Volumetric Efficiency of Engines

Dr. M. Zahurul Haq

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

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

ME 401: Internal Combustion Engines

Valve Flow & Discharge Coefficients

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

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

Hence, upstream stagnation pressure \( P_o \), temperature \( T_o \), density \( \rho_o \) and sound speed \( c_o = \sqrt{\gamma R T_o} \), and static pressure just downstream of the flow restriction \( P_T \).

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.

Example: Maximum Flow Through a Valve

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

\[ \frac{P_o}{P_{down}} = \frac{500}{105} = 4.76 > 1.86: \text{ choked flow.} \]
\[ \rho_o = \frac{P_o}{\gamma R T_o} = \frac{500 \times 10^3}{287 \times 1000} = 1.74 \text{ kg/m}^3 \]
\[ c_o = \sqrt{\gamma R T_o} = \sqrt{1.35 \times 287 \times 1000} = 622.45 \text{ m/s} \]
\[ \dot{m}_{cr} = \rho_o c_o A_C C_D \left( \frac{2}{\gamma + 1} \right)^{(\gamma + 1)/(\gamma - 1)} = 1.02 \text{ kg/s} \]
Definitions/Terminology

- **Induction Process**: the events that take place between inlet valve opening ($\theta_{vo}$) and inlet valve closing ($\theta_{vc}$).
- **Fresh Mixture**: the new gases introduced to the engine cylinder through the inlet valve. These gases 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 in referring to the fresh mixture, and subscript ‘a’ in referring to the air in the fresh mixture.
- **Charge**: the contents of the cylinder after closing of all valves; the charge consists of the fresh mixture and the residual gases.
- **Residual Gas**: the gases left in the charge from the previous cycle. Subscript ‘r’ is used in referring to these gases.

### $e_v$ of an Ideal Cycle

**Throttled constant volume cycle**  
**Supercharged constant volume cycle**

$$e_v = \frac{m_a}{\rho_{a,o} V_d} = \frac{m(1 - x_r)}{\rho_{a,o}[1 + (F/A)]} \frac{r_c}{(r_c - 1) V_1}$$

$$e_v = \left[ \frac{M}{M_a} \right] \left( \frac{P_1}{P_{a,o}} \right) \left( \frac{T_{a,o}}{T_1} \right) \frac{1}{1 + (F/A)} \left[ \frac{r_c}{r_c - 1} - \frac{1}{\gamma(r_c - 1)} \left( \frac{P_1}{P_{a,o}} \right)^\gamma (\gamma - 1) \right]$$

- For $(P_1/P_{a,o}) = 1$, the term in brackets $= 1$.0.
- $x_r$ = residual gas fraction.
- For ideal case: $e_v \sim (T_{a,o}/T_1)$; Actual engine: $e_v \sim \sqrt{(T_{a,o}/T_1)}$

### Factors Affecting $e_v$

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 (i.e. their impact is either independent of speed or can be described adequately in terms of mean engine speed), 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.)
Effect of IVO/IVC & Engine Speed on $e_v$

- Mass induced during valve open time, $m_i = \frac{1}{\omega} \int_{\theta_{i_0}}^{\theta_{i_c}} \dot{m} d\theta$
- Average effective intake flow area, $\overline{A_i} = \frac{1}{\theta_{i_c} - \theta_{i_0}} \int_{\theta_{i_0}}^{\theta_{i_c}} A_i d\theta = C_D A_C$
- Mean Mach number at inlet throat, $Z = \frac{A_P}{\overline{A_i}} \frac{\overline{S_p}}{c_i}$
- Volumetric efficiency, $e_v = \frac{m_i}{\rho_i V_d} = \frac{1}{\omega \rho_i V_d} \int_{\theta_{i_0}}^{\theta_{i_c}} \dot{m} d\theta$
- In a limiting case in which flow is always choked:
  
  $e_v = \frac{\overline{A_e} c_i}{\omega V_d} (\theta_{i_c} - \theta_{i_0}) \left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/2(\gamma-1)}$ for choked condition
  
  $\Rightarrow e_v = 0.58 \left(\frac{\theta_{i_c} - \theta_{i_0}}{\pi}\right) \frac{1}{Z}$ for $\gamma = 1.4$

For good volumetric efficiency, $Z \leq 0.6$: 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
  
  $\overline{A_i} \geq 1.3 b^2 \overline{S_p} \frac{c_i}{c_e} \quad \overline{S_p} = 2sN$

  $b =$ 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.

If $(\theta_{i_c} - \theta_{i_0})/\pi = 1.3$, $e_v = 0.75/Z$

$e_{vo} = e_v(Z = 0.5)$ 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 $\gamma = 1.4$.

Example: Intake Valve Sizing

What is the intake valve area $\overline{A}$, 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, $\gamma = 1.4, R = 287$ J/kg K and average flow coefficient, $C_F = 0.35$.

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

$\Rightarrow c_i = \sqrt{\gamma R T_i} = \sqrt{1.4 \times 287} = 364$ m/s

$\Rightarrow \overline{A_i} = 1.3 b^2 \overline{S_p}/c_i = 1.3 \times (0.1)^2 \times 26/364 = 9.3 \times 10^{-3}$ m$^2$ <

$\Rightarrow \overline{A_i} = C_F A_v \Rightarrow A_v = 2.65 \times 01^{-3}$ m$^2$

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

$\Rightarrow A_v/\overline{A_p} = 2.65/7.86 = 0.34 <$
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 $Z_i = 0.6$, $c_i = 400 \text{ m/s}$, $A_i = 0.35n_i(\pi/4)d_i^2$ ($n_i$ = number of intake valves), what is the maximum piston speed in each case?

![Figure showing valve configurations](image)

Volumetric Efficiency | Factors Affecting $\epsilon_v$
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Effect of Fuel, Humidity, Phase and Equiv. Ratio ($\phi$)

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

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

$$P_{a,i} = 1 + \left( \frac{m_f}{m_a} \right) \left( \frac{M_f}{M_a} \right)$$

$$P_{f,i} = 1 + (F/A) \left( \frac{M_f}{M_a} \right) + 1.6 \left( \frac{m_f}{m_a} \right)$$

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

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

Effect of Fuel Vaporization & Heat Transfer

▶ For constant pressure steady-state flow with liquid fuel evaporation ($x_e$) and heat transfer:

$$T_2 - T_1 \approx \frac{x_e (F/A) h_{fuel,fg} - (\dot{Q}/m_a)}{c_{p,a} + (F/A) c_{fuel,f}}$$

▶ If no heat transfer to mixture, mixture temperature decreases as liquid fuel is vaporized. For complete evaporation of iso-octane, with $\phi = 1.0$, $T_2 - T_1 = -19^\circ\text{C}$. For methanol, temperature depression is $-128^\circ\text{C}$.

▶ 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, $e_v$ with fuel vaporization is higher by a few percent.
Similitude in Air System Design

By similar engines is meant 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 same volumetric efficiency within measurable limits.

Effect of Engine Size & Speed

No significant difference in $e_v$ 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 ($T_i$):**
  
  $$
  \frac{e_v}{e_{vb}} = \sqrt{\frac{T_i}{330}}
  $$
  
  $e_{vb} = e_v$ (at baseline temperature, $T_i = 330$ K).

- **Effect of Coolant Temperature ($T_c$):**
  
  $$
  \frac{e_v}{e_{vb}} = \sqrt{\frac{1450}{T_c + 1110}}
  $$
  
  $e_{vb} = e_v$ (at baseline temperature, $T_c = 340$ K).

Dimensional Analysis

$$
e_v = e_v \left( \frac{P_e}{P_i}, r_c, T_i, T_c, Z, \phi, \cdots \right)
$$

$$
e_v = e_{vb} \prod_{i=1}^{N} K_i
$$

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

- $P_e/P_i : \Rightarrow K_1 = 1.0 - \frac{1}{\gamma} \left[ \frac{P_e}{P_i} - 1 \right]$
- $T_i : \Rightarrow K_2 = \sqrt{\frac{T_i}{330}}$
- $T_c : \Rightarrow K_3 = \sqrt{\frac{1450}{T_c + 1110}}$
- $\cdots$