Internal combustion engines

Chapter two

OPERATION IC ENGINES

By

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Work

$$\left.\begin{array}{r} W = \int F\,dx = \int PA_p\,dx \\ A_p\,dx = dV \end{array}\right\} W = \int P\,dV$$

where: P = pressure in combustion chamber
A_P = area against which the pressure acts (i.e., the piston face)
x = distance the piston moves

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Indicator diagram

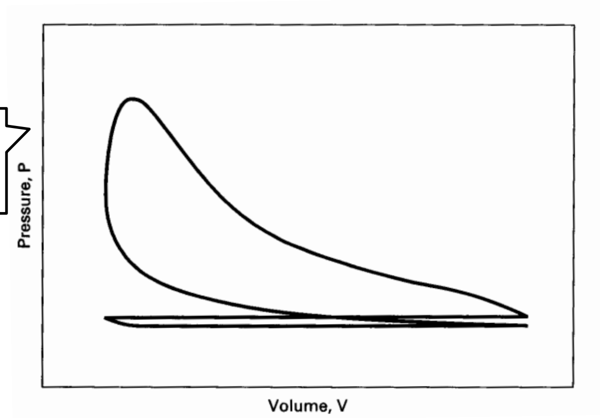

Figure 2-6 Indicator diagram for a typical four stroke cycle SI engine. An indicator diagram plots cylinder pressure as a function of combustion chamber volume over a 720° cycle. The diagram is generated on an oscilloscope using a pressure transducer mounted in the combustion chamber and a position sensor mounted on the piston or crankshaft.

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Specific work

Specific volume

$$w = W/m \qquad v = V/m$$

$$w = \int P\, dv$$

The area under the P-v diagram equal the work

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Break work + work due to mechanical friction and parasitic loads = Indicated work

Parasitic loads include the oil pump, supercharger, air conditioner compressor, alternator, etc.

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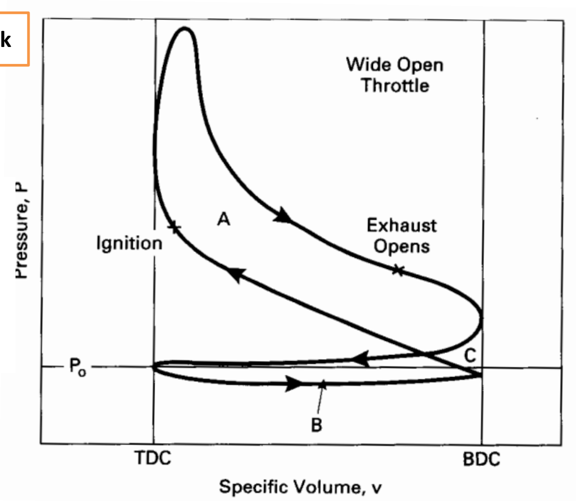
Net indicated specific work

$$w_{net} = w_{gross} + w_{pump}$$

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

Figure 2-9 Four-stroke cycle of typical SI engine plotted on P-v coordinates at (a) wide open throttle, and (b) part throttle. The upper loop consists of the compression stroke and power stroke and the area represents gross indicated work. The lower loop represents negative work of the intake stroke and exhaust stroke. This is called indicated pump work.



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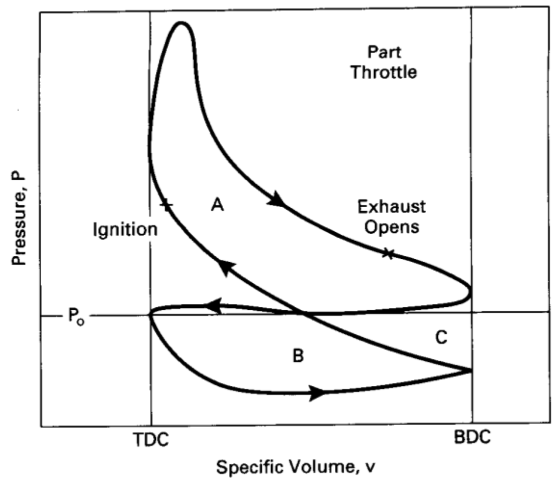

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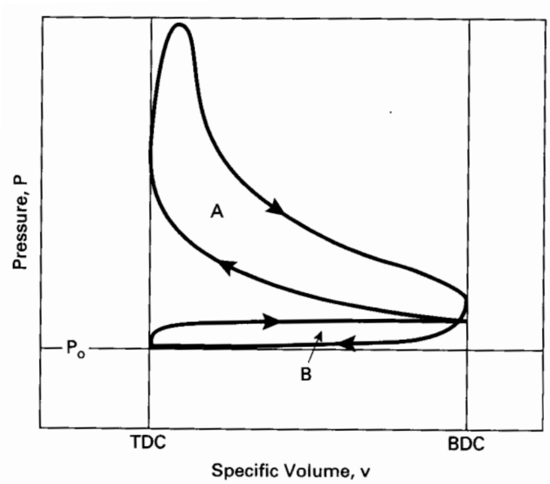
Figure 2-10 Four-stroke cycle of a SI engine equipped with a supercharger or turbocharger, plotted on P-v coordinates. For this cycle intake pressure is greater than exhaust pressure and the pump work loop represents positive work.

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



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mechanical efficiency

$$\eta_m = w_b / w_i = W_b / W_i$$

Care should be taken when using the terms "gross work" and "net work". In some older literature and textbooks, net work (or net power) meant the output of an engine with all components, while gross work (or gross power) meant the output of the engine with fan and exhaust system removed.

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2-3 MEAN EFFECTIVE PRESSURE

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

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

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

where: W = work of one cycle
w = specific work of one cycle
V_d = displacement volume

brake mean effective pressure

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

indicated mean effective pressure:

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

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

Pump mean effective pressure

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

Friction mean effective pressure:

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

$$\text{nmep} = \text{gmep} + \text{pmep}$$
$$\text{bmep} = \text{nmep} - \text{fmep}$$
$$\text{bmep} = \eta_m \text{imep}$$
$$\text{bmep} = \text{imep} - \text{fmep}$$

where: nmep = net mean effective pressure
η_m = mechanical efficiency of engine

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2-4 TORQUE AND POWER

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

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:

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

For a four-stroke cycle engine which takes two revolutions per cycle:

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

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Power is defined as the rate of work of the engine. If *n = number of revolutions* per cycle, and *N = engine speed, then:*

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

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

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

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

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

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

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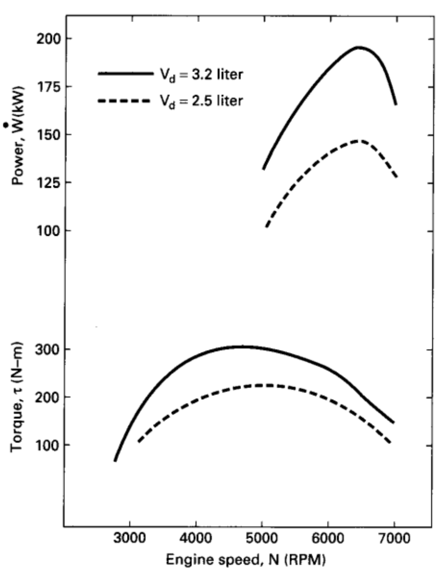

Figure 2-11 Brake power and torque of a typical automobile reciprocating engine as a function of engine speed. Speed at which peak torque occurs is called maximum brake torque (MBT) (or maximum best torque). Indicated power increases with speed while brake power increases to a maximum and then decreases. This is because friction power increases with engine speed to a higher power and becomes dominant at higher speeds. Fig. 2-8 shows power and torque curves for a specific engine.

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brake power — indicated power

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

net indicated power — gross indicated power — pumping power

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

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

friction power

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1 hp = 0.7457 kW = 2545 BTU/hr = 550 ft-lbf/sec

1 kW = 1.341 hp

specific power	SP = W_b / A_p
output per displacement	OPD = W_b / V_d
specific volume	SV = V_d / W_b
specific weight	SW = (engine *weight*)/W_b

where:

- W_b = *brake power*
- A_p = *piston face area of all pistons*
- V_d = *displacement volume*

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EXAMPLE PROBLEM 2-2

The engine in Example Problem 2-1 is connected to a dynamometer which gives a brake output torque reading of 205 N-m at 3600 RPM. At this speed air enters the cylinders at 85 kPa and 60°C, and the mechanical efficiency of the engine is 85%.

Calculate:

1. brake power
2. indicated power
3. brake mean effective pressure
4. indicated mean effective pressure
5. friction mean effective pressure
6. power lost to friction
7. brake work per unit mass of gas in the cylinder
8. brake specific power
9. brake output per displacement
10. engine specific volume

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1) Using Eq. (2-43) to find brake power:

$$\dot{W}_b = 2\pi N\tau = (2\pi \text{ radians/rev})(3600/60 \text{ rev/sec})(205 \text{ N-m})$$
$$= 77{,}300 \text{ N-m/sec} = \underline{77.3 \text{ kW} = 104 \text{ hp}}$$

2) Using Eq. (2-47) to find indicated power:

$$\dot{W}_i = \dot{W}_b / \eta_m = (77.3 \text{ kW})/(0.85) = \underline{90.9 \text{ kW} = 122 \text{ hp}}$$

3) Using Eq. (2-41) to find the brake mean effective pressure:

$$\text{bmep} = 4\pi\tau / V_d = (4\pi \text{ radians/cycle})(205 \text{ N-m})/(0.003 \text{ m}^3\text{/cycle})$$
$$\underline{= 859{,}000 \text{ N/m}^2 = 859 \text{ kPa} = 125 \text{ psia}}$$

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4) Equation (2-37c) gives indicated mean effective pressure:

$$\text{imep} = \text{bmep}/\eta_m = (859\ \text{kPa})/(0.85) = 1010\ \text{kPa} = 146\ \text{psia}$$

5) Equation (2-37d) is used to calculate friction mean effective pressure:

$$\text{fmep} = \text{imep} - \text{bmep} = 1010 - 859 = 151\ \text{kPa} = 22\ \text{psia}$$

6) Equations (2-15) and (2-44) are used to find friction power lost:

$$A_p = (\pi/4)B^2 = (\pi/4)(0.086\ \text{m})^2 = 0.00581\ \text{m}^2 \text{ for one cylinder}$$

$$\dot{W}_f = (1/2n)(\text{fmep})A_p\overline{U}_p$$

$$= (1/4)(151\ \text{kPa})(0.00581\ \text{m}^2/\text{cyl})(10.32\ \text{m/sec})(6\ \text{cyl})$$

$$= 13.6\ \text{kW} = 18\ \text{hp}$$

Or, it can be obtained from Eq. (2-49):

$$\dot{W}_f = \dot{W}_i - \dot{W}_b = 90.9 - 77.3 = 13.6\ \text{kW}$$

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7) First brake work is found for one cylinder for one cycle using Eq. (2-29):

$$W_b = (\text{bmep})V_d = (859\ \text{kPa})(0.0005\ \text{m}^3) = 0.43\ \text{kJ}$$

It can be assumed the gas entering the cylinders at BDC is air:

$$m_a = PV_{\text{BDC}}/RT = P(V_d + V_c)/RT$$

$$= (85\ \text{kPa})(0.0005 + 0.000059)\text{m}^3/(0.287\ \text{kJ/kg-K})(333\ \text{K})$$

$$= 0.00050\ \text{kg}$$

Brake specific work per unit mass:

$$w_b = W_b/m_a = (0.43\ \text{kJ})/(0.00050\ \text{kg}) = 860\ \text{kJ/kg} = 370\ \text{BTU/lbm}$$

8) Equation (2-51) gives brake specific power:

$$\text{BSP} = \dot{W}_b/A_p = (77.3\ \text{kW})/[(\pi/4)(0.086\ \text{m})^2(6\ \text{cylinders})]$$

$$= 2220\ \text{kW/m}^2 = 0.2220\ \text{kW/cm}^2 = 1.92\ \text{hp/in.}^2$$

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9) Equation (2-52) gives brake output per displacement:

$$BOPD = \dot{W}_b / V_d = (77.3\ \text{kW})/(3\ \text{L})$$

$$= \underline{25.8\ \text{kW/L} = 35\ \text{hp/L} = 0.567\ \text{hp/in.}^3}$$

10) Equation (2-53) gives engine specific volume:

$$BSV = V_d / \dot{W}_b = 1/BOPD = 1/25.8$$

$$= \underline{0.0388\ \text{L/kW} = 0.0286\ \text{L/hp} = 1.76\ \text{in.}^3/\text{hp}}$$