Volumetric Efficiency of Engines

Dr. Md. Zahurul Haq, *Ph.D., CEA, FBSME, FIEB*

Professor
Department of Mechanical Engineering
Bangladesh University of Engineering & Technology (BUET)
Dhaka-1000, Bangladesh

zahurul@me.buet.ac.bd
http://zahurul.buet.ac.bd/

ME 417: Internal Combustion Engines

`http://zahurul.buet.ac.bd/ME417/`

Definitions/Terminology

- **Induction Process**: events that take place between inlet valve opening (IVO, θ_{vo}) and inlet valve closing (IVC, θ_{vc}).
- **Fresh Mixture**: new gases inducted into the engine cylinder through the inlet valve. These consist of air, water vapour, and fuel in carbureted engines and of air and water vapour only in Diesel and other fuel-injection engines. Subscript 'i' is used to refer to the fresh mixture, and subscript 'a' to refer to the air in the fresh mixture.
- **Residual Gas**: the gases left in the charge from the previous cycle. Subscript 'r' is used in referring to these gases.
- **Charge**: the contents of the cylinder after closing of all valves; the charge consists of the fresh mixture and the residual gases.

Volumetric Efficiency, η_v

Engine intake system – air filter, carburettor, and throttle plate (in a SIE), intake manifold, port, valve – restricts the amount of air which an engine can induct. The parameter used to measure the effectiveness of an engine's induction process is the **volumetric efficiency, η_v**.

$$\eta_v \equiv \frac{m_a}{\rho_{a,i} V_d} = \frac{\dot{m}_a}{\rho_{a,i} V_d} \frac{X}{N} = \frac{\dot{m}_a}{\rho_{a,i}} \frac{2X}{A_p \overline{S}_p} \qquad X = \begin{cases} 1 & \text{for 2s engine} \\ 2 & \text{for 4s engine} \end{cases}$$

m_a = mass of air inducted into the cylinder per cycle
$\dot{m}_a$ = air induction rate into the cylinder
N = engine speed, A_p = piston area, $\overline{S}_p$ = av. piston speed
V_d = engine displacement volume

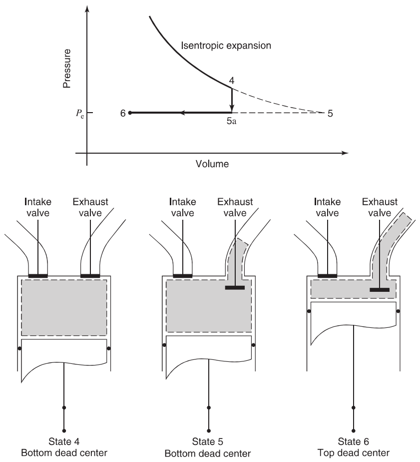
- If $\rho_{a,i} = \rho_{a,o}$ (atmospheric air density): $\Rightarrow \eta_v$ measures the pumping performance of the overall inlet system.
- If $\rho_{a,i}$ = inlet manifold air density: $\Rightarrow \eta_v$ measures the pumping performance of the cylinder, inlet port and valve alone.

Factors Affecting η_v

1. Fuel type, fuel/air ratio, fraction of fuel vaporized in the intake system, and fuel heat of vaporization
2. Mixture temperature as influenced by heat transfer
3. Ratio of exhaust to inlet manifold pressures
4. Compression ratio
5. Engine speed
6. Intake and exhaust manifold and port design
7. Intake and exhaust valve geometry, size, lift, and timings

Some of the variables are essentially **quasi steady in nature**, or **dynamic in nature** (i.e. their effects depend on the unsteady flow and pressure wave phenomena that accompany the time-varying nature of the gas exchange processes.)

Exhaust Stroke & Residual Mass



T510

Control mass is shaded

- $P_e \equiv$ exhaust gas pressure
- $T_e \equiv$ exhaust gas temperature
- $f_r \equiv$ residual gas fraction

$$\boxed{T_e = T_4 \left(\frac{P_e}{P_4}\right)^{\frac{k-1}{k}}}$$

$$\boxed{f_r = \frac{1}{r}\left(\frac{P_e}{P_4}\right)^{\frac{1}{k}}}$$

Valve Flow & Discharge Coefficients

- Mass flow rate through a Poppet valve is usually described by the equation for compressible flow through a flow restriction:

$$\dot{m} = \rho_o c_o A_E \left(\frac{P_T}{P_o}\right)^{1/k} \left[\frac{2}{k-1}\left\{1 - \left(\frac{P_T}{P_o}\right)^{(k-1)/k}\right\}\right]^{1/2}$$

Upstream stagnation pressure $\equiv P_o$, temperature $\equiv T_o$, density $\equiv \rho_o$ and sound speed $\equiv c_o = \sqrt{kRT_o}$; and static pressure just downstream of the flow restriction $\equiv P_T$.

- For flow into the cylinder through an intake valve:
  - P_o = the intake system pressure, P_i
  - P_T = the cylinder pressure.
- For flow out of the cylinder through an exhaust valve,
  - P_o = the cylinder pressure
  - P_T = the exhaust system pressure.

- **Choked flow** occurs at a valve throat if

$$\frac{P_{up}}{P_{down}} \geqslant \left(\frac{P_{up}}{P_{down}}\right)_{cr} = \left(\frac{k+1}{2}\right)^{k/(k-1)} = 1.86 \quad \text{if } k = 1.35$$

- For choked flow, valve static pressure, P_T depends on P_o and independent of downstream pressure. Choked flow rate, $\dot{m}_{cr}$ is

$$\dot{m}_{cr} = \rho_o c_o A_C C_D \left(\frac{2}{k+1}\right)^{(k+1)/2(k-1)}$$

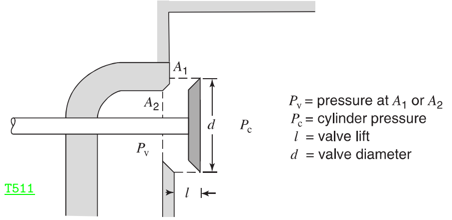
▷ Estimate the maximum flow rate through an exhaust valve, if the valve curtain area is $2.7 \times 10^{-3}\text{m}^2$, the valve C_D is 0.6 and cylinder pressure and temperature are 500 kPa and 1000 K. Assume that exhaust system pressure is 105 kPa, $k = 1.35$, and $R = 287$ J/kg K.

$\Rightarrow \frac{P_{up}}{P_{down}} = \frac{500}{105} = 4.76 > 1.86$: choked flow.

$\Rightarrow \rho_o = \frac{P_o}{RT_o} = \frac{500\times10^3}{287\times1000} = 1.74 \text{ kg/m}^3$

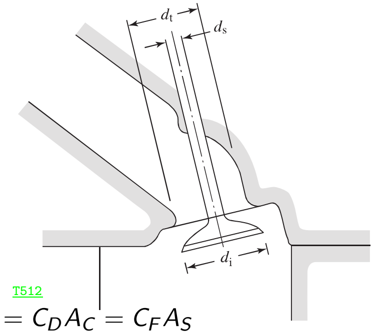
$\Rightarrow c_o = \sqrt{kRT_o} = \sqrt{1.35 \times 287 \times 1000} = 622.45 \text{ m/s}$

$\Rightarrow \dot{m}_{cr} = \rho_o c_o A_C C_D \left(\frac{2}{k+1}\right)^{(k+1)/2(k-1)} = 1.02 \text{ kg/s} \lhd$



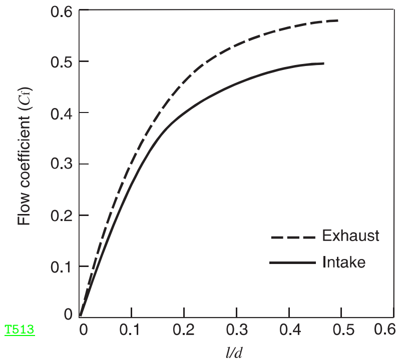
P_v = pressure at A_1 or A_2
P_c = cylinder pressure
l = valve lift
d = valve diameter

T511



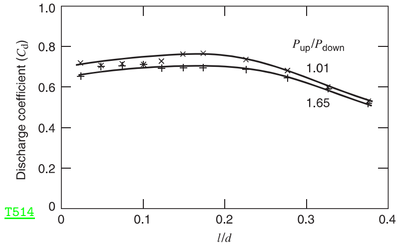
T512

- Effective area of valve assembly, $A_E = C_D A_C = C_F A_S$
- Valve curtain area, $A_C = \pi D_v L_v$, C_D = discharger coefficient and its value is not a strong function of lift.
- Valve seat area, $A_S = (\pi/4)D_v^2$, C_F = flow coefficient.
- L_v is valve lift, D_v is valve diameter. Typical maximum values of L_v/D_v are 0.25.



T513

Intake & exhaust port flow coefficients



T514

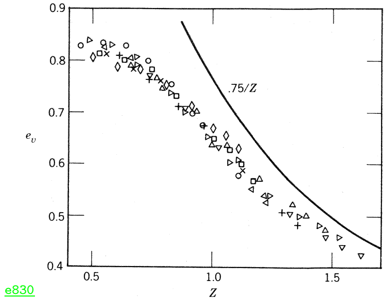
Coefficient of discharge of intake & exhaust ports

Effect of IVO/IVC & Engine Speed on η_v

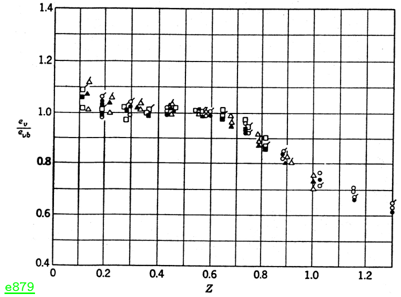
- Mass induced during valve open time, $m_i = \dfrac{1}{\omega}\displaystyle\int_{\theta_{io}}^{\theta_{ic}} \dot{m}\, d\theta$
- Average effective intake flow area, $\overline{A}_E \equiv \dfrac{1}{\theta_{ic}-\theta_{io}}\displaystyle\int_{\theta_{io}}^{\theta_{ic}} A_E\, d\theta \equiv \overline{C}_D A_C$
- Inlet valve **Mach Index**, $Z \equiv \frac{A_P}{\overline{A}_E}\frac{\overline{S}_p}{c_i}$
- Volumetric efficiency, $\eta_v = \dfrac{m_i}{\rho_i V_d} = \dfrac{1}{\omega \rho_i V_d}\displaystyle\int_{\theta_{io}}^{\theta_{ic}} \dot{m}\, d\theta$
- In a limiting case in which flow is always choked:

$$\eta_v = \frac{\overline{A}_E c_i}{\omega V_d}(\theta_{ic}-\theta_{io})\left(\frac{2}{k+1}\right)^{(k+1)/2(k-1)} \qquad \text{for choked condition}$$

$\Rightarrow \eta_v = 0.58\left(\frac{\theta_{ic}-\theta_{io}}{\pi}\right)\frac{1}{Z}$ for $k = 1.4$



e830



e879

If $(\theta_{ic}-\theta_{io})/\pi = 1.3$, $e_v = 0.75/Z$

$e_{vb} = e_v(Z = 0.5)$

⊞ The Mach index is not a parameter that characterizes the actual gas speed; rather, it characterizes what the average gas speed through the inlet valve would have to be to realize complete filling of the cylinder gas at that particular piston speed. The Mach number for that average inlet gas speeds would be $Z/0.58$ for $k = 1.4$.

Sizing of Intake & Exhaust Valves

- For good volumetric efficiency, $Z \leqslant 0.6$: the average gas speed through the inlet valve should be less than the sonic velocity, so that the intake flow is not choked.
- If $Z = 0.6$, average effective area of intake valves, $\overline{A}_i$ is

$$\overline{A}_i \geqslant 1.3 b^2 \frac{\overline{S}_p}{c_i} \qquad \overline{S}_p = 2sN$$

b = engine bore, s = stroke and N = engine speed in rev/s.

- If $Z = 0.6$, average effective area of exhaust valves, $\overline{A}_e$ is

$$\frac{\overline{A}_e}{\overline{A}_i} \simeq \frac{c_i}{c_e} = \sqrt{\frac{T_i}{T_e}}$$

- A smaller exhaust valve diameter and lift ($L_v \sim D_v/4$) can be used because of the speed of the sound is higher in the exhaust gases than in the inlet gas flow.
- Current practice dictates: $\overline{A}_e/\overline{A}_i \simeq 0.7$ to 0.8.

Example: Intake Valve Sizing

▷ What is the intake valve area $\overline{A}_i$ and the ratio of intake valve area to piston area required for a Mach index of 0.6 for an engine with a maximum speed of 8000 rpm, bore and stroke of 0.1 m, and inlet air temperature of 330 K? Assume, $k = 1.4$, $R = 287$ J/kg K and average flow coefficient, $\overline{C}_F = 0.35$.

$\Rightarrow$ $\overline{S}_p = 2sN = 2 \times 0.1 \times (8000/60) = 26 \text{ m/s}$

$\Rightarrow$ $c_i = \sqrt{kRT_o} = \sqrt{1.4 \times 287} = 364 \text{ m/s}$

$\Rightarrow$ $\overline{A}_i = 1.3b^2\overline{S}_p/c_i = 1.3 \times (0.1)^2 \times 26/364 = 9.3 \times 10^{-3} \text{ m}^2 \lhd$

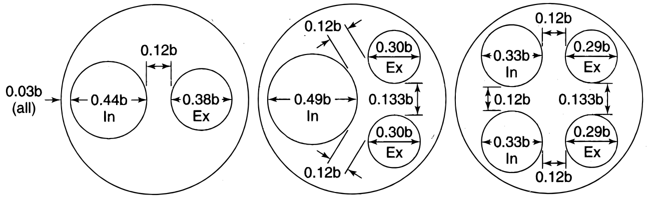
$\Rightarrow$ $\overline{A}_i = \overline{C}_F A_v \rightsquigarrow A_v = 2.65 \times 01^{-3} \text{ m}^2$

$\Rightarrow$ $\overline{A}_p = (\pi/4)b^2 = (\pi/4)(0.1)^2 = 7.85 \times 10^{-3} \text{ m}^2$

$\Rightarrow$ $A_v/\overline{A}_p = 2.65/7.86 = 0.34 \lhd$

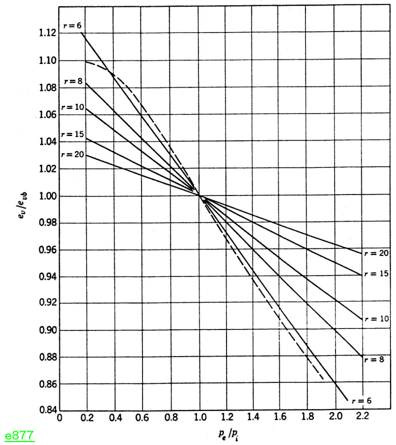
Homework Problems

- ▷ If an engine has a bore of 0.1 m, stroke of 0.08 m, inlet flow effective area of $4.0 \times 10^{-4}\text{m}^2$ and inlet temperature of 320 K, what is the maximum speed it is intended to be operated while maintaining good volumetric efficiency? (4137 rpm) ◁
- ▷ Calculate the ratios of the inlet valve area to piston area for the 3 configurations as shown in Figure below. If the Mach index in case is held to $Z_i = 0.6, c_i = 400 \text{ m/s}, \overline{A}_i = 0.35n_i(\pi/4)d_i^2(n_i =$ number of intake valves), what is the maximum piston speed in each case?



e896

Effect of (P_i/P_e) & Compression Ratio (r_c)



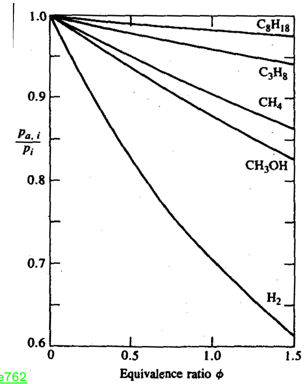
e877

$$\boxed{\eta_v/\eta_{vb} = 1.0 - \frac{1}{k}\left[\frac{P_e/P_i - 1}{r_c - 1}\right]}$$

$\eta_{vb} = \eta_v(P_e/P_i = 1.0)$

As values of P_e/P_i and r_c are varied, the fraction of the cylinder volume occupied by the residual gas at the intake pressure varies. As this volume increases so the e_v decreases.

Effect of Fuel, Phase and Humidity



e762

Presence of gaseous fuel & water vapour in the intake system reduces the air partial pressure below the mixture pressure.

$$P_i = P_{a,i} + P_{f,i} + P_{w,i}$$

$$\frac{P_{a,i}}{P_i} = \left[1 + \left(\frac{\dot{m}_f}{\dot{m}_a}\right)\left(\frac{M_a}{M_f}\right) + \left(\frac{\dot{m}_w}{\dot{m}_a}\right)\left(\frac{M_a}{M_w}\right)\right]^{-1}$$

$$\frac{P_{a,i}}{P_i} = \left[1 + (F/A)\left(\frac{M_a}{M_f}\right) + 1.6\left(\frac{\dot{m}_w}{\dot{m}_a}\right)\right]^{-1}$$

Correction for water vapour is small $\leqslant 0.03$.

For conventional liquid fuels such as gasoline the effect of fuel vapour (and humidity) is small. For gaseous fuels and for methanol vapour, η_v is significantly reduced by the fuel vapour in the intake mixture.

Effect of Fuel Vaporization & Heat Transfer

- If no heat transfer to mixture, mixture temperature decreases as liquid fuel is vaporized. For complete evaporation of iso-octane, with $\phi = 1.0$, $T_2 - T_1 = -19^\circ$C. For methanol, temperature depression is -128°C.
- In practice, heating occurs; also, fuel is not completely vaporized prior to entry to the cylinder.
- Experimental data show that decrease in T_i due to fuel evaporation more than offsets the reduction in $P_{a,i}$ due to the increased amount of fuel vapour: for same heating rate, η_v with fuel vaporization is higher by a few percent.

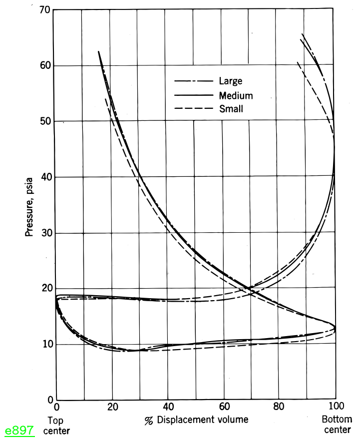
Similitude in Air System Design

Similar engines: engines which have the following characteristics:

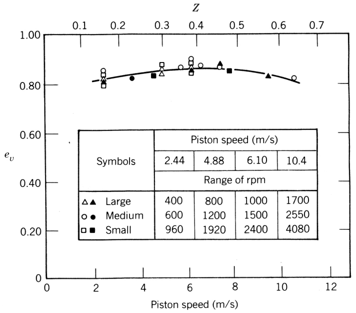
- All design ratios are the same. Similar engines are built from the same set of detail drawings, only the scale of the drawings is different for each engine.
- The same materials are used in corresponding parts. For example, in the MIT similar engines all the pistons are of same aluminium alloy and all crankshafts are of the same steel alloy.

Similar engines running at the same values of mean piston speed and at the same inlet and exhaust pressures, inlet temperature, coolant temperature, and fuel-air ratio will have the similar volumetric efficiency within measurable limits.

Effect of Engine Size & Speed



e897



Symbols	Piston speed (m/s)			
	2.44	4.88	6.10	10.4
	Range of rpm			
△▲ Large	400	800	1000	1700
○● Medium	600	1200	1500	2550
□■ Small	960	1920	2400	4080

e880

▶ No significant difference in η_v between three engines at a given value of Z, in spite of the fact that the Reynold's numbers are different in the proportion of 2.5, 4 & 6.

Effect of Inlet Charge & Coolant Temperatures

- **Effect of Inlet Charge Temperature (T_i)**:

$$\frac{\eta_v}{\eta_{vb}} = \sqrt{\frac{T_i}{330}}$$

$\eta_{vb} = \eta_v$ (at baseline temperature, $T_i = 330$ K).

- **Effect of Coolant Temperature (T_c)**:

$$\frac{\eta_v}{\eta_{vb}} = \sqrt{\frac{1450}{T_c + 1110}}$$

$\eta_{vb} = \eta_v$ (at baseline temperature, $T_c = 340$ K).

Dimensional Analysis

$$\eta_v = \eta_v(P_e/P_i, r_c, T_i, T_c, Z, \phi, \cdots)$$

$$\eta_v = \eta_{vb} \prod_{i=1}^{N} K_i$$

where, η_{vb} are baseline volumetric efficiency obtained for the set of operation parameters:

1. $P_e/P_i \Rrightarrow K_1 = 1.0 - \frac{1}{k}\left[\frac{P_e/P_i - 1}{r_c - 1}\right]$
2. $T_i \Rrightarrow K_2 = \sqrt{\frac{T_i}{330}}$
3. $T_c \Rrightarrow K_3 = \sqrt{\frac{1450}{T_c + 1110}}$
4. $\vdots$

▶ Dimensional analysis is used <u>only</u> to assess the effect of a parameter qualitatively.