On Gas Dynamics of Exhaust Valves

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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

$$C_D = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}}$$

Subcritical:

$$\dot{m}_{ideal} = \frac{A_T p_0}{\sqrt{R T_0}} \left( \frac{p_T}{p_0} \right)^{\frac{1}{\gamma}} \left\{ \frac{2\gamma}{\gamma - 1} \left[ 1 - \left( \frac{p_T}{p_0} \right)^{\frac{\gamma - 1}{\gamma}} \right] \right\}^{\frac{1}{2}}$$

Choked:

$$\dot{m}_{ideal} = A_T p_0 \sqrt{\frac{\gamma}{R T_0}} \left( \frac{2}{\gamma + 1} \right)^{(\gamma + 1)/[2(\gamma - 1)]}$$

**Notation:**
- $A_T$ - Throat area
- $p_T$ - Throat pressure
- $p_0$ - Total pressure
- $T_0$ - Total temperature
- $\gamma$ - Ratio of specific heats
- $R$ - Specific gas constant
- $c_p$ - Specific heat at constant pressure
- $c_v$ - Specific heat at constant volume
- $R = 287$ J/kg K
Dynamic valve setup

Outlet

Linear motor

Linear transducer

Air supply

Cylinder

Spring

Outlet
Static valve setup
\[ \dot{m}_{\text{max}} = 0.5 \text{ kg/s} \]

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

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

\[
\dot{m} = \frac{dm}{dt} = \frac{V}{\gamma R T_0} \left( \frac{p_0}{p} \right)^{(\gamma-1)/\gamma} \frac{dp}{dt}
\]

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

$n = 900$ rpm

$C_D$ vs. Valve lift [mm]

$p_{0i}$

$p_{0i} = 300$ kPa
$p_{0i} = 350$ kPa
$p_{0i} = 400$ kPa
$p_{0i} = 450$ kPa
$p_{0i} = 500$ kPa
Static data
Engine speed

\[ p_{0i} = 500 \text{ kPa} \]

Diagram showing the relationship between valve lift [mm] and a coefficient \( C_D \) for different engine speeds (800 rpm, 900 rpm, 1100 rpm, 1350 rpm, and static data) at a constant inlet pressure of 500 kPa.
Quasi-steadiness

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

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

Classical idea
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

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

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

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

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

$p_{0i} = 500 \text{ kPa}$

$Q_S$

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:

"Charging for the future"
Double-valve setup

![Graph showing comparison between single and double valves](image)

- Single valve
- Double valves

Valve lift [mm] vs. Coefficients

- Single valve: Red dots
- Double valves: Blue dots

- Graphs for different valve heights (0.5 mm, 1 mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm)

Pressure vs. Coefficients

- Pressure range: $p_{0_{at}} [\text{Pa}]$ from $1 \times 10^3$ to $5 \times 10^3$
- Coefficients range: $C_D$ from 0.4 to 1.0

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Double-valve setup

$n = 1350 \text{ rpm}$

$C_D$ vs Valve lift [mm]

- Single valve
- Double valve

$p_{0i} = 300\text{kPa}$
$p_{0i} = 350\text{kPa}$
$p_{0i} = 400\text{kPa}$
$p_{0i} = 450\text{kPa}$
$p_{0i} = 500\text{kPa}$
Double-valve setup

\[ n = 1350 \text{ rpm} \]

- Single valve
- Double valve

\[ Q_s \]

Valve lift [mm]

- \( p_{0i} = 300\text{kPa} \)
- \( p_{0i} = 350\text{kPa} \)
- \( p_{0i} = 400\text{kPa} \)
- \( p_{0i} = 450\text{kPa} \)
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