Intake and Exhaust Valve Flows

• The flow rate through a valve can be given by using the isentropic flow relation and mass conservation:

$$\dot{m}_{is} = \rho A_v U = \rho A_v \left\{ 2\frac{\gamma}{\gamma-1}\frac{P_o}{\rho_o}\left(1-\left(\frac{P}{P_o}\right)^{(\gamma-1)/\gamma}\right)\right\}^{1/2},$$

where P_o & ρ_o are stagnation pressure and density, respectively, P=valve static pressure, A_v is a representative area of the valve.

$\Rightarrow$ The actual mass flow can be related to the ideal isentropic mass flow by: $\dot{m}_{actaul} = C_f \dot{m}_{is}$, where C_f is a valve flow coefficient and it is the ratio of an effective flow area (due to flow contraction or separation) to the valve seat area (that is when $A_v = \pi/4\, D^2$).

$C_f = A_f/A_v = A_f/\left(\pi/4\, D^2\right)$ and $C_f < 1$ to account for the non-isentopic nature of the flow.

Choked Condition

$\Rightarrow$ Choked flow occur when the flow speed at the throat reaches local speed of sound. As a result, the pressure ratio reaches a critical valve as

$$\left(\frac{\mathrm{P_o}}{\mathrm{P_{throat}}}\right)_{cr} = \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)}.$$

The choked mass flow rate is then

$$\dot{\mathrm{m}}_{\mathrm{choked}} = \rho_o C_f A_v a_o \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)} = \rho_o A_f a_o \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)},$$

where a_{o} is the stagnation speed of sound and $A_f = C_f A_v$.

$\Rightarrow$ Note: If the representative area is the valve curtain area, the flow coefficient is called the discharge coefficient:

$$A_f = C_D A_v = C_D\left(\pi D L\right).$$

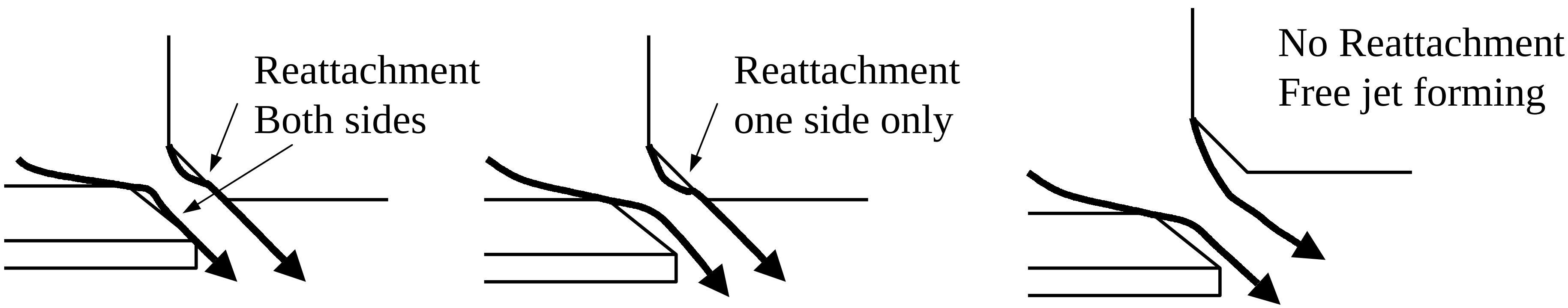
Valve Flow Pattern

➢ Due to the strong viscous effect at the valve, several types of flow patterns can exist at different valve lift positions.

(a) Low lift: flow reattachment on both sides and jet fills the gap.

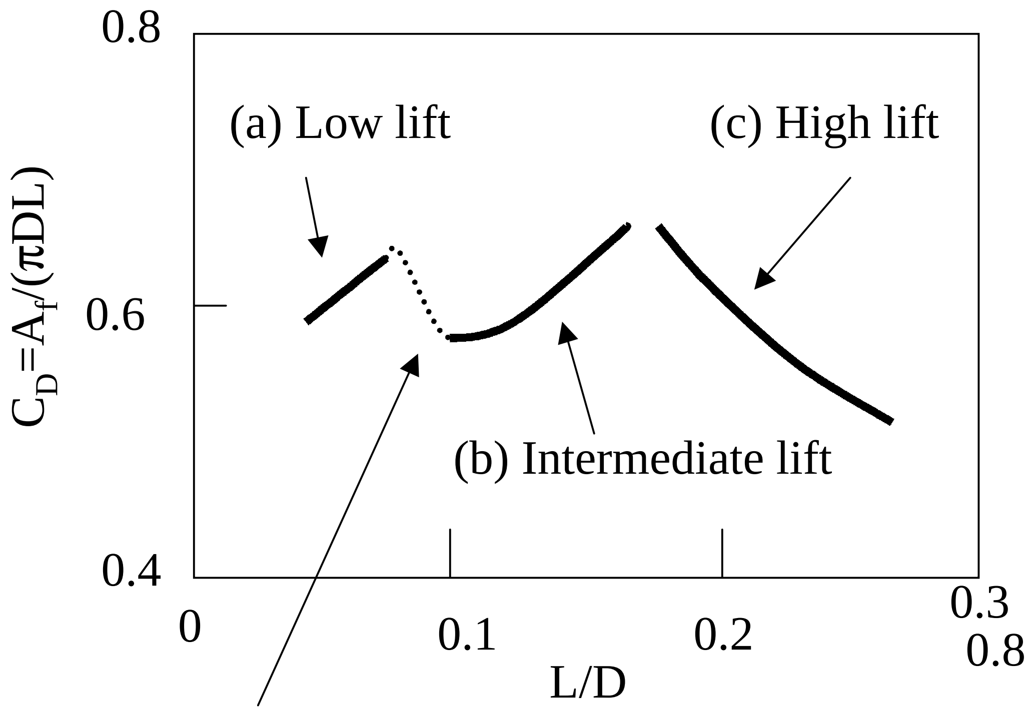
(b) Intermediate lift: one side reattach while the other side separates from the valve and jet partially fills the gap.

(c) High lift: both sides separate to form a free jet.



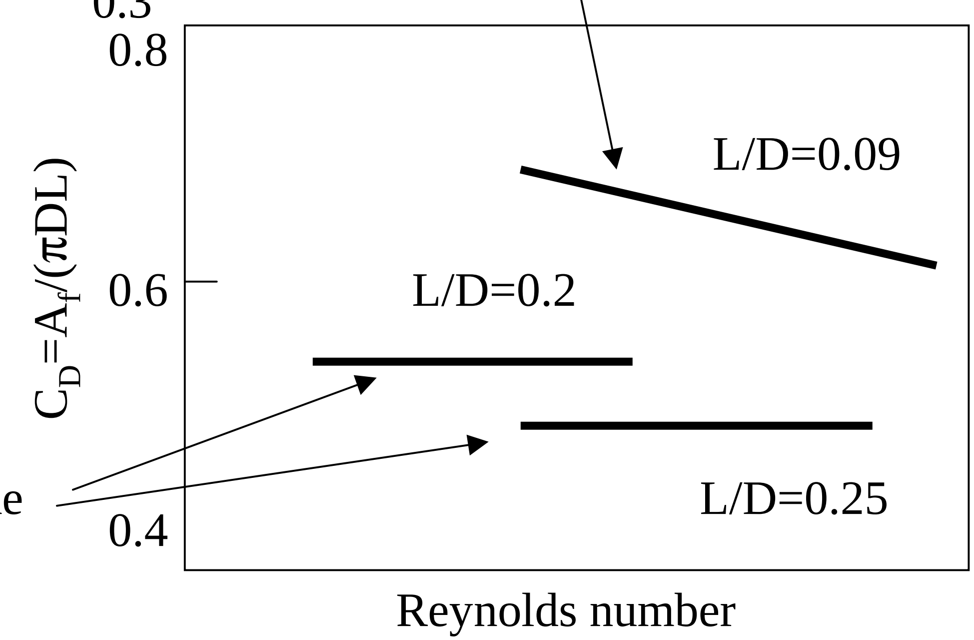
(a) Low lift (b) Intermediate lift (c) High lift

Discharge Coefficient



Significant drop due to flow separation

C_D at Low lift depends on the Reynolds number



C_D at high lift is insensitive of the Reynolds number (dominant by flow separation)

Volumetric Efficiency and Mach Index

We can define the mass inducted during the valve opening period as:

$$\mathrm{m_i} = \frac{\Delta t}{\Delta\theta}\int_{\theta_{io}}^{\theta ic} \dot{m}\,d\theta = \frac{1}{\omega}\int_{\theta_{io}}^{\theta ic} \dot{m}\,d\theta$$

where θ_{io} and θ_{ic} are crank angles at which the intake valve opens and closes, respectively.

Define an averaged effective intake flow area $\bar{\mathrm{A}}_{\mathrm{f}}$ such that

$$\bar{\mathrm{A}}_{\mathrm{f}} = \frac{1}{\theta_{\mathrm{ic}} - \theta_{\mathrm{io}}}\int_{\theta_{io}}^{\theta ic} A_f\,d\theta.$$

One can show that the choked volumetric efficiency

can be expressed as

$$\eta_{\mathrm{v}} = \frac{m_i}{\rho_i V_d} = \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)} \frac{\bar{\mathrm{A}}_{\mathrm{f}}\, a_i}{\omega V_d}\left(\theta_{\mathrm{ic}} - \theta_{\mathrm{io}}\right).$$

Volumetric Efficiency and Mach Index

Introduce Mach index Z as

$$Z=\frac{\frac{\pi}{4}b^2\bar{U}_P}{\bar{A}_f a_i}.$$

Z is clearly related to some reference Mach number $\bar{U}_P / a_i$.

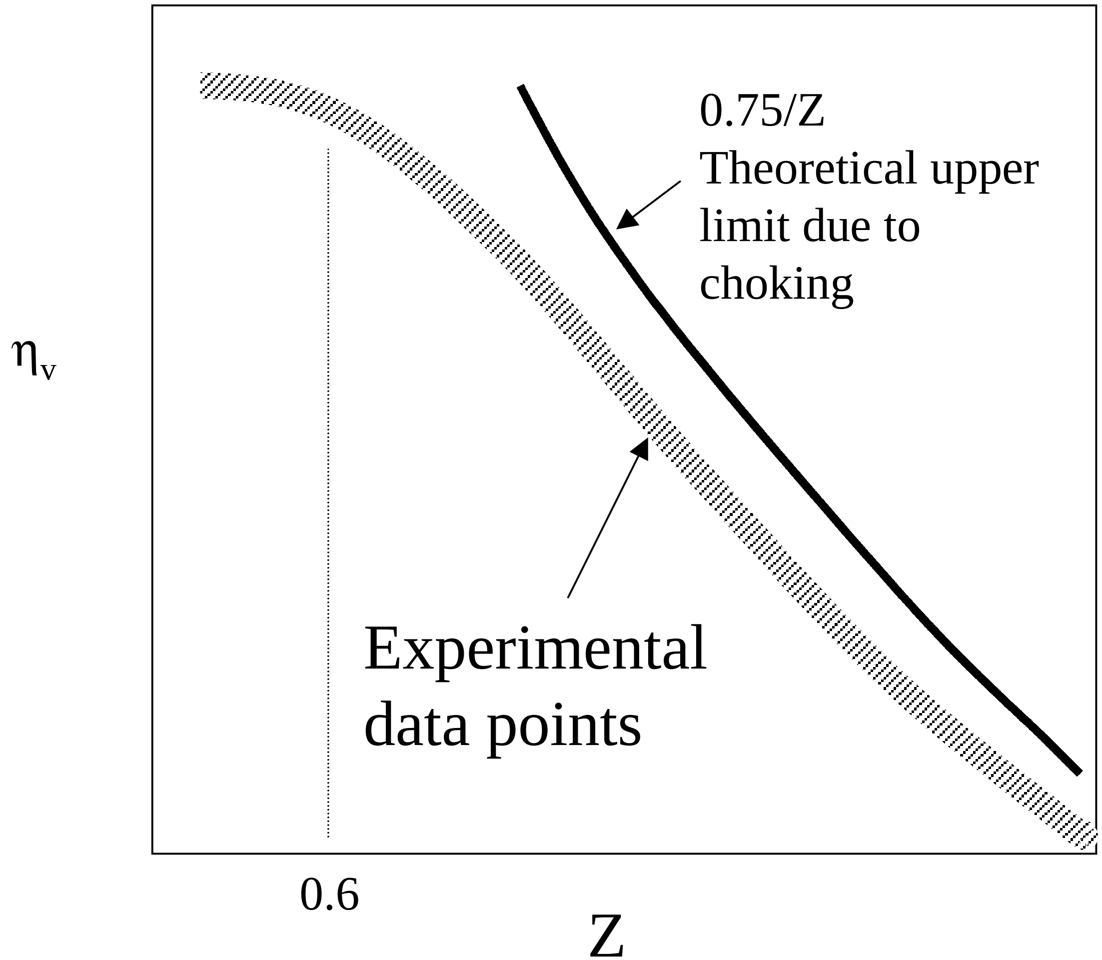
Using γ=1.4, the volumetric efficiency for a choked flow is

$$\left(\eta_{\mathrm{v}}\right)_{choked} = 0.58\left(\frac{\theta_{\mathrm{ic}} - \theta_{\mathrm{io}}}{\pi}\right)\frac{1}{Z}.$$

For an engine that $\left(\frac{\theta_{\mathrm{ic}} - \theta_{\mathrm{io}}}{\pi}\right)=1.3$, $\left(\eta_{\mathrm{v}}\right)_{choked} = \frac{0.75}{Z}$.

This represents an upper limit for the volumetric efficiency.

Volumetric Efficiency and Mach Index



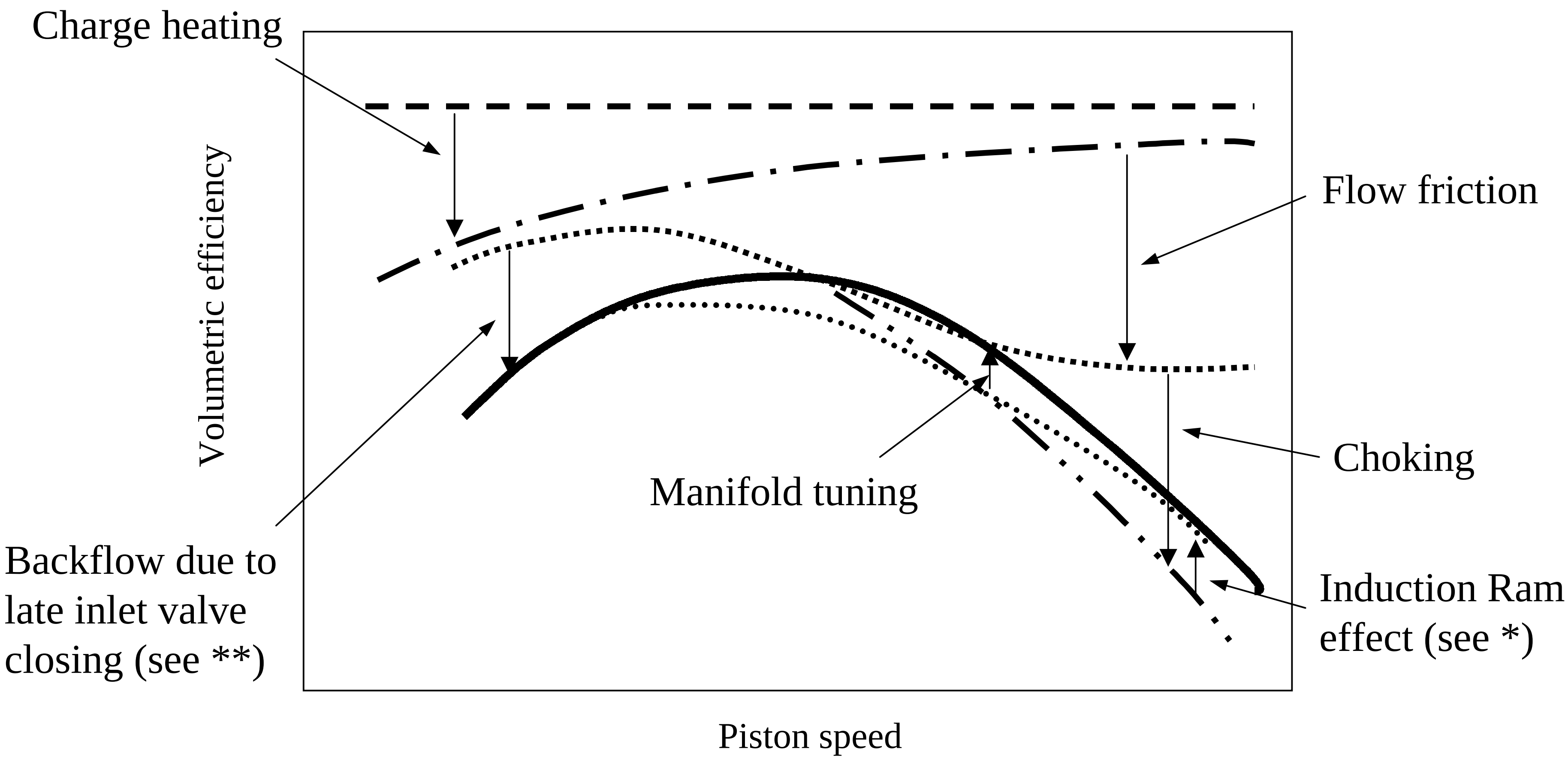
- Z>0.6, flow choked at the valve.
- $A_f > 1.3b^2(U_p/a_i)$
- Also note that, the intake and exhaust area can be related through their local speed of sound as

$$\frac{A_e}{A_i} \approx \frac{a_i}{a_e} = \left(\frac{T_i}{T_e}\right)^{1/2}.$$

Exhaust valves can be smaller than intake valves since exhaust gas has a higher local speed of sound.

Not as vulnerable to choking →

Effect on Volumetric Efficiency



* At high engine speeds, the inertia of the intake gas can assist to ram more gas into the cylinder, volumetric efficiency is increased by delaying the inlet valve closing

** On the other hand, at the low engine speeds, backflow can occur since the cylinder pressure increases as a result of upward piston movement, thus decreasing the volumetric efficiency.