Gas exchange Processes

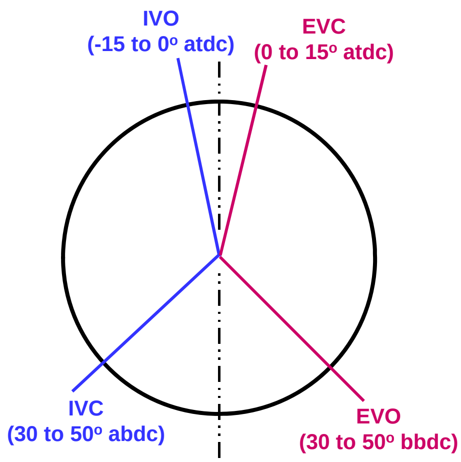
To move working fluid in and out of engine

- Engine performance is air limited
- Engines are usually optimized for maximum power at high speed

Considerations

- 4-stroke engine: volumetric efficiency
- 2-stroke engine: scavenging/ trapping efficiency
- Charge motion control; tuning; noise

Typical valve timing diagram

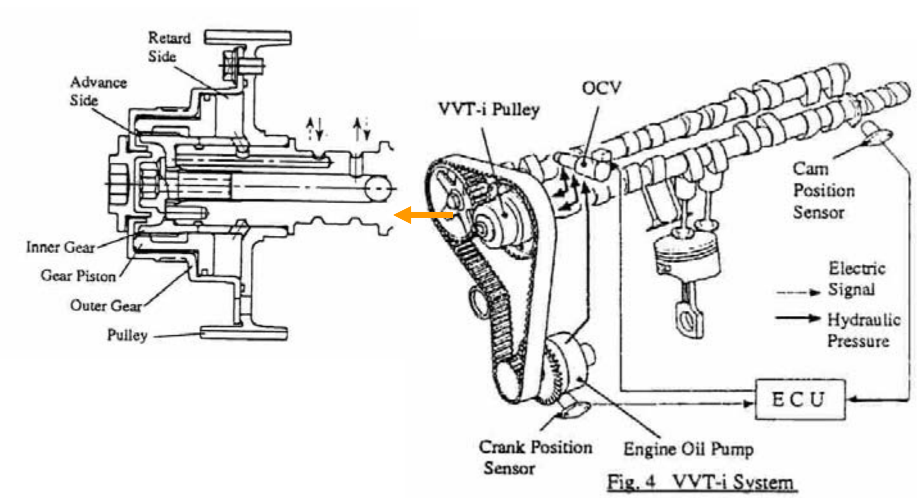


- Early EVO
  - Facilitates exhaust gas outflow via blow down
  - Incomplete expansion
- Late IVC
  - High speed: ram effect augments induction
  - Low speed: air loss by displacement flow
  - Lower effective compression ratio

Note that for typical passenger car engine, max piston speed is at ~70º from TDC

VVT technology –cam shifter

Toyota VVT-i
(SAE Paper 960579)



Volumetric efficiency: quasi-static effects

- Residual gas
  - Affected by:
    - Compression ratio
    - Exhaust gas temperature
    - Exhaust to intake pressure ratio
  - Impact:
    - Volumetric efficiency
    - Charge composition
    - Charge temperature

Volumetric efficiency: quasi-static effects
(cont.)

- Evaporative cooling effect
  - Higher charge density increases volumetric efficiency
  - Adiabatic evaporation in air to form λ=1 mixture:
    - Iso-octane: ΔT = -19°C
    - Ethanol: ΔT = -80°C
    - Methanol: ΔT = -128°C

    From both higher latent heat, lower LHV, and lower stoichiometric air/fuel ratio (Ethanol, Methanol)
  - In practice, most heat from the wall unless direct injection is used

Volumetric efficiency: quasi-static effects
(cont.)

- Air displacement by fuel and water vapor

$$\tilde{x}_a = \frac{p_{a,i}}{p_i}$$

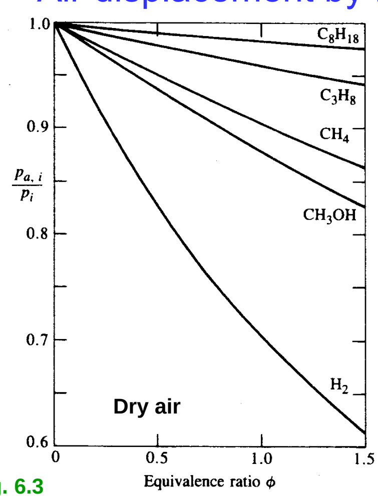


Fig. 6.3

V_i is volume inducted

P_i is intake pressure

$$m_a = \left(\frac{P_i V_i}{\tilde{R}T}\right)\tilde{x}_a W_a$$

$$\tilde{x}_a + \tilde{x}_f + \tilde{x}_w = 1$$

$$\tilde{x}_a = \frac{1}{1 + \frac{\tilde{x}_f}{\tilde{x}_a} + \frac{\tilde{x}_w}{\tilde{x}_a}}$$

$$= \frac{1}{1 + \frac{m_f}{m_a}\frac{W_a}{W_f} + \frac{\tilde{x}_w}{\tilde{x}_a}}$$

Volumetric Efficiency: dynamic effects

Friction

– Component i pressure drop due to friction:

- Vi = Fluid velocity
- ξ_i = Loss coefficient

$$\Delta P_i = \xi_i \rho v_i^2$$

Scaling:

$$v_i \propto S_P \frac{A_P}{A_i}; \quad \xi_i \propto \frac{\ell}{D_i}$$

$$\Delta P_i \sim \rho S_P^2 \frac{1}{A_i^{2.5}} \text{ or } \propto \rho S_P^2 \frac{1}{D_i^5}$$

Flow loss in gas exchange process

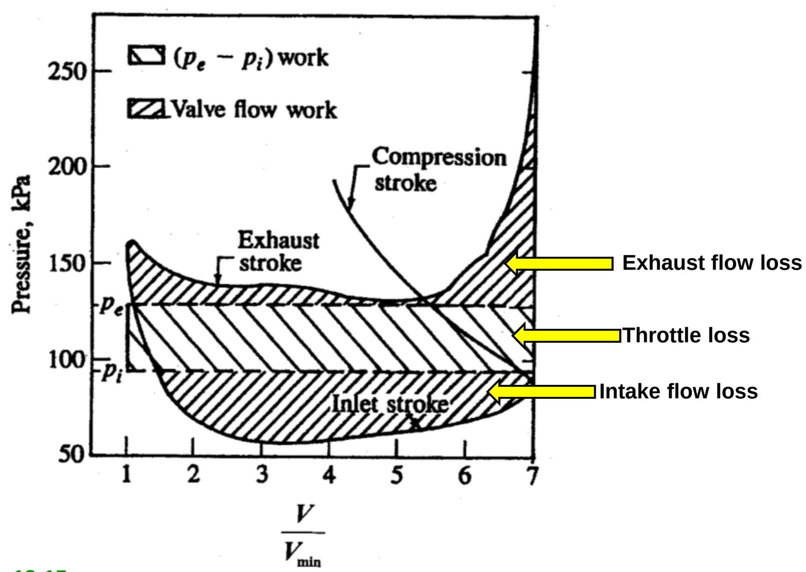


Fig. 13-15

Volumetric Efficiency: dynamic effects cont.

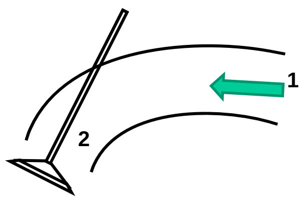
Ram effect

- Due to fluid inertia
- Intake and exhaust flow both exhibit effect

$$\Delta P = p_2 - p_1 = -\rho \int \frac{d\underline{u}}{dt} \cdot d\underline{\ell}$$

$$\sim \rho \frac{S_P}{\frac{1}{2N}} \left(\frac{A_P}{A_{intake}} \right) \ell$$

$$= \rho S_P^2 \left(\frac{A_P}{A_{intake}} \right) \frac{\ell}{L}$$

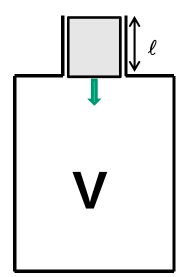


S_P **Mean piston speed**
ℓ **Runner length**
L **Stroke**

Volumetric Efficiency: dynamic effects cont.

Tuning

- Helmholtz frequency $N = \frac{a}{2\pi} \sqrt{\frac{A}{\ell V}}$



- a sound velocity
- ℓ runner length
- V volume

- Application:
  - V taken as $V_t/2$
  - Correction factor k=2

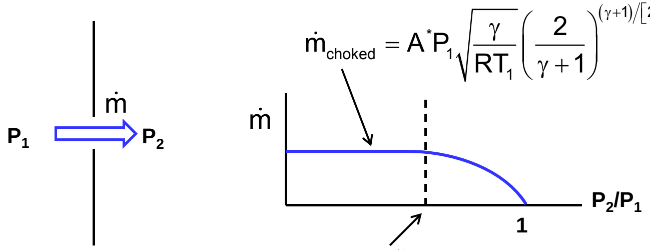
$$N = \frac{a}{2\pi} \sqrt{\frac{A}{\ell V}} \frac{1}{K}$$

Volumetric Efficiency: dynamic effects cont.

Choking effect

– Velocity becomes sonic at "throat"

$$\dot{m}_{choked} = A^{*}P_1\sqrt{\frac{\gamma}{RT_1}}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/[2(\gamma-1)]}$$



$$\left(\frac{P_2}{P_1}\right)_{critical} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}$$

$= 0.528$ for $\gamma = 1.4$; increases with γ

Volumetric Efficiency: dynamic effects cont.

Overlap back flow

– Back flow of burned gas from exhaust/cylinder to intake port

– Increases residual gas fraction

– Prominent at low speed and load

Heat transfer

– Loss in η_v because intake charge is heated up by the hot walls

– Prominent at low speed because of longer time (overrides lower rate)

Volumetric efficiency: summary

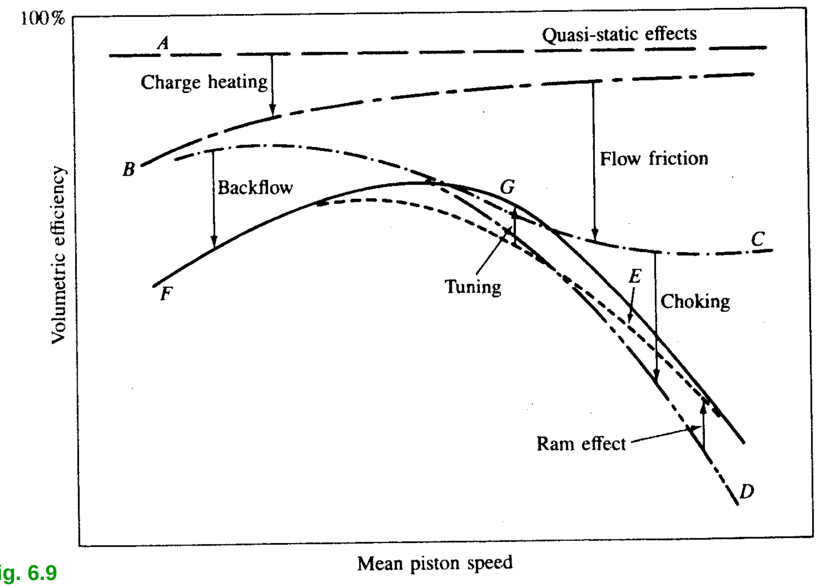


Fig. 6.9

2-Stroke engine gas exchange

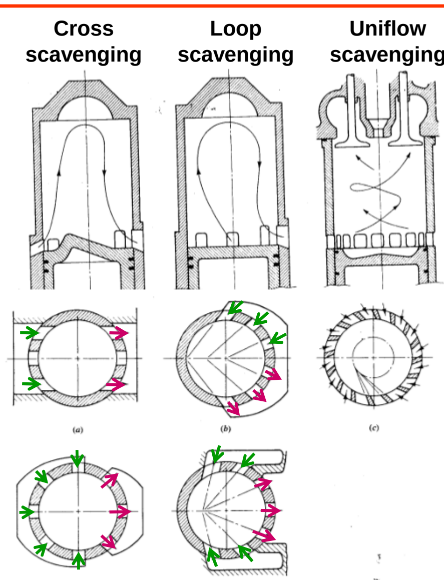
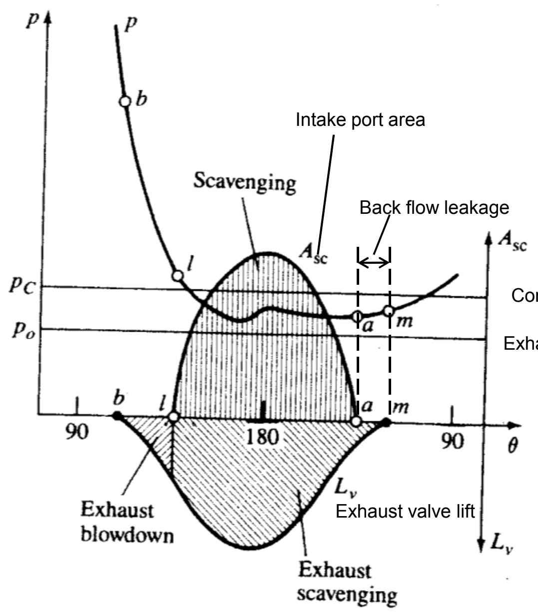


Fig. 6-23 & 24



Uniflow scavenging process

2-Stroke engine gas exchange

Delivery ratio $\Lambda = \dfrac{\text{Air mass delivered per cycle}}{\rho_{a,0} V_D}$

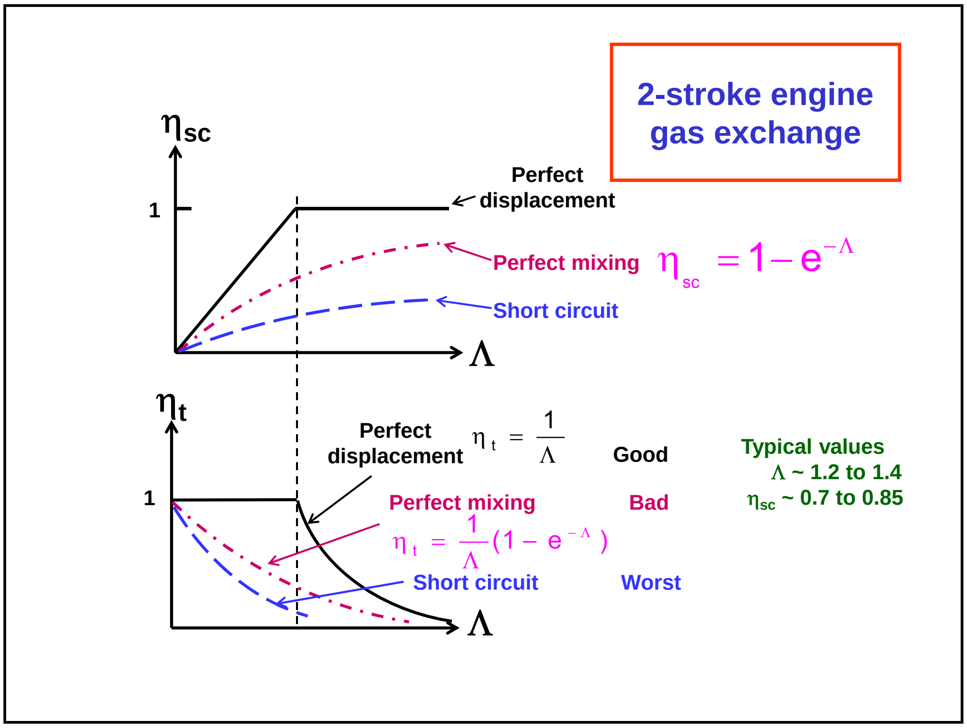
Trapping efficiency $\eta_t = \dfrac{\text{Air mass retained}}{\text{Air mass delivered}}$

Air mass retained

$$m_a = \rho_{a,0} V_D \Lambda \eta_t$$

Scavenging ratio $\eta_{sc} = \dfrac{\text{Air mass retained}}{\text{Trapped charge mass}}$

$1 - \eta_{sc}$ is the fraction of previous cycle charge that remains


2-stroke engine gas exchange
ηsc
1
Perfect displacement
Perfect mixing
$\eta_{sc} = 1 - e^{-\Lambda}$
Short circuit
Λ
ηt
1
Perfect displacement
$\eta_t = \frac{1}{\Lambda}$
Good
Perfect mixing
$\eta_t = \frac{1}{\Lambda}(1 - e^{-\Lambda})$
Bad
Short circuit
Worst
Λ
Typical values
Λ ~ 1.2 to 1.4
ηsc ~ 0.7 to 0.85