most of this water is flushed away at a temperature level 3 to 4°C lower than the initial temperature. This means that some 80 to 90% of the shower water energy is washed away.

18.3.1 Testing

The performance of a DHR can be described by its output (energy transferred to cold incoming water, in MJ) or by its efficiency (the amount of heat recovered from drain water, in %). The method for measuring these parameters has been developed by Gastec Certification in 2003 and essentially describes a steady-state measurement [78]. The table below shows data from brochures for models by two manufacturers.

Table 18-1. DHR output and efficiency

		Manufacturer A		Manufacturer B	
		Output (Mj)	Efficiency (%)	Output (Mj)	Efficiency (%)
single-wall pipe	at 5,5 l/min	4618	69,1		
	at 7,5 l/min	6061	66,2		
double-wall pipe	at 5,5 l/min		54,1	4279	65,3
	at 7,5 l/min		49,3	5604	62,3
single-wall floor	at 5,5 l/min				
	at 7,5 l/min		42,1		
double-wall floor	at 5,5 l/min			3521	55,0
	at 7,5 l/min			4298	51,3

The output is often the basis for taking into account the effect of an DHR in the DHW or whole building energy performance. For this the manufacturer can ask an independent third party to certify the performance of the product. The declaration mentions the amount of energy recovered in standard situations.

18.3.2 Real-life savings

A third performance parameter can be the (gas) savings realised by the DHR, but this value is very much dependent on the system the DHR forms part of.

Factors influencing the performance of the DHR are:

- the temperature of the cold incoming water (may vary between 5 tot 20°C according measurements [79]);

[78] Koot, M.J.M., Ontwikkeling meetmethode energieprestatie van douchewater-wtw producten, Gastec Certification B.V., 1 July 2003.

[79] Scheffer, W., Warmteterugwinning uit douchewater, Intech, September 2002.

- The temperature of the grey water at DHR entry point. In tests this is usually defined as 40°C (shower temperature), but practice shows that on the way down some 3 °C are lost. A sharp shower beam with much spray cools down more than a soft beam with larger water droplets. The average DHR inlet temperature is likely closer to 37°C;
- There are heat losses at the DHR drain inlet side (tiled shower floors absorb more heat than enamel or plastic floors) and at the DHR pre-heated water outlet side (if the DHR is installed at long distance from the water heater more heat is lost).
- Experiments have shown that DHR with larger diameter inner pipes show larger variations in performance. One suspects that with larger diameter inner pipes the formation of an even water flow film is less easy to achieve. The way the drain water enters the DHR is also of much importance to the creation of an evenly distributed water film;
- The flow through the DHR has an effect on the efficiency: The same DHR has an efficiency of 54,1 % at 5.5 l/min and 49,3 % at 7.5 l/min;

And the system configuration has various effects on the DHR performance and overall system performance:

- In configuration 'A' the grey water flow and the DHW water flow are equal. This results in the highest efficiency for the DHR.
- In configuration 'B' and 'C' the grey water flow is higher than the DHW flow through the water heater. This reduces the efficiency of the DHR.
- Considering the highest efficiency is achieved by configuration 'A' this configuration also has the smallest heat demand.
- If the heat demand in configuration A is lower, the water heater efficiency will also be lower (generally speaking), especially if the heat demand is below what is achieved by the minimum modulation range of the water heater. Furthermore the inlet temperature is higher than 'C', reducing water heater efficiency.
- In configuration 'B' the water supplied to the water heater is the coldest, thus contributing to higher efficiencies in DHW production.

Tests have shown that if a normal shower requires 15 kW the DHR can produce some 5 kW of this. For similar shower performance the size of the boiler thus can be lower, a modern house could do with a boiler of 10kW, even without DHW storage.

Summarising, the various configurations have different effects on overall DHW water heater efficiency regarding the balance of flows through the DHR (influencing overall DHR efficiency), the temperature of the water supplied to the water heater (colder water results in higher water heater efficiency) and the flow through the water heater (beware of minimum flow rate required).

A tube-in-tube DHR has been tested by GASTEC for a year in four households and resulted in average gas savings of 30% [80]. This prototype has been further optimised by at least Hei-tech and Bries (Itho also sells a DHR but the actual producer is probably linked to Hei-tech), a.o. by increasing the heat transfer surface and optimising flows. Laboratory test have shown efficiencies of 50%. In real-life an efficiency of 40% should be feasible.

Considering that in the Netherlands an average person consumes some 60 m³ natural gas during showering savings of 24m³ per person per year should be possible [81].

A shower floor version was tested by Gasunie Research and showed average gas savings in the area of 28%. The table below presents the outcome of this study[82].

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[80] Peereboom,P.W.E., Het terugwinnen van douchewaterwarmte – Een praktijkproef in nieuwbouwwoningen Gastec; januari 2001

[81] Quote from Itho website and brochures.

Table 18-2. DHR test results

		A	B	C
Power to DHW	kW	14,2	15,2	15,0
Share of DHR	%	0	35	29
Boiler power (DHW side)	kW	14,2	9,8	10,6
Boiler power (gas side)	kW	16,0	11,3	11,6
Boiler efficiency 1)	%	89	87	91
Gas savings 2)	%	0	29	27
Effective efficiency 3)	%	89	134	129

1) $\dfrac{\text{Boiler power (DHW side)}}{\text{Boiler power (gas side, lhv 31,7MJ)}}$ * 100*

2) $\dfrac{\text{diff. WH power (gas side) 'B' or 'C' vs. 'A'}}{\text{Boiler power (gas side) for 'A'}}$

3) $\dfrac{\text{Power to DHW}}{\text{Boiler power (gas side)}}$

The boiler efficiency calculated above includes first time start-up losses (boiler fires up to maximum power to heat up the heat exchanger, then turns down to maintain a constant 65ºC at required flow - essentially a cold start situation as opposed to steady-state). The test was based upon shower routine with the following parameters:

Table 18-3. DHR test set-up

Duration	7,5 min
Flow	7,5 l/min
DHW temperature from thermostatic valve/tap	40ºC
DHW temperature from boiler	65ºC
Distance shower head to shower floor	2 m
Other	un-manned shower, no soap, shampoo, etc.

No information was provided on other system aspects like the thermal losses of the pipes from the DHR to the boiler.

Other studies by GasUnie regarding a pipe-DHR concluded in possible gas savings of 30 to 49%, depending on the type of shower beam and floor (tiled or enamel) [83]. In this set-up the pre-heated water was directed to both the mixing valve and the water heater. In a similar set-up another shower-floor model resulted in gas savings of 28,5%. If the pre-heated water of the shower-floor DHR is only made available to the mixing valve the gas savings are 27,7% [84].

For calculation of whole building energy performance the Dutch institute Vereniging Stadswerk Nederland (representing the Dutch communities, responsible for checking compliance with building regulations) allows a reduction of Energy for hot water of 15,8% if flow is 5,5 l/min and 28% if flow is 7,5 l/min.

[82] Wit, G. de, et al, WTW onder de douche: CW4 halen, CW3 betalen, p.633-635, Verwarming & Ventilatie Oktober 2003.

[83] Darmeveil, J.H., Afvoerbuis met warmteterugwinning (voor docuhes), Gasunie, 25 September 2003

[84] Darmeveil, J.H., Douchebak met warmteterugwinning, Gasunie, 11 April 2003.

18.4 Manufacturers

18.4.1 Prices

The table below lists prices from known manufacturers / re-sellers of DHRs.

Table 18-4: prices of DHRs

USA	Price	Comments
GFX technologies (www.gfxtechnologies.com)	G3/S3-60: 540 - 560 USD (410 - 425 euro, incl. VAT, excl. shipping)	1 USD = 0.76 EUR this is for a 60 inch pipe
Netherlands		
Germontis (is GFX importer) (www.germontis.nl)	475,- excl. VAT, incl. transport in NL	for 1670 mm version
Bries (www.bries.nl)		
- pipe	475,- excl. VAT/shipping	
- shower floor 'Pristine'	575,- excl. VAT/shipping	
Hei-tech (www.hei-tech.nl)		sales through Technea (www.technea.nl) who supplies installer
- pipe	387 (excl. VAT, transport and fittings)	
- shower floor	735,- (excl. VAT, transport and accessories/fittings) 1425,- (excl. VAT/transport, incl accessories)	
Itho (www.itho.nl)	(unknown)	developed by Itho together with Heatex Waterheating
Nefit (www.nefit.nl)	(unknown)	re-seller of Bries products

18.4.2 Payback

Taking an average consumer price of 565 euro (475 plus 19% VAT) and gas prices of 13 euro/GJ or 0,46 euro per m³ (see Task 2 report) the device must produce gas savings of at least 1230 m³ over its life to repay itself.

Assuming an overall gas consumption of 60 m³ gas per person per year and gas savings of 30% some 18 m³ is saved per person per year. For a four person household this is 72m³ or 33 euro per year. Assuming constant energy prices and no interest on investment the payback time is 17 years for this family.

If the DHR has a real-life efficiency of say 50% (120m³ gas saved per family) the payback for this family becomes 10 years. In manufacturers brochures savings of 86 to 175 m³ gas per household are mentioned.

For electric water heaters one can assume savings of around 4500 MJ (typical output, see table in section 7.3.2, corresponds to 142 m³ gas lhv). With an electricity tariff of 0,15 euro/kWh (and 1 kWh is 3,6 MJ) annual savings are 1250 kWh or 187,50. The payback time becomes 3 years.

Assuming the DHR has a product life of 15 years and a street price of 565 euro the device costs (565/15) 37,67 euro per year (no interest accounted for). Considering the DHR may save some 4500 MJ per year (for a household) the cost price of saved MJs are in the range of 0,84 eurocent per MJ.

Please note that real-life gas or electricity savings depend heavily on the assumed efficiency or output of the DHR, which in turn are dependent on actual DHW consumption patterns and DHW system parameters.

ANNEX A - VACUUM INSULATION PANELS

Introduction

Vacuum insulation panels are very efficient thermal barriers, having a thermal conductivity 3 to 10 times lower than conventional thermal insulators (0,002 to 0,009 W/m*K). This makes them interesting for achieving a similar level of insulation (as with conventional materials) but with less thickness or achieve a higher level of insulation with equal thickness.

VIPs are produced by vacuum packaging an open-celled, micro-porous insulating core in a gas barrier bag. Due to high costs commercial applications of VIPs are still rare and limited to deep freezers and some small electric water heaters (besides several non-domestic, professional uses).

Figure A-1.
VIP cross-cut

Properties of the core materials [85]

The core is what provides stiffness to the panel and prevents it from collapsing under atmospheric pressure. Current commercial VIP core materials include polystyrene and polyurethane foams, precipitated silica, fumed silica and silica (aero)gel. The best insulation values are achieved with silica cores, even at higher pressure levels [86], although "micro-fleece" also performs very well.

All vacuum insulation panels rely on high vacuum to provide their low thermal conductivity values: the better the vacuum the lower the thermal conductivity. VIPs do not maintain a “perfect vacuum”. Most vacuum panels are initially evacuated to a internal pressure of 1 torr (1,3 mbar) to 0.05 torr (0,067 mbar). A better vacuum would cost significantly more while not contributing to insulation value that much.

What does make a difference is the core material. The relationship between internal pressure rise and increasing thermal conductivity varies tremendously with different core materials.

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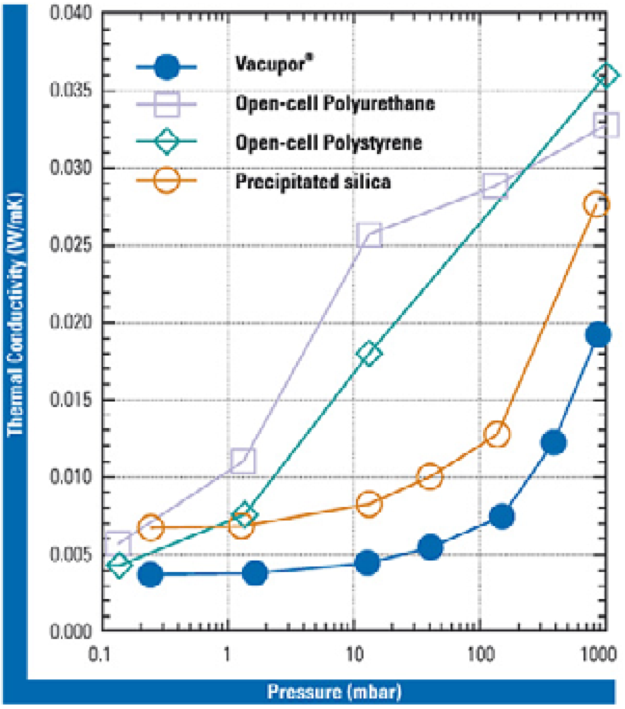
[85] Much of this text has been sourced from the Porextherm website (www.porextherm.de) which provides an excellent overview of VIP properties. Other text is based upon information from Glacierbay and Va-Q-tec.

[86] "Higher pressure" for vacuum panels means "less vacuum".

Figure A-2.
Effect of pressure on thermal conductivity



Gas molecules can enter through the barrier film and the sealant material that bonds the film envelop together. The larger the VIP the greater the film surface area vs. seal area and the smaller the VIP the greater the seal area vs. film surface area. Therefore, selecting a suitable barrier material requires that both the barrier film and sealant properties are appropriate for the type and size of panel.

Thickness also has much effect on panel performance. Halving the thickness of a panel will halve the lifetime of a panel because the surface and seal areas remain almost constant whereas the insulation volume is halved. So although the transfer rates through the seal and barrier will be almost the same the gas pressure will be doubled because of the smaller volume.

The performance during product life thus depends on the quality of the barrier/seal (how long is vacuum maintained) the core material (what happens to conductivity if vacuum is lost, gradually) and the dimensions of the panel.

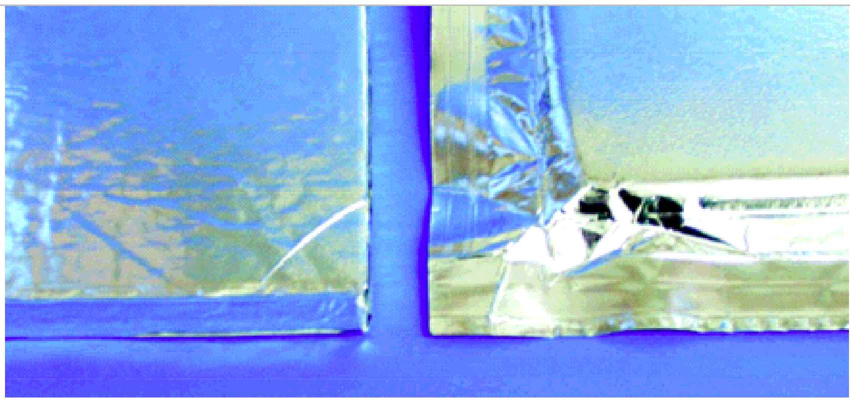
Membrane and Seal Permeation Rates

The membrane film is the material that forms the walls of the VIP. All membrane films in use today permit some molecules of gas and moisture to pass through over time. The amount of permeation through a particular membrane film will depend on the material of its construction and the resistance of this material to degradation during handling in the production process. Some films contain of a very thin metal film (usually aluminium) which is reinforced by laminating a plastic film to each side. These films can have excellent barrier properties but can conduct significant heat around the edges.

Figure A-3.
aluminised films as gas barriers (Source: Glacierbay.com)

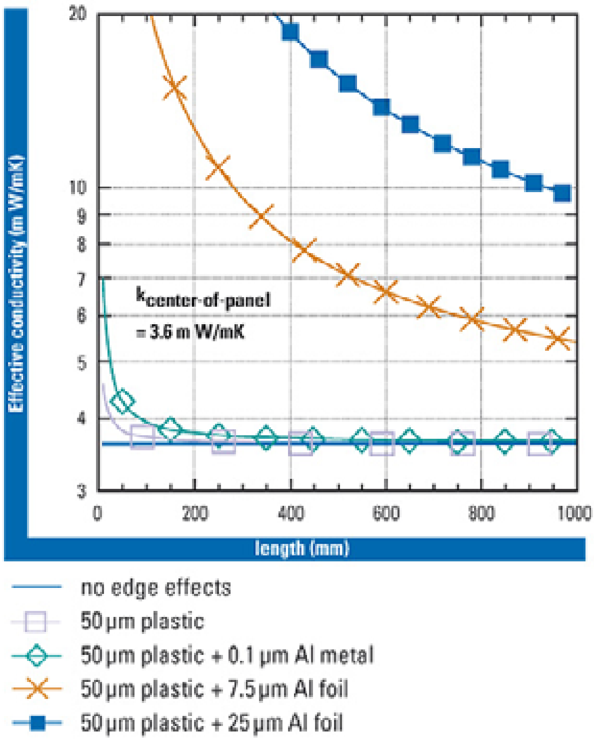
These “edge effects” can significantly reduce the effective performance of a VIP. In order to reduce the unwanted “Thermal Edge Effects” to a minimum, some films are based on a thin film deposition technique which builds the metal layer even thinner. The membrane films are sealed at the edges to form an envelope for the core material. A thin layer of low temperature plastic is laminated to the inside of the film so than it can be sealed using heat and pressure. These layers of heat-sealing plastic do not have the same resistance to gas and moisture permeation as does the rest of the film. To minimize the negative impact of permeation of the sealing layer, manufacturers use as thin a film layer as possible combined with a wide seal lip.

Figure A-4.
Folded edges
[Source: Va-Q-tec brochure]



Most barriers consist of layers PE, PET and Aluminised PET foils. Application of pure aluminium film is possible but increases edge losses.

Figure A-5.
Edge-effects on conductivity



Outgassing, Getters and Desiccants

Most materials release gases (outgas) when placed in a low pressure environment. The kind and quantity of gas released, as well as the length of time the outgassing will continue, varies from material to material. The released gases can contribute substantially to the rise in internal pressure (i.e. loss of vacuum) of a VIP. In some cases, the rate at which gas released from the core and membrane materials exceeds that at which it permeates through the membrane. Silica-based cores do not outgas, while some foam based cores may never stop. The core and membrane materials used by a particular manufacturer will determine what, if any, impact outgassing will have on the life of their product.

Getters are chemicals that absorb gases; desiccants are chemicals that absorb moisture. Getters and desiccants are used to extend the life of VIPs by absorbing unwanted gases and moisture that promote heat transfer within the evacuated space. To be effective, the getters and desiccants must be carefully matched to the kind and quantity of gas/moisture they will be expected to absorb. Besides that getters and desiccants must also be capable of effectively absorbing and holding the gasses and moisture at the low pressures inside the VIP. It is, therefore, important that the quantity and type used be selected in accordance to the core material, membrane film and required life expectancy. Foam-based panels have no absorbent capacity at all. It is, therefore, necessary to add these chemicals into the VIP envelope. Getters can add significant cost to a panel and because of their heavy metal composition create major safety and environmental concerns.

A popular type of getter is the COMBOGETTER by the Italian company SAES. SAES claims that the combo getter is a non-evaporable getter made of alloys based on metals such as zirconium, vanadium or titanium. The getters are made from fine powders of these alloys either compressed into the form of pills, granules, pellets or strips, or coated and deposited with proprietary techniques onto suitable surfaces and which act as metal "sponges" for the remaining gas molecules present within an evacuated device. The COLD II study mentions that COMBOGETTERS constitute of a Barium-Lithium alloy. When calcium oxide and Cobalt oxide are added it can absorb

SAES also produces desiccants under the trade names COMBOdryer and SAESdryer. Precipitated silica and silica aerogel acts as their own getters/desiccants.

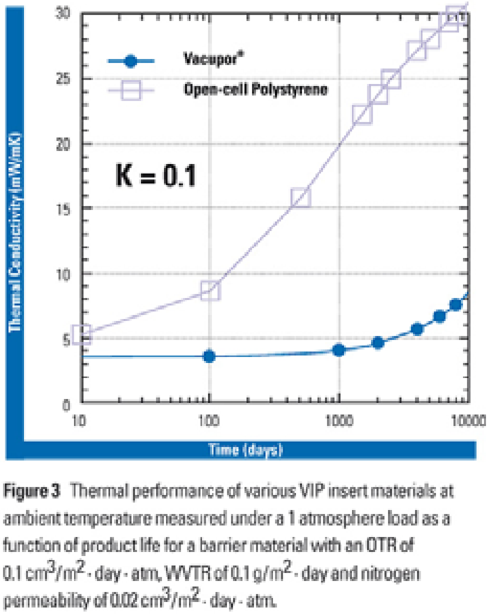
Also opacifiers may be added to the core material to reduce losses through infra-red radiation.

Operating conditions

Operating conditions are important for both usability and lifetime. Usability refers to a panel's suitability for a given operating environment. Foams being plastics have a limited temperature range over which they can be used. Most panels can be applied in environments of -20 to 80°C. Outside of this range shrinkage and deformation occur which can render a panel practically useless. For example the upper limit for polystyrene foams is 88°C (190°F) which rules out their use in applications such as hot water heaters and hot food delivery systems. Silica based core material can be used at temperatures up to 950°C (1742°F) with appropriate barrier films like e.g. a stainless steel envelope.

Operating conditions effect lifetime because the transfer rates of water vapour and gases through the barrier film and seals change with temperature. Higher temperatures promote increased transfer rates and lower temperatures slow down molecular movement. In addition, the higher the concentration of a gas surrounding the panel the higher will be it's concentration in the panel and consequently the greater it's effect on heat transfer. In general the smaller the gas molecule the faster it will penetrate into the panel and greater will be it's effect on thermal conductivity. So for example encasing a panel in polyurethane foam, the preferred method of application in refrigerators helps to prolong panel life because the heavy gas molecule of the foam blowing agent take longer to penetrate into the panel and when inside are not as good conductors of heat as nitrogen or oxygen because of their larger molecular sizes. Similarly for water vapour; the higher the humidity of the air around the panel the faster the transfer into the panel and the higher the final water concentration in the panel when equilibrium is reached.

Figure A-6.
Thermal performance over time



Shapes

The simplest shape of the VIP is a rectangular panel. Depending on specifications the edges can be folded or left "as is". Most manufacturers are bound by maximum panel sizes (often in the range of 80 - 100 cm per side).

Figure A-7.
Typical appearance of vacuum insulation panels

A little bit more complicated is the production of non-rectangular panels or panels with holes or other cut-outs. These are more costly since they require manual handling an preparation of the foam core. Much attention is given to avoiding and removing dust specks or other "contaminants". Tiny speckles of dust can easily damage the barrier film, reducing the lifetime of the panel. Some damages occur only after a some time has elapsed (creep of plastics).

Figure A-8.
Cylindrical panel shapes
(picture: va-q-tec)

By removing some material from the foam core in the form of long grooves the core can be bend. Depending on the type of core and the evacuation method the panel with grooved core assumes a curved shape during evacuation. Such panels allow some bending or stretching to be fit into place. Again the manual labour involved in producing such cores makes them very costly with current production techniques.

Figure A-9.
Cylindrical panel shapes
(picture: www.vip-bau.ch)

The technique of non-rectangular shapes and curving can be combined resulting in shapes as shown below that are used in experimental water heaters.

Figure A-10.
Cylindrical panel shapes
(picture: saesGetters)

Manufacturers

Production of VIPs is still costly. Especially the handling and processing of panels with a powdery core is more expensive than that of foam cores. The creation of non-rectangular and cylindrical shapes requires manual efforts and thus adds to the costs. Furthermore the quality of the panel depends on the level of vacuum applied and the working environments: Even tiny speckles of dust can damage the barriers when vacuum is applied. Some defects may occur only after some time has elapsed. Prices for VIPs range from 5000 to 10000 euro per m³.

The table below presents some cost price information (street prices, excl. VAT) of VIP manufacturers in Germany and the Unites States (SeasGetters from Italy does not provide general price information). These prices include getters and desiccants.

Table A-1. Prices of vacuum insulation panels

Glacier Bay "Barrier Ultra-R™ ", Core: silica aerogel Prices: 35 mm "small" panel (size up to 76*89cm) is 400 euro/m² (excl. VAT) 35 mm "large" panel (size up to 152*178cm) is 264 euro/m² (excl. VAT) Other: 25 years warranty
Porextherm "Vacupor NT" Core: Fumed silica Price: prices are for series of 10.000 pcs (excl. VAT) 10 mm is 60 euro/m² (70 euro/m² if taped) 13mm is 64 euro/m² (74 euro/m² if taped)
Va-Q-Tec panels Core: Silica powder Price: 10mm is 100 euro/m².Prices are for a series of 10.000 pcs (status 2004, excl. VAT)
RP Parts Core: DOW Instill (EPSM foam) core material Price: 25.4 mm is 200 euro/m² (max. size is 81*81 cm, excl. VAT)
Seasgetters "saesINSULA" Core: probably foam, possibly EPS Size: Maximum size 110*150 cm, Maximum thickness 5 cm Prices: No price information available Shapes: plane, cylindrical and customised

Savings

Reports indicate reduction of daily standing losses of water heaters of up to 25% when compared to conventional insulation [87]. For refrigerators/freezers savings of up to 35% have been recorded using metal film barriers [88]. Metalised plastic film barriers should result in even fewer edge losses.

Figure A-11. Improved Vacuum Insulated Panel Design for Water Heaters, 5th Annual Vacuum Insulation Symposium, May 2001, P. Di Gregorio, E. Rizzi, and M. Urbano.

Sample		Exp. value (kWh/day)	Average (kWh/day)	calculated (FEA)
1	with VIP	0,795	**0,784**	**0,780**
2	with VIP	0,765		
3	with VIP	0,801		
4	with VIP	0,776		
5	w/o VIP	0,969	**1,050**	
6	w/o VIP	1,130		
Improvement			**25%**	

Alternatives

Besides conventional insulation materials there are also advanced alternatives to application of vacuum insulation panels.

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[87] P. Di Gregorio, E. Rizzi, and M. Urbano, Improved Vacuum Insulated Panel Design for Water Heaters, 5th Annual Vacuum Insulation Symposium, May 2001.

[88] Malone, B., Weir, K. State of the Art for VIP Usage in Refrigeration Applications, International Appliance Manufacturing 2001.

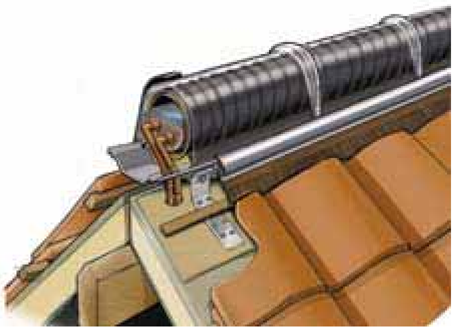
The first example is the application of completely evacuated vessels, e.g. the "thermos" flask (Dewar flask). Only a few products in the realm of water heaters apply this principle. There is the small kitchen countertop boiling water dispenser "Quooker" applies this principle in the 7 ltr. combi-version.

Figure A-12.
"Quooker Combi" with vacuum insulation. This application is interesting since it involves a commercial application of an evacuated cylinder. Standby loss is 10 Watt (picture: www.quooker.com)

Another application is found in solar collectors: Evacuated tubes are a well-known type of solar collector. And the larger ICS type solar water heater "Econok" applies an evacuated storage tank for minimising heat losses and the application of the heat-pipe heat transfer principle.

Figure A-13.
Evacuated tubes (picture: www.radiantcompany.com)

Figure A-14.
Eco-nok by Inventum / Lafarge (picture: www.dakweb.nl)



A major design attention point is the minimisation of heat losses through edges/ flanges.

Another alternative insulation method relies on the lower thermal conductivity of special gases such as Argon, Krypton and Xenon when compared to air. LBNL (USA) has conducted research for the application of "gas-filled panels"(GFP) [89]. Some results are shown below. GFP have been subject to study since 1995 but the first commercial applications still have to be developed.

[89] http://gfp.lbl.gov/performance/default.htm

Figure A-15.
Gas-filled panels in comparison with conventional and vacuum insulation
(picture: http://gfp.lbl.gov)

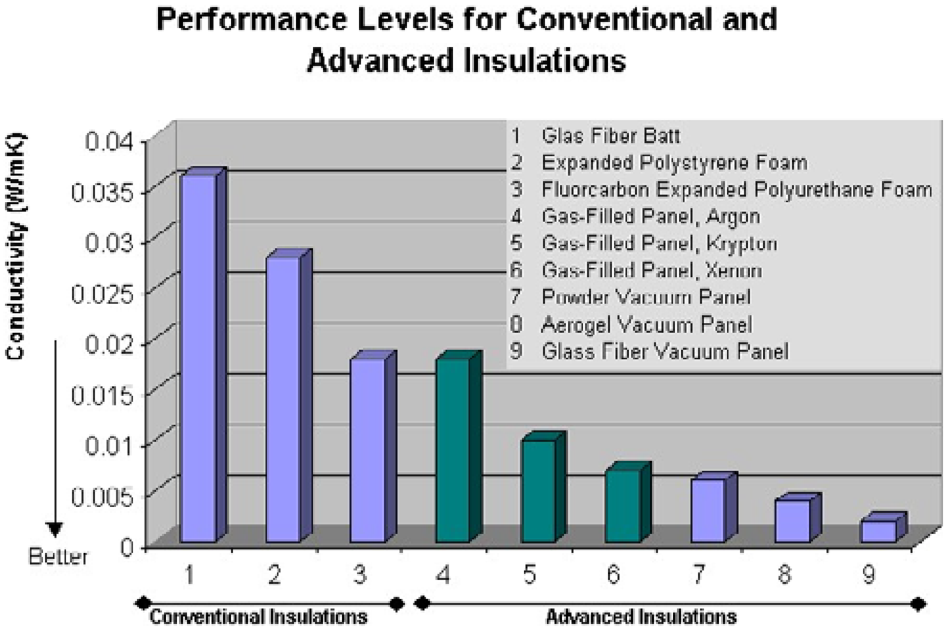


Figure A-16.
Picture of gas-filled panel (cross-cut)
(picture: http://gfp.lbl.gov)

Table A-2. Properties of GFP - center of panel measurements

Gas Fill	U-value Effective conductivity per Inch (W / m.K)	R-value Effective Resistance per Inch (hr.ft2 . °F / Btu . in)
Xenon	0.0074	19.5
Krypton	0.0116	12.5
Argon	0.0199	7.2
Air	0.0281	5.1