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Detailed Solutions

ESE-2024 Mains Test Series

Mechanical Engineering Test No : 8

Section A : Machine Design + Mechatronics & Robotics **[All Topics]**

Section B : IC Engine **[All Topics]**

Renewable Sources of Energy-2 + Industrial and Maintenance Engg.-2 **[Part syllabus]**

Section : A

1. (a)

Some of the common instructions are as follows:

1. **Load:** This instruction reads the contents of a particular memory location and copies to a specific register in the processor. Example: Say a data is stored in memory location 1110. This data would be copied to the accumulator (register).
2. **Store:** This is the reverse of load instruction. This copies data in a register to a specified memory location.
3. **Add:** This instruction adds the data or the contents of a specified memory location to the data in some particular register.
4. **Decrement:** This instruction subtracts 1 from the contents of a specified location. For example, we may have the accumulator as the specified location.
5. **Compare:** This instruction compares the contents of register and a specified memory location and indicates whether it is greater than, less than or equal to the contents of the memory location. This result appears as flag in the status register.
6. **AND, Exclusive-OR:** These instructions AND and Exclusive-OR do the logical operations of AND- ing and EX-ORing, respectively, the respective bits of the data element of a specified memory location and the data in some other register.

7. **Logical Shift (Left or Right):** These instructions move the pattern of bits one place to the left or to the right by moving a 0 to the end of the number. Logical shift right shifts in 0 into the MSB. For example, for logical shift right a 0 is shifted to the MSB and the LSB is shifted to the carry flag in the status register.
8. **Arithmetic Shift (Left or Right):** Arithmetic shift instruction involves moving the pattern of bits in the register one place to the right or left. Arithmetic shift right retains the MSB and shifts all others to the right. Arithmetic shift left shifts every bit one position left and the MSB is shifted to carry and whatever is there in carry is dropped.
9. **Rotate (Left or Right):** Rotate moves the pattern of bits in the register one place to the left or to the right and the bit that spills over is written back into the other end.
10. **Jump:** Jump instruction changes the sequence in which the program is being carried out. For example: Jump to the instruction if the accumulator is not zero.
11. **Branch:** This instruction makes the program to take a different branch of instructions when a particular condition is satisfied.
12. **Halt:** This instruction stops all further activity.

1. (b)

Given : P_{min} = 300 kN; P_{max} = 600 kN; σ_{ut} = 900 MPa; σ_{ut} = 700 MPa; $(F.S)_e$ = 4; $(F.S)_u$ = 3.5; k_f = 1.65

$$\text{Area, } A = \frac{\pi}{4}d^2 = 0.785d^2$$

Also,
$$P_m = \frac{P_{max}+P_{min}}{2} = \frac{600+300}{2} = 450 \text{ kN}$$

$$P_v = \frac{P_{max}-P_{min}}{2} = \frac{600-300}{2} = 150 \text{ kN}$$

Now, mean stress and variable stresses are

$$\sigma_m = \frac{P_m}{A} = \frac{4\times 450\times 10^3}{\pi d^2} = \frac{572957.79}{d^2} \text{ N/mm}^2$$

and
$$\sigma_v = \frac{P_v}{A} = \frac{4\times 150\times 10^3}{\pi d^2} = \frac{190985.93}{d^2} \text{ N/mm}^2$$

According to Goodman's formula

$$\frac{k_f \cdot \sigma_v \cdot (F.S)_e}{\sigma_e} + \frac{\sigma_m \cdot (F.S)_u}{\sigma_{ut}} = 1$$

$$\therefore \quad \frac{1.65\times 190985.93\times 4}{700} + \frac{572957.79\times 3.5}{900} = d^2$$

or
$$d = 63.47 \text{ mm}$$ **Ans.**

1. (c) (i)

For $\quad \text{Rot}(x, \theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C & -S \\ 0 & S & C \end{bmatrix}$ we have:

$$\mathbf{n}\cdot\mathbf{o} = 0 \text{ or } n_x o_x + n_y o_y + n_z o_z = 0$$

$$\mathbf{n}\cdot\mathbf{a} = 0$$

$$\mathbf{a}\cdot\mathbf{o} = 0$$

$$|\mathbf{n}| = 1$$

$$|\mathbf{o}| = \sqrt{S^2 + C^2} = 1$$

$$|\mathbf{a}| = \sqrt{(-S)^2 + C^2} = 1$$

Rot (y, θ) and Rot(z, θ) will be the same.

(ii)

The frame can be expressed by three vectors describing its directional unit vectors and a fourth vector describing its location as

$$F = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Hence, $\quad F = \begin{bmatrix} n_x & 0 & -1 & 5 \\ n_y & 0 & 0 & 3 \\ n_z & -1 & 0 & 2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

From $\quad n \times o = a$

$$\begin{bmatrix} i & j & k \\ n_x & n_y & n_z \\ 0 & 0 & -1 \end{bmatrix} = -i$$

or $\quad i(-n_y) - J(-n_x) + k(0) = -i$

and therefore, $\quad n_y = 1, n_x = 0, n_z = 0$

$$\therefore \quad F = \begin{bmatrix} 0 & 0 & -1 & 5 \\ 1 & 0 & 0 & 3 \\ 0 & -1 & 0 & 2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{Ans.}$$

1. (d)

Given : P = 50 kN; τ_{max} = 60 MPa; b = 100 mm; d = 150 mm; e = 500 mm

Let s = Size of weld, and t = throat thickness

$$\text{Area, } A = t\,(2b + 2d)$$
$$= t\,(2 \times 100 + 2 \times 150)$$
$$= 500t \text{ mm}^2$$

$$\therefore \quad \text{Direct shear stress, } \tau = \frac{P}{A} = \frac{50 \times 10^3}{500t} = \frac{100}{t} \text{ N/mm}^2$$

$$I_{xx} = I_{xx_1} + I_{xx_2}$$

$$= 2\left[\frac{bt^3}{12} + bt \times \left(\frac{d}{2}\right)^2\right] + 2\left[\frac{td^3}{12}\right]$$

Assuming b and d to be large as compared to the throat dimension t and neglecting the term containing t^3, we have

$$I_{xx} = t\left[\frac{bd^2}{2} + \frac{d^3}{6}\right]$$

Substituting the values,

$$I_{xx} = t\left[\frac{100 \times 150^2}{2} + \frac{150^3}{6}\right] = 1687500t \text{ mm}^4$$

$$\therefore \quad \text{Section modulus, } Z = \frac{I_{xx}}{y} = \frac{1687500t}{75}$$

$$Z = 22500t \text{ mm}^3$$

$$\therefore \quad \text{Bending stress, } \sigma_b = \frac{M}{Z} = \frac{50 \times 10^3 \times 500}{22500t}$$

$$\therefore \quad \sigma_b = \frac{1111.11}{t} \text{ N/mm}^2$$

We know that,

$$\tau_{max} = \frac{1}{2}\sqrt{(\sigma_b)^2 + 4\tau^2}$$

or $$60 = \frac{1}{2}\sqrt{1111.11^2 + 4\times 100^2} \times \frac{1}{t}$$

$$t = \frac{\sqrt{1111.11^2 + 4\times 100^2}}{2\times 60} = 9.4 \text{ mm}$$

$\therefore$ $$\text{Size of weld, } s = \frac{t}{0.707} = \frac{9.4}{0.707}$$

$$s = 13.29 \text{ mm}$$ **Ans.**

1. (e)

The following aspects should be considered for the selection of a PLC for given applications:

1. **System definition:** A technique of functional decomposition can be applied to define the whole system, with hardware and software, as it is defining the program alone.
2. **Choosing the I/O hardware:** Various types of input and output modules are available, based on the type and speed of operation. A list of modules and the size of the PLC system are determined by knowing the member of any type of I/O line we need, and the number of the lines available on a given module.
3. **I/O timing consideration:** It is most important to determine how fast (speed of operation) the sub-system of input program and output must react to changing input conditions. Normally, the speed of operation will be the sum of the input hardware delays, plus the PLC scan time plus any output hardware delays.
4. **Analog I/O module:** There are many terms used to set out to select analog modules for describing performance. They are as follows:
   - **Resolution:** Define how accurately the analog-to-digital (A/D) or digital-to-analog (D/A) converter within the module can represent an analog voltage as a binary number or vice versa.
   - **Isolation:** Refers to the ability of each unit/input to work at a voltage level independent of the system ground.
   - **Voltage level:** It is essential to know the maximum voltage of the input to be measured, and then the modules voltage range is selected just greater than this level. Most output modules provide ±10 V outputs. This can be scaled with a potential divider to the required level.
   - **Current level (I/O module):** A 4-20 mA current loop for input is the common choice in order to avoid all the problems of voltage level selection. A 4-10 A current loop output is always advantageous to use.

5. **Conversion speed:** The choice of conversion speed basically depends on the number of readings per second we need to capture. There are two types of A/D converters. A converter which performs a conversion every 20 ms gives a good clean reading free from line frequency interference. The other one will convert in 2-20 ms for measuring transient input data.
6. **Analog closed control:** Analog inputs sometimes are used as feedback to control a process by controlling relay outputs or varying an analog output. In such case, scan speed must be estimated from the program size taking into account the execution speed of the controller module.
7. **Counters, encoders and positioning:** In order to select the PLC hardware, we need to consider the speed, the total numbers of pulses to be counted, the positioning accuracy.
8. **Communications:** All PLCs have some sort of built in communications facility through the programmer port. If a built-in communication facility is not sufficient then the option of add-on ports, high-speed LAN, etc. should be considered.
9. **Choosing the correct processor:** A PLC processor is selected based on capacity, functionality, program speed and size. Capacity is determined by the capability of the processor to work with a number of each type of module. Functionality of PLC is the capability to be programmed to perform the logical operations required for the control of plant and sequences. The program scan speed is dependent upon the speed of operation of the PLC and the length of the program. The maximum speed of PLC that any input is read of any output is switched is equal to the program scan time. The size of program is dependent upon the complexity of the control problem and the skill and style of the programmer.
10. **Selecting suppliers:** The choice of supplier for a PLC is based on the following:
    - functionality and features;
    - customer support;
    - customer acceptability;
    - user knowledge;
    - cost.

2. (a)

Given : b = 200 mm; t = 10 mm; σ_t = 115 MPa; σ_c = 200 MPa; τ = 90 MPa; d = 24 mm

(i) Number of rivets,

Let, n = Number of rivets

We know that the maximum pull acting on the joint,

$$P_t = (b - d_h) \cdot t \times \sigma_t$$
$$= (200 - 24) \times 10 + 115$$
$$P_t = 202400 \text{ N}$$

Since there is a lap joint, therefore shearing resistance of one rivet.

$$P_{s_1} = \frac{\pi}{4} d^2 \times \tau = \frac{\pi}{4} \times 24^2 \times 90$$

$$\therefore \quad P_{s_1} = 40715.04 \text{ N}$$

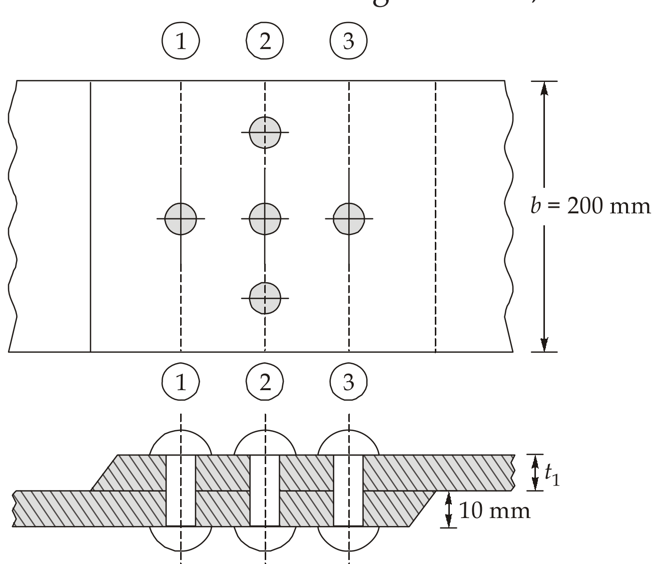
and crushing resistance of one rivet

$$P_{c_1} = \sigma_c \cdot d \cdot t$$
$$P_{c_1} = 200 \times 24 \times 10 = 48000 \text{ N}$$

Since shearing resistance is less than the crushing resistance, therefore number of rivets required for the joint,

$$n = \frac{P_e}{P_s} = \frac{202400}{40715.04} = 4.97 \simeq 5$$ **Ans.**

The arrangement of the rivets is shown in figure below,



(ii) Efficiency of the joint,

Resistance of the joint in tearing along section 1-1,

$$P_{t_1} = (b - d)t \times \sigma_t$$
$$= (200 - 24) \times 10 \times 115$$
$$P_{t_1} = 202400 \text{ N}$$

Similarly at section 2-2,

$$P_{t_2} = (b - 3d)t \times \sigma_t + \text{Shearing resistance of one rivet}$$
$$= (200 - 3 \times 24) \times 10 \times 115 + 40715.04$$
$$P_{t_2} = 187915.04 \text{ N}$$

Shearing and crushing of all the five rivets,

$$P_s = 5 \times 40715.04 = 203575.2 \text{ N}$$

and $$P_c = 5 \times 48000 = 240000 \text{ N}$$

Since the strength of the joint is the least value of P_{t_1}, P_{t_2}, P_s and P_c.

Therefore strength of the joint,

$$P_{min} = 187915.04 \text{ at section } 2 - 2$$

Strength of the un-riveted plated,

$$P_{solid} = bt\sigma_t = 200 \times 10 \times 115 = 230000 \text{ N}$$

$\therefore$ Efficiency of the joint, $$\eta = \frac{\text{Strength of the joint}}{\text{Strength of the un-riveted plate}}$$

$$\eta = \frac{187915.04}{2300000} \times 100 = 81.7\%$$ **Ans.**

2. (b) (i)

Dynamic Characteristics : In many practical cases, the parameters to be measured are time varying, that is, they are dynamic in nature. Thus, the output of an instrument is also time varying. The behavior of an instrument under such time- varying input-output conditions is called the dynamic response of an instrument. The analysis of such dynamic response is called dynamic analysis of the measurement system. Dynamic quantities are of two types, namely.

1. **Steady-state periodic:** An output whose magnitude has a definite repeating time cycle is called steady- state periodic.

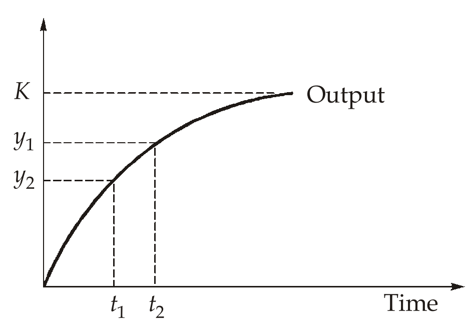


Fig. : Step response of the first order system

2. **Transient:** An output whose magnitude does not repeat with time is known as transient.

The system response of first order and second order can be described by following specification parameters.

1. **Over shoot:** The maximum amount by which the moving parts move beyond the steady state is known as an over shoot.
2. **Time constant:** Time constant is a measure of the inertia of the transducer. It is the measure of how fast a transducer reacts to change in its input. Therefore, the bigger the time constant the slower is its reaction to a changing input.
3. **Response time:** Response time is defined as the rapidity with which a measurement system responds to a change in the measured quantity or the time at which the transducer gives an output corresponding to some specified percentage. Step response of the first-order system is shown in figure. It indicates that the impulse function has infinite high magnitude and duration. Practically, this mode of operation is not used in any system due to large impulses in very short duration when compared to other types of input mode.
4. **Rise time:** This is the time taken for the output to rise to some specified percentage of the steady-state output. That is, it is the time taken for the output to rise from 10% to 90% or 95% of the steady-state value.
5. **Setting time:** This is the time taken for the output to settle within some percentage.
6. **Types of input:** The parameter which determines the behavior of any system is known as the input function. The various types of inputs are as follows:
   - step input;
   - ramp input;
   - impulse input;
   - sinusoidal input.

2. (b) (ii)

$$\text{Guage factor, } GF = \frac{\Delta R/R}{\Delta L/L}$$

$$\therefore \quad \Delta L = \frac{(\Delta R/R)\cdot L}{GF} = \frac{0.025 \times 0.15}{3 \times 250}$$

$$\therefore \quad \Delta L = 5 \times 10^{-6}\ \text{m}$$ **Ans.**

$$\text{Stress, } \sigma = E \times \epsilon = E\cdot\frac{\Delta L}{L}$$

$$\sigma = \frac{200 \times 10^9 \times 5 \times 10^{-6}}{0.15} = 6.67 \text{ MPa}$$

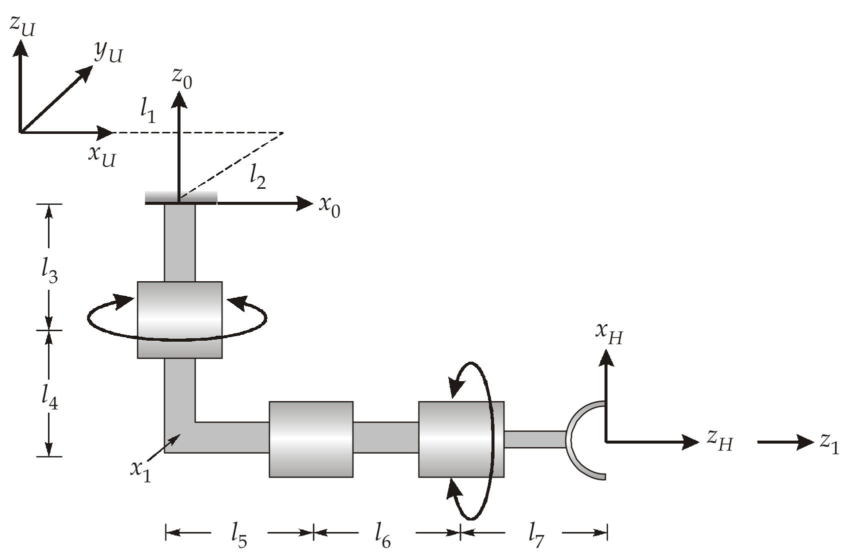
$\therefore$ Force applied, $F = \sigma \cdot A$

$$= 6.67 \times 10^6 \times 10 \times 10^{-4}$$

$$= 6.67 \text{ kN}$$ **Ans.**

2. (c)

We assume all positions are made relative to the base of the robot, and therefore, ${}^UT_0$ is not included in the solution. Using the Denavit-Hartenberg representation and the joint parameters shown, we get:



Link	θ	*d*	*a*	α
0 – 1	$-90 + \theta_1$	$-l_3 - l_4$	0	–90
1 – H	θ_2	$l_5 + l_6 + l_7$	0	0

$$A_1 = \begin{bmatrix} S_1 & 0 & C_1 & 0 \\ -C_1 & 0 & S_1 & 0 \\ 0 & -1 & 0 & -l_3 - l_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} C_2 & -S_2 & 0 & 0 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 1 & l_5 + l_6 + l_7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^0T_H = A_1A_2$$

$$\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} S_1 & 0 & C_1 & 0 \\ -C_1 & 0 & S_1 & 0 \\ 0 & -1 & 0 & -l_3 - l_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_2 & -S_2 & 0 & 0 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 1 & l_5 + l_6 + l_7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} S_1C_2 & -S_1S_2 & C_1 & C_1(l_5 + l_6 + l_7) \\ -C_1C_2 & S_2C_1 & S_1 & S_1(l_5 + l_6 + l_7) \\ -S_2 & -C_2 & 0 & -l_3 - l_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

From 1, 3 and 2, 3 elements we get: $\begin{cases} S_1 = a_y \\ C_1 = a_x \end{cases} \rightarrow \theta_1 = ATAN2(a_y, a_x)$

From 3, 1 and 3, 2 elements we get: $\begin{cases} S_2 = -n_z \\ C_2 = -o_x \end{cases} \rightarrow \theta_2 = ATAN2(-n_z, -o_z)$

From 1, 4 elements we get : $C_1(l_5 + l_6 + l_7) = p_x \rightarrow l_5 + l_6 + l_7 = \dfrac{p_x}{C_1}$

3. (a)

Given : $P = 40$ kW; $N = 180$ rpm; $\dfrac{T_1}{T_2} = 3.5$; $W_B = 800$ N; $W_A = 2500$ N; $t = 72$ MPa; $k_m = 2$; $k_t = 1.5$; $D_B = 750$ mm or $R_B = 375$ mm; $D_A = 1250$ mm or $R_A = 625$ mm

Torque transmitted by the shaft,

$$T = \frac{60P}{2\pi N} = \frac{60 \times 40 \times 10^3}{2\pi \times 180}$$

$\therefore \quad T = 2122.065$ Nm

Let T_1 and T_2 are Tensions in the tight and slack side of the belt on pulley A, respectively

$\therefore \quad (T_1 - T_2) \cdot R_A = 2122.065$

or $\quad (3.5T_2 - T_2) \times 0.625 = 2122.065$

$\therefore \quad T_2 = 1358.12$ N

and $\quad T_1 = 4753.42$ N

$\therefore$ Total vertical load acting downward on the shaft at A

$$= T_1 + T_2 + W_A$$

$$= 4753.42 + 1358.12 + 2500$$
$$= 8611.54 \text{ N}$$

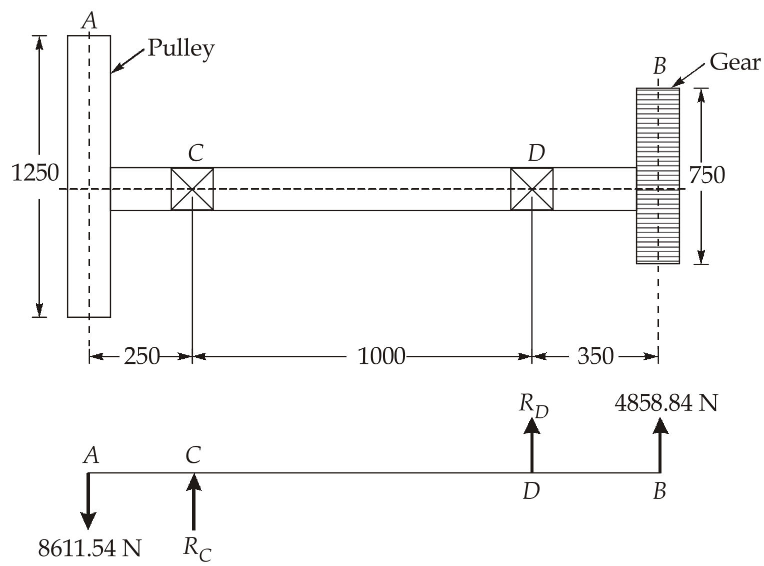
Tangential force acting vertically upward at B,

$$F_t = \frac{T}{R_B} = \frac{2122.065}{0.375} = 5658.84 \text{ N}$$

∴ Total vertical load acting upward on shaft at B

$$= F_t - W_B$$
$$= 5658.84 - 800$$
$$= 4858.84 \text{ N}$$

Let R_C and R_D be the reactions at C and D respectively



(All dimensions are in mm)

Taking moments about D, we get

$$R_C \times 1000 = 8611.54 \times 1250 + 4858.84 \times 350$$

∴ $$R_C = 12465.02 \text{ N}$$

For the equilibrium of the shaft,

$$R_D + 8611.54 = R_C + 4858.84$$

∴ $$R_D = 8712.32 \text{ N}$$

Now, B.M. at A and B = 0

B.M. at C = $8611.54 \times 0.25 = 2152.88$ Nm

B.M. at D = $4858.84 \times 0.35 = 1700.59$ Nm

∴ Maximum B.M., M_C = 2152.88 Nm

Equivalent twisting moment,

$$T_e = \sqrt{(k_m \times M_c)^2 + (k_t \times T)^2}$$

$$T_e = \sqrt{(2 \times 2152.88)^2 + (1.5 \times 2122.065)^2}$$

$$T_e = 5354.59 \text{ Nm}$$

Also, $$\tau_{per} = \frac{16T_e}{\pi d^3}$$

or $$d^3 = \left(\frac{16 \times 5354.59 \times 10^3}{\pi \times 72}\right)$$

or $$d = 72.35 \text{ mm}$$ **Ans.**

3. (b)

From a free body diagram as shown in figure (a), spring forces and damping force can be determined. Analyzing free body diagram for mass M_1, we get

$$SF_1 = K_1 x_1$$

$$SF_2 = K_2(x_1 - x_2)$$

$$DF_1 = B_1 \frac{dx_1}{dt}$$

$$DF_2 = B_2 \frac{d(x_1 - x_2)}{dt}$$

From Newton's second law of motion,

$$\text{Mass} \times \text{Acceleration} = -SF_1 - DF_1 - SF_2 - DF_2$$

$$M_1 \frac{d^2 x_1}{dt^2} = -K_1 x_1 - B_1 \frac{dx_1}{dt} - K_2(x_1 - x_2) - B_2 \frac{d(x_1 - x_2)}{dt} \quad \text{...(i)}$$

$$M_1 \frac{d^2 x_1}{dt^2} + (B_1 + B_2)\frac{dx_1}{dt} + (K_1 + K_2)x_1 = B_2 \frac{dx_2}{dt} + K_2 x_2$$

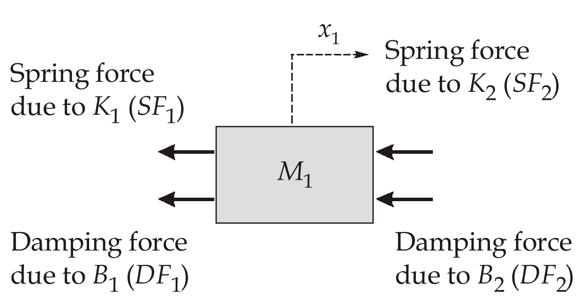


Figure (a) : Free body diagram for M_1

Taking Laplace transform of equation (i), we get

$$\left[M_1 s^2 + (B_1 + B_2)s + (K_1 + K_2)\right]X_1(s) = [B_2 s + K_2]X_2(s) \quad \text{...(ii)}$$

Free body diagram for mass M_2 as shown in figure (b), we get

$$\text{Mass} \times \text{Acceleration} = F + SF_2 + DF_2$$

$$M_2 \frac{d^2 x_2}{dt^2} = +K_2(x_1 - x_2) + B_2 \frac{d(x_1 - x_2)}{dt} + F$$

$$M_2 \frac{d^2 x_2}{dt^2} + B_2 \frac{dx_2}{dt} + K_2 x_2 = K_2 x_1 + B_2 \frac{dx_1}{dt} + F \quad \text{...(iii)}$$

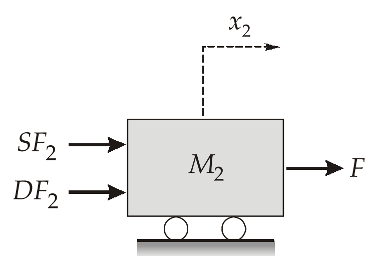


Figure (b) : Free body diagram for M_2

Laplace transform of equation (iii) can be written as

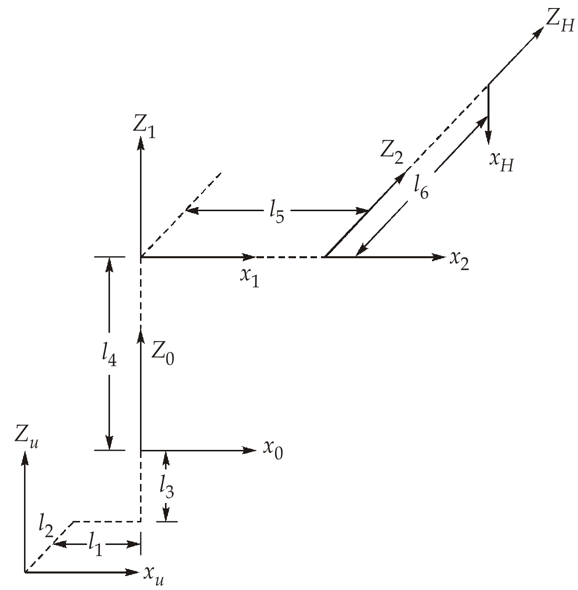
$$\left[M_2 s^2 + B_2 s + K_2\right]X_2(s) = [K_2 + B_2 s]X_1(s) + F(s) \quad \text{...(iv)}$$

Substituting the value of $X_2(s)$ from equation (iv) in equation (ii), we can related $X_1(s)$ and $F(s)$ as

$$\left[\frac{\left\{M_1 s^2 + (B_1 + B_2)s + (K_1 + K_2)\right\}\left(M_2 s^2 + B_2 s + K_2\right) - (K_2 + B_2 s)^2}{K_2 + B_2 s}\right]X_1(s) = F(s)$$

3. (c)

In this solution, the locations of the origins of the some of the frames are arbitrary. Therefore intermediate matrices might be different for each case. However, the final answer should be the same.



From above frame assignment, we will prepare the DH parameter table as shown below:

Link	θ_i	d_i	a_i	α_i
$\theta - 1$	θ_1	l_4	0	0
$1 - 2$	0	0	l_5	–90
$2 - H$	90	l_6	0	0

The composite transformation matrix, which describes frame $\{i\}$ with respect to frame $\{i - 1\}$, is obtained as

$$^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where, $C\theta_i = \cos\theta_i$, $S\theta_i = \sin\theta_i$, $C\alpha_i = \cos\alpha_i$, $S\alpha_i = \sin\alpha_i$.

By making substitutions, we get individual transformation matrix as,

$$A_1 = \begin{bmatrix} C_1 & -S_1 & 0 \\ S_1 & C_1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}; \quad A_2 = \begin{bmatrix} 1 & 0 & 0 & l_5 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \quad A_3 = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & l_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\therefore \quad {}^{U}T_H = {}^{U}T_R\,{}^{R}T_H = {}^{U}T_R \times A_1 \times A_2 \times A_3$$

Where, $$^{U}T_R = \begin{bmatrix} 1 & 0 & 0 & l_1 \\ 0 & 1 & 0 & l_2 \\ 0 & 0 & 1 & l_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{U}T_H = \begin{bmatrix} 1 & 0 & 0 & l_1 \\ 0 & 1 & 0 & l_2 \\ 0 & 0 & 1 & l_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & l_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & l_5 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & l_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

On solving and simplifying, we get,

$$^{U}T_H = \begin{bmatrix} 0 & -C_1 & -S_1 & -S_1 l_6 + C_1 l_5 + l_1 \\ 0 & -S_1 & C_1 & C_1 l_6 + S_1 l_5 + l_2 \\ -1 & 0 & 0 & l_4 + l_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4. (a)

Given : $P = 30$ kW; $N_P = 320$ rpm; V.R. $= \dfrac{T_G}{T_P} = 3$; $\sigma_P = 120$ MPa; $\sigma_G = 100$ MPa;

$T_P = 15$; $b = 14$ m

Let m = Module in mm, D_P = Pitch circle diameter of pinion

$$\therefore \quad \text{Pitch line velocity, } v = \frac{\pi D_P N_P}{60} = \frac{\pi m \times 15 \times 320}{60 \times 1000}$$

$$\therefore \quad v = 0.251\,m \text{ m/s}$$

$$\text{Tangential tooth load, } F_{eff} = \frac{P}{v} \times C_s = \frac{30 \times 10^3}{0.251\,m} \times 1$$

$$\therefore \quad F_{eff} = \frac{119521.91}{m} \text{N}$$

$$\text{and velocity factor, } C_v = \frac{3}{3+v} = \frac{3}{3 + 0.251m}$$

Tooth form factor for pinion and gear

$$y_p = 0.154 - \frac{0.912}{T_P} = 0.154 - \frac{0.912}{15}$$

$$y_p = 0.0932$$

and $$y_p = 0.154 - \frac{0.912}{T_G} = 0.154 - \frac{0.912}{3 \times 15}$$

$$y_G = 0.1337$$

$\therefore$ $\sigma_P \cdot y_p = 120 \times 0.0932 = 11.184$

and $\sigma_G \cdot y_G = 100 \times 0.1337 = 13.37$

Since the value of $(\sigma_P \cdot y_P)$ is less than the value of $(\sigma_G \cdot y_G)$, therefore the pinion is weaker. Now using the Lewis equation to the pinion, we have

$$F_{eff} = \sigma_P \cdot y_P \cdot \pi \cdot m \cdot b \cdot C_v$$

$$\frac{119521.91}{m} = 120 \times 0.0932 \times \pi \times m \times 14m \times \left(\frac{3}{3+0.251m}\right)$$

$$\frac{119521.91}{m} = \frac{1475.69m^2}{3+0.251m}$$

or $358565.73 + 29999.99\, m = 1475.69\, m^3$

On solving above equation, we get

$$m = 7.3 \text{ mm} \simeq 8 \text{ mm}$$ **Ans. (i)**

Face width, $b = 14\, m = 14 \times 8 = 112$ mm **Ans.(ii)**

$$D_P = mT_P = 8 \times 15 = 120 \text{ mm}$$

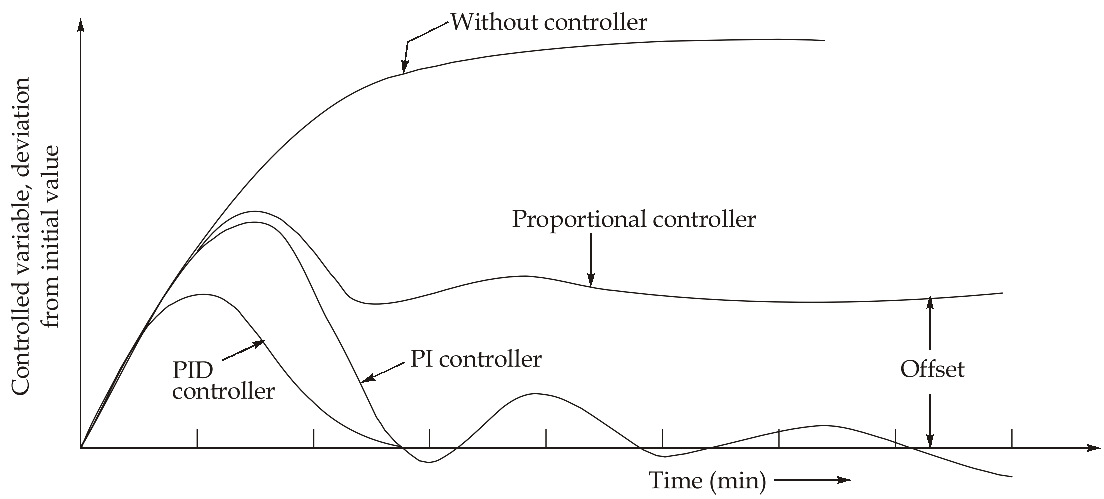
$$D_G = mT_G = 8 \times 45 = 360 \text{ mm}$$ **Ans.(iii)**

4. (b) (i)

With proportional action only, the control system is able to arrest the rise of the controlled variable and ultimately bring it to rest at a new steady-state value. However, there is no offset between new value and steady-state value. Table gives a comparison of common control actions.

The addition of integral controller eliminates the offset; the controlled variable ultimately returns to the original value, but has more oscillatory behavior. The PID controller gives a definite improvement with little or no offset and oscillations. The response of a typical control system with various modes of controller action is shown in Figure.

Comparison of control actions



Comparison of controller action

Control action	Advantages	Disadvantages
On/off	Simple, inexpensive	Mechanical problems and inaccuracy
Proportional	Simple and fast response	Offset errors and instability
Integral	Reduce noise effect and offset error	Slow response and instability
Derivative	Fast response, good stability	Insensitive to error, noise problem

4. (b) (ii)

(a) Offset value : Bias value is the output value with zero error at the steady-state operation. Hence,

$$\text{Steady-state output} = \text{Outflow rate} = 40 \text{ LPM}$$

Therefore,
$$\text{Offset value} = \frac{\text{Steady-state output}}{\text{Valve inflow rate}}$$

$$= \frac{40\,\text{LPM}}{10\,\text{LPM/V}} = 4V \qquad \textbf{Ans.}$$

(b) Tank level when output flow changes : As the output is changed, an error is produced. The generation equation for controller output is

$$\text{Output of the controller} = k_p . e + \text{Offset}$$

Now, $k_p = 5$ and Bias $(m_0) = 4\text{V}$

$\therefore$ $m = 5e + 4$

The required control output for an outflow of 60 LPM = Output rate/Valve inflow rate i.e.Output of the controller $(m) = \dfrac{60\,\text{LPM}}{10\,LPM/V} = 6V$

Therefore, $6V = 5e + 4V$

∴ $e = 0.4\text{V} = 400 \text{ mV}$

Level corresponding to error voltage of 400 mV $= \dfrac{\text{Error voltage}}{\text{Level transmitter ouput}}$

$$= \frac{400\,\text{mV}}{12\,\text{mV/cm}} = 33.33 \text{ cm}$$ **Ans.**

4. (c)

Dynamic equivalent radial load considering service factor is

$$P = (xvF_R + yF_A)\cdot k_s$$

Now substituting the values, we have

$$P_1 = (2000 + 1.5 \times 1200) \times 3 = 11400 \text{ N}$$
$$P_3 = (1500 + 1.5 \times 1000) \times 1.5 = 4500 \text{ N}$$
$$P_3 = (1000 + 1.5 \times 1500) \times 2 = 6500 \text{ N}$$
$$P_4 = (1200 + 1.5 \times 2000) \times 1 = 4200 \text{ N}$$

Life of bearing in revolutions

$$L = 60\ N\cdot L_H = 60\cdot N \times 20000$$
$$= 1.2 \times 10^6 \text{ N rev}$$

∴ Life of bearing for different operating cycles,

$$L_1 = \frac{1}{10} \times 1.2 \times 10^6 \times 400 = 48 \times 10^6 \text{ rev}$$
$$L_2 = \frac{1}{10} \times 1.2 \times 10^6 \times 500 = 60 \times 10^6 \text{ rev}$$
$$L_3 = \frac{1}{5} \times 1.2 \times 10^6 \times 600 = 144 \times 10^6 \text{ rev}$$
$$L_4 = \frac{3}{5} \times 1.2 \times 10^6 \times 800 = 576 \times 10^6 \text{ rev}$$

∴ Equivalent dynamic load for the complete work cycle,

$$P_{eq} = \left(\frac{L_1P_1^3 + L_2P_2^3 + L_3P_3^3 + L_4P_4^3}{L_1 + L_2 + L_3 + L_4}\right)^{1/3}$$

$$P_{eq} = \left(\frac{(48\times 11400^3 + 60\times 4500^3 + 144\times 6500^3 + 576\times 4200^3)\times 10^6}{(48+60+144+576)\times 10^6}\right)^{1/3}$$

∴ $P_{eq} = 5766.89$ N

and $L = L_1 + L_2 + L_3 + L_4$

$= (48 + 60 + 144 + 576) \times 10^6$

$= 828 \times 10^6$ rev

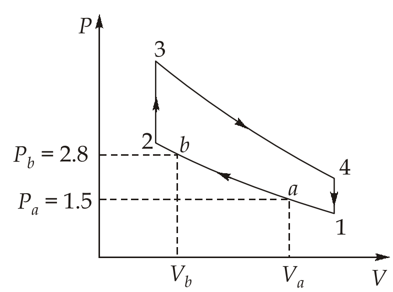
∴ Dynamic load capacity, $C = P_{eq}\left(\frac{L}{10^6}\right)^{1/3}$

$$= 5766.89\left(\frac{828\times 10^6}{10^6}\right)^{1/3}$$

$= 54.15$ kN **Ans.**

Section : B

Q.5 (a) Solution:



$V_2 = V_c$ = Clearance volume, V_s = stroke volume

We know compression ratio ,

$$r = \frac{V_1}{V_2} = \frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c}$$

or, $\frac{V_s}{V_c} = r - 1$ ...(i)

$V_a = V_c + 0.6\ V_s$

$V_b = V_c + 0.3\ V_s$

Given $PV^{1.4} = C$

$$\therefore \quad \frac{P_b}{P_a} = \frac{2.8}{1.5} = \left(\frac{V_a}{V_b}\right)^{1.4} = \left(\frac{V_c + 0.6V_s}{V_c + 0.3V_s}\right)^{1.4}$$

From equation (i)

$$\left(\frac{2.8}{1.5}\right)^{\frac{1}{1.4}} = \frac{1+0.6(r-1)}{1+0.3(r-1)} = \frac{0.4+0.6r}{0.7+0.3r}$$

or $r = 5.273$

So, air-standard efficiency,

$$\eta_{air} = 1-\frac{1}{r^{0.4}} = 1-\frac{1}{(5.273)^{0.4}}$$

$$= 0.4857 \text{ or } 48.57\%$$

$$\text{Relative efficiency} = \frac{\text{Indicated thermal efficiency}}{\text{Air-standard efficiency}}$$

$$\eta_{ith} = 0.6 \times 0.4857 = 0.29142$$

We know, $$\eta_{ith} = \frac{IP}{\dot{m}_f \times CV}$$

or, $$\frac{\dot{m}_f}{IP} = \frac{1}{43000 \times 0.29142} = 7.98 \times 10^{-5} \text{ kg/kWs}$$

$$isfc = 7.98 \times 10^{-5} \times 3600 = 0.28728 \text{ kg/KWh}$$

5. (b) (ii)

1. **Solid to Moisture Ratio in the Biomass :** Water is essential for survival and activity of microorganisms, hydrolysis process and activity of extracellular enzymes. This helps in (a) better mixing of various constituents of the biomass, (b) movement of bacteria, and (c) faster digestion rate. However, when water content is too high, the mean slurry temperature and hence gas production drops. If water content is too low, acids accumulate and hinder fermentation process. The optimum total solid concentration is 7 to 9%. Hence for various input materials, the optimum ratio of solid to moisture should be adjusted by mixing extra water for best results. Raw cow dung contains about 80-82% moisture (by weight). It is usually mixed with equal amount of water to reduce the solid content to 9-10%.
2. **pH value :** pH Value In the initial acid-forming stage of the digestion process, pH value may be around 6 or less. However, during the methane-formation stage, a pH value of 6.5 to 7.5 is maintained, as methane-forming bacteria are very sensitive to acidity. Too much and sudden deviation from this value is likely to cause imbalance in bacteria population affecting the production of gas.
3. **Carbon to Nitrogen (C/N) Ratio :** A digester is a culture of bacteria feeding upon organic wastes. For optimal growth and activity of bacteria, it is essential that required nutrients are available in correct chemical form and concentration. Carbon (in carbohydrate) and nitrogen (in proteins, nitrates, etc.) are the main nutrients for

anaerobic bacteria. While carbon supplies energy, nitrogen is needed for building up cell structure. The fact that anaerobic bacteria use carbon 25 to 30 times faster than nitrogen, necessitates the optimum C : N ratio as 30 : 1 for maximum microbiological activity. Deviation from this ratio slows down the digestion process.

Q.5 (c) Solution:

Given, Lattice parameters, a = 0.479 nm, b = 0.725 nm, c = 0.978 nm

Atomic radius, r = 0.177 nm

Atomic packing factor, APF = 0.547

Assume, Number of atoms per unit cell = n

Atomic weight of Iodine, A = 126.9 g/mol

Avogadro's number, $N_A = 6.023 \times 10^{23}$ atoms/mol

(a) We know that,

$$\text{Atomic packing factor} = \frac{\text{Volume of atoms}}{\text{Volume of unit cell}}$$

$$\text{APF} = \frac{n \times \left(\frac{4}{3}\pi r^3\right)}{(abc)}$$

$$n = \frac{(\text{APF})(abc)}{\left(\frac{4}{3}\pi r^3\right)} = \frac{0.547 \times 0.479 \times 0.725 \times 0.978}{\frac{4}{3} \times \pi \times (0.177)^3}$$

$$n = 7.998 \simeq 8 \text{ atoms/unit cell}$$

(b)

$$\text{Density, } \rho = \frac{nA}{V_C \times N_A} = \frac{8 \times 126.90}{(abc) \times 6.023 \times 10^{23}}$$

$$\rho = \frac{8 \times 126.90}{[0.479 \times 0.725 \times 0.978 \times 10^{-27}] \times 6.023 \times 10^{23}} \text{ g/cm}^3$$

$$\rho = 4.962795 \text{ g/cm}^3$$

Density of Iodine, ρ = 4962.795 kg/m^3

5. (d)

Polymer Electrolyte Membrane Fuel Cell (PEMFC) or Solid Polymer Fuel Cell (SPFC):

A solid membrane of organic material (such as polystyrene sulphonic acid) that allows H^+ ions to pass through it, is used as an electrolyte. The desired properties of the membrane are

(i) high ionic conductivity,

(ii) non-permeable (ideally) to reactant gases, i.e., hydrogen and oxygen,

(iii) low degree of electro-osmosis,

(iv) high resistance to dehydration,

(v) high resistance to its oxidation or hydrolysis, and

(vi) high mechanical stability.

The basic components of the cell are shown in figure below. A thin layer (about 0.076 cm thickness) of the membrane is used to keep the internal resistance of the cell as low as possible. Finely divided platinum deposited on each surface of the membrane serves as the electrochemical catalyst and current collector. Hydrogen enters a closed compartment, interacts with negative electrode and gets converted into H^+ ions and equal number of electrons (e^-)

$$H_2 \rightarrow 2H^+ + 2e^-$$

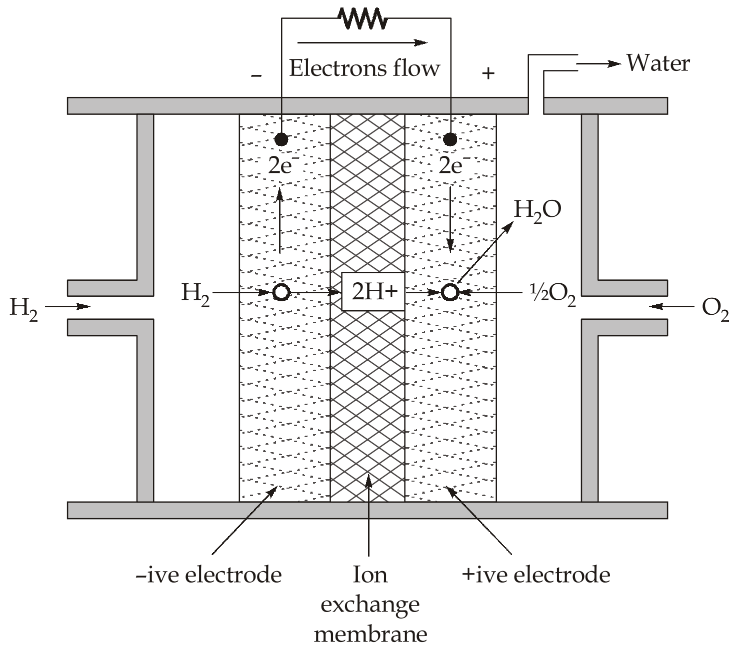
The H^+ ions are transported to a positive electrode through the membrane and electrons return to a positive electrode through external resistance. At positive electrode, the ions, electrons and oxygen (O_2) interact to produce water.

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

Thus the overall reaction is

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

On the positive electrode, the coolant tubes run through the ribs of current collectors. The current collectors also hold wicks, which absorb water, produced in electrochemical reaction and carry it over by capillary action. Water leaves the oxygen compartment through an exit. The advantageous feature of this membrane is that it retains only limited quantity of water and rejects excess water produced in the cell. The cell operates at 40°C-60°C. The ideal emf produced is 1.23 V at 25°C.



Polymer Electrolyte Membrane Fuel Cell

5. (e)

$$\text{Indicated power, } IP = \frac{P_m \cdot L \cdot A \cdot nK}{60000}$$

where, $n = \frac{N}{2}$, for four stroke engine, and n = N, for two stroke engine

$$\text{Mean piston speed, } \bar{S}_p = 2\,LN$$

For engine I :
$$80 = \frac{(P_m)_I \times A_I \times \frac{(\bar{S}_P)_I}{4} \times 4}{60000}$$

For engine II :
$$20 = \frac{(P_m)_{II} \times A_{II} \times \frac{(\bar{S}_P)_{II}}{2} \times 2}{60000}$$

$$\frac{80}{20} = \frac{A_I}{A_{II}} \times \frac{20}{(\bar{S}_P)_{II}}$$

$$\Rightarrow \quad (\bar{S}_P)_{II} = \left(\frac{d_I}{d_{II}}\right)^2 \times \frac{20}{4} = (2)^2 \times 5$$

$$= 20 \text{ m/s}$$ **Ans.**

6. (a)

Advantages of Two-stroke Engines:

(i) As there is a working stroke for each revolution, the power developed will be nearly twice that of a four-stroke engine of the same dimensions and operating at the same speed.

(ii) The work required to overcome the friction of the exhaust and suction strokes is saved.

(iii) As there is a working stroke in every revolution, a more uniform turning moment is obtained on the crankshaft and therefore, a lighter flywheel is required.

(iv) Two-stroke engines are lighter than four-stroke engines for the same power output and speed.

(v) For the same output, two-stroke engines occupies lesser space.

(vi) The construction of a two-stroke cycle engine is simple because it has ports instead of valves. This reduces the maintenance problems considerably.

(vii) In case of two-stroke engines because of scavenging, burnt gases do not remain in the clearance space as in case of four-stroke engines.

Disadvantages of Two-Stroke Engines:

(i) High speed two-stroke engines are less efficient owing to the reduced volumetric efficiency.

(ii) With engines working on Otto cycle, a part of the fresh mixture is lost as it escapes through the exhaust port during scavenging. This increases the fuel consumption and reduces the thermal efficiency.

(iii) Part of the piston stroke is lost with the provision of the ports thus the effective compression is less in case of two-stroke engines.

(iv) Two-stroke engines are liable to cause a heavier consumption of lubricating oil.

(v) With heavy loads, two-stroke engines gets heated due to excessive heat produced. Also at light loads, the running of engine is not very smooth because of the increased dilution of charge.

We know that,

$$\text{Compression ratio, } r = \frac{V}{V_c} = \frac{V_s + V_c}{V_c} = 1 + \frac{V_s}{V_c}$$

$$\Rightarrow \quad V_c = \frac{V_s}{r-1}$$

$$\Rightarrow \quad V = V_c + V_s = \frac{V_s}{r-1} + V_s$$

$$\Rightarrow \qquad V = \frac{r}{r-1} \times V_s$$

$$\text{Scavenging efficiency, } \eta_{sc} = \frac{\text{Actual mass of air}}{\text{Ideal mass of air}}$$

$$\dot{m}_{ideal} = V_s\left(\frac{r}{r-1}\right)\rho_{sc} \times N$$

$$\dot{m}_a = \eta_{sc}\rho_{sc}NV_s\left(\frac{r}{r-1}\right)$$

$$\eta_{ith} = \frac{ip}{\dot{m}_f CV} = \frac{ip}{\dot{m}_a\left(\frac{F}{A}\right)CV}$$

$$ip = p_{im}V_s\frac{N}{60 \times 10^3}$$

$$p_{im}V_s\frac{N}{60000} = \eta_{ith}\dot{m}_a\frac{F}{A}CV$$

$$p_{im}V_s\frac{N}{60000}\rho_{sc}\frac{r}{r-1} = \eta_{ith}\dot{m}_a\frac{F}{A}CV\rho_{sc}\frac{r}{r-1}$$

$$p_{im}\dot{m}_{ideal} = \eta_{ith}\dot{m}_a\frac{F}{A}CV\rho_{sc}\frac{r}{r-1} \times 60000$$

$$p_{im}\frac{\dot{m}_a}{\eta_{sc}} = \eta_{ith}\dot{m}_a\frac{F}{A}CV\rho_{sc}\frac{r}{r-1} \times 60000$$

$$p_{im} = \rho_{sc}\left(\frac{r}{r-1}\right)\eta_{sc}\eta_{ith} \times \frac{F}{A}CV \times 60000$$

6. (b) (i)

A suitable site should preferably have some of the following features:

1. No tall obstructions for some distance (about 3 km) in the upwind direction (i.e., the direction of incoming wind) and also as low a roughness as possible in the same direction.
2. A wide and open view i.e., open plain, open shoreline or offshore locations.
3. Top of smooth well-rounded hill with gentle slopes (about 1 : 3 or less) on a flat plain.
4. An island in a lake or the sea.
5. A narrow mountain gap through which wind is channelled.
6. Site reasonably close to power grid.

7. Soil conditions must be such that building of foundations of the turbines and transport of road-construction materials loaded in heavy trucks is feasible.
8. Production results of existing wind turbines in the area to act as a guide to local wind conditions.

The principal disadvantages of VAWTs are

(i) many vertical-axis machines have suffered from fatigue arising from numerous natural resonances in the structure,

(i) rotational torque from the wind varies periodically within each cycle, and thus unwanted power periodicities appear at the output,

(iii) it normally requires guy ropes attached to the top for support, which could limit its applications particularly for offshore sites,

(iv) it is noisier than HAWT,

(v) as wind speed increases significantly with height, for the same tower height HAWT captures more power than VAWT, and

(vi) the technology is under development stage and far less is known about them as compared to HAWTs.

6. (b) (ii)

Given : U_∞ = 24 m/s; P = 101.325 kPa; T = 27°C = 300 K; D = 80 m; N = 45 rpm

$$\text{Air density, } \rho = \frac{P}{RT} = \frac{101.325}{0.287 \times 300} = 1.18 \text{ kg/m}^3$$

$$\text{Speed of rotor, } \omega = \frac{2\pi \times 45}{60} = 4.71 \text{ rad/s}$$

$$\text{Area of rotor, } A = \pi R^2 = \pi \times 40^2 = 5026.55 \text{ m}^2$$

$$\text{For maximum output,} \quad a = \frac{1}{3} \text{ and } c_{p,\max} = 0.593$$

$$\text{Tip-speed ratio, } \lambda = \frac{\omega R}{U_\infty} = \frac{4.71 \times 40}{24} = 7.85$$

$$\text{Power available, } P_0 = \frac{1}{2}\rho A U_\infty^3 = \frac{1}{2} \times 1.18 \times 5026.55 \times 24^3$$

$$\simeq 41 \text{ MW}$$

$$T_m = \frac{P_0 R}{U_\infty} = 41 \times \frac{40}{24} = 68.33 \text{ MNm}$$

$$C_{T,\max} = \frac{C_{P,\max}}{\lambda} = \frac{0.593}{7.85} = 0.0755$$

Torque produced at the shaft at maximum output,

$$T_{\text{shaft}} = 68.33 \times 0.0755 = 5.16 \text{ MNm}$$ **Ans.**

6. (c)

$$\rho_a = \frac{P}{RT} = \frac{100}{0.287 \times 300} = 1.16 \text{ kg/m}^3$$

$$\dot{V}_a = C_{d,o} \cdot A\sqrt{2g\Delta H \times \frac{\rho_{Hg}}{\rho_a}}$$

$$= 0.6 \times \frac{\pi \times 0.03^2}{4} \times \sqrt{2 \times 9.81 \times 0.15 \times \frac{13600}{1.16}}$$

$$= 0.0788 \text{ m}^3/\text{s}$$

$$\dot{V}_s = \frac{\pi}{4} D^2 L \times N_i K$$

$$= \frac{\pi}{4} \times 0.1^2 \times 0.12 \times \frac{2400}{2 \times 60} \times 6 = 0.1331 \text{ m}^3/\text{s}$$

$\therefore$ Volumetric efficiency, $\eta_v = \frac{\dot{V}_a}{\dot{V}_s} = \frac{0.0788}{0.1131} = 0.6967 \text{ or } 69.67\%$ **Ans.**

Brake power, $BP = \frac{WN}{20000} = \frac{570 \times 2400}{20000} = 68.4 \text{ kW}$ **Ans.**

Torque, $T = \frac{BP \times 60 \times 1000}{2\pi N} = \frac{68.4 \times 60 \times 1000}{2\pi \times 2400} = 272.15 \text{ Nm}$ **Ans.**

$$\dot{m}_f = \frac{100}{20} \times 10^{-6} \times 830 \times 3600 = 14.94 \text{ kg/h}$$

$\therefore$ $bsfc = \frac{\dot{m}_f}{BP} = \frac{14.94}{68.4} = 0.218 \text{ kg/kWh}$ **Ans.**

O_2 required / kg of fuel $= 0.83 \times \frac{32}{12} + 0.17 \times \frac{8}{1} = 3.57$ kg/kg of fuel

Since, air contains 23.3% of O_2 by weight (given),

Air required/ kg of fuel $= \frac{3.57}{0.233} = 15.32$ kg of air/kg of fuel

Actual mass flow rate of air $= 0.0788 \times 1.16 = 0.0914$ kg/s

Actual mass A/F ratio $= \frac{0.0914 \times 3600}{14.94} = 22.02$ kg of air/kg of fuel

$\therefore$ Percentage of excess air $= \frac{22.02 - 15.32}{15.32} \times 100 = 43.73\%$ **Ans.**

7. (a)

Torrefaction is the process of converting different types of biomass into high-quality solid fuels by performing suitable heat treatment under inert conditions. It can be used for diverse feedstock such as wood, agro-residue, algal biomass, and sewage sludge. Pre-heating is carried out at 100°C to remove the moisture content in the biomass. Then, the biomass is heated to around 200°C to vaporize the light fractions in the second stage of the aforementioned process. Torrefaction starts at a temperature of 200°C and is heated up to 300°C where a large amount of mass is lost (complete decomposition of hemicellulose and partial decomposition of lignin and cellulose), and it cools down to the initial temperature. At last, an annealing process is carried out to cool down the solid fuel to ambient temperature.

In the case of the torrefaction mechanism, the decomposition of biomass into a carboxyl group happens with the emission of CO_2 and is followed by an aromatization reaction. Hence, the nature of biomass can change from hydrophilic to hydro- phobic with dark brown solid fuel during torrefaction with inert conditions. The mass of feedstock can be deduced to around 29 wt.% based on operating parameters and composition, later the solid fuels can be developed with 89.5% of energy content from the initial biomass. So, there are a few advantages of the biofuels obtained from the torrefaction process including more homogeneity, fine particle, calorific value, better bulk density, and high durability. It is observed that the solid products obtained from dry torrefaction have higher alkali content and slightly less calorific value than another type of torrefied product. Therefore, dry torrefaction is well-suited for less moisture biomass because most of the decarboxyl reaction starts after the removal of moisture content.

Dry matter produced by two cows = 2.4 × 2 = 4.8 kg/day

$$\text{Cow dung produced} = \frac{4.8}{0.18} = 26.67 \text{ kg/day}$$

Amount of slurry produced per day = 26.67 + 26.67 = 53.34 kg/day

$$\text{Slurry volume produced per day} = \frac{53.34}{1090} = 0.0489 \text{ m}^3/\text{kg}$$

$$\text{Total slurry in digester} = 0.0489 \times 28 = 1.3692 \text{ m}^3$$

$$\text{Digester size} = \frac{1.3692}{1-0.16} = 1.63 \text{ m}^3$$ **Ans.**

$$\text{Gas produced} = 4.8 \times 0.20 = 0.96 \text{ m}^3/\text{day}$$

$$\text{Thermal energy available} = 0.96 \times 24 \times 0.64 = 14.74 \text{ MJ/day}$$

$$\text{Thermal power available} = \frac{14.74 \times 10^6}{3600 \times 24} = 170.60 \text{ W}$$ **Ans.**

7. (b)

The phenomenon of knocking in Sl engines is known as detonation. The phenomenon of knock may be explained with reference to the cross-section of the combustion chamber with flame advancing from the spark plug location A without knock in Fig. (a) whereas Fig. (b) shows the combustion process with knock.

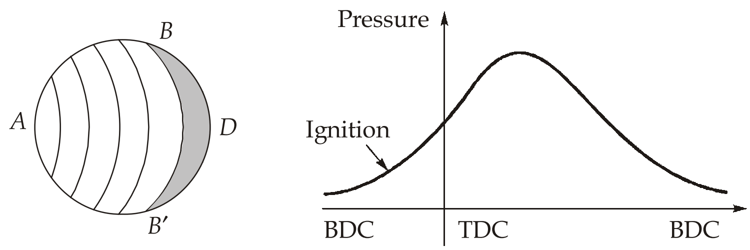


Figure (a) : Normal combustion

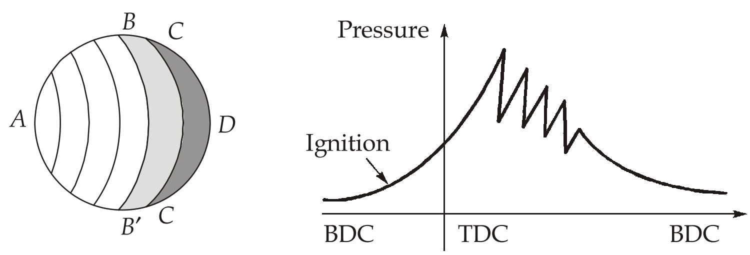


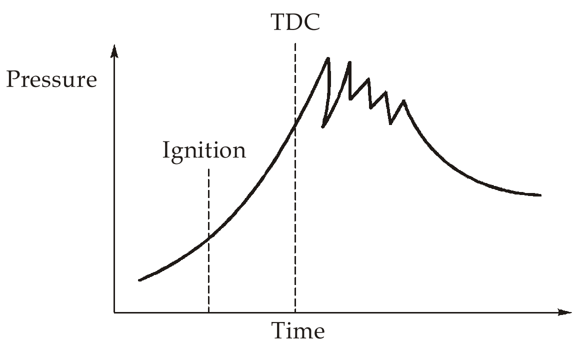
Figure (b) : Combustion with detonation

In the normal combustion the flame travels across the combustion chamber from *A* towards *D*. The advancing flame front compresses the end charge BB′D farthest from spark plug, thus raising its temperature. The temperature is also increased due to heat transfer from the hot advancing flame-front. Inspite of these factors if the temperature of the end charge does not reach its self-ignition temperature, the charge would not autoignite and the flame will advance further and consume the charge BB′D. This is the normal combustion. However if the end charge BB′D reaches its autoignition (self-ignition) temperature and remains upto the time of preflame reactions the charge will autoignite, leading to knocking combustion. Because of the autoignition, another flame front starts travelling in the opposite direction to the main front. When the two flame fronts collide, a severe pressure pulse is generated. This condition is known as detonation.

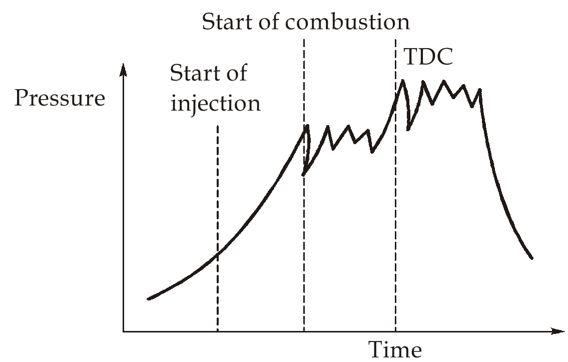
Comparison of detonation in SI engines with that of knocking in CI engines:

1. In spark ignition (SI) engines, the autoignition of the end gas occurring away from the spark plug, most likely near the end of the combustion causes detonation. But in the CI engine the autoignition of the charge causing knocking is at the start of

combustion. It is the first charge that autoignites and causes knocking in the compression ignition engines.



(SI Engine)



(CI Engine)

Thus it can be seen, in order to avoid knocking in SI engines, it is necessary to prevent autoignition of the end gas to take place at all. In CI engines, the earliest possible autoignition is necessary to avoid knocking.

2. In SI engines, the charge that autoignites is homogeneous and therefore the intensity of knocking or the rate of pressure rise at explosive autoignition is likely to be more severe that in CI engines where the fuel and air are not homogeneously mixed even when the explosive autoignition of the charge occurs. Therefore, it is often called detonation in SI engines.
3. In CI engines only air is compressed during the compression stroke and the ignition can take place only after the fuel is injected just before the top dead center. Thus there can be no preignition in CI engine as in spark-ignition engines.
4. The factors that tend to increase autoignition reaction time and prevent knock in SI engines promote knocking in CI engines. Also, a good fuel for SI engines is a poor for CI engines.

Methods to reduce knock in CI engines are:

1. Increase the compression ratio of engine.
2. Increase the inlet temperature and inlet pressure of incoming air (super charging).
3. Higher fuel injection pressures increase the degree of atomization which reduces ignition delay and prevents knocking.
4. Use of high octane number fuel.
5. Increase in the temperature of cooling water jacket.

7. **(c) (i)**

The main limitations of tidal energy are the following:

(i) Economic recovery of energy from tides is feasible only at those sites where energy is concentrated in the form of tidal range of about 5 m or more and the geography provides a favourable site for economic construction of a tidal plant. Thus it is site specific.

(ii) Due to mismatch of lunar driven period of 12 hours 25 min and human (solar) period of 24 hours, the optimum tidal power generation is not in phase with demand.

(iii) Changing tidal range in two-week periods produces changing power.

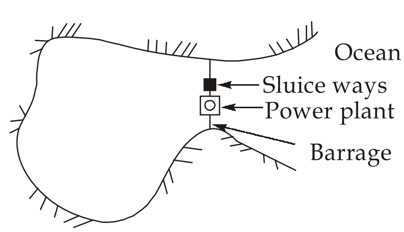
(iv) The turbines are required to operate at variable head.

(v) Requirement of large water volume flow at low head necessitates parallel operation of many turbines.

(vi) Tidal plant disrupts marine life at the location and can cause potential harm to ecology.

7. **(c) (ii)**

Single Basin: Single-effect Scheme The single-basin scheme has only one basin as shown in Fig. (a). In the single-effect scheme, power is generated either during filling or emptying the basin. Two types of operation cycles are possible In the ebb generation cycle operation, the sluice way is opened to fill the basin during high tide. Once filled, the impounded water is held till the receding cycle creates a suitable head. Water is now allowed to flow through the turbine coupled to the generator till the rising tide reduces the head to the minimum operating point. The flow is held till the next generating cycle. The sequence of events is illustrated in Fig. (b). This cycle is repeated and power is generated intermittently. In the flood generation cycle operation, the sequences are altered to generate power during filling operation of the basin. However, the sloping nature of the basin shores usually makes ebb generation the more productive method.



(a) Layout of single-basin tidal energy conversion scheme

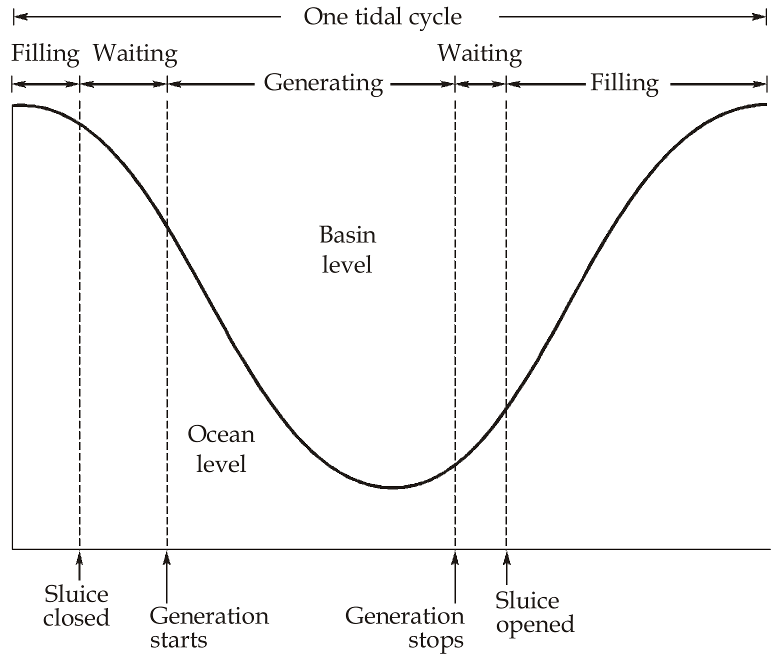


Fig. (b) Sequence of operation

Single-basin, single-effect tidal energy conversion schme

Increased output can also be obtained by pumping during high tide to increase the basin level and therefore the generation head. The energy required for pumping must be borrowed and repaid. The pumping is done against a small head at high tide, whereas the same water is released through the turbine during low tide at a great head, producing a net energy gain.

8. (a) (i)

All gases, except mono-atomic gases, show an increase in specific heat with temperature. The increase in specific heat does not follow any particular law. However, over the temperature range generally encountered for gases in heat engines (300 K to 2000 K) the specific heat curve is nearly a straight line which may be approximately expressed in the form

$$\left.\begin{aligned} C_p &= a_1 + k_1 T \\ C_v &= b_1 + k_1 T \end{aligned}\right\} \quad \text{...(i)}$$

where a_1, b_1 and k_1 are constants. Now,

$$R = C_p - C_v = a_1 - b_1 \quad \text{...(ii)}$$

where R is the characteristic gas constant .

Above 1500 K the specific heat increases much more rapidly and may be expressed in the form

$$C_p = a_1 + k_1T + k_2T^2 \quad \text{...(iii)}$$

$$C_v = b_1 + k_1T + k_2T^2 \quad \text{...(iv)}$$

In Eqn.(iv) if the term T^2 is neglected it becomes same as Eqn.(i). Many expressions are available even upto sixth order of T (i.e. T_6) for the calculation of C_p and C_v.

The physical explanation for increase in specific heat is that as the temperature is raised, larger fractions of the heat would be required to produce motion of the atoms within the molecules. Since temperature is the result of motion of the molecules, as a whole, the energy which goes into moving the atoms does not contribute to proportional temperature rise. Hence, more heat is required to raise the temperature of unit mass through one degree at higher levels. This heat by definition is the specific heat.

Since the difference between C_p and C_v is constant, the value of decrease with increase in temperature. Thus, if the variation of specific heats is taken into account during the compression stroke, the final temperature and pressure would be lower than if constant values of specific heat are used. This point is illustrated in figure below.

Cycle 1-2-3-4 with constant specific heat

Cycle 1-2′-3′-4′ with variable specific heat

Cycle 1-2-3-4″ with constant specific heat from point 3′

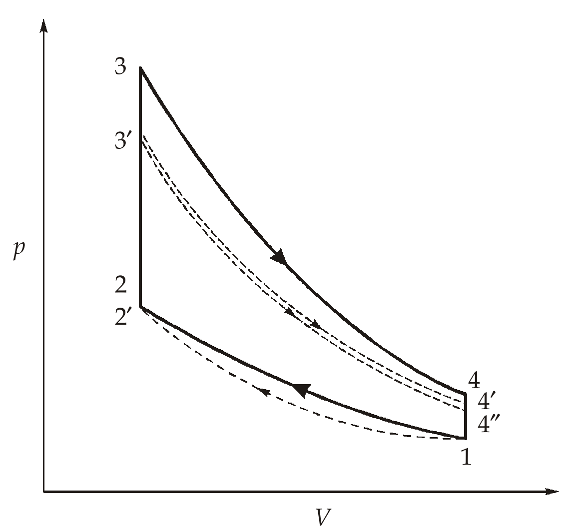


Fig. : Loss of power due to various of specific heat

With variable specific heats, the temperature at the end of compression will be 2′. instead of 2. The magnitude of drop in temperature is proportional to the drop in the value of ratio of specific heats. For the process $1 \rightarrow 2$, with constant specific heats

$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{\gamma-1} \quad ...(i)$$

with variable specific heats,

$$T_{2'} = T_1\left(\frac{v_1}{v_{2'}}\right)^{k-1} \quad ...(ii)$$

where $k = \frac{C_p}{C_v}$. Note that $v_{2'} = v_2$ and $\frac{v_1}{v_2} = \frac{v_1}{v_{2'}} = r$

For given values of T_1, p_1 and r, the magnitude of $T_{2'}$ depends on k. Constant volume combustion, from point 2′ will give a temperature $T_{3'}$ instead of T_3. This is due to the fact that the rise in the value of C. because of variable specific heat, which reduces the temperature as already explained.

The process, 2′ → 3′ is heat addition with the variation in specific heat. From 3′, if expansion takes place at constant specific heats, this would result in the process 3′ → 4″ whereas actual expansion due to variable specific heat will result in 3′ → 4′ and 4′ is higher than 4″. The magnitude in the difference between 4′ and 4″ is proportional to the reduction in the value of γ Consider the process 3′4″

$$T_{4''} = T_{3'}\left(\frac{v_3}{v_4}\right)^{(k-1)} \quad ...(iii)$$

for the process 3′4′

$$T_{4''} = T_{3'}\left(\frac{v_3}{v_4}\right)^{(\gamma-1)} \quad ...(iv)$$

Reduction in the value of k due to variable specific heat results in increase of temperature from $T_{4''}$ to $T_{4'}$.

8. (a) (ii)

Given : BP = 120 kW; η_m = 0.80; $\dot{m}_{f_1}$ = 1.2 kg/min

$$\text{Mechanical efficiency, } \eta_m = \frac{BP}{IP_1}$$

$$\Rightarrow \quad IP_1 = \frac{120}{0.8}$$

$$\Rightarrow \quad IP_1 = 150 \text{ kW}$$

$$\text{Friction power, } FP_1 = IP_1 - BP = 150 - 120 = 30 \text{ kW}$$

Friction power for modified engine,

$$FP_2 = 30 - 10 = 20 \text{ kW}$$

$$\therefore \quad IP_2 = BP + FP_2 = 120 + 20 = 140 \text{ kW}$$

As given in question, $(\eta_{ith})_1 = (\eta_{ith})_2$

$$\Rightarrow \quad \frac{IP_1}{\dot{m}_{f_1} \times CV} = \frac{IP_2}{\dot{m}_{f_2} \times CV}$$

$$\Rightarrow \quad \frac{150}{1.2 \times CV} = \frac{140}{\dot{m}_{f_2} \times CV}$$

$$\Rightarrow \quad \dot{m}_{f_2} = 1.12 \text{ kg/min}$$

Percentage saving in fuel consumption $= \dfrac{\dot{m}_{f_1} - \dot{m}_{f_2}}{\dot{m}_{f_1}} = \dfrac{1.2 - 1.12}{1.2} \times 100$

$= 6.67\%$ **Ans.**

8. **(b) (i)**

Reliability-Centred Maintenance (RCM)

In a sample survey of maintenance management effectiveness for complex and large capacity equipment, it is found that more than one third of all maintenance costs are wasted as a result of unnecessary or improperly carried maintenance over maintenance. It is seen that task selection in maintenance need not be optimal but still very subjective in approach. The reliability-centred maintenance (RCM), suitably blended with predictive maintenance and maintenance prevention can help in reducing maintenance costs.

The RCM is defined as a process or method used to determine maintenance of equipment in its environment after proper evaluation of failure consequences. The RCM is a systematic approach to quantitatively assess the need to perform or revise preventive maintenance tasks and plans. The RCM focuses on the system function, functional failures, dominant failures and their effects. The RCM uses Decision tree to classify the criticality based on the consequences of analysis to identify applicable and significant tasks. Once the significant maintenance tasks are identified, their maintenance intervals can be estimated either by using condition monitoring devices or by reliability analysis of the failure statistics. Close analysis of RCM approach indicates that it concerns with system effects (safety, economic, social) on consequences without any reference to human aspects are advocated and treated as key to success in business and maintenance. The philosophy of RCM focuses on enhancing the probability of the machine not failing in the given time span and assuring or building up the confidence of using the equipment in the specified time.

Given : λ_1 = 0.005 failure/hour; λ_1 = 0.008 failure/hour

For a parallel system, at least one of the units must work normally for system success.

$$\therefore \quad R_{ps} = 1-\left(1-e^{-\lambda_1 t}\right)\left(1-e^{-\lambda_2 t}\right)$$

$$= 1-\left(1-e^{-0.005t}\right)\left(1-e^{-0.008t}\right)$$

$$= e^{-0.005t} + e^{-0.008t} - e^{-0.013t}$$

$$\therefore \text{Mean time to failure, MTTF} = \int_0^\infty \left(e^{-0.005t}+e^{-0.008t}-e^{-0.013t}\right)dt$$

$$= \frac{1}{0.005}+\frac{1}{0.008}-\frac{1}{0.013} = 448.08 \text{ hours}$$

(ii)

The probability of failure in initial condition with vacuum tubes

$$P_1 = \frac{n_1 \cdot t}{T_1} = \frac{5 \cdot t}{8000} = \frac{t}{1600}$$

The probability of failure with ICs

$$P_2 = \frac{n_2 \cdot t}{T_2} = \frac{25 \cdot t}{90000}$$

$$P_2 = \frac{t}{3600}$$

Reliability improvement factor, (RIF)

$$= \frac{P_1}{P_2} = \frac{t}{1600}\times\frac{3600}{t} = 2.25$$

With application of ICs, the reliability of the system has improved (because the probability of failure has reduced). Hence, it is better to use ICs.

The probability of failure with 40 transistors,

$$P_3 = \frac{n_3 \cdot t}{T_3} = \frac{40 \cdot t}{80000} = \frac{t}{2000}$$

The reliability improvement factor = $\frac{P_1}{P_3} = \frac{t}{1600}\times\frac{2000}{t} = 1.25$

Thus we observe that the increase in number of transistors i.e. elements in general, the reliability of the system has reduced. Hence, the number of parts or components should be as less as possible for higher reliability.

8. (c)(i)

$$\text{Quantity of sea-water} = \frac{25 \times 12 \times 10^6}{1025 \times 9.81 \times 15 \times 0.94 \times 0.97} = 2181.41 \text{ m}^3/\text{s}$$

For 6 hours, the total quantity involved = Basin capacity

$$= 2181.41 \times 6 \times 3600 = 47.12 \times 10^6 \text{ m}^3$$ **Ans.**

$$\text{Average annual energy production} = \frac{1}{2} \times (25 \times 12) \times (6 \times 2) \times 365 \times 10^{-3}$$

$$= 657 \text{ GWh}$$ **Ans.**

(ii)

Some of the important advantages of fuel cell power plants are: efficiency is affected.

1. Fuel cell power plants are eco-friendly, noiseless, carry no rotating components. In contrast, in coal- based stations, ash slurry, discharge of smoke through chimney adversely affect the environment.
2. It is a decentralized plant, can be operated in isolation for military installations and hospitals where noise and smoke are prohibited. Besides, no power is wasted in transmission and distribution.
3. Fuel cell power sources attain a high efficiency up to 55% whereas conventional thermal plants operate at 30% efficiency.
4. A large degree of modularity is available, with capacity ranging from 5 kW to 2 MW. The number of fuel cells can be increased as per the requirement.
5. There is a wide choice of fuels for fuel cells. These can be operated with natural gas, ethanol, methanol, LPG and biogas supplied from local biomass. All these are hydrogen rich materials and hydrogen gas can be produced by using fuel reformers.
6. Fuel cells can operate at landfills and wastewater treatment plants from the methane gas they produce. Fuel cells operate on waste gases at breweries, also on gas from sewage sludge proving to be the cleanest and most cost-effective energy conversion technology.
7. In addition to electric power, fuel cell plants also supply hot water, space heat and steam. Fuel cells have cogeneration capabilities.
8. Potential areas of cogeneration systems where fuel cells can be effectively installed are sugar, paper, cotton, textile, caustic soda, iron and steel mills and refineries which will enhance system efficiency and reduce demand on grid.

Characteristics of various fuel cells:

S.No.	Fuel cell	Op. Temp.	Fuel	Efficiency
1.	PEMFC	40 - 60°C	H_2	48 - 58%
2.	AFC	90°C	H_2	64%
3.	PAFC	150 - 200°C	H_2	42%
4.	MCFC	600 - 700°C	H_2 and CO	50%
5.	SOFC	600 - 1000°C	H_2 and CO	60 - 65%

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