CHAPTER ONE

1- INTRODUCTION

1-1 Basic Engine Types:

Heat engines can be classified as:

I - External Combustion Engine: the products of combustion of air and fuel transfer heat to a second fluid which then becomes the motive or working fluid for producing power. For example, steam engine, steam turbine, heat air engine and closed-cycle gas turbine.

II – Internal Combustion Engine: the products of combustion are directly the motive fluid. For example, gasoline engine, diesel engine, gas engine, jet engine, rocket engine.

1-2 Engines Classifications: Internal Combustion Engines (gasoline and diesel engines) can be classified in a number of different ways:

1-2-1 Cylinder Arrangements:

a) In-Line: cylinders are positioned in a straight line, one behind the other along the length of the crankshaft, as shown in figure (1-1) below. They consist of (2 to 11) cylinders or possibly more.

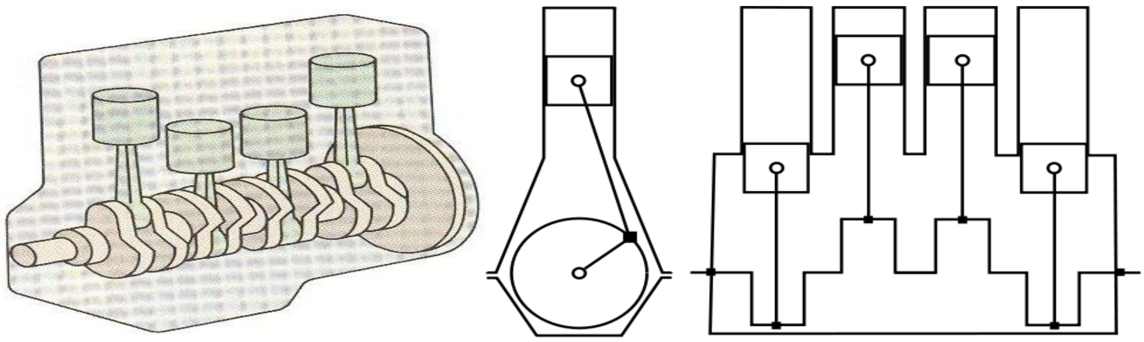


Figure (1-1): In-Line Engine.

b) V- Engines: two banks of cylinders at an angle with each other along a single crankshaft, as shown in figure (1-2). The angle between the banks of cylinders can be any where from $(15^{\circ}-120^{*})$ with $(60\text{-}90)^{\circ}$ being common.

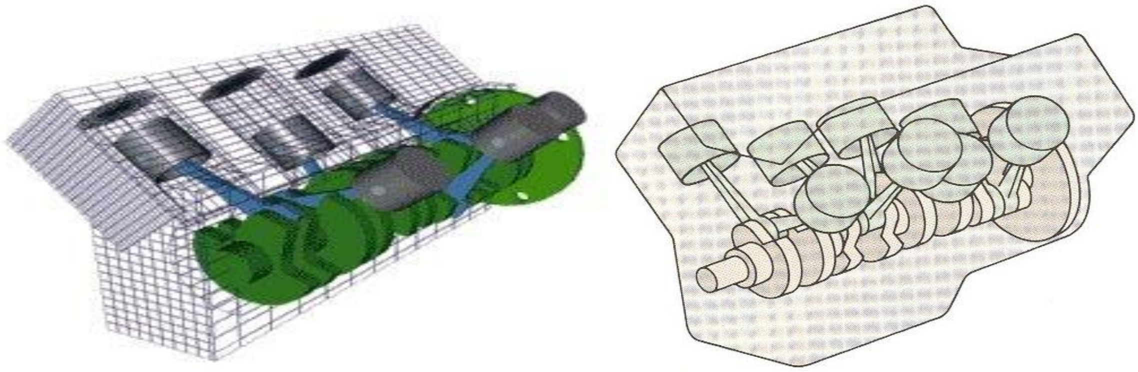


Figure (1-2): V- Engine.

c) W-Engine: same as a V-Engine with three banks of cylinders on the same crankshaft, as shown in figure (1-3). Not common, but some have been developed for racing automobiles, both modern and historic. Usually 12 cylinders with about 60° angle between each bank.

Figure (1-3): W – Engine.

d) Radial Engine: engine with pistons positioned in a circular plane around the central crankshaft, as shown in figure (1-4). The connecting rods of the pistons are connected to a master rod which in turn is connected to the crankshaft. A bank of cylinders on a radial engine always has an odd number of cylinders ranging from (3 to 13) or more. For large aircraft, two or more banks of cylinders are mounted together, one behind the other on a single crankshaft, making one powerful smooth engine. Very large ship engine exist with up to (54) cylinders, 6 banks of 9 cylinders each.

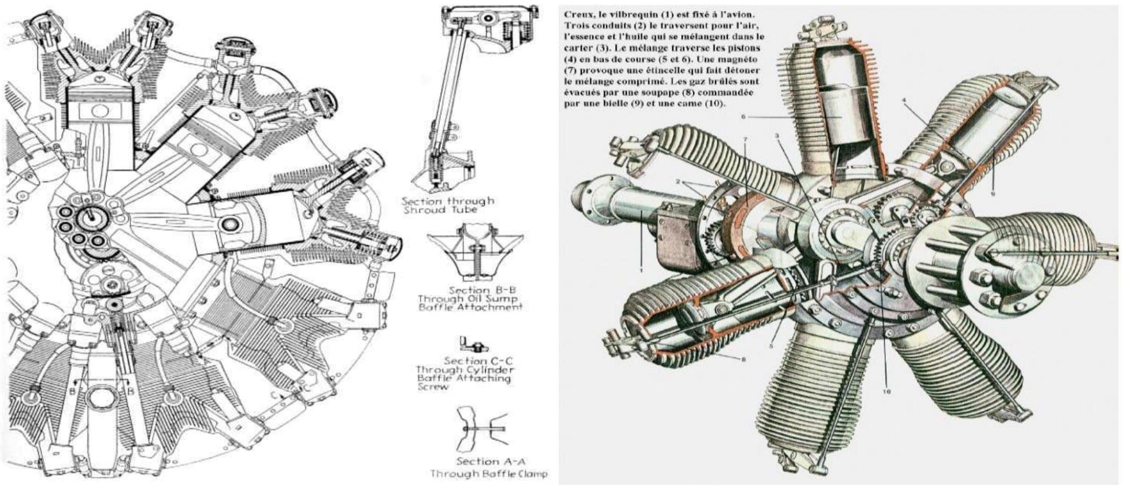


Figure (1-4): Radial Engine.

e) Opposed Cylinder Engine: two banks of cylinders opposite each other on a single crankshaft (also called V-Engine with a 180° angle), as shown in figure (1-5). These are common on small aircraft and automobiles with an even number of cylinders from (2 to 8) or more. These engines are often called (flat engines).

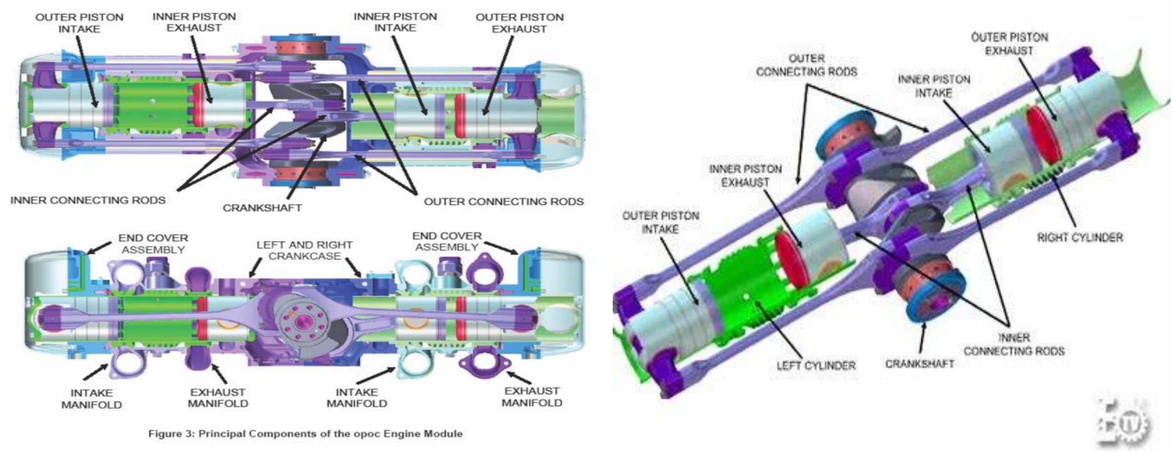


Figure (1-5): Opposed Cylinder Engine.

f) Opposed Piston Engine: two pistons in each cylinder with the combustion chamber in the center between the pistons. A single combustion process causes two power strokes at the same time with each piston being pushed away from center and delivering power to a separate crankshaft at each end of the cylinder, as shown in figure (1-6) below. Engine output is either on two rotating crankshafts or on one crankshaft incorporating complex mechanical linkage.

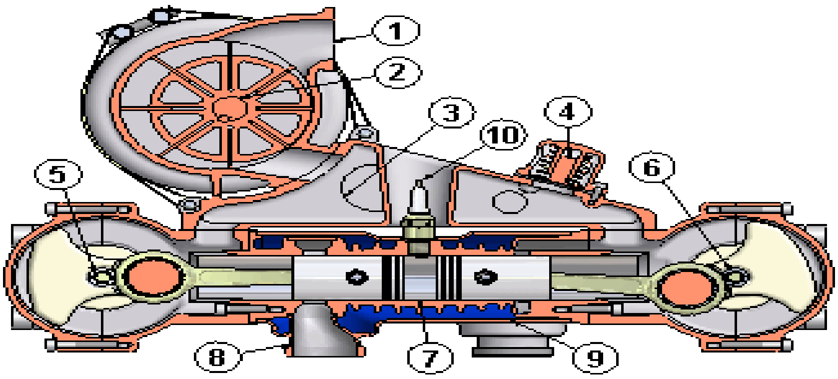


Figure (1-6): Opposed Piston Engine.

1-2-2 Basic Design (Piston Motion):

a) Reciprocating Engine: have one or more cylinders in which pistons reciprocate back and forth the combustion chamber is located in the closed end of each cylinder.

b) Rotary Engine: is made of a block (stator) built around a large non-concentric rotor and crankshaft. The combustion chambers are built in the non-rotating block.

1-2-3 Fuel Used:

a) Gasoline.

b) Diesel oil.

c) Gas, Natural Gas, Methane.

d) LPG (Low Pressure Gas).

e) Alcohol-Ethyl, Methyl.

f) Dual Fuel: there are a number of engines that use a combination of two or more fuels. For example, for CI (Diesel Engine) engines use a combination of methane and diesel fuel. Also, combined gasoline-alcohol fuels.

g) Gasohol: common fuel consisting 90% gasoline and 10% alcohol.

1-2-4 Engine Cycle:

a) Four Stroke Cycle: a four stroke cycle experiences four piston movements over two engine revolutions for each cycle.

b) Two Stroke Cycle: a two stroke cycle has two piston movements over one revolution for each cycle.

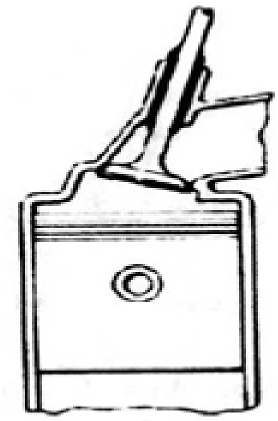
1-2-5 Types of Ignition:

a) Spark Ignition (SI): an SI engine starts the combustion process in each cycle by using of a spark plug. The spark plug gives a high-voltage electrical discharge (voltage of 5-15 KV) between two electrodes which ignites the air-fuel mixture in the combustion chamber surrounding the plug.

b) Compression Ignition (CI): the combustion process in CI engine starts when air-fuel mixture self-ignites due to high temperature in combustion chamber caused by high compression.

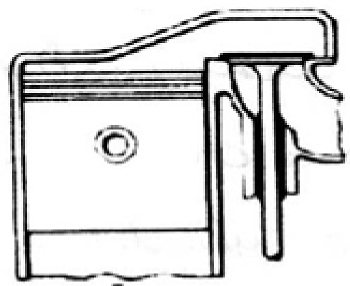
1-2-6 Valve Location:

a) Head Engine (I): An engine where both intake and exhaust valves are placed directly over the piston.



I

b) Head Engine (L): valves in block (flat head). Some historic engines with valves in block head, the intake valves on side of the cylinder and the exhaust valve on the other side. These were called T-head engines.



L

c) Head Engine (F): one valve in head (usually intake) and one in block, and this is much less common.

1-2-7 Types of Cooling:

a) Air Cooled, **b)** Liquid Cooled (Water Cooled).

1-2-8 Applications:

a) automobile, **b)** locomotive, **c)** stationary, **d)** marine, **e)** aircraft, **f)** small portable, chain saw, model airplane.

1-2-9 Methods of Fuel Input for SI Engines:

a) Carbureted.

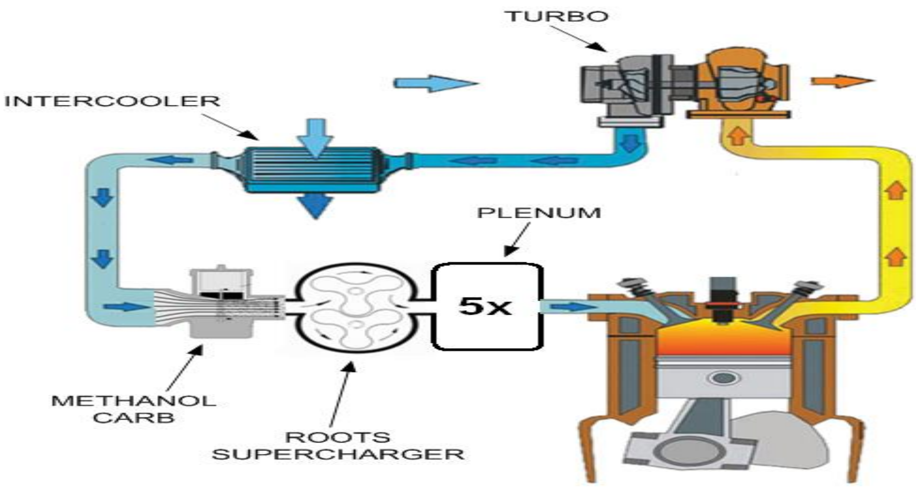
b) Multipoint port fuel injection one or more injectors at each cylinder intake.

c) Throttle Body Fuel Injection. Injectors upstream in intake manifold.

1-2-10 Air Intake Process:

a) Naturally Aspirated: no intake air pressure boots system.

b) Turbocharged: intake air pressure increases with the turbo-compressor driven by the engine exhaust gases.



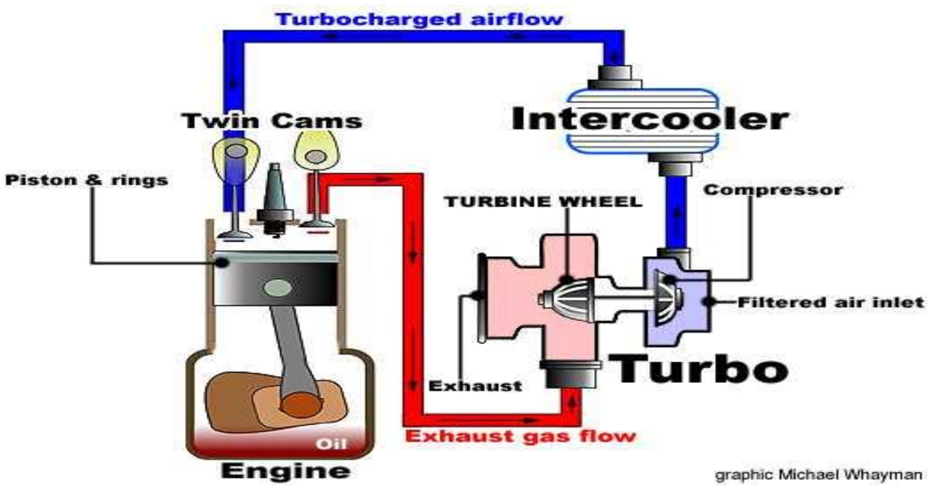


Figure (1-7): Supercharged &Turbocharged Air-Flow system.

c) Supercharged: intake air pressure increased with the compressor driven off of the engine crankshaft.

d) Crankcase Compressed: two stroke cycle engine which uses the crankcase as the intake air compressor.

1-2-11 Mean Piston Speed:

a) Low piston speed < 6 [m/s]

b) Medium piston speed, (6 to 9) [m/s]

c) High piston speed > 9 [m/s].

1-3 Engine Components:

The following is a list of major components found in most reciprocating intake combustion engines, as shown in figure (1-8).

A- Block body of engine containing the cylinders made of cast-iron or aluminum. The block of water –cooled engine includes a water jacket cast around the cylinders. On air cooler engines, the exterior surface of the block has cooling fins.

B- Camshaft: rotating shaft used to push open valves at the proper time in the engine cycle either directly or through mechanical or hydraulic linkage (push rod, rocker arms). Camshafts are generally made of forged steel or cast-iron and are driven off the crankshaft by means of belts or chain. In four stroke engines, the camshaft rotates at half engine speed.

C- Combustion Chamber: the end of the cylinder between the head and the piston face where combustion occurs. The size of the combustion chamber continuously changes from a minimum volume when the piston is at TDC, a maximum value of volume is when the piston at BDC.

D- Connecting Rod: rod connecting the piston with the rotating crankshaft. Usually made of steel or alloy forging in most engines, but may be aluminum in some small engines.

E- Crankcase: part of the engine block surrounding the rotating crankshaft. In many engines, the oil pan makes up part of the crankcase housing.

F- Crankshaft: rotating shaft through which engine work output is supplied to external system. The crankshaft is connected to the engine block with the main bearings. It is rotated by reciprocating pistons through connecting rods connected to the crankshaft, offset from the axis of rotation. This offset is sometimes called crank throw or crank radius. Most crankshafts are made of forged steel, while some are made of cast-iron.

G- Cylinders: the circular cylinders in the engine block in which the pistons reciprocating back and forth. The walls of the cylinders have highly polished hard surfaces. Cylinders may be machined directly in the engine block, a hard metal (drown steel) may be pressed into the softer metal block.

H- Exhaust Manifold: piping system which carries exhaust gases away from the engine cylinders, usually made of cast-iron.

I- Head: the piece which closes the end of the cylinders usually containing part of the clearance volume of the combustion chamber.

J- Intake Manifold: piping system which delivers incoming air to the cylinders usually made of cast-iron metal, plastic or composite material. The individual pipe to a single cylinder is called runner.

L- Piston: is cylindrical-shaped mass that reciprocates back and forth in the cylinder transmitting the pressure forces in the combustion chamber to the rotating crankshaft. The top of the piston is called the (crown) and the sides are called the (skirt). Pistons are made of cast-iron, steel or aluminum.

M- Piston Rings: metal rings that fit into circumferential grooves around the piston and form a sliding surface against the cylinder walls. Near the top of the piston are usually two or more compression rings made of highly polished hard chrome steel. The propose of these is to form a seal between the piston and cylinder walls and to restrict the high pressure gases in combustion chamber from leaking past the piston into the crankcase. Below the compression rings on the piston is at least one oil ring which assists in lubricating the cylinder walls and scrapes away excess oil to reduce oil consumption.

N- Push Rods: mechanical linkages between the camshaft and valve.

O- Spark Plug: electrical device used to initiate combustion in an spark ignition engine (SIE) by creating a high-voltage discharge across an electrode gap. Spark plugs are usually made of metal surrounded with ceramic insulation.

P- Valves: used to allow flow into and out of the cylinder at the proper time in the cycle. Most engines use vales, which are spring loaded closed and pushed open by camshaft action. Valves are usually made of forged steel. Surfaces against which valves close are called valve seats and are made of hardened steel or ceramic. Rotary valves sometimes used, but are much less common.

Q- Water Jacket: system of liquid flow passages surrounding the cylinder, usually constructed as part of engine block and head. Engine coolant flows through the water jacket and keeps the cylinder walls from overheating. The coolant is usually a water-ethylene glycol mixture.

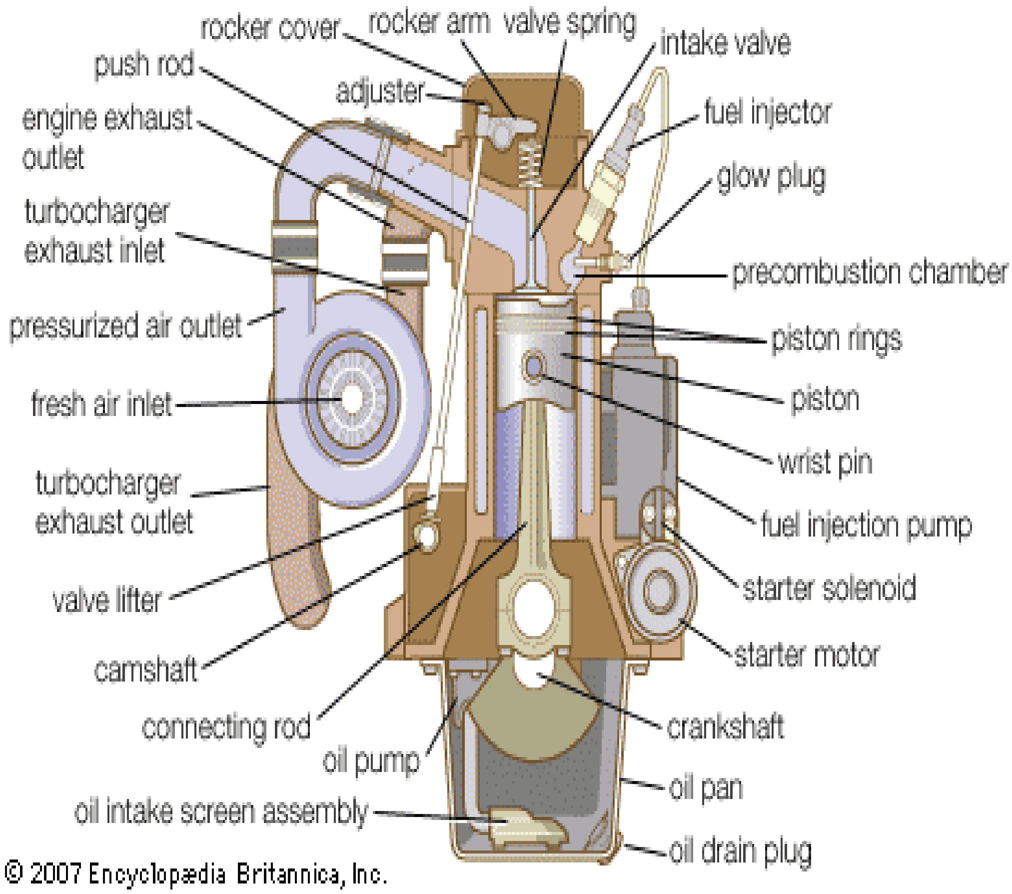


Figure (1-8): Engine Components.

1-4 Operating Characteristics - Engine Parameters:

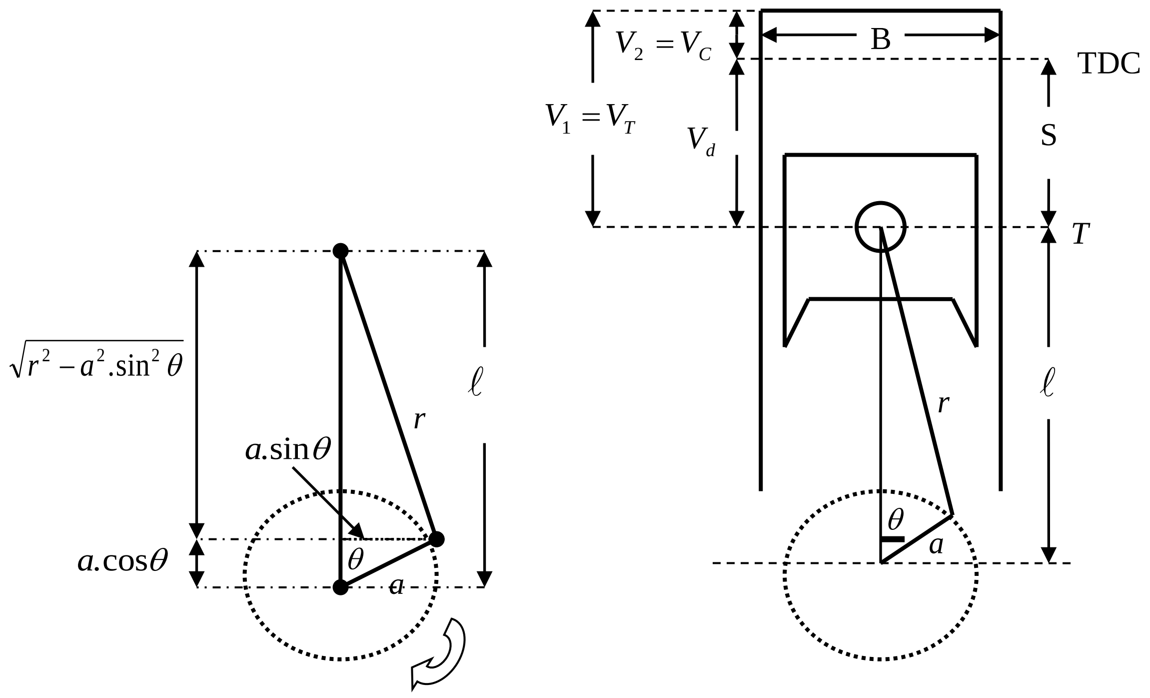


Figure (1-9): Engine Parameters.

For an engine with bore (B), crank offset-radius (a), stroke length (S) and turning at engine speed of (N):

$$S = 2a \qquad \text{… (1-1)}$$

$$\overline{U}_P = 2SN \quad \left(m/_{min}\right) \qquad \text{… (1-2)}$$

or:

$$\overline{U}_P = \frac{S * N}{30} \quad \left(m/_{s}\right) \qquad \text{… (1-3)}$$

Where:

$\overline{U}_P =$ Average piston speed

$S =$ Stroke, displacement, length (m)

$a =$ Crank offset or crank radius (m)

$N =$ Engine speed (rpm)

Average piston speed for all engines will normally be in the range of [5 to 15] $\left(m/s\right)$. There are two reasons why engines operate in this range:

a) For safe limit which can be tolerated by material strength of the engine components.

b) The gas flow into and out-of the cylinders, piston speed determines the instantaneous flow rate of air-fuel into the cylinder during intake and exhaust flow out-of the cylinder during the exhaust stroke. Higher piston speeds would require larger valves to allow for higher flow rates. In most engines, valves are at a maximum size with no room for enlargement.

The distance (ℓ) between crank axis and wrist pin axis is given by:

$$\ell = a.\cos\theta + \sqrt{r^2 - a^2.\sin^2\theta} \quad \text{… (1-4)}$$

Where: $\theta =$ Crank angle, which is measured from cylinder center line and is zero when the piston at TDC.

$$V_d = V_T - V_C \quad \text{… (1-5)}$$

V_d = Displacement volume, swept volume $\left(m^3\right)$

V_T = Total volume $(V_T = V_1)$ $\left(m^3\right)$

V_C = Clearance volume $(V_C = V_2)$ $\left(m^3\right)$

Displacement volume per one cylinder can be expressed as:

$$V_d = \frac{\pi.B^2}{4}.S \quad \left(m^3\right) \quad \text{… (1-6)}$$

Also, displacement volume for the engine can be determined:

$$V_D = \frac{\pi.B^2}{4}.S.i \quad \left(m^3\right) \quad \text{… (1-7)}$$

Where (i) is No. of cylinders.

The compression ratio:

$$r_C = \frac{V_d + V_C}{V_C} = \frac{V_T}{V_C} = \frac{V_1}{V_2} \qquad \text{… (1-8)}$$

The cylinder volume (V) at any crank angle is:

$$V = V_C + \left(\frac{\pi.B^2}{4}\right).(r + a - \ell) \quad (m^3) \qquad \text{… (1-9)}$$

Piston area:

$$A_P = \frac{\pi.B^2}{4} \quad (m^2) \qquad \text{… (1-10)}$$

Combustion chamber surface area:

$$A = A_{ch} + A_P + \pi B(r + a - \ell) \quad (m^2) \qquad \text{… (1-11)}$$

Where: (A_{ch})- cylinder head surface area.

1-4-1 Work: the work is the result of force acting through a distance. Force that acts due to gas pressure on the moving piston generate the work in internal combustion engine cycle.

$$W = \int F.dx = \int P.A_P.dx \qquad \text{… (1-12)}$$

Where:

$P =$ Pressure in combustion chamber $\left(N/m^2\right)$

$x =$ Distance that piston moves (m)

But:

$$A_P.dx = dV \qquad \text{… (1-13)}$$

$$\therefore W = \int P.dV \qquad \text{… (1-14)}$$

$$\boxed{W_b = W_i - W_f} \qquad (J)$$

or: $$\boxed{w_b = w_i - w_f} \qquad \left(J/kg\right) \qquad \text{… (1-15)}$$

Where:

$w_b =$ Brake work (actual work available at the crankshaft).

$w_i =$ Indicated work generates inside combustion chamber.

$w_f =$ Work lost due to friction and parasitic loads (parasitic load include the oil pump, supercharger, air-conditions, alternator, etc).

Mechanical Efficiency (η_m):

$$\boxed{\eta_m = \frac{w_b}{w_i}} \qquad \text{… (1-16)}$$

Mechanical efficiency will be on the order of (75% to 95%).

1-4-2 Mean Effective Pressure: From the figure (1-10) below, it can be seen that pressure in the cylinder of an engine is continuously changing during the cycle. An average or mean effective pressure (mep) is defined by:

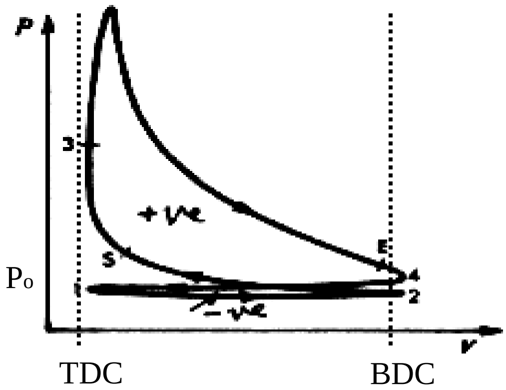


Figure (1-10): Pressure Changing During the Cycle.

$$w = (mep).\Delta v$$
$$mep = w/\Delta v \qquad \text{… (1-17)}$$

$$\boxed{mep = \frac{W}{V_d}} \qquad \text{… (1-18)}$$

$$\Delta v = v_{BDC} - v_{TDC} = V_T - V_C \qquad \text{… (1-19)}$$

Where:

$W =$ Work of one cycle.

$w =$ Specific work of one cycle.

$V_d =$ Displacement volume.

Mean effective pressure is good parameter to compare of design or output because it is independent of engine size and/or speed.

$$\boxed{bmep(P_e) = w_b/\Delta v} \qquad \text{… (1-20)}$$

$$\boxed{imep(P_i) = w_i/\Delta v} \qquad \text{… (1-21)}$$

Where: $bmep =$ Brake Mean Effective Pressure

$imep =$ Indicated Mean Effective Pressure

Pump mean effective pressure (which can have negative value):

$$pmep = {w_{pump}}/{\Delta v} \qquad \text{… (1-22)}$$

Friction mean effective pressure:

$$fmep = {w_f}/{\Delta v} \qquad \text{… (1-23)}$$

$$bmep = imep - fmep \qquad \text{… (1-24)}$$

$$\eta_m = \frac{bmep(P_e)}{imep(P_i)} \qquad \text{… (1-25)}$$

1-4-3 Torque (T): it is defined as a force acting at a moment distance.

$$w_b = 2.\pi.T = {(bmep * V_d)}/{n}$$
$$or: \qquad (N.m) \qquad \text{… (1-26)}$$
$$T = \frac{bmep * V_d}{2.\pi.n}$$

Where:

$n =$ Number of revolutions per cycle, [n=1 for two stroke cycle & n=2 for four stroke cycle].

$w_b =$ Brake work of one revolution.

1-4-4 Power $(P)or(\dot{W})$: it can be defined as the rate of work of the engine.

$$\dot{W} = \frac{w_{cycle}}{\tau_{cycle}} \quad \dots (1\text{-}27)$$

$$w_{cycle} = P.V_d \quad \dots (1\text{-}28)$$

$$\tau_{cycle} = \frac{Z}{2.N_S} \quad \dots (1\text{-}29)$$

Where: Z = No of strokes.

From (1-27), (1-28) and (1-29) becomes:

$$\therefore \dot{W} = \frac{2.P.V_d.N_S}{Z} \quad \dots (1\text{-}30)$$

Where: $\dot{W}(watt)$, $N_S(rps)$, $P\left(N/m^2\right)$ and $V_d\left(m^3\right)$.

Also,
$$\dot{W} = \frac{P.V_d.N_S}{Z/2} = \frac{w.N_S}{n} \quad \dots (1\text{-}31)$$
$$where: n = \frac{Z}{2}$$

Also, $\dot{W} = 2.\pi.N_S.T = \frac{2.\pi.N.T}{60}$ … (1-32)

$$\dot{W} = \frac{mep * A_P * \overline{P}_S\left(or : \overline{U}_P\right)}{2.n} \quad \dots (1\text{-}33)$$

Specific Power: $SP = \dot{W}_b / A_P$ … (1-34)

Output per displacement: $OPD = \dot{W}_b / V_d$ … (1-35)

Specific volume: $SV = V_d / \dot{W}_b$ … (1-36)

Specific weight: $SW = engineweight / \dot{W}_b$ … (1-37)

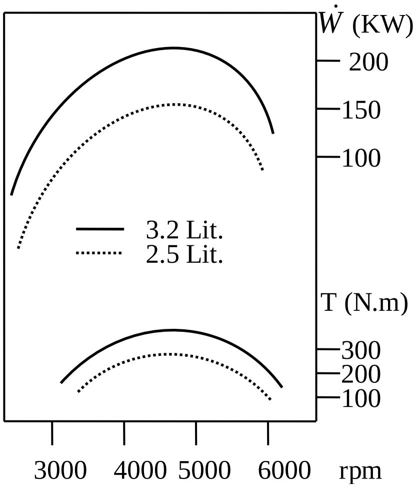
Where: $\dot{W}_b$ = Brake power.

A_P = Pistons face area of all pistons.

V_d = Displacement volume.

Note: in case multi-cylinders, (V_D) must be used, where: ($V_D = V_d * i$) and (i) is the number of cylinders.

These parameters are important for engines used in transportation vehicles such as boats, automobiles and especially air planes, where keeping weight to a minimum is necessary. For large stationary engines, weight is not important.



From equation (1-30):

$$\dot{W} = \frac{P * i * V_d . N}{30Z} \qquad (kW) \qquad \dots (1\text{-}38)$$

Where:

$\dot{W}$ = Engine power (kW)

P = Pressure (MPa)

V_d = Cylinder displacement $(liter)$

i = Number of cylinders

Z = Number of strokes

Power may be effective (brake) or may be indicated.

$$(\dot{W}_b) or (\dot{W}_e) = \frac{bmep * V_D * N}{30Z} \qquad (kW) \qquad \dots (1\text{-}39)$$

$$\dot{W}_i = \frac{imep * V_D * N}{30Z} \qquad (kW) \qquad \dots (1\text{-}40)$$

Mean indicated power is higher than the mean effective power due to many losses such as:

1- Mechanical friction (piston, bearings)
2- Aerodynamic losses (flow losses)
3- Input of auxiliary devices (parasitic loads) such as; water pump, oil pump, fan generator, valve timing mechanism …etc.

$$\dot{W}_e = \dot{W}_i - \dot{W}_{lost} \qquad \text{… (1-41)}$$

Where: $\dot{W}_{lost} =$ Lost power (kW)

$$\therefore \eta_m = \frac{\dot{W}_e}{\dot{W}_i} \qquad \text{… (1-42)}$$

1-4-5 Air-Fuel & Fuel-Air Ratio:

$$AF = {m_a}/{m_f} = {\dot{m}_a}/{\dot{m}_f} \qquad \text{… (1-43)}$$

Where: $AF =$ Air-fuel ratio.

$\dot{m}_a =$ Air mass flow rate $\left({kg}/{s}\right)$.

$\dot{m}_f =$ Fuel mass flow rate $\left({kg}/{s}\right)$.

$$FA = {m_f}/{m_a} = {\dot{m}_f}/{\dot{m}_a} \qquad \text{… (1-44)}$$

Where: $FA =$ Fuel-air ratio.

$$AF = {1}/{FA} \qquad \text{... (1-45)}$$

Equivalence ratio (ϕ) is defined as the actual ratio of fuel-air ratio to ideal (stoichiometric) fuel-air ratio.

$$\phi = {(FA)_{actual}}/{(FA)_{stoich.}} = {(AF)_{stoich.}}/{(AF)_{actual}} \qquad \dots (1\text{-}46)$$

1-4-6 Specific Fuel Consumption:

$$sfc = {\dot{m}_f}/{\dot{W}} \qquad \dots (1\text{-}47)$$

Brake specific fuel consumption:

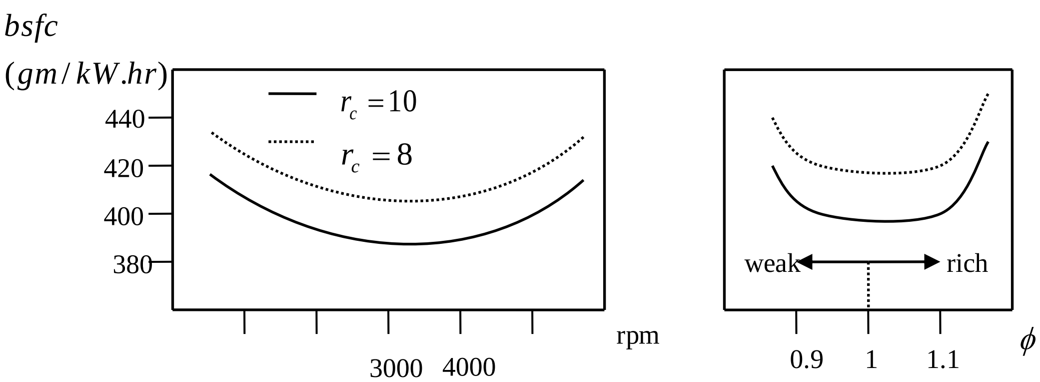
$$\boxed{\begin{aligned} &bsfc = {\dot{m}_f}/{\dot{W}_b} \\ &or: \\ &mfe = {\dot{m}_f}/{\dot{W}_b} \end{aligned}} \qquad \dots (1\text{-}48)$$

Where: $mfe =$ Effective specific fuel consumption $(= bsfc)$

Indicated specific fuel consumption:

$$\boxed{\begin{aligned} &isfc = {\dot{m}_f}/{\dot{W}_i} \\ &or: \\ &mfi = {\dot{m}_f}/{\dot{W}_i} \end{aligned}} \qquad \dots (1\text{-}49)$$

Where: $mfi =$ Indicated specific fuel consumption $(= isfc)$



1-4-7 Engine Efficiencies:

$$Q_A = \dot{m}_f * H_L * \eta_C \quad \dots (1\text{-}50)$$

$$\eta_{th} = \frac{\dot{W}}{Q_A} = \frac{\dot{W}}{\dot{m}_f * H_L * \eta_C} \quad \dots (1\text{-}51)$$

Where:

$(H_L) or (Q_{HV})$ = Heating value of fuel

η_c = Combustion efficiency

η_{th} = Thermal efficiency

$$\eta_f = \frac{\dot{W}}{\dot{m}_f * H_L} \quad \dots (1\text{-}52)$$

Where: η_f = Fuel conversion efficiency

$$\eta_{th} = \dot{W} / Q_A = \dot{m}_f * H_L * \eta_f / \dot{m}_f * H_L * \eta_C = \eta_f / \eta_c$$

$$\eta_{th} = \eta_f / \eta_C \quad \dots (1\text{-}53)$$

(η_{th}) Could be indicated or effective as follows:

$$\eta_{th})_i = \eta_i = \dot{W}_i / \dot{m}_f * H_L * \eta_C \quad \dots (1\text{-}54)$$

$$\eta_{th})_b = \eta_b = \eta_e = \dot{W}_e / \dot{m}_f * H_L * \eta_C \quad \dots (1\text{-}55)$$

$$\eta_i = 1 / (isfc * H_L * \eta_C) \quad \dots (1\text{-}56)$$

$$\eta_b = 1 / (bsfc * H_L * \eta_C) \quad \dots (1\text{-}57)$$

Where:

η_i = Indicated thermal efficiency

η_b = Brake thermal efficiency = Total thermal efficiency = Effective thermal efficiency

$$\eta_m = \eta_{th})_b \Big/ \eta_{th})_i \qquad \text{… (1-58)}$$

$$\therefore \eta_m = \frac{\dot{W}_b}{\dot{W}_i} = \frac{isfc}{bsfc} = \frac{\eta_b}{\eta_i} \qquad \text{… (1-59)}$$

1-4-8 Volumetric Efficiency:

$$\eta_V = \frac{m_a}{\rho_a * V_d} \qquad \text{… (1-60)}$$

$$\eta_V = \frac{n * \dot{m}_a}{\rho_a * V_d * N} \qquad \text{… (1-61)}$$

Where: m_a = Mass of air into the engine or cylinder for one cycle

ρ_a = Air density evaluated at atmospheric conditions outside the engine

$$\rho_a = P_o \Big/ R * T_o$$

$P_o = 101(KPa), T_o = 298(K)$ & $R = 0.287\left(kJ \big/ kg.K \right)$

1-4-9 Emissions:

The four main engine exhaust emissions which must be controlled are oxides of nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC) and solid particulates parts. Two common methods of measuring the amounts of these pollutants are *specific emission (SE)* and the *emission index (EI)*.

$$(SE)_{NO_x} = \frac{\dot{m}_{NO_x}}{\dot{W}_b} \qquad \text{… (1-62)}$$

$$(SE)_{CO} = \frac{\dot{m}_{CO}}{\dot{W}_b} \qquad \text{… (1-63)}$$

$$(SE)_{HC} = \frac{\dot{m}_{HC}}{\dot{W}_b} \qquad \text{… (1-64)}$$

$$(SE)_{part} = \frac{\dot{m}_{part}}{\dot{W}_b} \qquad \text{… (1-65)}$$

$$(EI)_{NO_x} = \frac{\dot{m}_{NO_x}\left[{}^{gm}/_{\sec}\right]}{\dot{m}_f\left[{}^{kg}/_{\sec}\right]} \qquad \text{… (1-66)}$$

$$(EI)_{CO} = \frac{\dot{m}_{CO}\left[{}^{gm}/_{\sec}\right]}{\dot{m}_f\left[{}^{kg}/_{\sec}\right]} \qquad \text{… (1-67)}$$

$$(EI)_{HC} = \frac{\dot{m}_{HC}\left[{}^{gm}/_{\sec}\right]}{\dot{m}_f\left[{}^{kg}/_{\sec}\right]} \qquad \text{… (1-68)}$$

$$(EI)_{part} = \frac{\dot{m}_{part}\left[{}^{gm}/_{\sec}\right]}{\dot{m}_f\left[{}^{kg}/_{\sec}\right]} \qquad \text{… (1-69)}$$

Example (1): John's automobile has a three liter SI V6 engine that operates on a four-stroke cycle at 3600 rpm. The compression ratio is 9.5, the length of connecting rods is 16.6 mm, and the engine is square (B=S). At this speed, combustion end at 20° a TDC. Calculate:

1- Cylinder bore and stroke length.
2- Average piston speed.
3- Clearance volume of one cylinder.
4- Distance the piston has traveled from TDC at the end of combustion.

Solution:

1- For one cylinder, using equation (1-6) with (S=B).

$$V_d = \frac{\pi . B^2}{4} . S$$

$$V_d = V_{total}/6 = 3L/6 = 0.5L = 0.0005(m^3) = \frac{\pi . B^2}{4} . S = \frac{\pi}{4} . B^3$$
$$\Rightarrow B = 0.086(m) = 8.6(cm) = S$$

2- Using equation (1-2) to find average piston speed:

$$\overline{U}_P = 2.S.N = 2\left(\frac{strokes}{rev}\right) * 0.086\left(\frac{m}{stroke}\right) * \frac{3600}{60}\left(\frac{rev}{ses}\right) = 10.32\left(m/\sec\right)$$

3- Using equation (1-8) to find the clearance volume of one cylinder:

$$r_C = 9.5 = (V_d + V_C)/V_C = (0.0005 + V_C)/V_C$$
$$\Rightarrow V_C = 0.000059(m^3) = 59(cm^3)$$

4- Using equation (1-4) to find piston position:

$$\ell = a.\cos\theta + \sqrt{r^2 - a^2.\sin^2\theta}$$

$$\ell = 0.043.\cos 20^\circ + \sqrt{(0.166)^2 - (0.043)^2.\sin 20^\circ}$$

ℓ = 0.206 (m).

Example (2): The engine of ***example (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 ($^{\circ}C$), and a 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.

Solution:

1. Using equation (1-32) to find brake power:

$$\dot{W} = \frac{2.\pi.N.T}{60} = 2\pi\left(\frac{radians}{rev}\right)*\frac{3600}{60}\left(\frac{rev}{\sec}\right)*205(N.m) = 77300(W) = 77.3(kW)$$

2. Using equation (1-42) to find indicated power:

$$\eta_m = \frac{\dot{W}_e}{\dot{W}_i} \Rightarrow \dot{W}_i = \frac{\dot{W}_e}{\eta_m} = \frac{77.3}{0.85} = 90.9(kW)$$

3. Using equation (1-26) to find the brake mean effective pressure:

$$w_b = 2.\pi.T = {(bmep*V_d)}/{n}$$

$$or:$$

$$T = \frac{bmep*V_d}{2.\pi.n}$$

Where (n = 2), because it is four stroke cycle engine.

$$T = \frac{bmep*V_d}{2.\pi.n}$$

$$\Rightarrow bmep = 4.\pi\left(\frac{radians}{cycle}\right)*T(N.m)*V_d\left(\frac{m^3}{cycle}\right) = 4\pi*205*0.003 = 859000\left(\frac{N}{m^2}\right)$$

$$\therefore bmef = 859(KPa)$$

4. Equation (1-25) gives indicated mean effective pressure:

$$\eta_m = \frac{bmep}{imep} \Rightarrow imep = \frac{bmep}{\eta_m} = \frac{859}{0.85} = 1010(KPa)$$

5. Using equation (1-24) to calculate friction mean effective pressure:

$$bmep = imep - fmep \Rightarrow fmep = imep - bmep = 1010 - 859 = 151(KPa)$$

6. Using equation (1-33) to find friction power lost:

$$\dot{W}_f = \frac{fmep * A_P * \overline{P}_S \left(or : \overline{U}_P\right)}{2.n}$$

$$where: A_P = \frac{\pi}{4}.B^2$$

$$\therefore \dot{W}_f = \frac{\pi}{8.n} * B^2 * fmep * \overline{U_P} = \frac{\pi}{16} * (0.086)^2 * 151 * 10.32 = 13.6(kW)$$

<u>Or</u> it can be found from equation (1-41):

$$\dot{W}_e = \dot{W}_i - \dot{W}_{lost} \Rightarrow \dot{W}_{lost} = \dot{W}_i - \dot{W}_e = 90.9 - 77.3 = 13.6(kW)$$

7. Equation (1-18):

$$W_b = mep * V_d = 859 * 0.0005 = 0.43(kJ)$$

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

$$m_a = (P * V_{BDC}) / (R * T) = [P * (V_d + V_c)] / (R * T)$$

$$m_a = \frac{85 * (0.0005 + 0.000059)}{0.287 * (60 + 273)} = 0.0005(kg)$$

Brake specific work per unit mass:

$$w_b = \frac{W_b}{m_a} = \frac{0.43}{0.0005} = 860\left(kJ/kg\right)$$

8. Equation (1-34) gives brake specific power:

$$BSP = \dot{W}_b / A_P = (77.3) / \left[\left(\frac{\pi}{4}\right).(0.086)^2.6(cylinders)\right] = 2220(kW/m^2)$$

9. Equation (1-35) gives brake output per displacement:

$$BOPD = \dot{W}_b / V_d = (77.3kW) / (3L) = 25.8(kW/L)$$

10. Equation (1-36) gives engine specific volume:

$$BSV = V_d / \dot{W}_b = 1/BOPD = 1/25.8 = 0.0388 \left(L/kW \right)$$

<u>Example (3)</u>: the engine in ***example (2)*** is running with an air-fuel ratio AF=15, a fuel heating value of 44000 (kJ/kg) and a combustion efficiency of 0.97. Calculate:

1. Rate of fuel flow into engine.
2. Brake thermal efficiency.
3. Indicated thermal efficiency.
4. Volumetric efficiency.
5. Brake specific fuel consumption.

<u>Solution</u>:

1. From example (2), the mass of air in one cylinder for one cycle is $\left(m_a = 0.0005 kg\right)$, then:

$$m_f = m_a / AF = 0.0005/15 = 0.000033 (kg)$$ of fuel per cylinder per cycle

Therefore, the rate of fuel into the engine is:

$$\dot{m}_f = 0.000033 \left(\frac{kg}{cylinder.cycle} \right) * 6 (cylinder) * \frac{3600}{60} \left(\frac{rev}{\sec} \right) * \left(\frac{1cycle}{2rev} \right)$$

$$\therefore \dot{m}_f = 0.006 \left(kg/\sec \right)$$

2. Using equation (1-55) to find brake thermal efficiency:

$$\eta_{th})_b = \eta_b = \eta_e = (\dot{W}_e) / (\dot{m}_f * H_L * \eta_C) = 77.3 (kW) \Big/ \left[0.006 \left(\frac{kg}{\sec} \right) * 44000 \left(\frac{kJ}{kg} \right) * 0.97 \right]$$

$$\therefore \eta_b = 0.302 = 30.2\%$$

Using equation (1-58):

$$\eta_m = \eta_{th})_b / \eta_{th})_i \Rightarrow \eta_{th})_i = \eta_{th})_b / \eta_m = 0.302/0.85 = 0.355$$

$$\therefore \eta_{th})_i = 35.5\%$$

3. Using equation (1-60):

$$\eta_V = \frac{m_a}{\rho_a * V_d} = \frac{0.0005(kg)}{1.181\left(\frac{kg}{m^3}\right) * 0.0005(m^3)} = 0.847 = 84.7\%$$

4. By using equation (1-48):

$$bsfc = \frac{\dot{m}_f}{\dot{W}_b} = \frac{0.006\left(\frac{kg}{\sec}\right)}{77.3(kW)} = 7.76*10^{-5}\left({kg}/{kW.\sec}\right)$$

(HW)

1) A four-cylinder, two stroke cycle diesel engine with 10.9 (cm) bore and 12.6 (cm) stroke produces 88 (kW) of brake power at 2000 RPM. Compression ratio is 18:1. Determine:

a) Engine displacement $\left[cm^3 \,\&\, L\right]$ … answer: (4703 & 4.703)
b) Brake mean effective pressure $[KPa]$ … answer: (561)
c) Torque $[N.m]$ … answer: (420)
d) Clearance volume of one cylinder $\left[cm^3\right]$ … answer: (69.2)

2) A four-cylinder, 2.4 liter engine operates on a four stroke cycle at 3200 RPM. The compression ratio is 9.4:1, the connecting rod length (r = 18 cm), and the bore and stroke are related as (S = 1.06*B). Calculate:

a) Clearance volume of one cylinder in $\left[cm^3 \,\&\, L\right]$
b) Bore and stroke in $[cm \,\&\, in]$
c) Average piston speed in $\left[{m}/{s}\right]$

3) A five-cylinder, 3.5 liter SI engine operates on a four-stroke cycle at 2500 RPM. At this condition, the mechanical efficiency of the engine is 62% and 1000 J of indicated work are produced each cycle in each cylinder. If B=S, calculate:

a) Indicated mean effective pressure $[KPa]$ … answer: (1429)
b) Brake mean effective pressure $[KPa]$ … answer: (886)
c) Friction mean effective pressure $[KPa]$ … answer: (543)
d) Brake power in $[kW \,\&\, hp]$ … answer: (64.4)
e) Torque $[N.m]$ … answer: (247)
f) Specific power $\left[kW/cm^2\right]$ … answer: (0.178)

g) Output per displacement $\left[kW/cm^3\right]$ … answer: (0.0185)
h) Specific volume $\left[cm^3/kW\right]$ … answer: (54.1)
i) Power lost in $\left[kW \,\&\, hp\right]$ … answer: (39.6)

4) A small single-cylinder, two stroke cycle SI engine operates at 800 RPM with a volumetric efficiency of 0.85. The engine is square (bore=stroke) and has a displacement of $6.28\left(cm^3\right)$. The fuel-air ratio FA=0.067. Determine:

a) Average piston speed (m/s)
b) Flow rate of air into engine (kg/s)
c) Flow rate of fuel into engine (kg/s)
d) Fuel input for one cycle $(kg/cycle)$