APPLIED THERMODYNAMICS

Internal Combustion Engines
(Module III)

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List of Topics

1. Internal Combustion Engine – Components, Nomenclature and Classifications
2. Basic Engine Cycle and Engine Kinematic Analysis
3. Engine Operating Characteristics
4. Thermodynamic Analysis of Air Standard Cycles
5. Valve Timing Diagram and Fuel – Air Cycle
6. Thermochemistry and Fuel Characteristics
7. Combustion Phenomena in Engines
8. Heat Transfer Analysis in Engines
9. Exergy Analysis and Engine Emission/Pollution

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Lecture 3

Engine Operating Characteristics

- Engine Parameters
- Mechanical and Combustion Performance
- Emission Index
- Characteristics Curves

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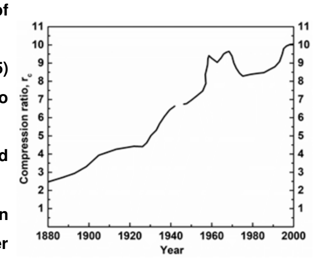
Operating Parameters

- Average compression ratios of automobile engine developments
  - Early days, CR (2.5 to 4.5) development is slower mainly due to low octane rating of fuels
  - No automobiles were manufactured during World War II.
  - After 1960, the fuels and combustion chamber technology allowed higher compression ratio in automobile sector.



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Operating Parameters

- An engine's performance is precisely defined by its maximum power (torque) and range of operating speed.

- Maximum rated power (highest power an engine is allowed to develop for short duration)
- Normal rated power (highest power an engine is allowed to develop for continuous duration)
- Rated ~~power~~ speed (rotational speed of engine at which rated power is developed)

- The important deciding factors of an engine within its operating range are as follows:

➢ Engine performance
➢ Fuel consumption (i.e. cost of the fuel)
➢ Engine noise and pollution
➢ Reliability, durability, maintenance requirement of engine
➢ Initial cost and its installation (for static engine)

Operating Parameters

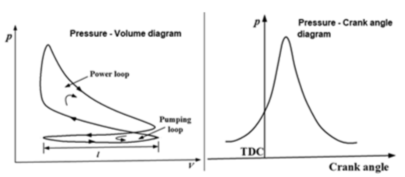
- A small high speed engine can have displacement volume of 0.075 cc, but they can operate at speeds at 3500 rpm with power output of 0.15-1.5 kW. The average piston speed is in the range of 5-20 m/s.
- Modern engines operate at CRs 8 to 11 (SI) and 12 to 24 (CI)
- An engine is selected to suit a particular application with following main considerations:
  - Compression Ratio
  - Mechanical output parameters (power, speed, work, toque characteristics)
  - Input requirements (air-fuel ratio, combustion efficiencies etc.)
  - Emission measurements in engine exhaust

- These are obtained by measurement of quantities concerned during bench tests and calculation by standard procedures. The results are plotted graphically in the form of performance curves.

Mechanical and Combustion Performance

Indicated power (IP)

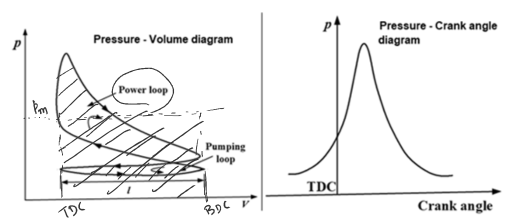
- It is defined as the rate of work done by the gas on the piston as evaluated from "indicator diagram".
- An indicator diagram is the "pressure-volume (p-v)" representation for a reciprocating engine with power and pumping loop.
- The upper loop consists of compression stroke and power stroke with area as representation of gross indicated work. The lower loop represents negative work of intake and exhaust stroke, known as indicated pump work.
- The net work done per cycle is the proportional to the difference in area of power loop and pumping loop.



Mechanical and Combustion Performance

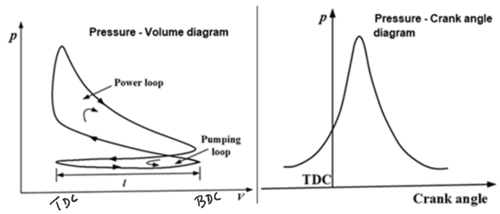
Indicated power (IP)

- The concept of "mean effective pressure" can be applied. It is defined as the height of rectangle having same length area on the same p-v diagram/indicator diagram.
- The variation of pressure in the cylinder is detected by piezo–electric pickup installed in the crankshaft. A signal is given to an oscilloscope to plot pressure variation. This traces are known as pressure-crank angle diagram.
- Modern methods of instrumentation, data acquisition and analysis is based on recent advances electronics, digital methods to be incorporated in engine testing and control.



Mechanical and Combustion Performance

Indicated power (IP)



Indicated mean effective pressure, $p_i = \left(\frac{\text{Net area of diagram}}{\text{Length of diagram}}\right) \times$ constant (depends on recorder)

An engine with bore, B; stroke, S; RPM, N; No. of cylinder, k

Work done per cycle per cylinder $= p_i A S, \quad A = \frac{\pi}{4} B^2$

Power output per unit time = Work done per cycle × No. of cycles per minute (n)

No. of cycles per minute $= \frac{N}{2}$ (four stroke engine) or N (two stroke engine)

$n = \frac{N}{2}$ (4-stroke)
$= N$ (2-stroke)

$IP = \frac{p_i A S N k}{2}$ (four stroke engine); $IP = p_i A S N k$ (two stroke engine)

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Mechanical and Combustion Performance

Brake power (BP), Friction power (FP) & Mechanical efficiency

- **Actual work available at the crankshaft is called as "brake work". It is less than indicated work due to friction and other parasitic loads (other than engine loads) . So, BP is the measured output of the engine.**
- **Dynamometers are used to measure torque and power over engine operating ranges of speed and loads. Prony-brake (mechanical type), Hydraulic dynamometer and Eddy current dynamometers absorb energy output of the engine. Engine torque can be calculated from engine load with known radius or measured directly from the dynamometer.**
- **"Friction power" is the difference between IP and BP i.e. power required to overcome frictional resistance.**
- **"Mechanical efficiency" is the ratio of BP and IP (around 80 t0 90%).**

$BP = 2\pi N T; \; T = W R$ (Engine load, W; Radius, R; RPM, N)

$FP = IP - BP; \; \eta_m = \frac{BP}{IP}$

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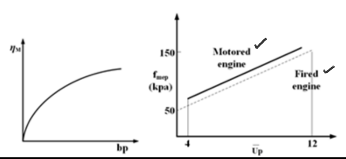
Mechanical and Combustion Performance

Brake power (BP), Friction power (FP) & Mechanical efficiency

- **Friction power is nearly constant at given engine speed.**
- **Mechanical efficiency increases with increase in BP.**
- **When the load is decreased giving lower value of BP, the mechanical efficiency decreases and at zero BP with same engine speed, the engine develops just sufficient power to overcome frictional resistance.**
- **Mechanical efficiency depends on IP & BP and can be found by evaluating them experimentally.**
- **In addition, there are other methods by which mechanical efficiency can be measured in a simplified manner for specific engines. These methods are, Motoring test, Morse test and Willan's Curve.**



$BP = 2\pi N T; \; T = W R$

$FP = IP - BP; \; \eta_m = \frac{BP}{IP}$

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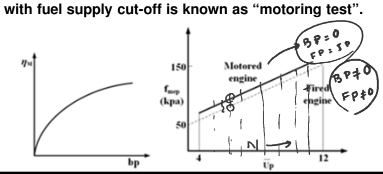
Mechanical and Combustion Performance

Mechanical efficiency (Motoring curve)

- **The engine is connected to the electric dynamometer that acts as motor instead of generator.**
- **The power required to drive the engine is given by the power consumed by the motor which is the frictional power (FP) at given speed. The values of FPs at different speed can also be calculated.**
- **The engine BP can also be calculated from the electric dynamometer, when it is connected as generator.**
- **The engine's IP (& hence mechanical efficiency) can then be obtained.**
- **So, the measurement of BP at a given speed followed by "motoring" of the engine with fuel supply cut-off is known as "motoring test".**



$BP = 2\pi N T; \; T = W R$

$FP = IP - BP; \; \eta_m = \frac{BP}{IP}$

All rpms

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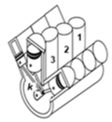
Mechanical and Combustion Performance

Mechanical efficiency (Morse test)

- It is applicable for multi-cylinder engines (either SI or CI).
- First, the engine is run at required speed and torque is measured.
- Consider *k* no. cylinders in an engine. The IPs are denoted as $I_1, I_2, \ldots I_k$ while BPs are denoted as $B_1, B_2 \ldots, B_k$ with respective losses $L_1, L_2, \ldots L_k$, respectively.
- Let us calculate BP of the engine by sequentially cutting of each cylinder. The speed will fall but it can be restored back by reducing the engine load. Then, toque can be measured when the speed is reached to original value.
- The cylinders can be cut-off by shorting spark plug for SI engines or disabling the fuel injectors for CI engines.



1: $IP_1 = BP_1 + L_1$

2: $IP_2 = BP_2 + L_2$

k: $IP_k = BP_k + L_k$

$\downarrow$ I $\quad \downarrow$ B

Mechanical and Combustion Performance

Mechanical efficiency (Morse test)

- When the first cylinder is cut, its contribution for IP is lost but its loss will still contribute in engine's BP calculation.
- By cutting each cylinder in turn, the IPs can be obtained in sequential manner.
- The fundamental assumption is that friction and pumping power of the shorted cylinder is same after shorting as they were when the engine is fully operative. This assumption is valid as long as speed remains constant.

The engine BP at test speed with all cylinders firing,

$$BP = (IP_1 - L_1) + (IP_2 - L_2) + \ldots\ldots + (IP_k - L_k)$$

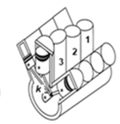
When first cylinder is cut, $BP_1 = (0 - L_1) + (IP_2 - L_2) + \ldots\ldots + (IP_k - L_k)$

When second cylinder is cut, $BP_2 = (IP_1 - L_1) + (0 - L_2) + \ldots\ldots + (IP_k - L_k)$

When k^{th} cylinder is cut, $BP_k = (IP_1 - L_1) + (IP_2 - L_2) + \ldots\ldots + (0 - L_k)$

$$\Rightarrow BP - BP_1 = IP_1;\ BP - BP_2 = IP_2 \ldots\ldots\ldots\ldots BP - BP_k = IP_k$$

$$\Rightarrow IP = IP_1 + IP_2 + \ldots\ldots + IP_k \quad \& \quad \eta_m = \frac{BP}{IP}$$



1: $IP_1 \; BP_1 \; L_1$

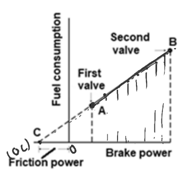
2: $IP_2 \; BP_2 \; L_2$

k: $IP_k \; BP_k \; L_k$

Mechanical and Combustion Performance

Mechanical efficiency (Willan's curve)

- This method is suitable for diesel engine where, engine's IP is measured graphically.
- At constant engine speed, the load is reduced in increments and the corresponding BP and gross fuel consumption is noted. A graph can be plotted against these two parameters which is known as Willan's line.
- The Willan's line when extrapolated back to cut the BP axis cuts at point 'C'.
- This is the friction power (FP) of the engine as the point 'C' is from origin. The IP can be found by adding FP to the BP of the engine.



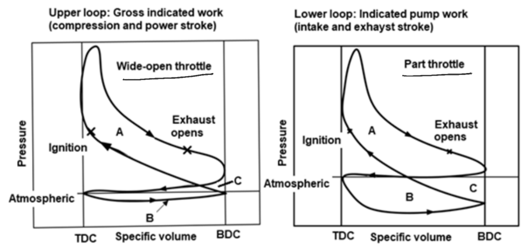
$\eta_m = \frac{BP}{IP}$

Mechanical and Combustion Performance

Brake mean effective pressure (BEMP) BMEP

- The BP of an engine can be measured accurately and conveniently by using a dynamometer. But, it is difficult to measure mechanical efficiency and indicated mean effective pressure of an engine.
- It is clear from *p-v* diagram that the pressure in the cylinder of an engine changes continuously during a cycle. So, an average mean effective pressure is defined for a fixed amount of work done per cycle.
- Based on MEP, one can define IMEP with respect to indicated power or BEMP with respect to brake power or FMEP with respect to friction power.
- BMEP is thought as mean effective pressure acting on pistons for a frictionless engine that would give measured BP.
- For instance, a large engine will provide higher torque while speed becomes important criteria when power consideration is important.
- BEMP is directly proportional to the engine torque, but independent on engine speed and size.

Mechanical and Combustion Performance



For a four stroke engine the BEMP expression may be written as follow:

$$w = mep(\Delta v) \;\; \Rightarrow mep = \frac{w}{\Delta v} = \frac{W}{V_d};\;\; \Delta v = v_{BDC} - v_{TDC}$$

$$BP = \eta_m IP = \eta_m (p_i A S k)\frac{N}{2} = (p_b A S k)\frac{N}{2};\;\; p_b = \eta_m p_i$$

$$BP = 2\pi NT;\; (p_b A S k)\frac{N}{2} = 2\pi NT \;\; \Rightarrow p_b = KT;\; K \text{ is an engine constant}$$

Mechanical and Combustion Performance

Thermal efficiency, Combustion efficiency and Specific fuel consumption

- The power output of the engine is obtained from chemical energy of the fuel. So, the overall efficiency of an engine is recognized as "brake thermal efficiency (BTE)" which is the ratio of brake work to the mass of fuel times its calorific value.
- The time available for combustion process of an engine cycle is very brief and not all fuel molecules find oxygen in short time. Local temperature also may not be favorable. So, "combustion efficiency" is defined as fraction of fuel burnt with respect to fuel supplied.
- Analogous to BTE, indicated thermal efficiency (ITE) can also be defined.
- The specific fuel consumption (SFC) is the mass of fuel consumed per unit power output and considered as criterion for economical power production.

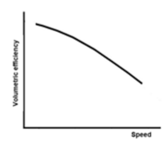
$$\eta_{BTE} = \frac{BP}{\dot{m}_f Q_{cv}};\; \eta_{ITE} = \frac{IP}{\dot{m}_f Q_{cv}};\; \frac{\eta_{BTE}}{\eta_{ITE}} = \frac{BP}{IP} = \eta_m \;\; \Rightarrow \eta_{BTE} = \eta_m \, \eta_{ITE}$$

$$\eta_c = \frac{Q_{in}}{\dot{m}_f Q_{cv}};\; sfc = \frac{\dot{m}_f}{BP};\; \eta_c = 0.95 \text{ to } 0.98;\; \eta_m = 0.8 \text{ to } 0.85;\; \eta_{ITE} = 0.4 \text{ to } 0.5;\; \eta_{BTE} = 0.3 \text{ to } 0.35$$

Mechanical and Combustion Performance

Volumetric efficiency

- The power output of an IC engine depends directly upon the amount of charge which can be inducted into the cylinder. It is referred as breathing capacity and expressed quantitatively by volumetric efficiency.
- It is the ratio of volume of air inducted measured at free atmospheric condition to the swept volume of the cylinder.
- The power output of the engine depends on its capacity to breathe. If a particular engine has constant thermal efficiency, then, the power output will be proportional to the amount of air induced.
- A normal natural aspiration engine has this value up to 80%. It can be increased through supercharging by a compressor/blower.
- It is affected by speed, compression ratio, valve timing, induction/port design, mixture strength, cylinder temperature, heating value of fuel and atmospheric condition.



$$\eta_v = \frac{V}{V_d}$$

Gaseous fuel

Emission Index

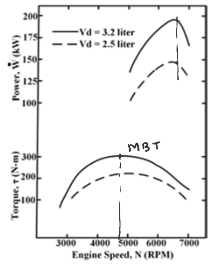
- There are four main exhaust emissions from the engine that should be controlled, namely, oxides of nitrogen (NOx), carbon monoxide (CO), hydrocarbons (HC) and solid particulates.
- The standard emissions norms have drive cycles that includes periods of acceleration, deceleration, steady state cruising and idling. The exhaust gases are continuously analyzed.
- The common methods for quantification of these emissions are, specific emissions [SE–(gm/kW-hr)] and emission index [EI–(gm/s)/(kg/s)].

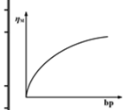
$$(SE)_{NO_x} = \frac{\dot{m}_{NO_x}}{BP};\; (SE)_{CO} = \frac{\dot{m}_{CO}}{BP};\; (SE)_{HC} = \frac{\dot{m}_{HC}}{BP};\; (SE)_{part} = \frac{\dot{m}_{part}}{BP}$$

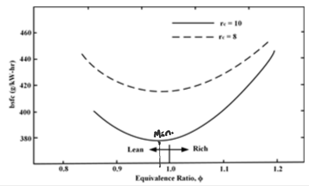
$$(EI)_{NO_x} = \frac{\dot{m}_{NO_x}}{\dot{m}_f};\; (EI)_{CO} = \frac{\dot{m}_{CO}}{\dot{m}_f};\; (EI)_{HC} = \frac{\dot{m}_{HC}}{\dot{m}_f};\; (EI)_{part} = \frac{\dot{m}_{part}}{\dot{m}_f}$$

Characteristics Curves

- Brake power / Torque as a function of engine speed and displacement
  - ➢ Indicated power increases with engine speed and displacement
  - ➢ Brake power increases to a maximum and then decreases because friction power increases with engine speed
  - ➢ The speed at which peak torque occurs is called as maximum brake torque (MBT).
- Brake specific fuel consumption (BSFC) as a function of fuel equivalence ratio
  - ➢ The fuel consumption is minimum at slightly lean condition

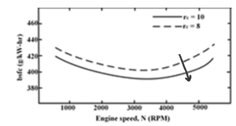


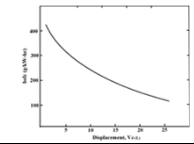




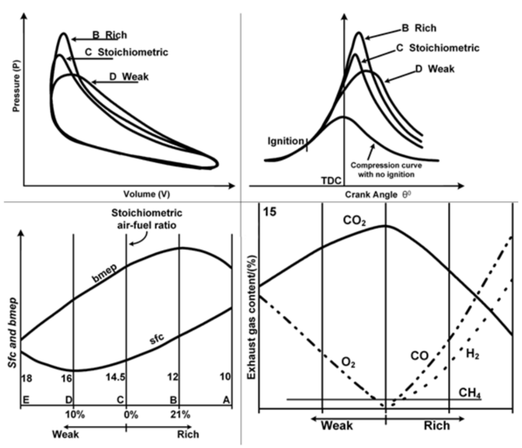
Characteristics Curves

- Brake specific fuel consumption (BSFC) as a function of engine speed and compression ratio
  - ➢ Fuel consumption decreases with increase in engine speed due to shorter time for heat loss during the cycle
  - ➢ At higher engine speed, the fuel consumption increases because of higher friction
  - ➢ As the compression ratio is increased, the fuel consumption decreases due to greater thermal efficiency
- Brake specific fuel consumption (BSFC) as a function of engine displacement
  - ➢ The average fuel consumption is less with larger engines
  - ➢ Larger engines have lower heat loss due to higher volume-to-surface-area ratio of combustion chamber
  - ➢ Larger engines operate at lower speeds to reduce friction losses



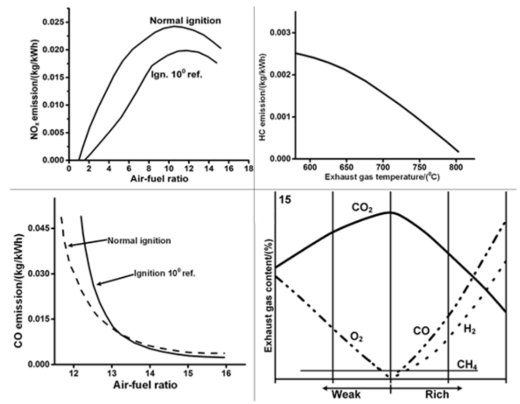


Characteristics Curves



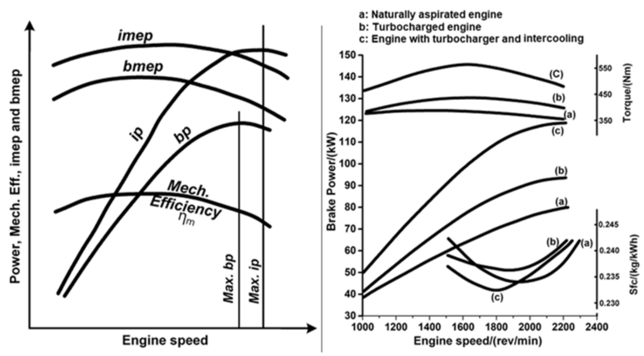
Spark Ignition Engines

Characteristics Curves



Spark Ignition Engines

Characteristics Curves



Compression Ignition Engines

Numerical Problems

Q1. A six –cylinder, 3-litre capacity engine operates on 4-stroke cycle at 3600 rpm. It is connected to a dynamometer that gives a torque reading 205 N-m. The mechanical efficiency of the engine is 85%. Calculate: (i) brake power; (ii) indicated power; (iii) brake mean effective pressure; (iv) indicated mean effective pressure; (v) friction mean effective pressure; (vi) power lost to friction.

Solⁿ

(i) $\dot{W}_b = 2\pi N \tau$ $\quad \tau = 205$ N.m., $N = 3600$ rpm.

$\dot{W}_b = 77.25$ kW

(ii) $\dot{W}_i = \frac{\dot{W}_b}{\eta_m} = \frac{77.25}{0.85} = 90.9$ kW

(iii) bmep $\quad \frac{\dot{W}_b}{N} = 2\pi\tau = \frac{bmep(V_d)}{n}$ $\quad V_d = 3L = 0.003$ m3.

$n = 2$ (4-stroke, 2 rev/cycle) $\quad bmep = \frac{2\pi\tau n}{V_d} = 859$ kPa

Numerical Problems

Q1. A six –cylinder, 3-litre capacity engine operates on 4-stroke cycle at 3600 rpm. It is connected to a dynamometer that gives a torque reading 205 N-m. The mechanical efficiency of the engine is 85%. Calculate: (i) brake power; (ii) indicated power; (iii) brake mean effective pressure; (iv) indicated mean effective pressure; (v) friction mean effective pressure; (vi) power lost to friction.

(iv) $imep = \frac{bmep}{\eta_m} = \frac{859}{0.85} = 1010$ kPa.

(v) $fmep = imep - bmep = 1010 - 859 = 151$ kPa.

(vi) $FP = \dot{W}_i - \dot{W}_b = 90.9 - 77.25 = 13.65$ kPa.

Numerical Problems

Q2. For the engine specified in Q1, the compression ratio is 9.5. It is connected to a dynamometer that gives a torque reading 205 N-m. The air enters the cylinder at 85 kPa and 60°C. The air-fuel ratio is 15 with fuel heating value of 44 MJ/kg and combustion efficiency of 97%. Calculate: (i) rate of fuel flow into the engine; (ii) brake thermal efficiency; (iii) indicated thermal efficiency; (iv) volumetric efficiency; (v) brake specific fuel consumption.

Solⁿ

(i) $m_f = \frac{m_a}{AF} = \frac{0.0005}{15} = 0.000033$ kg/cyl/cycle

$\dot{m}_f = 0.000033 \times 6 \times \frac{3600}{60} \times 2$

$\Rightarrow \dot{m}_f = 0.006$ kg/s.

(ii) $\eta_{BTE} = \frac{\dot{W}_b}{\dot{m}_f Q_{cv} \cdot \eta_c}$ $\quad \eta_c = 97\%$ $\quad Q_{cv} = 44000$ kJ/kg

$\dot{W}_b = 77.25$ kW.

$\eta_{BTE} = 30\%$

$m_a = \frac{pV}{RT} = \frac{p(V_d + V_c)}{RT}$

$R = 287$ J/kg.K $\quad CR = 9.5$

$T = (60 + 273)$ K $\quad \frac{V_d + V_c}{V_c} = 9.5$

$p = 85$ kPa. $\quad$ 6-cyl. $\quad V_d = \frac{3}{6} = 0.5$ L

$m_a = 0.0005$ kg. $\quad V_c = 0.0006$ m3.

Numerical Problems

Q2. For the engine specified in Q1, the compression ratio is 9.5. It is connected to a dynamometer that gives a torque reading 205 N-m. The air enters the cylinder at 85 kPa and 60°C. The air-fuel ratio is 15 with fuel heating value of 44 MJ/kg and combustion efficiency of 97%. Calculate: (i) rate of fuel flow into the engine; (ii) brake thermal efficiency; (iii) indicated thermal efficiency; (iv) volumetric efficiency; (v) brake specific fuel consumption.

(iii) $(\eta_t)_i = \frac{(\eta_t)_{BTE}}{\eta_m} = \frac{0.3}{0.85} = 35\%$

(iv) $\eta_v = \frac{m_a}{\rho_a V_d}$ $\quad m_a = 0.0005$ kg.

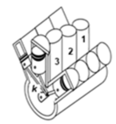
$\rho_a = 1.2\ kg/m^3$

$\eta_v = 85\%$ $\quad V_d = 0.0005\ m^3$.

(v) $bsfc = \frac{\dot{m}_f}{\dot{W}_b} = \frac{0.006\ kg/s}{77.3\ kW} = 7.76 \times 10^{-5}\ kg/kW.s.$

Numerical Problems

Q3. A Morse test is conducted for a four-cylinder petrol engine at a rated speed of 2800rpm with net brake load of 160N. The cylinders of the engine are cut out in the order 1, 2, 3, 4 with their corresponding brake loads of 110.8 N, 106.5 N, 104.2 N, and 110.2 N, respectively. Calculate the indicated load and mechanical efficiency of the engine.



1: $IP_1\ BP_1\ L_1$
2: $IP_2\ BP_2\ L_2$
k: $IP_k\ BP_k\ L_k$

$BP = 160$ N.

$BP_1 = 110.8$ N $\quad BP_2 = 106.5$ N

$BP_3 = 104.2$ N $\quad BP_4 = 110.2$ N.

$IP_1 = BP - BP_1 = 49.2$ N

$IP_2 = BP - BP_2 = 53.5$ N

$IP_3 = BP - BP_3 = 55.8$ N

$IP_4 = BP - BP_4 = 49.8$ N.

$IP = 208.3$ N.

$\eta_m = \frac{BP}{IP} = \frac{160}{208.3} = 76.8\%$

THANK YOU