On Gas Dynamics of Exhaust Valves

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1D/0D simulations

\[ C_D = \frac{\dot{m}_{\text{actual}}}{\dot{m}_{\text{ideal}}} \]

Measurements of \( C_D \) today assume:
- Static valve (quasi-steady)
- Low pressure ratios (insensitive to pressure ratio)
Objectives

Experimentally investigate the effects on $C_D$ due to:

- Engine speed (valve opening time)
- Pressure ratio
Ideal mass flow

\[ C_D = \frac{\dot{m}_{\text{actual}}}{\dot{m}_{\text{ideal}}} \]

Subcritical:

\[ \dot{m}_{\text{ideal}} = \frac{A_T p_0}{\sqrt{RT_0}} \left( \frac{p_T}{p_0} \right)^{\frac{1}{\gamma}} \left\{ \frac{2\gamma}{\gamma - 1} \left[ 1 - \left( \frac{p_T}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}} \]

Choked:

\[ \dot{m}_{\text{ideal}} = A_T p_0 \sqrt{\frac{\gamma}{RT_0}} \left( \frac{2}{\gamma + 1} \right)^{(\gamma+1)/[2(\gamma-1)]} \]

\( A_T \) - Throat area
\( p_T \) - Throat pressure
\( p_0 \) - Total pressure
\( T_0 \) - Total temperature
\( \gamma \) - Ratio of specific heats
\( R \) - Specific gas constant

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Dynamic valve setup

Outlet

Linear motor

Linear transducer

Air supply

Spring

Cylinder

Outlet
Static valve setup

Outlet

Diffuser

Cylinder

Flow
\[ \dot{m}_{max} = 0.5 \text{ kg/s} \]
\[ p_{max} = 500 \text{ kPa} \]
Time-resolved mass flow

\[ m(t) = \frac{V}{R} \frac{p(t)}{T(t)} \]

Expansion in the cylinder may be viewed as isentropic

\[ \frac{p_2}{p_1} = \left( \frac{T_2}{T_1} \right)^\gamma / (\gamma - 1) \]

Meaning the mass in the cylinder is a function of the pressure and initial temperature

\[ m(t) = f(p(t), T(t = 0)) \]
Time-resolved mass flow

\[ \dot{m} = \frac{dm}{dt} = \frac{V}{\gamma RT_0} \left( \frac{p_0}{p} \right)^{\gamma-1}/\gamma \frac{dp}{dt} \]

\[ n = 900 \text{ rpm} \]
\[ p_0 = 400 \text{ kPa} \]
Initial pressure

\[ n = 900 \text{ rpm} \]

\[ p_0^i \]

\[ C_D \]

Valve lift [mm]

\[ p_0^i = 300 \text{ kPa} \]
\[ p_0^i = 350 \text{ kPa} \]
\[ p_0^i = 400 \text{ kPa} \]
\[ p_0^i = 450 \text{ kPa} \]
\[ p_0^i = 500 \text{ kPa} \]

Static data
Engine speed

\[ p_{oi} = 500 \text{ kPa} \]

\[ C_D \]

Valve lift [mm]

800 rpm
900 rpm
1100 rpm
1350 rpm
Static data
Quasi-steadiness

\[ u_{\text{geometry}} \ll u_{\text{flow}} \]

\[ \tau_{\text{geometry}} \gg \tau_{\text{flow}} \Rightarrow \text{Quasi-steady} \]
Quasi-steadiness

Classical idea

\[ u_{\text{geometry}} \ll u_{\text{flow}} \]

\[ \tau_{\text{geometry}} \gg \tau_{\text{flow}} \Rightarrow \text{Quasi-steady} \]

Neglects the dynamics of the flow conditions

\[ \tau_{\text{condition}} \gg \tau_{\text{geometry}} \gg \tau_{\text{flow}} \Rightarrow \text{Quasi-steady} \]
A measure of quasi-steadiness

\[ Q_S = \frac{\dot{A}_T}{\dot{m}/m} \]

\[ Q_S = C \cdot \left( \frac{p_{0i}}{p_0} \right)^{(\gamma-1)/2\gamma} \frac{V}{A_T \sqrt{\gamma R T_{0i}}} \frac{\dot{A}_T}{A_T} \]

\[ Q_S \gg 1 \Rightarrow \text{Quasi-steady} \]

\[ C = \left( \frac{\gamma + 1}{2} \right)^{(\gamma+1)/[2(\gamma-1)]} \]
A measure of quasi-steadiness

$p_{0i} = 500$ kPa

$Q_s$

Valve lift [mm]

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Conclusions

It has been shown that:

- The assumptions of quasi-steadiness and pressure-ratio independence do not hold
  - $C_D$ decreases with initial pressure
  - $C_D$ increases with engine speed

Reference:

Competence Center for Gas Exchange

"Charging for the future"