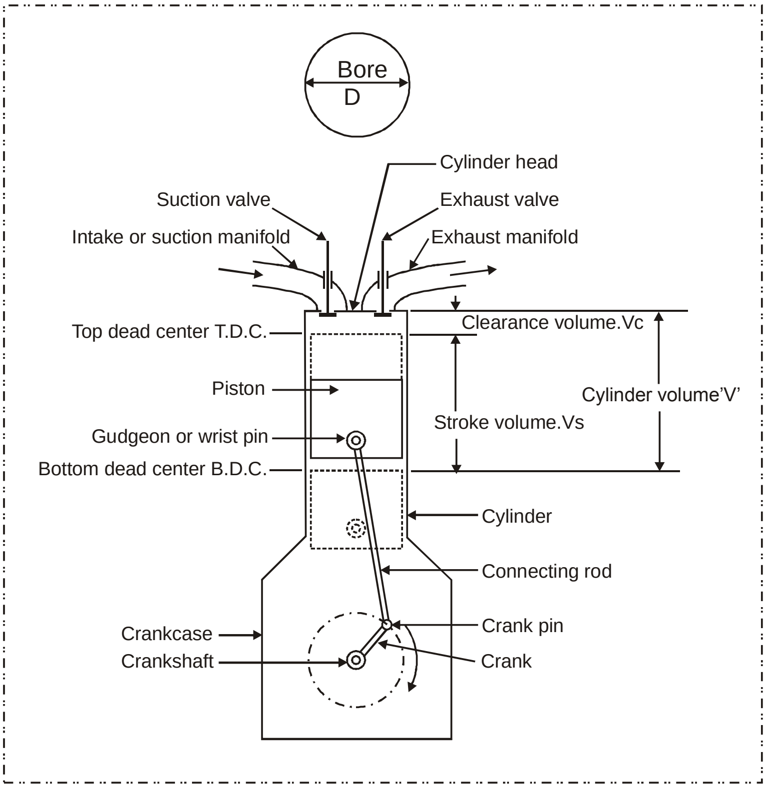
TERMINOLOGY



Important positions and volumes in reciprocating engine

Engine Cylinder diameter (bore) (D): The nominal inner diameter of the working cylinder.

Piston area (A): The area of a circle of diameter equal to engine cylinder diameter (bore). $A = \pi / 4 \times D^2$

Engine Stroke length (L): The nominal distance through which a working piston moves between two successive reversals of its direction of motion.

Dead center: The position of the working piston and the moving parts, which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).

Bottom dead center (BDC): Dead center when the piston is nearest to the crankshaft. Sometimes it is also called outer dead center (ODC).

Top dead center (TDC): Dead center when the position is farthest from the crankshaft. Sometimes it is also called inner dead center (IDC).

Swept volume (V_S): The nominal volume generated by the working piston when travelling from one dead center to next one, calculated as the product of piston area and stroke. The capacity described by engine manufacturers in cc is the swept volume of the engine. $V_s = A \times L = \pi / 4 \times D^2 L$

Clearance volume (V_C): The nominal volume of the space on the combustion side of the piston at top dead center.

Cylinder volume: The sum of swept volume and clearance volume. $V = V_s + V_c$

Compression ratio (CR): The numerical value of the cylinder volume divided by the numerical value of clearance volume. $CR = V / V_c$

Four stroke cycle engine

In four-stroke cycle engine, the cycle of operation is completed in four strokes of the piston or two revolutions of the crankshaft. Each stroke consists of 180^0 of crankshaft rotation and hence a cycle consists of 720^0 of crankshaft rotation. The series of operation of an ideal four-stroke engine are as follows:

1. Suction or Induction stroke: The inlet valve is open, and the piston travels down the cylinder, drawing in a charge of air. In the case of a spark ignition engine the fuel is usually pre-mixed with the air.

2. Compression stroke: Both valves are closed, and the piston travels up the cylinder. As the piston approaches top dead centre (TDC), ignition occurs. In the case of compression ignition engines, the fuel is injected towards the end of compression stroke.

3. Expansion or Power or Working stroke: Combustion propagates throughout the charge, raising the pressure and temperature, and forcing the piston down. At the end of the power stroke the exhaust valve opens, and the irreversible expansion of the exhaust gases is termed 'blow-down'.

4. Exhaust stroke: The exhaust valve remains open, and as the piston travels up the cylinder the remaining gases are expelled. At the end of the exhaust stroke, when the exhaust valve closes some exhaust gas residuals will be left; these will dilute the next charge.

Two stroke cycle engine

In two stroke engines the cycle is completed in two strokes of piston i.e. one revolution of the crankshaft as against two revolutions of four stroke cycle engine. The two-stroke cycle eliminates the separate induction and exhaust strokes.

1. Compression stroke: The piston travels up the cylinder, so compressing the trapped charge. If the fuel is not pre-mixed, the fuel is injected towards the end of the compression stroke; ignition should again occur before TDC. Simultaneously under side of the piston is drawing in a charge through a spring-loaded non-return inlet valve.

2. Power stroke: The burning mixture raises the temperature and pressure in the cylinder, and forces the piston down. The downward motion of the piston also compresses the charge in the crankcase. As the piston approaches the end of its stroke the exhaust port is uncovered and blowdown occurs. When the piston is at BDC the transfer port is also uncovered, and the compressed charge in the crankcase expands into the cylinder. Some of the remaining exhaust gases are displaced by the fresh charge; because of the flow mechanism this is called 'loop scavenging'. As the piston travels up the cylinder, the piston closes the first transfer port, and then the exhaust port is closed.

Performance of I.C.Engines

Indicated thermal efficiency (η_t): Indicated thermal efficiency is the ratio of energy in the indicated power to the fuel energy.

$$\eta_t = IndicatedPower / FuelEnergy$$

$$\eta_t(\%) = \frac{IndicatedPower(KW) \times 3600}{FuelFlow(Kg/Hr) \times CalorificValue(KJ/Kg)} \times 100$$

Brake thermal efficiency (η_{bth}): A measure of overall efficiency of the engine is given by the brake thermal efficiency. Brake thermal efficiency is the ratio of energy in the brake power to the fuel energy.

$$\eta_{bth} = BrakePower / FuelEnergy$$

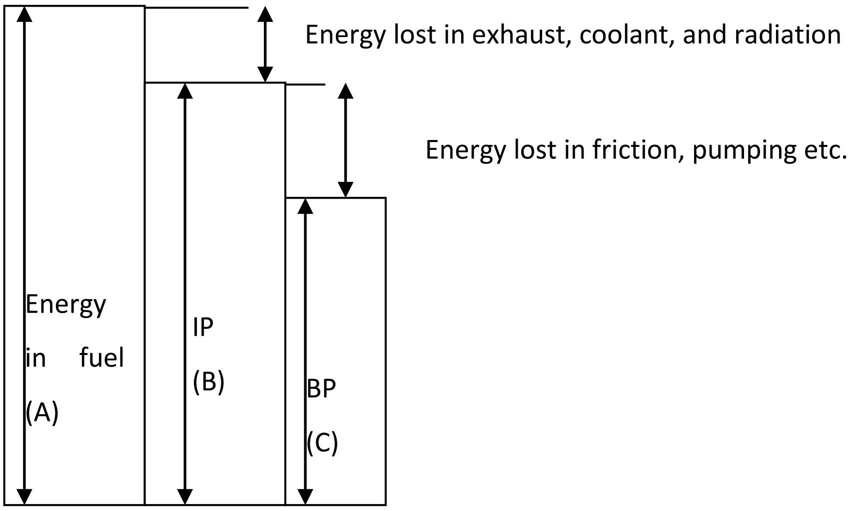
$$\eta_{bth}(\%) = \frac{BrakePower(KW) \times 3600}{FuelFlow(Kg/Hr) \times CalorificValue(KJ/Kg)} \times 100$$

Mechanical efficiency (η_m): Mechanical efficiency is the ratio of brake horse power (delivered power) to the indicated horsepower (power provided to the piston).

$$\eta_m = BrakePower / IndicatedPower$$

and Frictional power = Indicated power – Brake power

Following figure gives diagrammatic representation of various efficiencies,



Indicated thermal efficiency = B/A

Brake thermal efficiency = C/A

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Mechanical efficiency = C/B

Volumetric efficiency (η_v): The engine output is limited by the maximum amount of air that can be taken in during the suction stroke, because only a certain amount of fuel can be burned effectively with a given quantity of air. Volumetric efficiency is an indication of the ‘breathing’ ability of the engine and is defined as the ratio of the air actually induced at ambient conditions to the swept volume of the engine. In practice the engine does not induce a complete cylinder full of air on each stroke, and it is convenient to define volumetric efficiency as:

$$\eta_v\,(\%) = \frac{\text{Mass of air consumed}}{\text{mass of flow of air to fill swept volume at atmospheric conditions}}$$

$$\eta_v(\%) = \frac{AirFlow(Kg/Hr)}{\pi/4 \times D^2 L(m^3) \times N(RPM)/n \times NoofCyl \times AirDen(Kg/m^3) \times 60} \times 100$$

Where n= 1 for 2 stroke engine and n= 2 for 4 stroke engine.

Air flow:

For air consumption measurement air box with orifice is used.

$$AitFlow(Kg/Hr) = C_d \times \pi/4 \times D^2 \times \sqrt{2g \times h_{water} \times W_{den} / A_{den}} \times A_{den} \times 3600$$

Where C_d = Coefficient of discharge of orifice

D = Orifice diameter in m

g = Acceleration due to gravity (m/s^2) = 9.81 m/s^2

h = Differential head across orifice (m of water)

W_{den} = Water density (kg/m^3) =@1000 kg/m^3

W_{air} = Air density at working condition (kg/m^3) = p/RT

Where

p= Atmospheric pressure in kgf/m^2 (1 Standard atm. = $1.0332X10^4$ kgf/m^2)

R= Gas constant = 29.27 $kgf.m/kg^0k$

T= Atmospheric temperature in ^0k

Specific fuel consumption (SFC): Brake specific fuel consumption and indicated specific fuel consumption, abbreviated BSFC and ISFC, are the fuel consumptions on the basis of Brake power and Indicated power respectively.

Fuel-air (F/A) or air-fuel (A/F) ratio: The relative proportions of the fuel and air in the engine are very important from standpoint of combustion and efficiency of the engine. This is expressed either as the ratio of the mass of the fuel to that of the air or vice versa.

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Calorific value or Heating value or Heat of combustion: It is the energy released per unit quantity of the fuel, when the combustible is burned and the products of combustion are cooled back to the initial temperature of combustible mixture. The heating value so obtained is called the higher or gross calorific value of the fuel. The lower or net calorific value is the heat released when water in the products of combustion is not condensed and remains in the vapour form.

Power and Mechanical efficiency: Power is defined as rate of doing work and equal to the product of force and linear velocity or the product of torque and angular velocity. Thus, the measurement of power involves the measurement of force (or torque) as well as speed.

The power developed by an engine at the output shaft is called brake power and is given by

Power = NT/60,000 in kW

where T= torque in Nm = WR

W = 9.81 * Net mass applied in kg. R= Radius in m

N is speed in RPM

Mean effective pressure and torque: Mean effective pressure is defined as a hypothetical pressure, which is thought to be acting on the piston throughout the power stroke.

Power in kW = (P_m LAN/n 100)/60 in bar

where P_m = mean effective pressure

L = length of the stroke in m

A = area of the piston in m^2

N = Rotational speed of engine RPM

n= number of revolutions required to complete one engine cycle

n= 1 (for two stroke engine)

n= 2 (for four stroke engine)

Thus we can see that for a given engine the power output can be measured in terms of mean effective pressure. If the mean effective pressure is based on brake power it is called brake mean effective pressure (BMEP) and if based on indicated power it is called indicated mean effective pressure (IMEP).

$$BMEP(bar) = \frac{BrakePower(KW) \times 60}{L \times A \times (N/n) \times NoOfCyl \times 100}$$

$$IMEP(bar) = \frac{IndicatedPower(KW) \times 60}{L \times A \times (N/n) \times NoOfCyl \times 100}$$

Similarly, the friction means effective pressure (FMEP) can be defined as

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FMEP= IMEP – BMEP

Basic measurements

The basic measurements, which usually should be undertaken to evaluate the performance of an engine on almost all tests, are the following:

1 Measurement of speed

Following different speed measuring devices are used for speed measurement.

1 Photoelectric/Inductive proximity pickup with speed indicator

2 Rotary encoder

2 Measurement of fuel consumption

I) Volumetric method: The fuel consumed by an engine is measured by determining the volume flow of the fuel in a given time interval and multiplying it by the specific gravity of fuel. Generally a glass burette having graduations in ml is used for volume flow measurement. Time taken by the engine to consume this volume is measured by stopwatch.

II) Gravimetric method: In this method the time to consume a given weight of the fuel is measured. Differential pressure transmitters working on hydrostatic head principles can used for fuel consumption measurement.

3 Measurement of air consumption

Air box method: In IC engines, as the air flow is pulsating, for satisfactory measurement of air consumption an air box of suitable volume is fitted with orifice. The air box is used for damping out the pulsations. The differential pressure across the orifice is measured by manometer and pressure transmitter.

4 Measurement of brake power

Measurement of BP involves determination of the torque and angular speed of the engine output shaft. This torque-measuring device is called a dynamometer.

The dynamometers used are of following types:

I) Rope brake dynamometer: It consists of a number of turns of rope wound around the rotating drum attached to the output shaft. One side of the rope is connected to a spring balance and the other to a loading device. The power is absorbed in friction between the rope and the drum. The drum therefore requires cooling.

Brake power = ∏DN (W-S)/60,000 in kW

where D is the brake drum diameter, W is the weight and S is the spring scale reading.

II) Hydraulic dynamometer: Hydraulic dynamometer works on the principal of dissipating the power in fluid friction. It consists of an inner rotating member or impeller coupled to output shaft of the engine. This impeller rotates in a casing, due to the centrifugal force developed, tends to revolve with impeller, but is resisted by torque arm supporting the balance weight. The frictional forces between the impeller and the fluid are measured by the spring-balance fitted on the casing. Heat developed due to dissipation of power is carried away by a continuous supply of the working fluid usually water. The output (power absorbed) can be controlled by varying the quantity of water circulating in the vortex of the rotor and stator elements. This is achieved by a moving sluice gate in the dynamometer casing.

III) Eddy current dynamometer: It consists of a stator on which are fitted a number of electromagnets and a rotor disc and coupled to the output shaft of the engine. When rotor rotates eddy currents are produced in the stator due to magnetic flux set up by the passage of field current in the electromagnets. These eddy currents oppose the rotor motion, thus loading the engine. These eddy currents are dissipated in producing heat so that this type of dynamometer needs cooling arrangement. A moment arm measures the torque. Regulating the current in electromagnets controls the load.

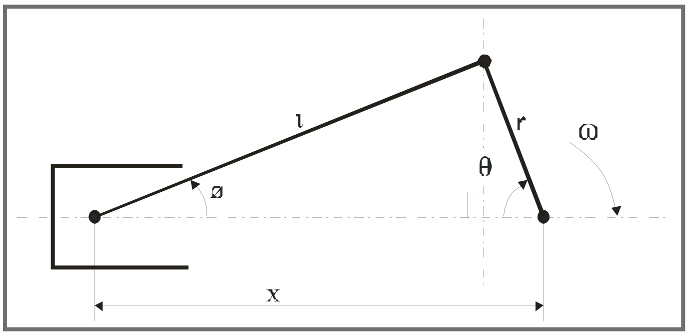
Note: While using with variable speed engines sometimes in certain speed zone the dynamometer operating line are nearly parallel with engine operating lines which result in poor stability.

5 Measurement of indicated power

There are two methods of finding the IHP of an engine.

I) Indicator diagram: A dynamic pressure sensor (piezo sensor) is fitted in the cylinder head to sense combustion pressure. A rotary encoder is fitted on the engine shaft for crank angle signal. Both signals are simultaneously scanned by an engine indicator (electronic unit) and communicated to computer. The software in the computer draws **pressure crank-angle** and **pressure volume** plots and computes indicated power of the engine.

Conversion of pressure crank-angle plot to pressure volume plot:



The figure shows crank-slider mechanism. The piston pin position is given by

$$x = r\cos\theta + l\cos\phi$$

From figure $r\sin\theta = l\sin\phi$ and recalling $\cos\phi = \sqrt{1-\sin^2\phi}$

$$x = r\left(\cos\theta + l/r\sqrt{\left\{1-(r/l)^2\sin^2\theta\right\}}\right)$$

The binomial theorem can be used to expand the square root term:

$$x = r\left\{\cos\theta + l/r\left[1 - \tfrac{1}{2}(r/l)^2\sin^2\theta - 1/8(r/l)^4\sin^4\theta + \ldots\right]\right\} \qquad \text{....1}$$

The powers of sin θ can be expressed as equivalent multiple angles:

$$\sin^2\theta = 1/2 - 1/2\cos 2\theta$$

$$\sin^4\theta = 3/8 - 1/2\cos 2\theta + 1/8\cos 4\theta \qquad \text{.......2}$$

Substituting the results from equation 2 in to equation 1 gives

$$x = r\left\{\cos\theta + l/r\left[1 - \tfrac{1}{2}(r/l)^2(1/2 - 1/2\cos 2\theta) - 1/8(r/l)^4(3/8 - 1/2\cos 2\theta + 1/8\cos 4\theta) + \ldots\right]\right\}$$

The geometry of the engine is such that $(r/l)^2$ is invariably less than 0.1, in which case it is acceptable to neglect the $(r/l)^4$ terms, as inspection of above equation shows that these terms will be at least an order of magnitude smaller than $(r/l)^2$ terms.

The approximate position of piston pin end is thus:

$$x = r\left\{\cos\theta + l/r\left[1 - \tfrac{1}{2}(r/l)^2(1/2 - 1/2\cos 2\theta)\right]\right\}$$

Where r =crankshaft throw and l = connecting rod length.

Calculate x using above equation; then $(l + r - x)$ shall give distance traversed by piston from its top most position at any angle θ

II) Morse test: It is applicable to multi-cylinder engines. The engine is run at desired speed and output is noted. Then combustion in one of the cylinders is stopped by short circuiting spark plug or by cutting off the fuel supply. Under this condition other cylinders “motor” this cylinder. The output is measured after adjusting load on the engine to keep speed constant at original value. The difference in output is measure of the indicated power of cut-out cylinder. Thus for each cylinder indicated power is obtained to find out total indicated power.

VCR Engines

There are different methods available for making variable compression ratio engines. In one of the methods, the standard available engines (with fixed compression ratio) are modified by providing tilting arrangement to the cylinder block. This arrangement changes the clearance volume keeping swept volume same. The compression ratio changes depending upon the amount of tilt and does not alter combustion chamber geometry.

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Calculations

Brake power (kw):

$$BP = \frac{2\pi NT}{60x1000}$$

$$= \frac{2\pi N(WxR)}{60000}$$

$$= \frac{0.785xRPMx(Wx9.81)xArmlength}{60000}$$

$$BHP = \frac{TxN}{75x60}$$

Brake mean effective pressure (bar):

$$BMEP = \frac{BPx60}{\pi / 4xD^2xLx(N/n)xNoOfCylx100}$$

n = 2 for 4 stroke

n = 1 for 2 stroke

Indicated power (kw) :From PV diagram

X scale (volume) 1cm = ..m^3

Y scale (pressure) 1cm = ..bar

Area of PV diagram = ..cm^2

$$workdone/cycle/cyl(Nm) = AreaofPVdiagram \times Xscalefactor \times Yscalefactor \times 100000$$

$$IP = \frac{workdone/cycle/cyl \times (N/n) \times NoOfCyl}{60 \times 1000}$$

Indicated mean effective pressure (bar):

$$IMEP = \frac{IPx60}{\pi / 4xD^2xLx(N/n)xNoOfCylx100}$$

Frictional power (kw):

$$FP = IP - BP$$

$$FHP = IHP - BHP$$

$$BHP = IHP - FHP$$

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Brake specific fuel consumption (Kg/kwh):

$$BSFC = \frac{FuelflowIn\,kg/hr}{BP}$$

Brake Thermal Efficiency (%):

$$BThEff = \frac{BP \times 3600 \times 100}{FuelFlowIn\,Kg/hr \times CalVal}$$

$$BThEff = \frac{IThEff \times MechEff}{100}\ OR\ \frac{BHP}{FuelHP}$$

Indicated Thermal Efficiency (%):

$$IThEff = \frac{IP \times 3600 \times 100}{FuelFlowIn\,Kg/hr \times CalVal}$$

$$IThEff = \frac{BThEff \times 100}{MechEff}$$

Mechanical Efficiency (%):

$$MechEff = \frac{BP \times 100}{IP}$$

Air flow (Kg/hr):

$$AirFlow = Cd \times \pi/4 \times d^2 \sqrt{2gh \times (Wden/Aden)}\ \text{X3600 X Aden}$$

Volumetric Efficiency:

$$VolEff = \frac{AirFlow \times 100}{TheoreticalAirFlow}$$

$$= \frac{AirFlow \times 100}{\pi/4 \times D^2 \times Stroke \times (N/n) \times 60 \times NoOfCyl \times Aden}$$

Air fuel ratio:

$$A/F = \frac{AirFlow}{FuelFlow}$$

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Heat Balance (KJ/h):

a) $HeatSuppliedbyFuel = FuelFlow \times CalVal$

b) $HeatEquivalentToUsefulWork = BP \times 3600$

$$HeatEquivalentToUsefulWorkIn\% = \frac{HeatEquivalentToUsefulWork \times 100}{HeatSuppliedByFuel}$$

C) $HeatInJacketCoolingWater = F3 \times C_P W \times (T2 - T1)$

Where F3 is rate of Jacket cooling water, T2 is jacket water outlet temperature and T1 is jacket water inlet temperature.

$$HeatInJacketCoolingWaterIn\% = \frac{HeatInJacketCoolingWater \times 100}{HeatSuppliedByFuel}$$

d) Heat in Exhaust (Calculate $C_P$ex value):

$$C_P ex = \frac{F4 \times C_P w \times (T4 - T3)}{(F1 + F2) \times (T5 - T6)} ..KJ / Kg\,^0k$$

Where,

$C_p$ex	Specific heat of exhaust gas	kJ/kg^{0}K
C_{pw}	Specific heat of water	kJ/kg^{0}K
F1	Fuel consumption	kg/hr
F2	Air consumption	kg/hr
F4	Calorimeter water flow	kg/hr
T3	Calorimeter water inlet temperature	^{0}K
T4	Calorimeter water outlet temperature	^{0}K
T5	Exhaust gas to calorimeter inlet temp.	^{0}K
T6	Exhaust gas from calorimeter outlet temp.	^{0}K

$$HeatInExhaust(KJ / h) = (F1 + F2) \times C_P ex \times (T5 - Tamb)$$

$$HeatInExhaust\% = \frac{HeatInExhaust \times 100}{HeatSuppliedByFuel}$$

e) Heat to radiation and unaccounted (%)

$$= HeatSuppliedByFuel\,(100\%) - \{(HeatEquivalentToUsefulWork(\%) + HeatInJacketCoolingWater\,(\%) + HeatToExhaust(\%)\}$$