

## Chapter 1

### ENGINE TYPES AND THEIR OPERATION

#### 1.1

Piston: Transmit the gas pressure force to the connecting rod; seal the cylinder (with piston rings); compress the fuel-air mixture prior to combustion; draw in fresh mixture, expel burned gases (4-stroke cycle).

Connecting rod: Transform the rotating motion of crank to reciprocating motion of piston; transmit forces from crank to piston and piston to crank.

Crankshaft: Transmit the usable mechanical power; crank throws with connecting rods convert reciprocating motion of piston to rotating motion.

Cams and camshaft: Open and close the valves (inlet and exhaust) at appropriate times in the cycle, via the lifters and rocker arms. Camshaft driven off crankshaft.

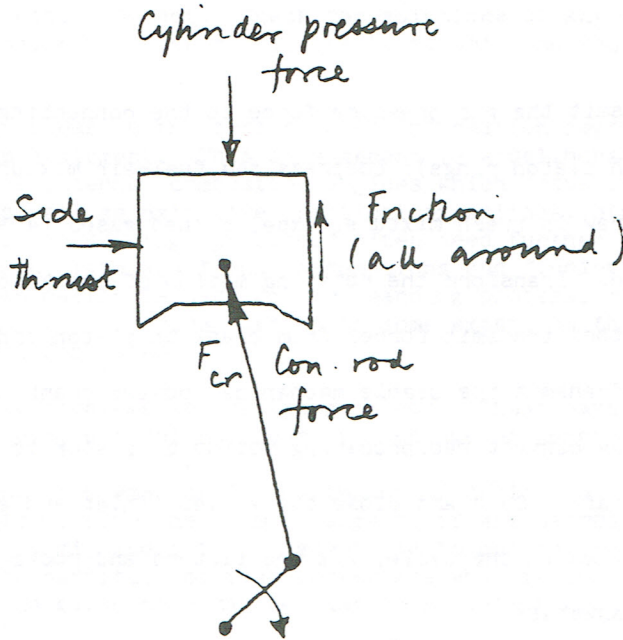
Valves: Control the flow of gas into and out of the cylinder.

Intake manifold: Direct approximately equal masses of air (and in some cases fuel) to each cylinder; in SI engines acts as a sub-atmospheric pressure plenum to reduce engine load below WOT levels.

Exhaust manifold: Collect exhaust gases from individual cylinders and feed to common pipe which contains muffler (and sometimes catalytic converter).

1.2

Note: piston accelerating towards crankshaft axis.



1.3

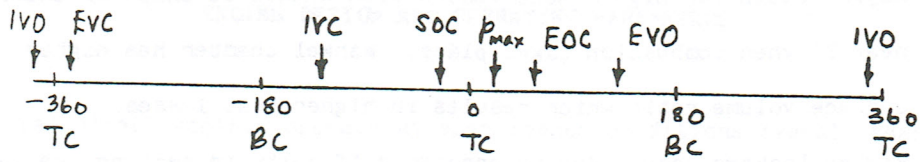
Spark-ignition

Diesel

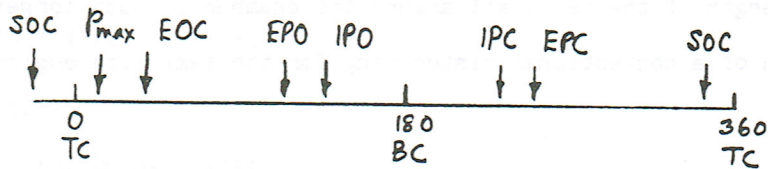
1. Premixed charge drawn into cylinder; mixture prepared in intake system.
2. Spark-ignition of fuel-air mixture.
3. Load reduced by throttling air and fuel.
4. Fuel: gasoline. Volatile, does not spontaneously ignite easily.
5. Lower compression ratio (~10) due to knock limits.
6. Lighter construction since pressure forces lower and less durability required.
7. Only turbocharged in high performance applications.

- Air drawn in; fuel injection into cylinder just before combustion.
- Spontaneous ignition of fuel-air mixture.
- Load reduced by reducing fuel injected per cycle: no throttling.
- Fuel: distillate oil. Must ignite easily at high temperatures.
- Higher compression ratio (15 to 22); not knock limited.
- Heavier construction; higher forces and durability more important.
- Usually turbocharged (except in smaller sizes) to increase power.

#### 1.4 (a) 4-stroke cycle



#### (b) 2-stroke cycle



1.5 Intake and exhaust strokes of four-stroke cycle are much more effective at removing the burned gases from the cylinder and filling the cylinder volume with fresh fuel-air mixture than is two-stroke cycle scavenging process. Hence, full load four-stroke cycle cylinder pressures are substantially higher than two-stroke cycle pressures. Also, power is required to boost scavenging air (mixture) pressure prior to entry to cylinder.

#### 1.6

- (1) With multicylinder engine, more firing strokes per crank revolution hence smoother output torque versus time.
- (2) Forces on each piston, connecting rod, etc. reduced with multicylinder engine.
- (3) Inertia forces that result from the acceleration and deceleration of piston (and connecting rod) reduced and with suitable arrangement of crank throws can be balanced so there is no (or only small) net inertia force. Reduces engine vibration problems substantially.

## 1.7

- (1) Major reason for higher heat losses with Wankel is shape of chamber near TC when combustion takes place. Wankel chamber has higher surface/volume ratio which results in higher heat losses.
- (2) Higher leakage occurs due to greater difficulty in sealing the Wankel chamber effectively. Sealing the four corners of the chamber is hard. The length of the seals all around the chamber is much longer than the length of a conventional piston ring for the same size engine.

## ENGINE DESIGN AND OPERATING PARAMETERS

2.1 (a) Diesel engines operate at much leaner conditions overall than spark-ignition engines.

$$0.056 < (F/A)_{S.I.} < 0.083$$

$$0.014 < (F/A)_D < 0.056$$

From Eq. (2-41)

$$mep = \eta_f \eta_v Q_{HV} p_{a,i} (F/A)$$

Although  $\eta_f$  and  $\eta_v$  of a diesel engine are higher than those of an S.I. engine, the maximum bmep of a diesel engine is lower than that of a spark-ignition engine due to lower (F/A).

(b) Maximum rated power occurs at higher speed than does maximum rated torque because the volumetric efficiency is lower at the maximum-rated-power speed, and the friction mep is higher since it increases with increasing speed.

2.2 Four valves per cylinder has lower flow resistance than two valves per cylinder due to larger valve open area. The airflow increase due to lower flow resistance will result in higher volumetric efficiency. Both the maximum torque and power will increase due to higher volumetric efficiency. A secondary effect is reduced flow resistance to gas flow out of the cylinder during exhaust. Another effect of four valves is the valve response. Valves can respond faster to a change in operating conditions due to reduced inertia.

2.3 (a) Engine in Fig. 1-4 (4-stroke):

$$\bar{S}_p = 2LN = 2 \times 0.092 \times 5000/60 = \underline{15.3 \text{ m/s}}$$

$$b_{mep} = \frac{P n_R}{V_d N} = \frac{(65 \times 10^3) \times 2}{2.2 \times 5000/60} = \underline{709 \text{ kPa}}$$

$$P/A_p = P / (\pi B^2 / 4) = \frac{65 \times 10^{-3} \times 4}{4 \times \pi \times 0.0875^2} = \underline{2.7 \text{ MW/m}^2}$$

(n = no. of cylinders)

(b) Engine in Fig. 1-9 (4-stroke):

$$\bar{S}_p = 2LN = 2 \times 0.076 \times 4800/60 = \underline{12.2 \text{ m/s}}$$

$$b_{mep} = \frac{P n_R}{V_d N} = \frac{86 \times 10^3 \times 2}{2.8 \times 4800/60} = \underline{768 \text{ kPa}}$$

$$P/A_p = \frac{86 \times 10^{-3} \times 4}{6 \times \pi \times 0.089^2} = \underline{2.3 \text{ MW/m}^2}$$

(c) Engine in Fig. 1-12 (2-stroke):

Assume bore = stroke:

$$2 \times \frac{\pi}{4} B^3 = 737 \text{ cm}^3, \quad B = L = 78 \text{ mm}$$

$$\bar{S}_p = 2LN = 2 \times 0.078 \times 5500/60 = \underline{14.2 \text{ m/s}}$$

$$b_{mep} = \frac{P n_R}{V_d N} = \frac{41 \times 10^3 \times 1}{0.737 \times 5500/60} = \underline{607 \text{ kPa}}$$

$$P/A_p = \frac{41 \times 10^{-3} \times 4}{2 \times \pi \times 0.078^2} = \underline{4.3 \text{ MW/m}^2}$$

Engine in Fig. 1-12 is a two-stroke cycle engine. It has lower maximum rated b<sub>mep</sub> due to incomplete scavenging. Specific power is higher (but not twice as high) because there is one power stroke per revolution.

2.4 (a) Engine in Fig. 1-20 (turbocharged 4-stroke DI):

$$\bar{S}_p = 2LN = 2 \times 0.136 \times 2100/60 = \underline{9.5 \text{ m/s}}$$

$$b_{mep} = \frac{P n_R}{V_d N} = \frac{168 \text{ (or 246)} \times 10^3 \times 2}{10 \times 2100/60} = \underline{960 \text{ to } 1406 \text{ kPa}}$$

$$P/A_p = \frac{P}{n(\pi B^2/4)} = \frac{168 \text{ (or 246)} \times 10^3 \times 4}{6 \times \pi \times 0.125^2} = \underline{2.3 \text{ to } 3.34 \text{ MW/m}^2}$$

(b) Engine in Fig. 1-21 (naturally aspirated 4-stroke IDI)

$$\bar{S}_p = 2 \times 0.08 \times 5000/60 = \underline{13.3 \text{ m/s}}$$

$$b_{mep} = \frac{37 \times 10^3 \times 2}{1.47 \times 5000/60} = \underline{604 \text{ kPa}}$$

$$P/A_p = \frac{37 \times 10^3 \times 4}{4 \times \pi \times 0.0765^2} = \underline{2.01 \text{ MW/m}^2}$$

(c) Engine in Fig. 1-22 (turbocharged 4-stroke DI)

$$\bar{S}_p = 2 \times 0.165 \times 2100/60 = \underline{11.6 \text{ m/s}}$$

$$b_{mep} = \frac{300 \times 2}{6 \times (\pi/4) \times 0.137^2 \times 0.165 \times 2100/60} = \underline{1175 \text{ kPa}}$$

$$P/A_p = \frac{300 \times 10^3 \times 4}{6 \times \pi \times 0.137^2} = \underline{3.4 \text{ MW/m}^2}$$

(d) Engine in Fig. 1-23 (aircooled naturally aspirated 4-stroke DI)

$$\bar{S}_p = 2 \times 0.130 \times 2300/60 = \underline{10.0 \text{ m/s}}$$

$$b_{mep} = \frac{188 \times 10^3 \times 2}{13.4 \times 2300/60} = \underline{732 \text{ kPa}}$$

$$P/A_p = \frac{188 \times 10^3 \times 4}{8 \times \pi \times 0.128^2} = \underline{1.83 \text{ MW/m}^2}$$

(e) Engine in Fig. 1-24 (turbocharged two-stroke marine DI)

$$\bar{S}_p = 2 \times 2.9 \times 78/60 = \underline{7.54 \text{ m/s}}$$

$$b_{mep} = \frac{1.9 \times 10^3 \times 1}{(\pi/4) \times 0.84^2 \times 2.9 \times 78/60} = \underline{909 \text{ kPa}}$$

$$P/A_p = \frac{1.9}{(\pi/4) \times 0.84^2} = \underline{3.43 \text{ MW/m}^2}$$

Note turbocharged engines have higher maximum b<sub>mep</sub> and specific power than naturally aspirated engines.

Two-stroke cycle has lower max. bmep due to poorer scavenging but higher specific power due to power stroke every revolution.

Maximum rated speed generally decreases as engine size increases.

2.5 The power required to move vehicle up hill of slope  $\alpha$  is:

$$P_g = (M_v g \sin \alpha) S_v$$

Now:  $S_v = 50 \text{ mile/h} = 22.4 \text{ m/s}$   $A_v = 2 \text{ m}^2$

Use Eq. (2.18a). Road load plus hill climbing power is:

$$P = [C_R M_v g + \frac{1}{2} \rho_a C_D A_v S_v^2 + M_v g \sin \alpha] S_v$$

$$P = [0.0135 \times 1500 \times 9.81 + 0.5 \times 1.18 \times 0.4 \times 2 \times 22.4^2 + 1500 \times 9.81 \times \sin 15^\circ] \times 22.4 \times 10^{-3}$$

$$P = \underline{95 \text{ kW}}$$

Note: 90 percent of this power is required for hill climbing.

2.6 Eq. (2-27a) gives  $\eta_v = \frac{2\dot{m}_a}{\rho_{a,i} V_d N}$ . Since  $\bar{S}_p = 2NL$ ,

$$\eta_v = \frac{\dot{m}_a 4L}{\rho_{a,i} V_d \bar{S}_p} = \frac{60 \text{ g/s} \times 4 \times 0.092 \text{ m}}{1.184 \text{ g/l} \times 2.2 \times 10 \text{ m/s}} = \underline{0.85} \text{ Ans.}$$

2.7 Eqs. (2.27a) and (2.9) give:

$$\dot{m}_a = \eta_v \times \frac{\rho_{a,i} V_d \bar{S}_p}{4L}$$

$$= 0.92 \times \frac{1.184 \times 10 \times 8}{4 \times 0.136}$$

$$\dot{m}_a = \underline{160 \text{ g/s}} \text{ Ans.}$$

$$\dot{m}_f = (F/A) \dot{m}_a = 8 \text{ g/s}$$

$$m_f/\text{cyl} = \dot{m}_f \times \frac{1}{6} \times (2100 \frac{\text{rev}}{\text{min}} \times \frac{1 \text{ cycle}}{2 \text{ rev}} \times \frac{1 \text{ min}}{60 \text{ s}})^{-1}$$

$$= 8 \times \frac{1}{6} \times \frac{1}{17.5} \quad 90 \text{ mg/cycle}$$

$$= \underline{76 \text{ mg/cycle/cylinder}} \text{ Ans.}$$

2.8 Eq. (2.24b) gives:

$$\eta_{f,b} = \frac{1}{\text{bsfc (mg/J)} Q_{HV} \text{ (MJ/kg)}} = 0.3$$

$$\text{bsfc (mg/J)} = \frac{1}{\eta_f Q_{HV}}$$

$$1 = Q_{HV} \cdot \text{bsfc} \cdot 0.3$$

$$\text{bsfc} = \frac{1}{Q_{HV} \cdot 0.3}$$

Fuel	$Q_{HV}$ (MJ/kg)	sfc (mg/J)	sfc (g/kW·h)
Isooctane	44.3	0.0732	271
Gasoline	44.0	0.0758	273
Methanol	20.0	0.167	601
Hydrogen	120.0	0.0278	100

2.9 (a)  $mep = W_c/V_d = \eta_f m_f Q_{HV} = \eta_f v \rho_{a,i} Q_{HV} (F/A)$

So,  $b_{mep} = \eta_m \eta_f \eta_v \rho_{a,i} Q_{HV} (F/A)$

Now,  $\rho_{a,i} = p_{a,i} / (RT_{a,i})$

Hence,  $p_{a,i} (F/A) = \frac{b_{mep} \times R \times T_{a,i}}{\eta_m \eta_f \eta_v Q_{HV}}$

(b)  $P_b = \frac{b_{mep} \times V_d \times N}{n_R} \quad (n_R = 2 \text{ for 4-stroke cycle})$

With units:

$$P_b \text{ (kW)} = \frac{b_{mep} \text{ (kPa)} V_d \text{ (dm}^3 \text{ = liters)} N \text{ (rev/s)}}{n_R \times 1000}$$

Now:  $V_d = n_{\text{cylinders}} \times \pi \frac{B^2}{4} L$

$$N_{\text{max}} = S_{p_{\text{max}}} / (2L)$$

Careful with units (B and L in cm):

$$P_b \text{ (kW)} = b_{mep} \text{ (kPa)} \times n_{\text{cyl}} \pi \frac{B^2 L}{4} \times \frac{1}{10^3} \times \frac{\bar{S}_p \text{ (m/s)}}{2L} \times 100/2 \times 1000$$

$$\text{Or, } n_{\text{cyl}} B^2 = \frac{300 \times 16 \times 10^4}{900 \times \pi \times 12} = 1415 \text{ cm}^2$$

$$6 \text{ cylinders: } B = 15.4 \text{ cm}$$

(either is a reasonable choice)

$$8 \text{ cylinders: } B = 13.3 \text{ cm}$$

Assume stroke = bore

$$\text{Then: } N_{\text{max}} = \frac{12 \times 100}{2 \times B \text{ (cm)}}$$

$$6 \text{ cyl: } N_{\text{max}} = 39 \text{ rev/s}$$

$$8 \text{ cyl: } N_{\text{max}} = 45 \text{ rev/s}$$

(c) Use eqn from (a) to find (F/A)

$$p_{a,i} = 2 \text{ atm} = 2 \times 10^5 \text{ Pa}$$

$$\eta_m = 0.9, \quad \eta_{f,i} = 0.42, \quad \eta_v = 0.9$$

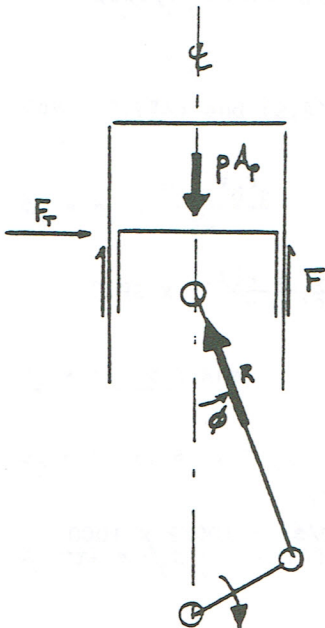
$$Q_{HV} = 42 \text{ MJ/kg}, \quad R_{\text{air}} = 8314/28 = 297 \text{ J/kg K}$$

$$T_{a,i} = 325 \text{ K}$$

$$\text{So: } 2 \times 10^5 (F/A)_{\text{max}} = \frac{900 \times 10^3 \times 297 \times 325}{0.9 \times 0.42 \times 0.9 \times 42 \times 10^6}$$

$$(F/A)_{\text{max}} = \underline{0.0304}, \quad (A/F)_{\text{max}} = \underline{32.9}$$

2.10 (a) Force balance for the piston along the cylinder axis:



Let  $F$  be the friction force

$F_p$  be the gas pressure force

$F_p = pA_p$ , where  $p$  is the pressure and  $A_p$  is the projected area of the piston.

$R$  be the reaction force in the connecting rod.

$\phi$  is the angle of the connecting rod with the cylinder axis.

$M$  be the mass of the piston.

$a$  be the acceleration of the piston.