INTERNAL COMBUSTION ENGINES

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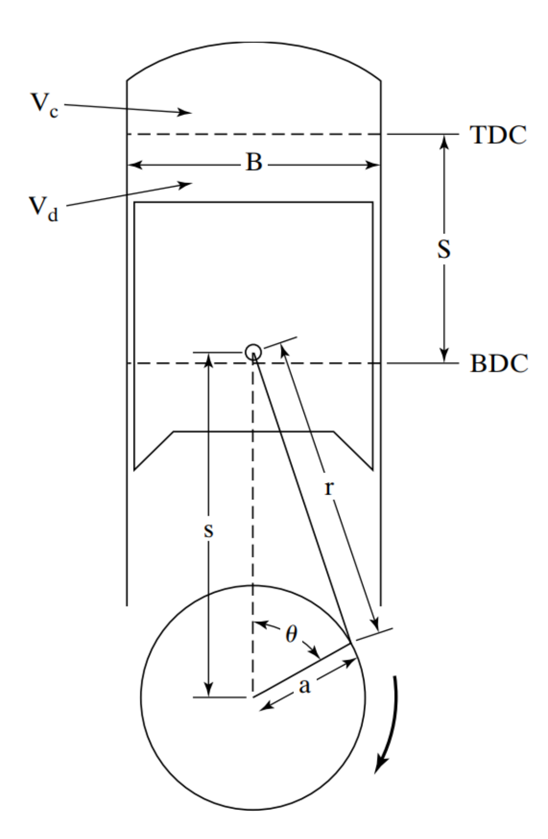
Lecture # 2 (Operating Characteristics)

OPERATING CHARACTERISTICS

- **This chapter examines the operating characteristics of reciprocating internal combustion engines.**
  - Mechanical output parameters of work, torque, and power;
  - The input requirements of air, fuel, and combustion; efficiencies;
  - Emission measurements of engine exhaust.

1. ENGINE PARAMETERS



For an engine with bore B (see Fig. 1), crank offset a, stroke length S, turning at an engine speed of N,

$$S = 2a \tag{1}$$

The average piston speed is

$$\overline{U}_p = 2SN \tag{2}$$

N is generally given in RPM (revolutions per minute), $\overline{U}_p$ in m/sec (ft/sec), and B, a, and S in m or cm (ft or in.).

The maximum average piston speed for all engines will normally be in the range of 5 to 20 m/sec.

FIGURE 1

Piston and cylinder geometry of reciprocating engine. B = bore; S = stroke; r = connecting rod length; a = crank offset; s = piston position; θ = crank angle; V_c = clearance volume; V_d = displacement volume.

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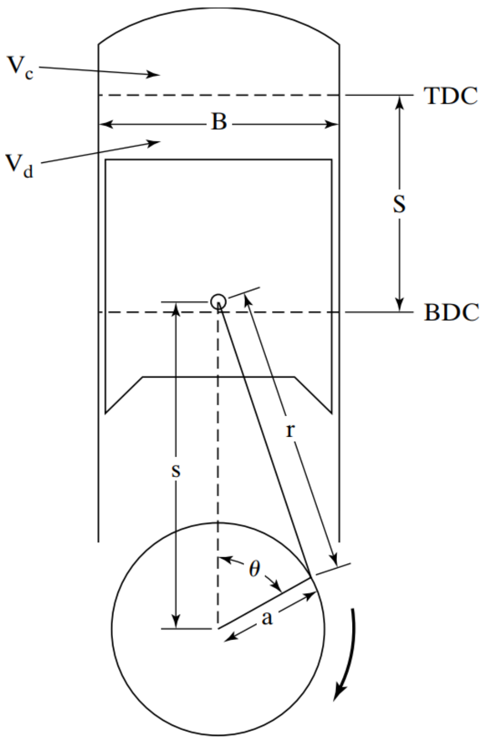

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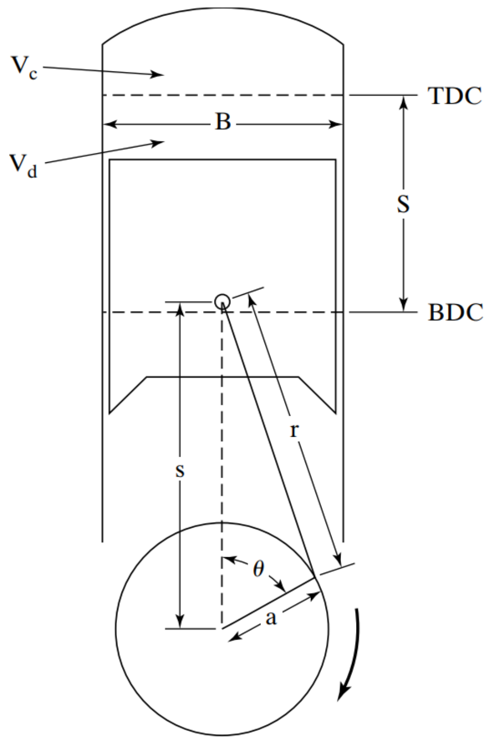
Bore sizes of engines range from 0.5 m down to 0.5 cm (20 in. to 0.2 in.). The ratio of bore to stroke, B/S, for small engines is usually from 0.8 to 1.2. An engine with $B = S$ is often called a *square* engine. If stroke length is longer than bore diameter the engine is *under square*, and if stroke length is less than bore diameter the engine is *over square*. Very large engines are always under square, with stroke lengths up to four times bore diameter.

The distance between the crank axis and wrist pin axis is given by

$$s = a \cos \theta + \sqrt{r^2 - a^2 \sin^2 \theta} \tag{3}$$

1. ENGINE PARAMETERS



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When s is differentiated with respect to time, the instantaneous piston speed U_p is obtained:

$$U_p = ds/dt \tag{4}$$

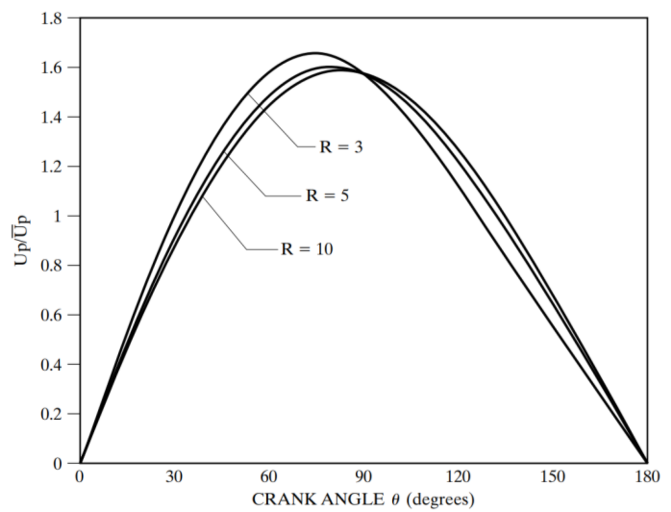
The ratio of instantaneous piston speed divided by the average piston speed can then be written as

$$U_p/\bar{U}_p = (\pi/2) \sin\theta[1 + (\cos\theta/\sqrt{R^2 - \sin^2\theta})] \tag{5}$$

where

$$R = r/a \tag{6}$$

R is the ratio of connecting rod length to crank offset and usually has values of 3 to 4 for small engines, increasing to 5 to 10 for the largest engines. Figure 2 shows the effect of R on piston speed.



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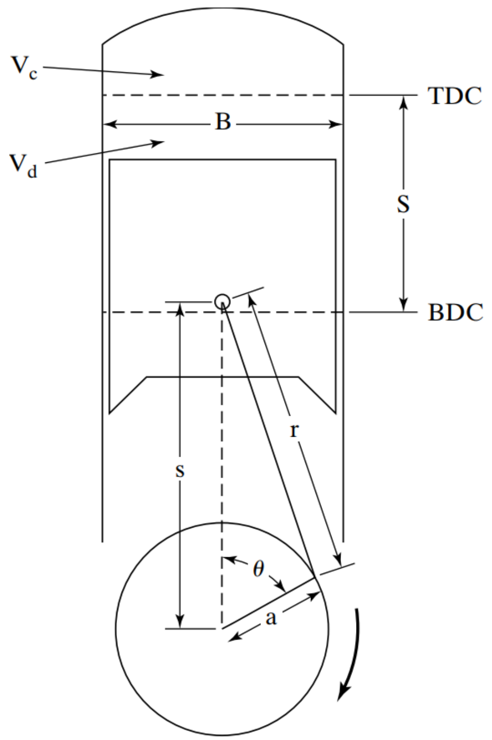

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Displacement, or displacement volume, V_d, is the volume displaced by the piston as it travels from BDC to TDC:

$$V_d = V_{BDC} - V_{TDC} \tag{7}$$

Some books call this swept volume. Displacement can be given for one cylinder or for the entire engine. For one cylinder,

$$V_d = (\pi/4)B^2S \tag{8}$$

For an engine with N_c cylinders,

$$V_d = N_c(\pi/4)B^2S \tag{9}$$

where

B = cylinder bore
S = stroke
N_c = number of engine cylinders

Minimum cylinder volume occurs when the piston is at TDC and is called the clearance volume V_c. We have

$$V_c = V_{TDC} \tag{10}$$

$$V_{BDC} = V_c + V_d \tag{11}$$

Engine displacements can be given in m^3, cm^3, $in.^3$, and, most commonly, in liters (L).

$$1\ L = 10^{-3}\ m^3 = 10^3\ cm^3 = 61.2\ in.^3$$

cubic centimeters (**cc**)

1. ENGINE PARAMETERS

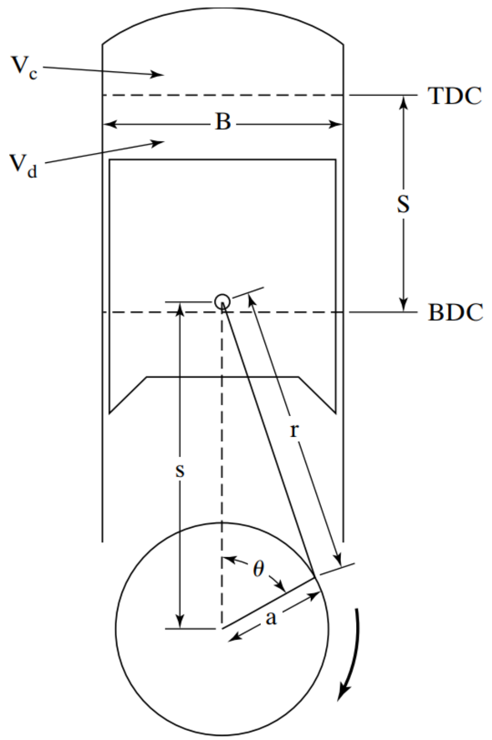


FIGURE 1

Piston and cylinder geometry of reciprocating engine. B = bore; S = stroke; r = connecting rod length; a = crank offset; s = piston position; θ = crank angle; V_c = clearance volume; V_d = displacement volume.

The compression ratio of an engine is defined as

$$r_c = V_{BDC}/V_{TDC} = (V_c + V_d)/V_c = v_{BDC}/v_{TDC} \tag{12}$$

Modern spark ignition (SI) engines have compression ratios of 8 to 11, while compression ignition (CI) engines have compression ratios in the range 12 to 24.

The cylinder volume at any crank angle is

$$V = V_c + (\pi B^2/4)(r + a - s)$$

where

V_c = clearance volume

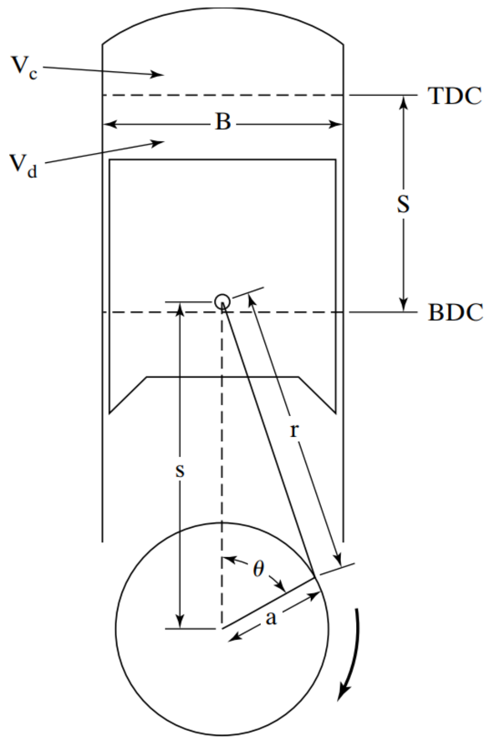
B = bore

r = connecting rod length

a = crank offset

s = piston position shown in Fig. 1

1. ENGINE PARAMETERS



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The cylinder volume at any crank angle is

This can also be written in a nondimensional form by dividing by V_c, substituting for r, a, and s, and employing the definition of R.

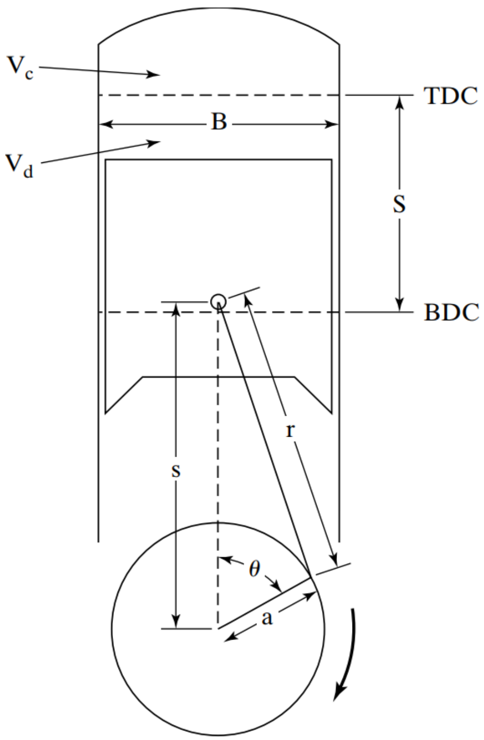
$$V/V_c = 1 + \tfrac{1}{2}(r_c - 1)[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}] \qquad (14)$$

where

r_c = compression ratio

$R = r/a$

1. ENGINE PARAMETERS



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Piston and cylinder geometry of reciprocating engine. B = bore; S = stroke; r = connecting rod length; a = crank offset; s = piston position; θ = crank angle; V_c = clearance volume; V_d = displacement volume.

The cross-sectional area of a cylinder and the surface area of a flat-topped piston are each given by

$$A_p = (\pi/4)B^2 \tag{15}$$

The combustion chamber surface area is

$$A = A_{ch} + A_p + \pi B(r + a - s) \tag{16}$$

where A_{ch} is the cylinder head surface area, which will be somewhat larger than A_p. Then if the definitions for r, a, s, and R are used, Eq. (16) can be rewritten as

$$A = A_{ch} + A_p + (\pi BS/2)[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}] \tag{17}$$

2. WORK

- Work is the output of any heat engine
- In a reciprocating IC engine this work is generated by the gases in the combustion chamber of the cylinder.
- Def: Work is the result of a force acting through a distance.
- The force due to gas pressure on the moving piston generates the work in an IC engine cycle.

$$W = \int F dx = \int P A_p \, dx$$

where

P = pressure in combustion chamber

2. WORK

$$W = \int F dx = \int P A_p \, dx$$

where

P = pressure in combustion chamber

A_p = area against which the pressure acts (i.e., the piston face)

x = distance the piston moves

and

$$A_p \, dx = dV \tag{19}$$

dV is the differential volume displaced by the piston as it travels a distance d/x, so the work done can be written

$$W = \int P \, dV \tag{20}$$

2. WORK

- Specific Work and Specific Volume

Because engines are often multicylinder, it is convenient to analyze engine cycles per unit mass of gas m within the cylinder. To do so, volume V is replaced with specific volume v and work is replaced with specific work:

$$w = W/m \qquad v = V/m \tag{21}$$

2. WORK

- Indicator Diagram

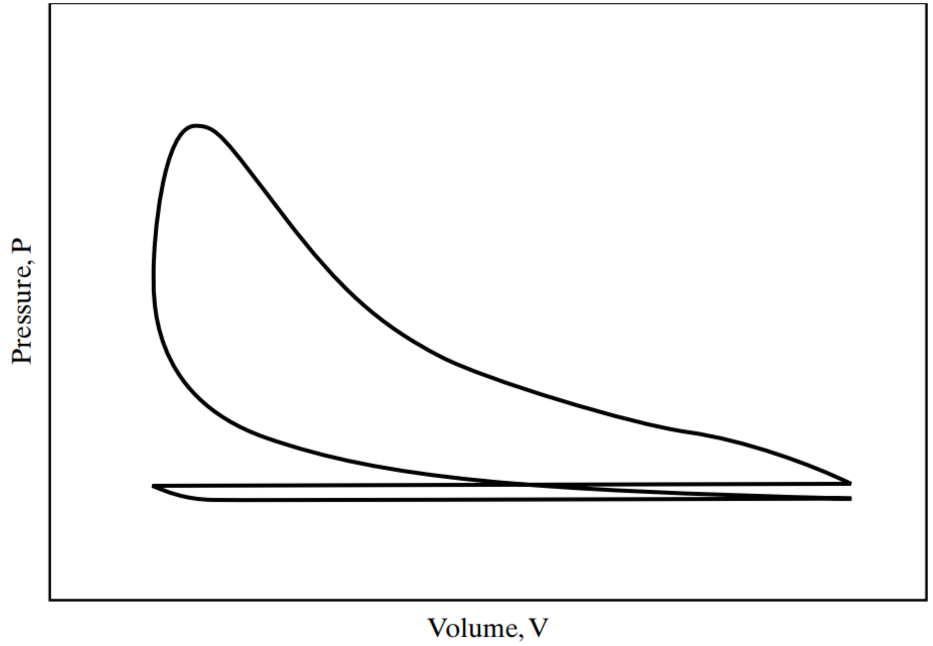


FIGURE 6

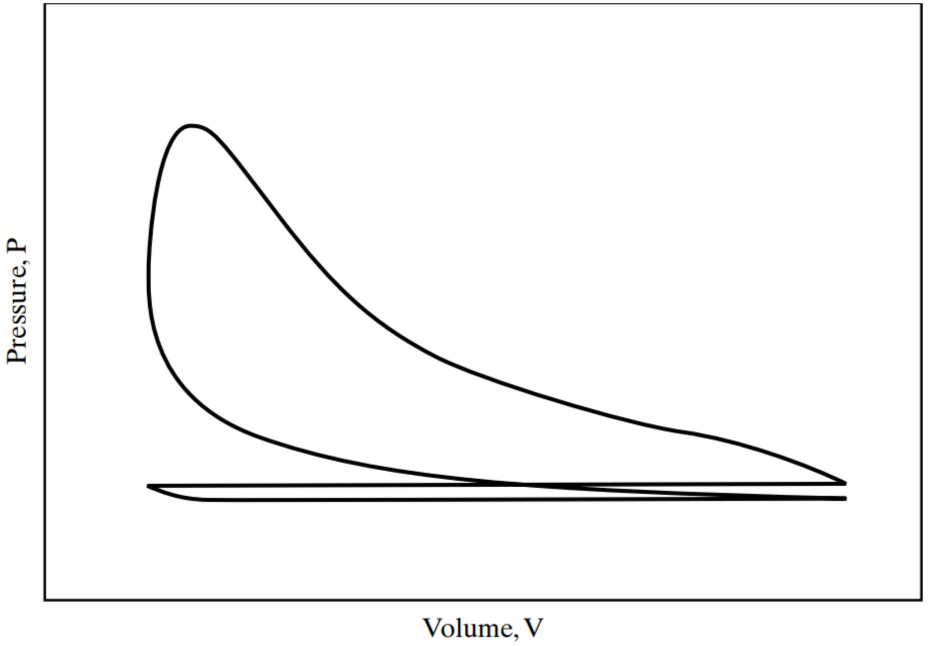
Indicator diagram for a typical four stroke cycle SI engine at WOT. An indicator diagram plots cylinder pressure as a function of combustion chamber volume over a 720° cycle. The diagram is generated on an oscilloscope using a pressure transducer mounted in the combustion chamber and a position sensor mounted on the piston or crankshaft.

Figure 6, which plots the engine cycle on *P–V* coordinates, is often called an indicator diagram. Early indicator diagrams were generated by mechanical plotters linked directly to the engine. Modern *P–V* indicator diagrams are generated on an oscilloscope using a pressure transducer mounted in the combustion chamber and an electronic position sensor mounted on the piston or crankshaft.

WOT?

2. WORK

- Indicator Diagram



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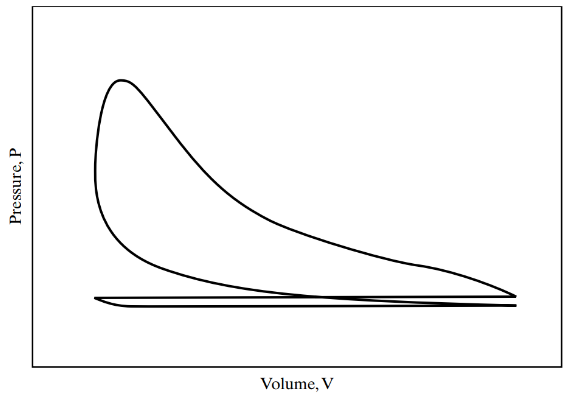
Wide open throttle or **wide-open throttle** (**WOT**), also called **full throttle refers to Full speed or maximum intake of air and fuel**

$$w = \int P\,dv \tag{22}$$

The specific work w is equal to the area under the process lines on the $P-v$ coordinates of Fig. 9.

2. WORK

- The areas shown in Fig. 9 give the work inside the combustion chamber
- This is called indicated work
- Work delivered by the crankshaft is less than indicated work, due to
  - mechanical friction
  - parasitic loads of the engine. Parasitic loads include the oil pump, supercharger, air c
  - onditioner compressor, alternator, etc.



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- Actual work available at the crankshaft is called brake work

$$w_b = w_i - w_f \tag{23}$$

where

w_i = indicated specific work generated inside combustion chamber
w_f = specific work lost due to friction and parasitic loads

Units of specific work will be kJ/kg or BTU/lbm.

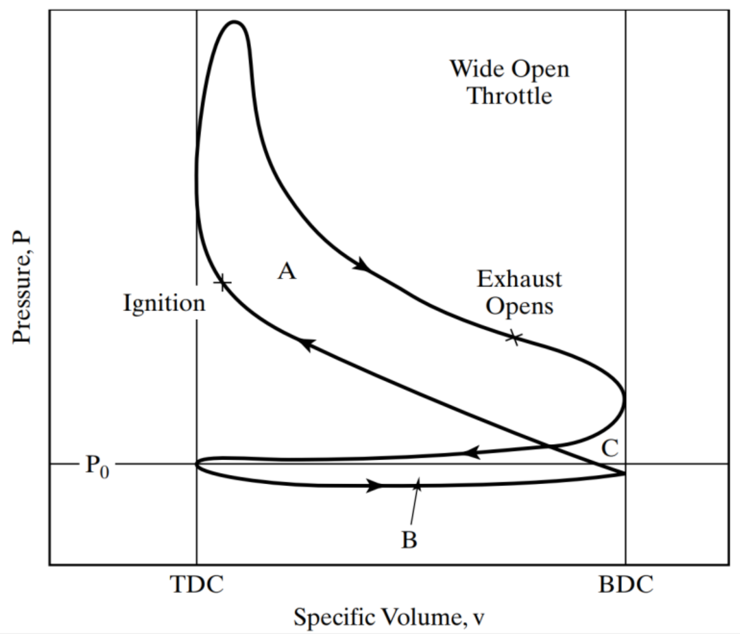
2. WORK

The upper loop of the engine cycle in Fig. 9 consists of the compression and power strokes where output work is generated and is called the **gross indicated work** (areas A and C in Fig. 9). The lower loop, which includes the intake and exhaust strokes, is called **pump work** and absorbs work from the engine (areas B and C). **Net indicated work** is

$$w_{net} = w_{gross} + w_{pump} \tag{24}$$

Pump work w_{pump} is negative for engines without superchargers, so

$$w_{net} = (\text{Area A}) - (\text{Area B}) \tag{25}$$

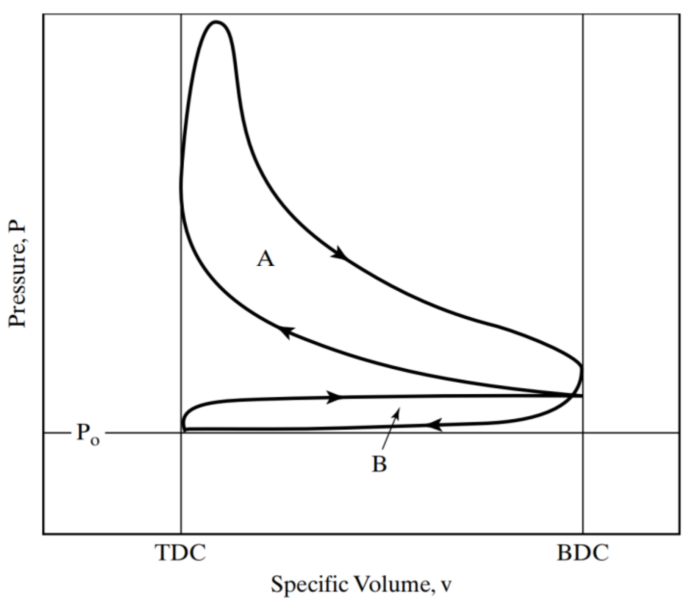


2. WORK

Engines with superchargers or turbochargers can have intake pressure greater than exhaust pressure, giving a positive pump work (Fig. 10). When this occurs,

$$w_{net} = (\text{Area A}) + (\text{Area B}) \tag{26}$$

Superchargers increase net indicated work but add to the friction work of the engine since they are driven by the crankshaft.

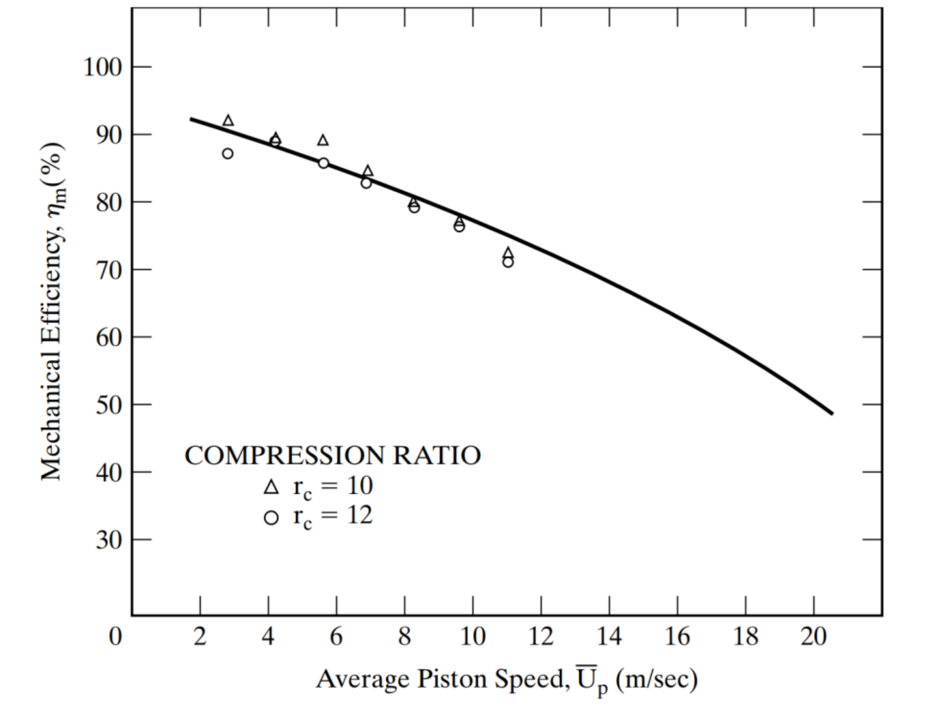


2. WORK

- **Mechanical Efficiency**

The ratio of brake work at the crankshaft to indicated work in the combustion chamber defines the **mechanical efficiency** of an engine:

$$\eta_m = w_b/w_i = W_b/W_i \tag{27}$$



3. MEAN EFFECTIVE PRESSURE

- Pressure in the cylinder of an engine is continuously changing during the cycle.
- An average or **mean effective pressure (mep)** is defined by

$$w = (\text{mep})\Delta v \tag{28}$$

or

$$\text{mep} = w/\Delta v = W/V_d \tag{29}$$

$$\Delta v = v_{\text{BDC}} - v_{\text{TDC}} \tag{30}$$

where

W = work of one cycle

w = specific work of one cycle

V_d = displacement volume

3. MEAN EFFECTIVE PRESSURE

Various mean effective pressures can be defined by using different work terms in Eq. (29). If brake work is used, **brake mean effective pressure** is obtained:

$$\text{bmep} = w_b/\Delta v \tag{31}$$

Indicated work gives **indicated mean effective pressure**.

$$\text{imep} = w_i/\Delta v \tag{32}$$

The imep can further be divided into gross indicated mean effective pressure and net indicated mean effective pressure:

$$(\text{imep})_{\text{gross}} = (w_i)_{\text{gross}}/\Delta v \tag{33}$$

$$(\text{imep})_{\text{net}} = (w_i)_{\text{net}}/\Delta v \tag{34}$$

Pump mean effective pressure (which can have negative values) is given by

$$\text{pmep} = w_{\text{pump}}/\Delta v \tag{35}$$

and **friction mean effective pressure** is given by

$$\text{fmep} = w_f/\Delta v \tag{36}$$

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3. MEAN EFFECTIVE PRESSURE

The following equations relate some of the previous definitions:

$$
\begin{aligned}
\text{nmep} &= \text{gmep} + \text{pmep} && \text{(a)} \\
\text{bmep} &= \text{nmep} - \text{fmep} && \text{(b)} \\
\text{bmep} &= \eta_m \,\text{imep} && \text{(c)} \\
\text{bmep} &= \text{imep} - \text{fmep} && \text{(d)}
\end{aligned}
\tag{37}
$$

where

$$
\begin{aligned}
\text{nmep} &= \text{net mean effective pressure} \\
\eta_m &= \text{mechanical efficiency of engine}
\end{aligned}
$$

4. TORQUE AND POWER

Torque is a good indicator of an engine's ability to do work. It is defined as force acting at a moment distance and has units of N-m or lbf-ft. Torque τ is related to work by

$$2\pi\tau = W_b = (\text{bmep})\, V_d/n \tag{38}$$

where

W_b = brake work of one revolution
V_d = displacement volume
n = number of revolutions per cycle

For a two-stroke cycle engine with one cycle for each revolution,

$$2\pi\tau = W_b = (\text{bmep})V_d \tag{39}$$

$$\tau = (\text{bmep})V_d/2\pi \qquad \text{two-stroke cycle} \tag{40}$$

For a four-stroke cycle engine that takes two revolutions per cycle,

$$\tau = (\text{bmep})V_d/4\pi \qquad \text{four-stroke cycle} \tag{41}$$

In these equations, bmep and brake work W_b are used because torque is measured off the output crankshaft.

4. TORQUE AND POWER

- Power is defined as the rate of work of the engine.
- If n = no. of revolutions per cycle and speed, then N = engine speed

$$\dot{W} = WN/n \tag{42}$$

$$\dot{W} = 2\pi N\tau \tag{43}$$

$$\dot{W} = (1/2n)(\text{mep})A_p\overline{U}_p \tag{44}$$

$$\dot{W} = (\text{mep})A_p\overline{U}_p/4 \qquad \text{four-stroke cycle} \tag{45}$$

$$\dot{W} = (\text{mep})A_p\overline{U}_p/2 \qquad \text{two-stroke cycle} \tag{46}$$

where

W = work per cycle
A_p = piston face area of all pistons
$\overline{U}_p$ = average piston speed

Depending upon which definition of work or mep is used in Eqs. (42)–(46), power can be defined as brake power, net indicated power, gross indicated power, pumping power, and even friction power. Also,

$$\dot{W}_b = \eta_m\dot{W}_i \tag{47}$$

4. TORQUE AND POWER

$$(\dot{W}_i)_{\text{net}} = (\dot{W}_i)_{\text{gross}} - (\dot{W}_i)_{\text{pump}} \tag{48}$$

$$\dot{W}_b = \dot{W}_i - \dot{W}_f \tag{49}$$

where η_m is the mechanical efficiency of the engine.

Power is normally measured in kW, but horsepower (hp) is still common:

$$\begin{aligned} 1\ \text{hp} &= 0.7457\ \text{kW} = 2545\ \text{BTU/hr} = 550\ \text{ft-lbf/sec} \\ 1\text{kW} &= 1.341\ \text{hp} \end{aligned} \tag{50}$$

ENGINE SPECIFICATION

Other ways which are sometimes used to classify engines are as follows:

$$\text{specific power} \qquad \mathrm{SP} = \dot{W}_b / A_p \tag{51}$$

$$\text{output per displacement} \qquad \mathrm{OPD} = \dot{W}_b / V_d \tag{52}$$

$$\text{specific volume} \qquad \mathrm{SV} = V_d / \dot{W}_b \tag{53}$$

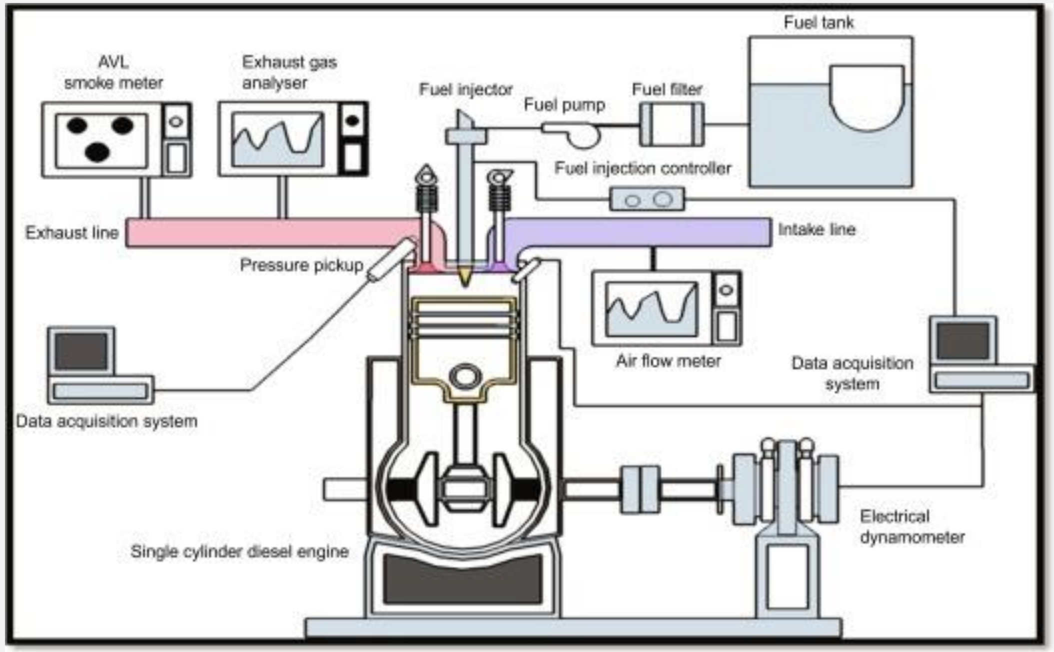
$$\text{specific weight} \qquad \mathrm{SW} = (\text{engine weight}) / \dot{W}_b \tag{54}$$

where

$\dot{W}_b$ = brake power
A_p = piston face area of all pistons
V_d = displacement volume

5. DYNAMOMETERS

- Dynamometers are used to measure torque and power over the engine operating ranges of speed and load.
- By using various methods to absorb the energy output of the engine.
- **Type of Dynamometers**
  1. mechanical friction brake (not so accurate)
  2. Fluid or hydraulic dynamometers (can take large amount of energy)
  3. Eddy current dynamometers (drives a disk)
  4. electric dynamometer
     - connected to generator
     - Load can be varied (varying resistance in the circuit connected)
     - Can work in reverse to test mechanical friction (motor drives engine)



6. AIR–FUEL RATIO AND FUEL–AIR RATIO

- Energy input to an engine comes from the combustion of a hydrocarbon fuel.
- Air is used to supply the oxygen needed for this chemical reaction.

Air–fuel ratio (AF) and fuel–air ratio (FA) are parameters used to describe the mixture ratio. We have

$$\mathrm{AF} = m_a/m_f = \dot{m}_a/\dot{m}_f \tag{55}$$

$$\mathrm{FA} = m_f/m_a = \dot{m}_f/\dot{m}_a = 1/\mathrm{AF} \tag{56}$$

where

m_a = mass of air
$\dot{m}_a$ = mass flow rate of air

6. AIR–FUEL RATIO AND FUEL–AIR RATIO

- **Spark Ignition (SI Engines)**
- The ideal or stoichiometric AF for many gasoline-type hydrocarbon fuels is very close to 15:1
  - with combustion possible for values in the range of 6 to 25
  - AF less than 6 is too rich to sustain combustion
  - AF greater than 25 is too lean
  - A vehicle will often be operated with a rich mixture when accelerating or starting cold
  - When cruising at light load, vehicles are often operated lean to save fuel.
  - SI lean-burn engines can have AF as high as 25 to 40 but need special intake and mixing for proper ignition (More fuel near spark zone).

6. AIR–FUEL RATIO AND FUEL–AIR RATIO

- **Compression Ignition (CI Engines)**
- AF input in the range of 18 to 70 (outside the limits within which combustion is possible?)

- Combustion occurs because the cylinder of a CI engine, unlike an SI engine, has a very nonhomogeneous air–fuel mixture, with reaction occurring only in those regions in which a combustible mixture exists, other regions being too rich or too lean.

6. AIR–FUEL RATIO AND FUEL–AIR RATIO

Equivalence ratio ϕ is defined as the actual ratio of fuel–air to ideal or stoichiometric fuel–air:

$$\phi = (\mathrm{FA})_{\mathrm{act}}/(\mathrm{FA})_{\mathrm{stoich}} = (\mathrm{AF})_{\mathrm{stoich}}/(\mathrm{AF})_{\mathrm{act}} \qquad (57)$$

Some literature uses lambda value instead of equivalence ratio, lambda value being the reciprocal of the equivalence ratio:

$$\lambda = 1/\phi = (\mathrm{FA})_{\mathrm{stoich}}/(\mathrm{FA})_{\mathrm{act}} = (\mathrm{AF})_{\mathrm{act}}/(\mathrm{AF})_{\mathrm{stoich}} \qquad (58)$$

7. SPECIFIC FUEL CONSUMPTION

Specific fuel consumption is defined as

$$\text{sfc} = \dot{m}_f/\dot{W} \tag{59}$$

where

$$\dot{m}_f = \text{rate of fuel flow into engine}$$
$$\dot{W} = \text{engine power}$$

Brake power gives the **brake specific fuel consumption**:

$$\text{bsfc} = \dot{m}_f/\dot{W}_b \tag{60}$$

Indicated power gives **indicated specific fuel consumption**:

$$\text{isfc} = \dot{m}_f/\dot{W}_i \tag{61}$$

Other examples of specific fuel consumption parameters can be defined as follows:

fsfc = friction specific fuel consumption
igsfc = indicated gross specific fuel consumption
insfc = indicated net specific fuel consumption
psfc = pumping specific fuel consumption

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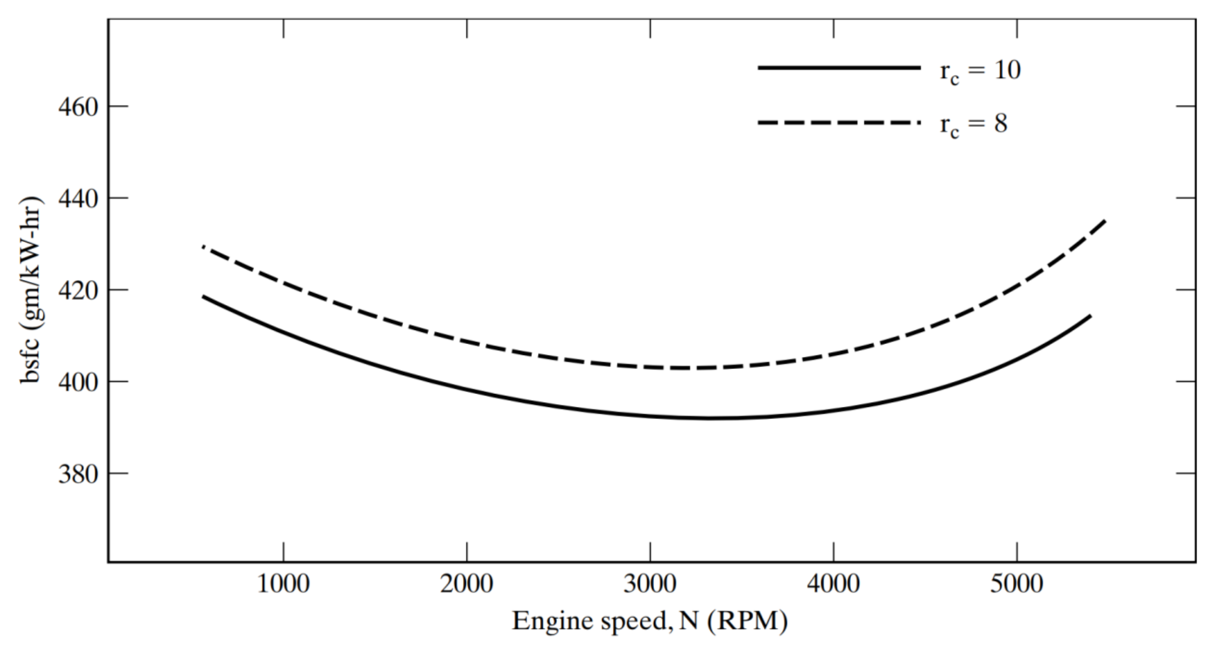
It also follows that

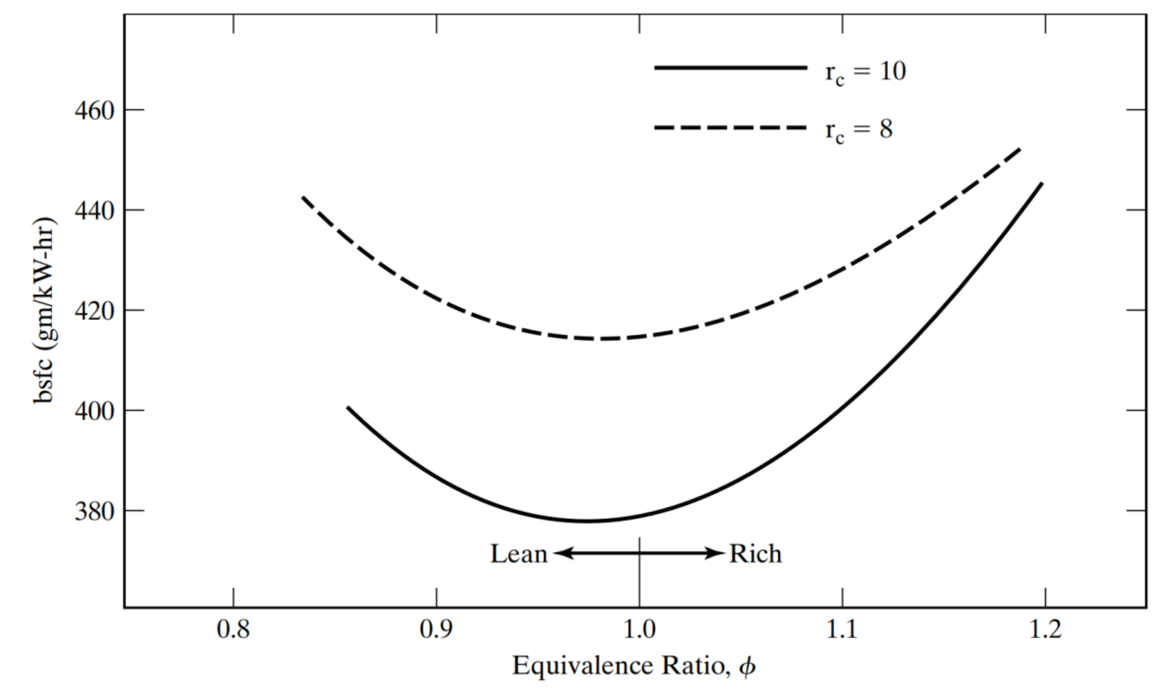
$$\eta_m = \dot{W}_b/\dot{W}_i = (\dot{m}_f/\dot{W}_i)/(\dot{m}_f/\dot{W}_b) = (\text{isfc})/(\text{bsfc}) \tag{62}$$

where

η_m = mechanical efficiency of the engine

7. SPECIFIC FUEL CONSUMPTION





More heat loss due to high cycle time at low speed.
Friction increases at high speed
High thermal efficiency for higher compression ratio

8. ENGINE EFFICIENCIES

- A combustion efficiency η_c is defined to account for the fraction of fuel that burns.
  - Typically has a value of 0.95 to 0.98
- For one engine cycle in one cylinder, the heat added is

$$Q_{\text{in}} = m_f Q_{\text{HV}} \eta_c \tag{63}$$

$$\dot{Q}_{\text{in}} = \dot{m}_f Q_{\text{HV}} \eta_c \tag{64}$$

Fuel conversion efficiency is defined as

$$\eta_f = W/m_f Q_{\text{HV}} = \dot{W}/\dot{m}_f Q_{\text{HV}} \tag{67}$$

$$\eta_f = 1/(\text{sfc}) Q_{\text{HV}} \tag{68}$$

and **thermal efficiency** is

$$\eta_t = W/Q_{\text{in}} = \dot{W}/\dot{Q}_{\text{in}} = \dot{W}/\dot{m}_f Q_{\text{HV}} \eta_c = \eta_f/\eta_c$$

where

$$W = \text{work of one cycle}$$
$$\dot{W} = \text{power}$$
$$m_f = \text{mass of fuel for one cycle}$$
$$\dot{m}_f = \text{mass flow rate of fuel}$$
$$Q_{\text{HV}} = \text{heating value of fuel}$$

END OF THE LECTURE