MADE EASY

Leading Institute for ESE, GATE & PSUs

Detailed Solutions

ESE-2024 Mains Test Series

Mechanical Engineering Test No : 9

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

Section B : Power Plant **[All Topics]**

Section : A

1. (a)

Given : $N = 900$ rpm; V.R. $= \dfrac{T_G}{T_P} = 5$; $\sigma_{OP} = 84$ MPa; $\sigma_{OG} = 105$ MPa; $T_P = 16$; $m = 10$ mm; $b = 95$ mm

Now, $$D_P = mT_P = 10 \times 16 = 160 \text{ mm}$$

Pitch line velocity, $$v = \frac{\pi D_P N_P}{60} = \frac{\pi \times 0.16 \times 900}{60} = 7.54 \text{ m/s}$$

Since the pitch line velocity is less than 12.5 m/s,

Therefore, velocity factor, $$C_V = \frac{3}{3+v} = \frac{3}{3+7.54} = 0.284$$

For 20° full depth involute teeth, tooth form factor. For pinion and gear, are

$$y_P = 0.154 - \frac{0.912}{T_P} = 0.154 - \frac{0.912}{16} = 0.097$$

Similarly for gear, $$y_G = 0.154 - \frac{0.912}{T_G} = 0.154 - \frac{0.912}{5 \times 16} = 0.1426$$

$\therefore$ $$\sigma_{OP} \times y_P = 84 \times 0.097 = 8.148$$

$$\sigma_{OG} \times y_G = 105 \times 0.1426 = 14.973$$

$\because$ $$\sigma_{OP} \times y_P < \sigma_{OP} \times y_G$$

therefore the pinion is weaker, so tangential load,

$\therefore$ $$F_{\text{eff}} = \sigma_{op} \cdot m \cdot b \cdot \pi y_p \times C_V$$

$$= 84 \times 10 \times 95 \times \pi \times 0.097 \times 0.284$$

$$= 6906.26 \text{ N}$$

$\therefore$ Power that can be transmitted,

$$P = F_{\text{eff}} \cdot v$$

$$= 6906.26 \times 7.54 = 52073.20 \text{ W}$$

$$= 52.073 \text{ kW}$$

1. (b)

(i) Active and passive transducers: Active transducers are defined as those transducers which do not require any external or auxiliary power source to generate the equivalent output, viz. voltage or current. They are self-generating transducers. For example, a piezoelectric crystal transducer, being an active transducer, converts pressure into emf.

Passive transducers are defined as those transducers that require external or auxiliary power supply for their operation of conversion of physical quantity into electrical signal. They are externally powered transducers, for example, a potentiometer.

(ii) Analog and digital transducers: An analog transducer converts the input physical quantity into analog output, which is a continuous function of time, e.g. a thermocouple. A digital transducer converts the input physical quantity into digital form, i.e. in the form of pulses having logic 0 and logic 1 levels, e.g. a rotary encoder.

(iii) Transducers and inverse transducers : A transducer is a device which converts the physical quantities into electrical signals (by electrical means). An inverse transducer is a device which converts the electrical quantities (signals) into non-electrical quantities. When electrical charge or voltage is applied to the surface of piezoelectric crystals, the dimensions of crystal get changed due to deformation. This deformation results into mechanical displacement.

These devices receive the input quantity current or voltage (electrical quantity) and provide mechanical displacement (deflection) in accordance with the magnitude of input quantity.

1. (c)

Polar (Spherical) Configuration : The polar configuration is illustrated in figure (a). It consists of a telescopic link (prismatic joint) that can be raised or lowered about a horizontal revolute joint. These two links are mounted on a rotating base. This arrangement of joints, known as RRP configuration, gives the capability of moving the arm end-point within a partial spherical shell space as work volume, as shown in figure (a).

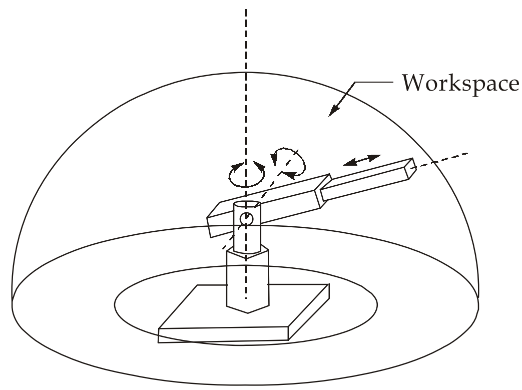


Fig. (a) A 3-DOF polar arm configuration and its workspace

This configuration allows manipulation of objects on the floor because its shoulder joint allows its end-effector to go below the base. Its mechanical stiffness is lower than Cartesian and cylindrical configurations and the wrist positioning accuracy decreases with the increasing radial stroke. The construction is more complex. Polar arms are mainly employed for industrial applications such as machining, spray painting and so on. Alternate polar configuration can be obtained with other joint arrangements such as RPR, but PRR will not give a spherical work volume.

Articulated (Revolute or Jointed-arm) Configuration : The articulated arm is the type that best simulates a human arm and a manipulator with this type of an arm is often referred as an anthropomorphic manipulator. It consists of two straight links, corresponding to the human "forearm" and "upper arm" with two rotary joints corresponding to the "elbow" and "shoulder" joints. These two links are mounted on a vertical rotary table corresponding to the human waist joint. Figure (b) illustrates the joint-link arrangement for the articulated arm. This configuration (RRR) is also called revolute because three revolute joints are employed. The work volume of this configuration is spherical shaped, and with proper sizing of links and design of joints, the arm endpoint can sweep a full spherical space. The arm endpoint can reach the base point and below the base, as shown in figure (b) This anthropomorphic structure is the most dexterous one, because all the joints are revolute, and the positioning accuracy varies with arm endpoint location in the workspace. The range of industrial applications of this arm is wide.

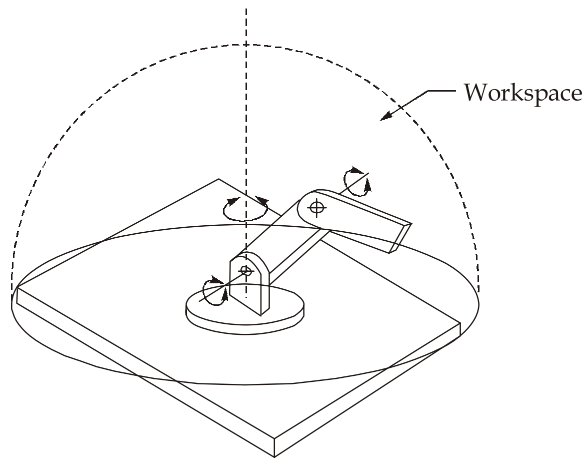


Fig. (b) A 3-DOF articulated arm configuration and its workspace

1. (d)

Stress concentration is defined as the localization of high stresses due to the irregularities present in the component and abrupt changes of the cross-section.

In order to consider the effect of stress concentration and find out localized stresses, a factor called 'stress concentration factor' is used. It is denoted by K_t and defined as,

$$K_t = \frac{\text{Highest value of actual stress near discontinuity}}{\text{Nominal stress obtained by elementary equations for minimum cross-section}}$$

$$\text{or } K_t = \frac{\sigma_{max}}{\sigma_0} = \frac{\tau_{max}}{\tau_0}$$

where σ_0 and τ_0 are stresses determined by and elementary equations and σ_{max} and τ_{max} are localized the stresses at the discontinuities. The subscript '*t*' denotes the 'theoretical' stress concentration factor. The magnitude of stress concentration factor depends upon the geometry of the component.

The causes of stress concentration are as follows

(i) Variation in properties of materials : In design of machine components, it is assumed that the material is homogeneous throughout the component. In practice, there is variation in material properties from one end to another due to following factors:

(a) internal cracks and flaws like blow holes;

(b) cavities in welds;

(c) air holes in steel components; and

(d) nonmetallic or foreign inclusions.

These variations act as discontinuities in the component and cause stress concentration.

(ii) Load application : Machine components are subjected to forces. These forces act either at a point or over a small area on the component. Since the area is small, the pressure at these points is excessive. This results in stress concentration. The examples of these load applications are as follows:

(a) Contact between the meshing teeth of the driving and the driven gear.

(b) Contact between the cam and the follower.

(c) Contact between the balls and the races of ball bearing.

(d) Contact between the rail and the wheel.

(e) Contact between the crane hook and the chain.

In all these cases, the concentrated load is applied over a very small area resulting in stress concentration.

(iii) Abrupt changes in section: In order to mount gears, sprockets, pulleys and ball bearings on a transmission shaft, steps are cut on the shaft and shoulders are provided from assembly considerations. Although, these features are essential, they create change of the cross-section of the shaft. This results in stress concentration at these cross-sections.

(iv) Discontinuities in the component : Certain features of machine components such as oil holes or oil grooves, keyways and splines, and screw threads result in discontinuities in the cross-section of the component. There is stress concentration in the vicinity of these discontinuities.

(v) Machining scratches : Machining scratches, stamp mark or inspection mark are surface irregularities, which cause stress concentration.

1. (e)

Power input to the rotor = Stator input – Stator loss = 60 – 5 = 55 kW

Rotor loss = 2 kW

$$\therefore \quad \text{Percentage slip } (\%s) = \frac{\text{Rotor loss}}{\text{Power input to the rotor}} \times 100$$

$$= \frac{2}{55} \times 100 = 3.63\% \qquad \textbf{Ans.}$$

Now, Shaft power, $P = (1 - s) \times 55$

$= (1 - 0.0363) \times 55 = 53.0035$ kW

Shaft speed $= (1 - s) \times N_s$

$= (1 - 0.0363) \times 960 = 925.152$ rpm

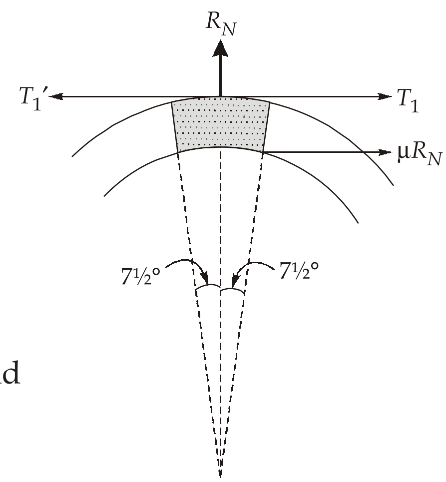
Therefore, Toque $= \dfrac{P \times 60 \times 10^3}{2\pi N} = \dfrac{60 \times 53.0035 \times 10^3}{2\pi \times 925.152}$

$= 547.095$ Nm **Ans.**

2. (a)

Since $OA > OB$, therefore the force at C must act downward. Also, the drum rotates clockwise, therefore the end of the band attached to A will be slack with tension T_2 (least tension) and the end of the band attached to B will be tight with tension T_1 (greatest tension).

Consider one of the blocks (say first block) as shown is figure.



This is in equilibrium under the action of the following four forces :

1. Tension in the tight side (T_1),
2. Tension in the slack side (T'_1) or the tension in the band between the first and second block,
3. Normal reaction of the drum on the block (R_N), and
4. The force of friction (μR_N).

Resolving the forces radially, we have

$$(T_1 + T'_1)\sin 7.5° = R_N$$

Resolving the forces tangentially, we have

$$(T_1 - T'_1)\cos 7.5° = \mu R_N$$

Dividing equation (ii) by (i), we have

$$\frac{(T_1 - T_1')\cos 7.5°}{(T_1 + T_1')\sin 7.5°} = \mu$$

or $$\frac{(T_1 - T_1')}{(T_1 + T_1')} = \mu \tan 7.5°$$

$\therefore$ $$\frac{T_1}{T_1'} = \frac{1 + \mu \tan 7.5°}{1 - \mu \tan 7.5°}$$

Similarly, for the other blocks, the ratio of tensions $\dfrac{T_1'}{T_2'} = \dfrac{T_2'}{T_3'}$ etc., remains constant.

Therefore for 12 blocks having greatest tension T_1 and least tension T_2 is

$$\frac{T_1}{T_2} = \left(\frac{1+\mu\tan 7.5^{\circ}}{1-\mu\tan 7.5^{\circ}}\right)^{12}$$

Least force required at C

Let P = Least force required at C

Now, diameter of band, $D = d + 2t = 0.85 + 2 \times 0.75$

$$D = 1 \text{ m}$$

and power absorbed $= \dfrac{(T_1 - T_2)\times \pi DN}{60}$

$$\therefore \quad T_1 - T_2 = \frac{250\times 10^3 \times 60}{\pi \times 1 \times 320} = 14920.77 \text{ N}$$

We have proved that,

$$\frac{T_1}{T_2} = \left(\frac{1+\mu\tan 7.5^{\circ}}{1-\mu\tan 7.5^{\circ}}\right)^{12}$$

$$\frac{T_1}{T_2} = \left(\frac{1+0.4\tan 7.5^{\circ}}{1-0.4\tan 7.5^{\circ}}\right)^{12} = 3.54$$

$$\therefore \quad T_1 = 3.54T_2$$

Also, $3.54T_2 - T_2 = 14920.77$

$$\therefore \quad T_2 = 5874.32 \text{ N}$$

and $T_1 = 20795.09$ N

Now taking moments about O, we have

$$P \times 500 = T_2 \times 150 - T_1 \times 30$$

or $P \times 500 = 5874.32 \times 150 - 20795.09 \times 30$

$$\therefore \quad P = 514.59 \text{ N}$$

Ans.

2. (b)

A stepper motor is an electromechanical device (special type of synchronous motor), which rotates through specific angle (i.e. step) for each electrical pulse received by its control unit. The input applied to this motor is in the form of train of pulses to turn a shaft through a specific angle. Stepper motors are available in different steps like 7.5°, 15° or more. It can be used as an actuator element where incremental motion is required. Stepper motor is widely used in the following applications: printers, positioning of printer heads, *XY* plotters, tape drives, process control systems, numerically-controlled machining equipments, machine tools, position control, capstan drives and integrated circuit fabrication processes.

Variable reluctance stepper motor

Figure (a) shows the cross-sectional view of a stepper motor with 3 stacks. A stepper motor consists of a single or several stacks of stators and rotors. The stator has a common frame and the rotor has a common shaft as shown in Figure (a). The stator and rotor teeth are of the same size and aligned as shown in Figure (b). The stators are provided by stator windings a, b and c which are excited, whereas the rotors are unexcited. Consider Figure (c), which shows view of teeth of a pair of stator and rotor.

When at the inputs *a*, *b* and *c*, train of pulses is applied, the rotor is shifted or pulled to the nearest minimum reluctance position where the teeth of the stator and rotor are aligned. This results in developing a torque and hence the teeth of the stator and rotor get misaligned. The static torque acting on the rotor is a function of angular misalignment θ.

Now we will consider the following two cases:

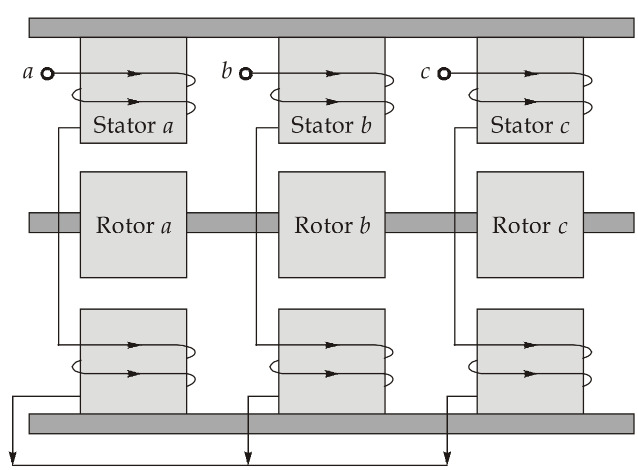
Case (i). When θ : 0°, i.e. torque is zero and teeth of the stator and rotor are aligned.

Case (ii). When $\theta = 360°/2T = 180°/T$, where T is number of teeth of the rotor and teeth of the rotor are aligned with the stator. Both the cases are illustrated in Figure (d).

Case (i) (when teeth are aligned, i.e. $\theta = 0$) is a stable position. Similarly case (ii) (stator slots and rotor teeth are aligned, i.e. $\theta = 180°/\text{T}$) is a stable position. The teeth on all the rotors are perfectly aligned. Stator teeth of various stacks differ by an angular displacement of $\alpha = 360°/nT$, where n is the number of stacks.

If number of teeth is 12 and that of stacks is 3, then $\alpha = 10°$.

Figure (e) shows rotor and stator stack view for a 3-stack stepper motor.



(a) Cross-sectional view of stepper motor with 3 stacks

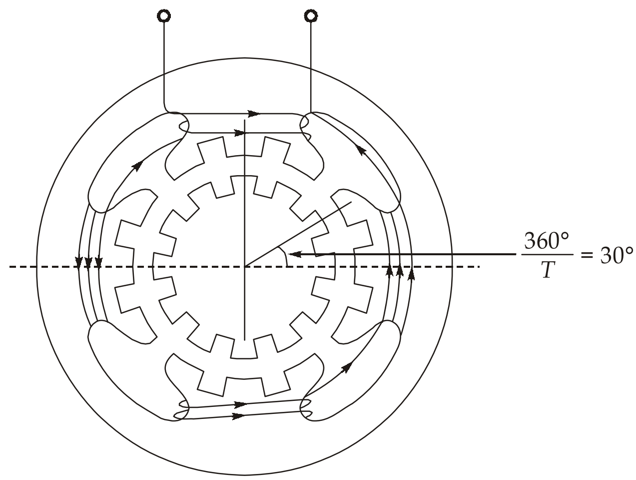


Fig. (b) : Multistack variable reluctance stepper motor with 12 teeth

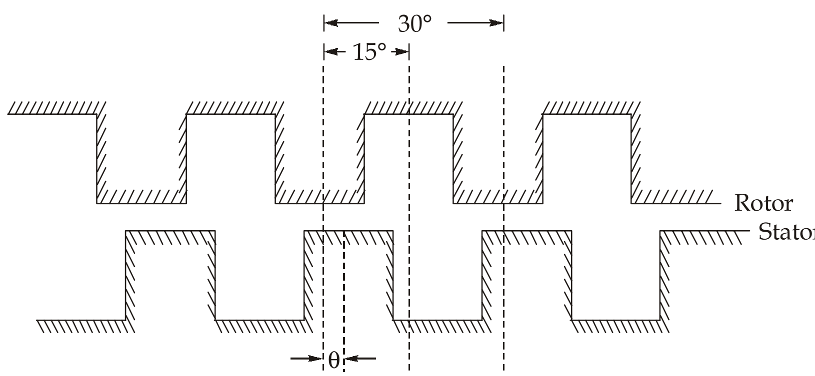


Fig. (c): View of teeth of a pair of stator and rotor

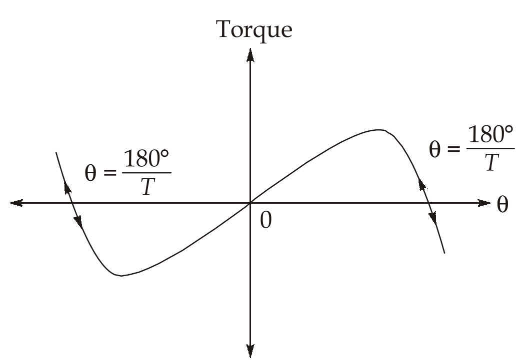


Fig. (d): Static torque-angle curve

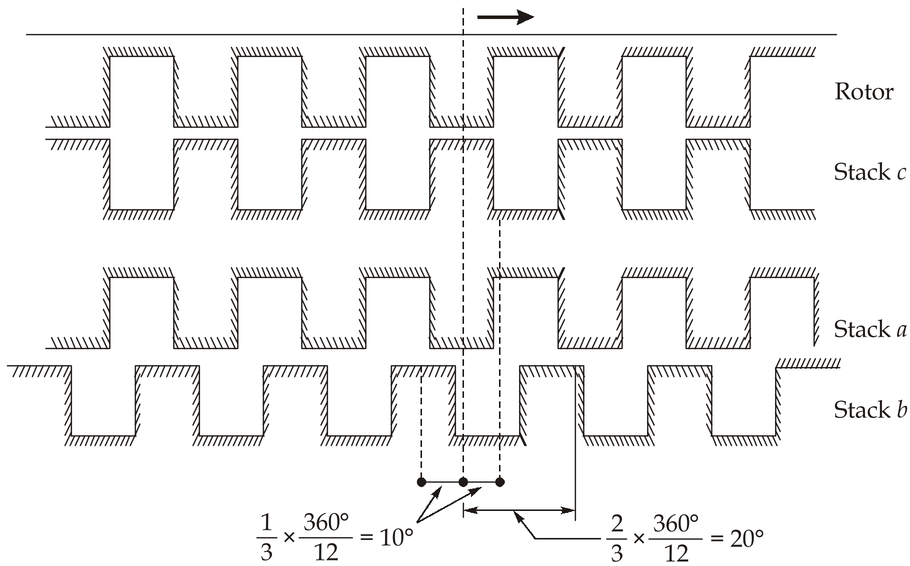


Fig. (e) : View of rotor and stator stacks for a 3-slack stepper motor

Figure : Stepper motor

2. (c)

As per given information

$$L_{12} + d_3 - L_4 = r_{34}$$

$$d_3 = r_{34} + L_4 - L_{12}$$

$$L_2C_{12} + L_{11}C_1 = r_{14} \quad ...(1)$$

$$L_2S_{12} + L_{11}S_1 = r_{24} \quad ...(2)$$

Squaring eqn. (1) and (2), then adding

$$(r_{14})^2 + (r_{24})^2 = L_{11}^2 + L_2^2 + 2L_{11}L_2C_2$$

$$C_2 = \frac{r_{14}^2 + r_{24}^2 - L_{11}^2 - L_2^2}{2L_{11}L_2} \quad ...(3)$$

$$S_2 = \pm\sqrt{1 - C_2^2} \quad ..(4)$$

The solution for θ_2 is obtained from equation (3) and (4)

$$\theta_2 = A \tan 2(S_2, C_2)$$

Now, θ_2 is used to compute θ_1

$$L_2(C_1C_2 - S_1S_2) + L_{11}C_1 = r_{14} \text{ (expanding } C_{12}\text{, i.e., } \cos(\theta_1 + \theta_2)]$$

$$L_2(S_1C_2 + C_1S_2) + L_{11}S_1 = r_{24} \text{ (expanding } S_{12}\text{, i.e., } \sin(\theta_1 + \theta_2)]$$

$$(L_{11} + L_2C_2)C_1 - (L_2S_2)S_1 = r_{14} \quad ...(5)$$

$$(L_{11} + L_2C_2)S_1 + (L_2S_2)C_1 = r_{24} \quad ...(6)$$

Let

$$L_{11} + L_2C_2 = r\cos\phi$$

$$L_2S_2 = r\sin\phi$$

$$r = \sqrt{(L_{11} + L_2C_2)^2 + (L_2S_2)^2}$$

$$\phi = A\tan 2\left(\frac{L_2S_2}{r}, \frac{L_{11} + L_2C_2}{r}\right)$$

From equation (5) and (6)

$$r\cos(\theta_1 + \phi) = r_{14} \quad ...(7)$$

$$r\sin(\theta_1 + \phi) = r_{24} \quad ...(8)$$

From (7) and (8)

$$\theta_1 = A\tan 2\left(\frac{r_{24}}{r}, \frac{r_{14}}{r}\right) - \phi$$

Now, θ_1, θ_2 and d_3 are known, θ_4 can be computed.

$$C_{124} = r_{11}$$

$$S_{124} = r_{21}$$

$$\theta_1 + \theta_2 - \theta_4 = A\tan 2(r_{21}, r_{11})$$

$$\theta_4 = \theta_2 + \theta_1 - A\tan 2(r_{21}, r_{11})$$

Now all variables θ_1, θ_2, θ_4, d_3 are known.

3. (a)

Given : $P = 150$ kW; $N = 3000$ rpm; $T = 800$ N-m; $p = 0.24$ N/mm^2; $\mu = 0.3$; $N = 8$; $k = 50$ N/mm

Let r_1 = Outer radius of the friction plate, and

r_2 = Inner radius of the friction plate

Also, $r_1 = 1.25r_2$ (Given)

For uniform wear conditions

$$p \cdot r = c$$

Since the intensity of pressure is maximum at the inner radius

$$\therefore \quad p \cdot r_2 = c \text{ or } c = 0.24 r_2$$

Axial load acting on the friction plate

$$W = 2\pi c (r_1 - r_2)$$

$$= 2\pi \times 0.24 \times r_2 (1.25 r_2 - r_2)$$

$$W = 0.377 r_2^2 \text{ N} \qquad \text{...(i)}$$

For uniform wear, mean radius

$$R = \frac{r_1 + r_2}{2} = \frac{1.25 r_2 + r_2}{2} = 1.125 r_2$$

$$\therefore \quad \text{Torque transmitted, } T = n \cdot \mu \cdot w \cdot R$$

$$800 \times 10^3 = 2 \times 0.3 \times 0.377 r_2^2 \times 1.125 \times r_2$$

$$\therefore \quad r_2^3 = 3143727.28$$

$$\therefore \quad r_2 = 146.5 \text{ mm}$$

$$\text{and} \quad r_1 = 1.25 r_2 = 183.1 \text{ mm}$$

Total stiffness of the springs,

$$k_{eq} = \text{Stiffness per spring} \times \text{Number of springs}$$

$$= 50 \times 8 = 400 \text{ N/mm}$$

Axial force required to engage the clutch

$$W = 0.377 \times r_2^2 = 0.377 \times 146.5^2$$

$$W = 8091.27 \text{ N}$$

$\therefore$ Initial compression in the springs,

$$x = \frac{W}{k_{eq}} = \frac{8091.27}{400}$$

$$x = 20.23 \text{ mm}$$ **Ans.**

3. (b)

Figure shows the block diagram of Inlet 8085 microprocessor.

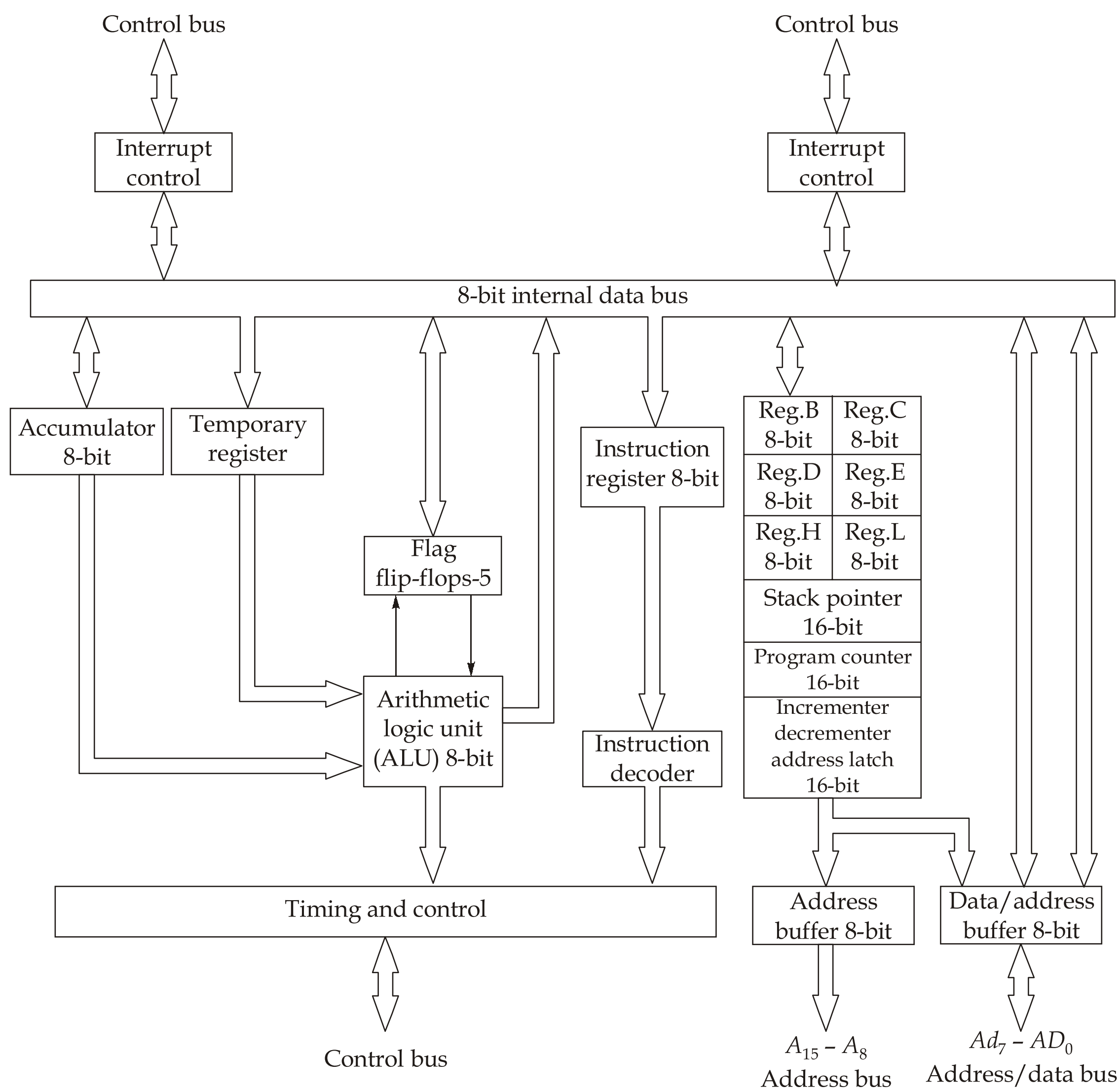


Fig. : Block diagram of intel 8085 microprocessor

Some important functional units/parts are enumerated and discussed as follows:

1. **Arithmetic and logic unit (ALU).**
2. **Timing and control unit.**
3. **Registers**
4. **Data and address bus**
5. **Pin configuration**

1. Arithmetic and logic unit (ALU):

ALU performs the following arithmetic and logical operations:

1. Addition
2. Subtraction
3. Logical AND
4. Logical OR
5. Logical EXCLUSIVE OR
6. Complement (logical NOT)
7. Increment (add 1)
8. Decrement (subtract 1)
9. Left shift, Rotate left, Rotate right.
10. Clear etc.

2. Timing and control unit:

This unit is a section of CPU.

It generates timing and control signals which are necessary for the execution of instructions. It controls data flow between CPU and peripherals (including memory).

It provides status, control and timing signals which are required for the operation of memory and input/output devices.

It controls the entire operations of microprocessor and peripherals connected to it.

3. Registers

Registers are digital devices used by the microprocessor for temporary storage and manipulation of data and instructions. Data remain in the registers till they are sent to the memory of I/O devices.

- Operationally, registers exhibit two notable characteristics: they are edge-triggered devices and all switching of flip-flops is synchronised by applying the clock pulse to each flip-flop simultaneously.

Activation of the register itself is achieved by means of an appropriate control signal Registers like counters may be either parallel registers or serial (shift) registers, although combined versions are also possible.

- In parallel registers all the binary data that appear at input terminals of the flip-flops are transferred to the output terminals in a single clock pulse. This makes the operation of the register very fast; it is the reason for its preference in digital computers.
- Serial or shift register processes each bit of word in succession and, therefore, operation is slow. However the shift register does offer the compensating advantage of requiring less equipment.

Intel 8085 microprocessor has the following registers:

1. **Accumulator (ACC):**
   - It is an 8-bit special purpose register that is a part of the ALU. It is also identified as register A.
   - In arithmetic and logical operations the accumulator may store the operand execute an instruction with the help of other registers, and memory and final store the result of the operation. In the former case it acts as a source, and the latter a destination.
2. **General purpose registers:**
   - The 8085 microprocessor contains six 8-bit general purpose registers. These identified as *B, C, D, E, H* and *L* as shown in figure above.
   - These registers are used in microprocessor for temporary storage of operands or intermediate data in calculations.
   - These registers can be used either simply for storage of 8-bit data or in pairs for storage of 16-bit data. When used in pairs, only selected combination can be used for pairing, i.e., B-C, D-E and H-L. When registers are used in pairs the high order byte resides in the first register and low order byte in the second register.
3. **Stack pointer (SP):**
   - It is a 16-bit special function register.
   - The stack is a sequence of memory locations set aside by a programmer to store/ retrieve the contents of accumulator, flags, program counter and general purpose registers during the execution of a program. Any portion of the memory can be used as a stack.
   - In this register, data is stored temporarily on first come and last go basis.
4. **Program counter (PC):**
   - It is a 16-bit special-purpose register and is used to hold the memory address of the next instruction to be executed.
   - The contents of the PC are automatically updated by the microprocessor during the execution of an instruction so that at the end of execution it points to the address of the next instruction in the memory.
   - The microprocessor uses the PC for sequencing the execution of instructions.

5. **Instruction register:**
   - During the execution of a program, microprocessor addresses some memory, which supplies an 8-bit data of instruction code to the data bus which gets stored in the register called the instruction register.
   - The instruction register holds the op-code (operation code or instruction code) of the instruction which is being decoded and executed.
6. **Temporary register:**
   - It is an 8-bit register associated with ALU.
   - It holds data during an arithmetic/logical operation.
   - It is used by the microprocessor and is not accessible to programmer.

3 (c) Solution:

As per given information, $\phi = 30°, \theta = 40°, \psi = 50°$

$$\text{Euler}(\phi, \theta, \psi) = \text{Rot}(a, \phi).\text{Rot}(o, \theta).\text{Rot}(a, \psi)$$

$$\text{Euler}(30°, 40°, 50°) = \begin{bmatrix} C\phi & -S\phi & 0 & 0 \\ S\phi & C\phi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\theta & 0 & S\theta & 0 \\ 0 & 1 & 0 & 0 \\ -S\theta & 0 & C\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\psi & -S\psi & 0 & 0 \\ S\psi & C\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos 30° & -\sin 30° & 0 & 0 \\ \sin 30° & \cos 30° & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos 40° & 0 & \sin 40° & 0 \\ 0 & 1 & 0 & 0 \\ -\sin 40° & 0 & \cos 40° & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos 50° & -\sin 50° & 0 & 0 \\ \sin 50° & \cos 50° & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

By using matrix multiplication function,

$$\text{Euler}(30°, 40°, 50°) = \text{Euler}(\phi, \theta, \psi)$$

$$= \begin{bmatrix} 0.0434 & -0.8296 & 0.5566 & 0 \\ 0.9096 & 0.2632 & 0.3213 & 0 \\ -0.4134 & 0.4924 & 0.766 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Above matrix compared with

$$\text{RPY}(\phi_a, \phi_o, \phi_n) = \begin{bmatrix} n_x & o_x & a_x & 0 \\ n_y & o_y & a_y & 0 \\ n_z & o_z & a_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Now for RPY system,

$$\text{Rot}^{-1}(a, \phi_a)\begin{bmatrix} n_x & o_x & a_x & 0 \\ n_y & o_y & a_y & 0 \\ n_z & o_z & a_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \text{Rot}(o, \phi_o).\text{Rot}(n, \phi_n)$$

$$\begin{bmatrix} n_x c\phi_a + n_y s\phi_a & o_x c\phi_a + o_y s\phi_a & a_x c\phi_a + a_y s\phi_a & 0 \\ n_y c\phi_a - n_x s\phi_a & o_y c\phi_a - o_x s\phi_a & a_y c\phi_a - a_x s\phi_a & 0 \\ n_z & o_z & a_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\phi_o & s\phi_o.s\phi_n & s\phi_o c\phi_n & 0 \\ 0 & c\phi_n & -s\phi_n & 0 \\ -s\phi_o & c\phi_o.s\phi_n & c\phi_o.c\phi_n & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

On comparing

$$\phi_a = \tan^{-1}\left(\frac{n_y}{n_x}\right) = \tan^{-1}\left(\frac{0.9096}{0.0434}\right) = 87.26°$$

or

$$\phi_a = \tan^{-1}\left(\frac{-n_y}{-n_x}\right) = \tan^{-1}\left(\frac{-0.9096}{-0.0434}\right) = 267.26°$$

$$\phi_o = \tan^{-1}\left(\frac{-n_z}{n_x c\phi_a + n_y S\phi_a}\right)$$

$$= \tan^{-1}\left[\frac{-(-0.4134)}{(0.0434\cos 87.26° + 0.9096\sin 87.26°)}\right]$$

$$\phi_o = 24.416°$$

or

$$\phi_o = \tan^{-1}\left[\frac{-(-0.4134)}{0.0434\cos 267.26° + 0.9096\sin 267.26°}\right]$$

$$\phi_o = 155.583°$$

$$\phi_n = \tan^{-1}\left(\frac{-a_y c\phi_a + a_x S\phi_a}{o_y c\phi_a - o_x S\phi_a}\right)$$

$$= \tan^{-1}\left(\frac{-0.3213\cos 87.26° + 0.5566\sin 87.26°}{0.2632\cos 87.26° - (-0.8296\sin 87.26°)}\right)$$

$$\phi_n = 32.726°$$

or

$$\phi_n = \tan^{-1}\left(\frac{-0.3213\cos 267.26° + 0.5566\sin 267.26°}{0.2632\cos 267.26° - (-0.8296\sin 267.26°)}\right)$$

$$\phi_n = \tan^{-1}\left(\frac{-0.5406}{-0.8421}\right) = 212.726°$$

4. (a)

Given : $P = 10$ kN; $S_{yt} = 400$ N/mm^2; $f_s = 4$

$$\text{Permissible shear stress, } \tau_{max} = \frac{0.5S_{yt}}{(f_s)} = \frac{0.5 \times 400}{4} = 50 \text{ N/mm}^2$$

Tensile and shear stresses in bolts:

The axial force in the tie rod (P) is resolved into vertical and horizontal components.

$$\therefore \quad P_V = P\sin\theta = 10000 \sin 30°$$

$$P_V = 5000 \text{ N}$$

and
$$P_H = P\cos\theta = 10000 \cos 30°$$

$$= 8660.25 \text{ N}$$

The vertical component produces directly tensile force on each bolt. It is given by

$$P_1 = P_2 = \frac{5000}{4} = 1250 \text{ N}$$

The horizontal component produces direct shear force on each bolt. It is given by

$$P_1' = P_2' = \frac{P}{4} = \frac{8660.25}{4} = 2165.06 \text{ N}$$

In addition, the horizontal component produces tensile force on each bolt due to its moment about the tilting edge C. The bolts at A are denoted by 2 and bolts at B by 1. The bolts at B are located at farthest distance from the tilting edge C.

$$P_1'' = \frac{Pel_1}{2\left(l_1^2 + l_2^2\right)} = \frac{8660.25 \times 75 \times 175}{2\left(25^2 + 175^2\right)}$$

$$\therefore \quad P_1'' = 1818.65 \text{ N}$$

$$\therefore \quad \text{Tensile stress, } \sigma_t = \frac{P_1 + P_1''}{A} = \frac{1250 + 1818.65}{A}$$

$$= \frac{3068.65}{A} \text{N/mm}^2$$

$$\text{and shear stress, } \tau = \frac{P_1'}{A} = \frac{2165.06}{A} \text{ N/mm}^2$$

$$\therefore \quad \text{As per MSST,} \quad \tau_{max} = \sqrt{\left(\frac{\sigma_t}{2}\right)^2 + \tau^2}$$

$$50 = \frac{1}{A}\sqrt{\left(\frac{3068.65}{2}\right)^2 + (2165.06)^2}$$

$\therefore \quad A = 53.07 \text{ mm}^2$

$\therefore \quad d = \sqrt{\dfrac{4 \times 53.07}{\pi}} = 8.22 \text{ mm}$ **Ans.**

or $\quad d = 9 \text{ mm}$ **Ans.**

4. (b)

Construction and working of the load cell :

Figure shows a simple strain gauge load cell. It consists of a steel cylinder, on which are mounted four identical strain gauges. The gauges R_{g1} and R_{g4} are along the direction of applied load and the gauges R_{g2} and R_{g3} are attached circumferentially to gauges R_{g1} and R_{g4}. All the four gauges are connected electrically to the four limbs of a Wheatstone bridge circuit.

When there is no load on the cell, all the four gauges have the same resistance (i.e., $R_{g1} = R_{g2} = R_{g3} = R_{g4}$). Obviously the terminals B and D are at the same potential, the bridge is balanced and the output voltage is zero.

$$v_{AB} = v_{AD} = \frac{v}{2}$$

and $$v_{AB} - v_{AD} = v_0 = 0$$

On the application of a compressive load to the unit, the vertical gauges (R_{g1} and R_{g4}) undergo compression (i.e., negative strain) and, therefore, there is decrease in resistance. The circumferential gauges R_{g2} and R_{g3}, simultaneously, undergo tension (i.e., positive strain) leading to increase in resistance. The two strains are not equal; these are related to each other by a factor, μ, the Poisson's ratio. Thus when strained, the resistances of various gauges are:

$$R_{g1} = R_{g4} = R - dR \qquad \text{...(Compression)}$$

$$R_{g2} = R_{g3} = R + dR \qquad \text{...(Tension)}$$

Potential at terminal B, $\nu_{AB} = \dfrac{R_{g1}}{R_{g1} + R_{g3}}\nu = \dfrac{R - dR}{(R - dR) + (R + \mu dR)} \times \nu$

$$= \frac{R - dR}{2R - dR(1 - \mu)} \times \nu \qquad \text{...(i)}$$

Potential at terminal D, $\nu_{AD} = \dfrac{R_{g2}}{R_{g2} + R_{g4}}\nu = \dfrac{R + \mu\, dR}{(R + \mu\, dR) + (R - dR)} \times \nu$

$$= \frac{R + \mu\, dR}{2R - dR(1 - \mu)} \times \nu \qquad \text{...(ii)}$$

The changed output voltage,

$$v_0 + dv_0 = \frac{R - dR}{2R - dR(1-\mu)} \times v - \frac{R + \mu\, dR}{2R - dR(1-\mu)} \times v$$

[Using (i) and (ii)]

$$= \frac{dR(1+\mu)}{2R} = 2(1+\mu)\left(\frac{dR}{R}\cdot\frac{v}{4}\right) \quad ...(iii)$$

[Neglecting dR(1 – μ), as $dR(1 - \mu) << 2R$] ... in magnitude

Since the output voltage $v_0 = 0$ under unloaded conditions, therefore, change in output voltage due to applied load becomes :

$$dv_0 = 2(1+\mu)\left(\frac{dR}{R}\cdot\frac{v}{4}\right) \quad ...(iv)$$

Obviously, this voltage is a measure of the applied load.

The use of four identical strain gauges in each arm of the bridge provides full temperature compensation and also increases the sensitivity of the bridge 2(1 + μ) times.

Given : d = 80 mm; R = 120 W; G_f = 2.0; v = 5 V; E = 200 GPa; μ = 0.3

Now,

$$\text{Stress, } \sigma = \frac{P}{A} = \frac{2.5 \times 10^3}{\frac{\pi}{4} \times 0.08^2} = 497.36 \text{ kN/m}^2$$

$$\text{Strain, } \varepsilon = \frac{\sigma}{E} = \frac{497.36 \times 10^3}{200 \times 10^9} = 2.48 \times 10^{-6}$$

Fractional change in resistance,

$$\frac{dR}{R} = G_f \times e$$

$$= 2 \times 2.48 \times 10^{-6} = 4.96 \times 10^{-6}$$

∴ Output voltage,

$$dv_0 = 2(1+\mu)\left(\frac{dR}{R}\cdot\frac{v}{4}\right)$$

$$= 2(1+0.3)\left(4.96 \times 10^{-6} \times \frac{5}{4}\right)$$

$$dv_0 = 16.12\ \mu\text{V}$$

Hence, the sensitivity of the load cell $= \frac{dv_0}{F} = \frac{16.12}{2.5} = 6.45\ \mu\text{V/kN}$ **Ans.**

4. (c)

Given : d = 50 mm; l = 120 mm; p = 1.5 N/mm²; N = 1200 rpm; $\frac{d}{c} = 1000$;

z = 0.02 kg/m-s; t_0 = 85°C; t_a = 30°C; k = 0.002; c_{po} = 1850 J/kg°C; C = 280 W/m²°C; ΔT_0 = 15

$$\text{Coefficient of friction, } \mu = \frac{33}{10^8}\left(\frac{zN}{p}\right)\left(\frac{d}{c}\right) + k$$

$$\mu = \frac{33}{10^8}\left(\frac{0.02 \times 1200}{1.5}\right)(1000) + 0.002$$

$$\therefore \quad \mu = 0.00728$$

$$\text{Load on the bearing, } W = p \times dl$$

$$= 1.5 \times 50 \times 120 = 9000 \text{ N}$$

$$\text{Rubbling velocity, } v = \frac{\pi dN}{60} = \frac{\pi \times 0.05 \times 1200}{60} = 3.14 \text{ m/s}$$

$$\therefore \quad \text{Heat generated, } Q_g = \mu W v = 0.00728 \times 9000 \times 3.14$$

$$Q_g = 205.73 \text{ W}$$

Let, t_b = Temperature of the bearing surface

$$\therefore \quad t_b - t_a = \frac{1}{2}(t_o - t_a) = \frac{1}{2}(85 - 30)$$

$$t_b - t_a = 27.5°\text{C}$$

$$\therefore \quad \text{Heat dissipated, } Q_d = C \cdot A \cdot (t_b - t_a) = C \cdot l \cdot d(t_b - t_a)$$

$$= 280 \times 0.05 \times 0.12 \times 27.5$$

$$\therefore \quad Q_d = 46.2 \text{ W}$$

$\therefore$ Amount of artificial cooling required,

$$= Q_g - Q_d$$

$$= 205.73 - 46.2$$

$$= 159.53 \text{ W}$$

Ans.

Let m = mass of lubricating oil required in kg/s

We know that the amount of artificial cooling required = $Q_g - Q_d$

Equating the amount of artificial cooling required to the heat taken away by the oil.

$$Q_g - Q_d = Q_t$$

$$205.73 - 46.5 = m_0 \cdot C_{po} \cdot \Delta T_0$$

$$\therefore \quad 159.53 = m_0 \times 1850 \times 15$$

$$\text{or} \quad m_0 = 5.749 \times 10^{-3} \text{ kg/s}$$

$$\text{or} \quad m_0 = 0.345 \text{ kg/min}$$

Ans.

Section : B

5. **(a)**

There are certain drawbacks with steam as the working substance in a power cycle. The maximum temperature gained in steam cycles using the best available material is about 600°C, while the critical temperature of steam is 375°C, which necessitates large superheating and permits the addition of only an infinitesimal amount of heat at the highest temperature.

High moisture content is involved during expansion of steam in going to higher steam pressures in order to obtain higher mean temperature of heat addition (T_{m1}) The use of reheat thus becomes necessary. Since reheater tubes are costly and the steam plant layout becomes complex, the use of more than two reheats is hardly recommended. Also, as pressure increases, the metal stresses increase, and the increase in thicknesses of the walls of boiler drums, tubes, pipe-lines and so on is not in proportion to the pressure increase, but much faster because of the prevalence of high temperature.

It may be noted that high T_{m1} is desired for high cycle efficiency. The need for high pressures is only forced due to weak characteristics of steam.

The desirable characteristics of the working fluid in a vapour power cycle to obtain the best thermal efficiency are given as follows:

(a) The fluid should have a high critical temperature so that the saturation pressure at the maximum permissible temperature (metallurgical limit) is relatively low. It should have a large enthalpy of vaporization at that pressure.

(b) The saturation pressure at the temperature of heat rejection should be above the atmospheric pressure so as to avoid the necessity of maintaining vacuum in the condenser.

(c) The specific heat of liquid should be small so that little heat transfer is required to raise the liquid to the boiling point.

(d) The saturated vapour line of T-s diagram should be steep, very close to the turbine expansion process so that excessive moisture does not appear during expansion.

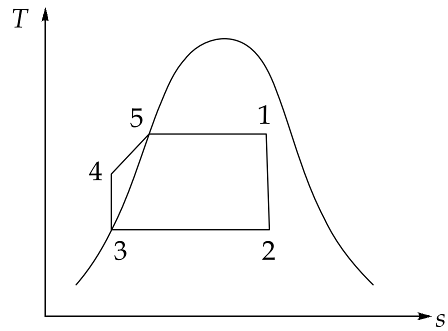
(e) The freezing point of the fluid should be below the room temperature, so that it does not get solidified while flowing through the pipelines.

(f) The fluid should be chemically stable and should not contaminate the materials of construction at any temperature.

5. (b)

Given : $P_1 = P_5 = P_4 = 10$ bar; $T_4 = 37°C$, $x_1 = 0.9$, $\dot{m}_s = 5500$ kg/h; $\dot{m}_f = 700$ kg/h;

C.V. = 30 MJ/kg



Increment in boiler efficiency = 6%

@ 10 bar,

$$h_5 = h_f = 750 \text{ kJ/kg}$$

$$h_{fg} = 2050 \text{ kJ/kg}$$

$$\therefore \quad h_1 = h_f + xh_{fg}$$

$$= 750 + 0.9 \times (2050)$$

$$= 2595 \text{ kJ/kg}$$

$$(h_w)_{35°C} = 145 \text{ kJ/kg}$$

$$(h_w)_{40°C} = 165 \text{ kJ/kg}$$

By linear interpolation,

$$(h_w)_{37°C} = 153 \text{ kJ/kg}$$

Now,

$$\text{Efficiency of boiler, } \eta = \frac{\dot{m}_s \times (h_1 - h_w)}{\dot{m}_f \times C.V.}; \qquad (h_w = (h_w)_{37°C})$$

$$= \frac{5500 \times (2595 - 153)}{700 \times 30 \times 1000}$$

$$= 0.639 \simeq 0.64$$

$$\simeq 64\%$$

When economiser is used then,

$$\text{New efficiency, } \eta' = (64 + 6)\% = 70\%$$

$$\therefore \qquad \eta' = \frac{\dot{m}_s \times (h_1 - h_w)}{\dot{m}_f \times C.V.}; \qquad (h_w = (h_w)_{100°C})$$

$$0.7 = \frac{5000 \times (2595 - 420)}{\dot{m}_f \times 30 \times 1000}$$

$$\Rightarrow \qquad \dot{m}_f = 569.64 \text{ kg/hr}$$

$\therefore$ Saving in coal consumption per hour

$$= (700 - 569.64) \text{ kg/hr}$$

$$= 130.357 \text{ kg/hr}$$

5. (c)

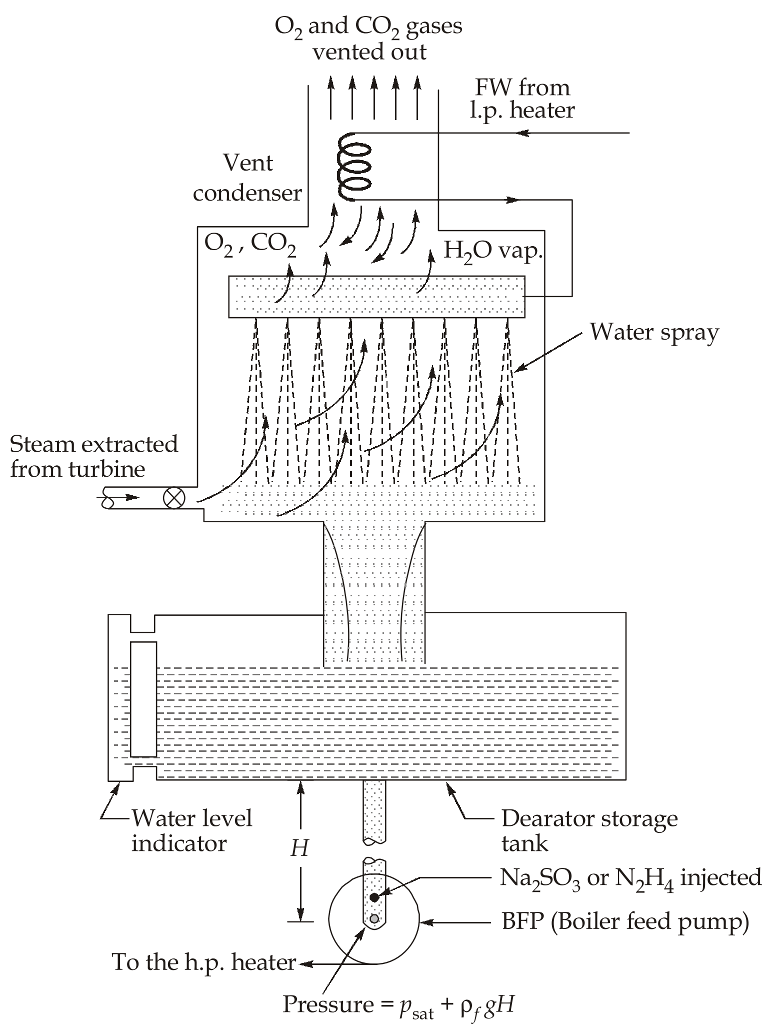
One of the feedwater heaters is a contact-type open heater, known as deaerator, others being closed heaters. It is used for the purpose of deaerating the feedwater.

The presence of dissolved gases like oxygen and carbon dioxide in water makes the water corrosive, as they react with the metal to form iron oxide. The solubility of these gases in water decreases with increase in temperature and becomes zero at the boiling or saturation temperature. These gases are removed in the deaerator, where feedwater is heated to the saturation temperature by the steam extracted from the turbine. Feedwater, after passing through a heat exchanger, called vent condenser, is sprayed from the top so as to expose large surface area, and the bled steam from the turbine is fed from the bottom as shown in figure below. By contact the steam condenses and the feedwater is heated to the saturation temperature. Dissolved oxygen and carbon dioxide gases get released from the water and leave along with some vapour, which is condensed back in the vent condenser, and the gases are vented out.

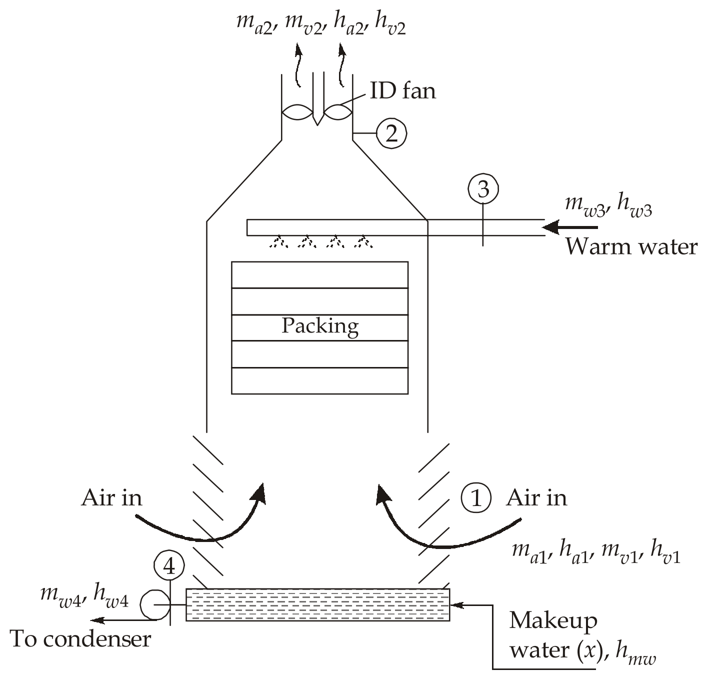
To neutralize the effect of residual dissolved oxygen and carbon dioxide gases in water, sodium sulphite (Na_2SO_4) or hydrazine (N_2H_2) is injected in suitable calculated doses into the feedwater at the suction of the boiler feed pump (BFP).

During suction of the BFP, some of the saturated feedwater may flash into vapour due to reduction in pressure causing vapour lock and cavitation problems in the pump. To prevent this from occurring and to provide a net positive suction head (NPSH) for the pump, the deaerator is located at a sufficient height (H) from the basement where the pump is installed so that the pressure before suction is (P_{sat} + $\rho_f gH$). When this water is sucked by the pump, the pressure does not fall below P_{sat} and there is no flashing of any water into vapour, which protects the BFP from any damage due to vapour lock and cavitation.

The deaerator is usually placed near the middle of the feedwater system so that the total pressure difference between the condenser and the boiler is shared equitably between the condensate pump and boiler feed pump. The feedwater heaters before the deaerator are often termed as high pressure (*h.p.*) heaters and those after the deaerator are termed as low pressure (*l.p.*) heaters.



5. (d)



Refering to the above figure. Since relative humidity of air is given, so we can work directly for humid air.

Using energy balance,

$$m_{a_1}h_1 + m_w h_{w_3} + xh_{mw} = m_{a_2}h_2 + m_w h_{w_4}$$

Considering humid air,

$$m_{a_1} = m_{a_2} = m_a \qquad \text{(given)}$$

$$\Rightarrow \quad \frac{m_w}{m_a}\left(h_{w_3} - h_{w_4}\right) = (h_2 - h_1) - (\omega_2 - \omega_1) \times h_{mw}$$

$$\Rightarrow \quad 1.25 \times 4.18 \times \left(30 - t_{w_4}\right) = (83.5 - 43) - (0.02132 - 0.00881) \times 84$$

$$\Rightarrow \quad t_{w_4} = 22.45°\text{C}$$ **Ans.**

$$\text{Approach} = t_{w_4} - t_{wb_1} = 22.45 - 15.2 = 7.25°\text{C}$$ **Ans.**

$$\text{Range} = t_{w_3} - t_{w_4} = 30 - 22.45 = 7.55°\text{C}$$ **Ans.**

The function of water evaporated,

$$x = \omega_2 - \omega_1$$

$$= 0.02132 - 0.00881 = 0.01251 \text{ kg/kgd.a.}$$

5. (e)

The principal components of an electrostatic precipitator (ESP) are two sets of electrodes insulated from each other. The first set is composed of rows of electrically grounded vertical parallel plates, called the collection electrodes, between which the dust-laden gas flows. The second set of electrodes consists of wires, called the discharge or emitting electrodes that are centrally located between each pair of parallel plates as shown in figure below. The wires carry a unidirectional negatively charged high-voltage (between 20 and 100 kV) current from an external dc source. The applied high voltage generates a unidirectional, non-uniform electrical field whose magnitude is greatest near the discharge electrodes. When that voltage is high enough, a blue luminous glow, called a corona, is produced around them. Electrical forces in the corona accelerate the free electrons present in the gas so that they ionize the gas molecules, thus forming more electrons and positive gas ions. The new electrons create again more free electrons and ions, which result in a chain reaction.

The positive ions travel to the negatively charged wire electrodes. The electrons follow the electrical field toward the grounded electrodes, but their velocity decreases as they move away from the corona region around the wire electrodes toward the grounded plates. Gas molecules capture the low velocity electrons and become negative ions. As these ions move to the collecting electrode, they collide with the fly ash particles in the gas stream and give them negative charge. The negatively charged fly ash particles are driven to the collecting plate by the force which is proportional to the product of this charge and the strength of the electric field.

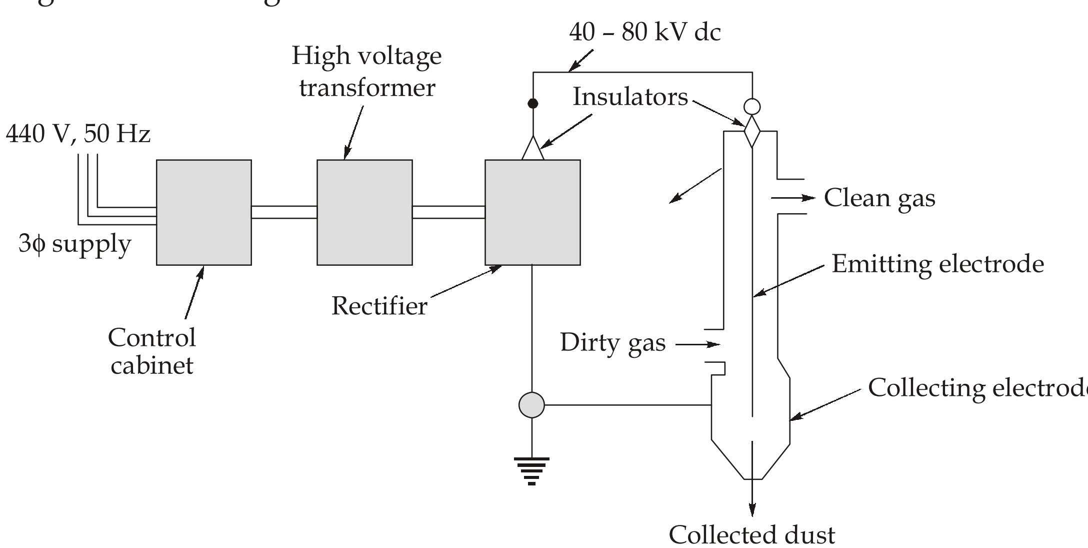


Fig. Basic elements of an electrostatic precipitator

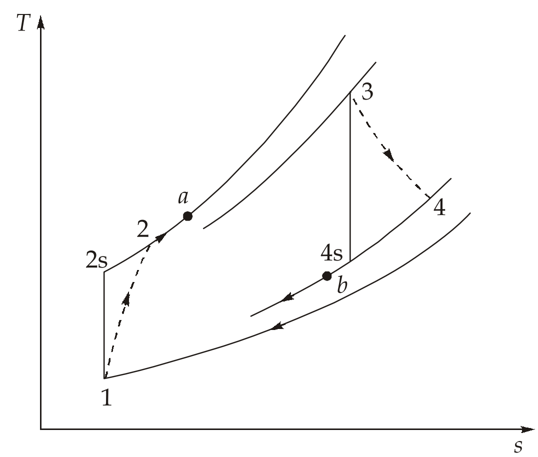
When the particles collect on the grounded plates, they lose their charge on the ground.

The electrical resistivity of the particles, however, cause only partial discharging, and the retained charge tends to hold the particles to the plates. High resistivity causes retention of most of the charge, which increases the forces holding the particles to the plates and makes removal more difficult. This can be rectified either by operating at high gas temperatures (before APH) or by superimposing a high voltage pulse on the base voltage to enhance ESP performance during operation under high-resistivity conditions.

Collected particulate matter must be removed from the collecting plates on a regular schedule to ensure efficient collector operation. Removal is usually accomplished by a mechanical hammer scrapping system.

6. (a)

Given : $T_1 = 17°C = 290$ K; $P_1 = 1$ bar; $T_3 = 1427°C = 1700$ K; $P_2 = 12$ bar; $\in = 0.75$; $\eta_c = 0.80$; $\eta_T = 0.85$; $P_3 = 12 - 0.2 = 11.8$ bar; $P_4 = 1 + 0.2 = 1.2$ bar



For isentropic compression process 1 - 2s:

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\Rightarrow \quad \frac{T_{2s}}{290} = \left(\frac{12}{1}\right)^{\frac{0.4}{1.4}} = 589.84 \text{ K}$$

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$\Rightarrow \quad T_2 = \frac{589.84 - 290}{0.80} + 290 = 664.8 \text{ K}$$

For isentropic expansion process 3 - 4s:

$$\frac{T_3}{T_{4s}} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\Rightarrow \quad T_{4s} = \frac{1700}{\left(\frac{11.8}{1.2}\right)^{\frac{0.4}{1.4}}} = 884.75 \text{ K}$$

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_{4s}}$$

$$\Rightarrow \quad 0.85 = \frac{1700 - T_4}{1700 - 884.75}$$

$$\Rightarrow \quad T_4 = 1007.04 \text{ K}$$

$$\text{Effectiveness of regenerator, } \in = \frac{T_a - T_2}{T_4 - T_2}$$

$$\Rightarrow \quad 0.75 = \frac{T_a - 664.8}{1007.04 - 664.8}$$

$$\Rightarrow \quad T_a = 921.48 \text{ K}$$

$$\text{Network, } W_{net} = W_T - W_C = c_p[(T_3 - T_4) - (T_2 - T_1)]$$
$$= 1.005[(1700 - 1007.04) - (664.8 - 290)]$$
$$= 319.75 \text{ kJ/kg}$$

$$\text{Heat supplied, } Q_s = c_p(T_3 - T_a) = 1.005 \times (1700 - 921.48)$$
$$= 782.41 \text{ kJ/kg}$$

$$\text{Thermal efficiency, } \eta_{th} = \frac{W_{net}}{Q_s} = \frac{319.75}{782.41} = 0.4087 \text{ or } 40.87\%$$ **Ans.**

6. (b) (i)

By modifying the initial steam pressure and exhaust pressure, it is possible to generate the required power and make available the required quantity of exhaust steam at the desired temperature for process work. In figure (a), the exhaust steam from the turbine is utilized for process heating.

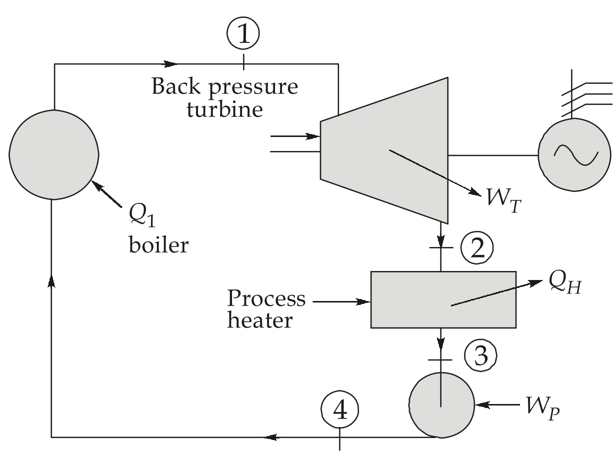


Fig. (a) Cogeneration plant with a back pressure turbine

The process heater replacing the condenser of the ordinary Rankine cycle. The pressure at exhaust from the turbine is the saturation pressure corresponding to the temperature desired in the process heater. Such a turbine is called a back pressure turbine. A plant producing both electrical power and process heat simultaneously is called a cogeneration plant. When the process steam is the basic need, and the power is produced incidentally as a by-product, the cycle is often called a by-product power cycle. Figure (b) shows the T-s plot for such a cycle. If W_T is the turbine output in kW, Q_H is the process heat required in kJ/h, and w_s is the steam flow rate in kg/h.

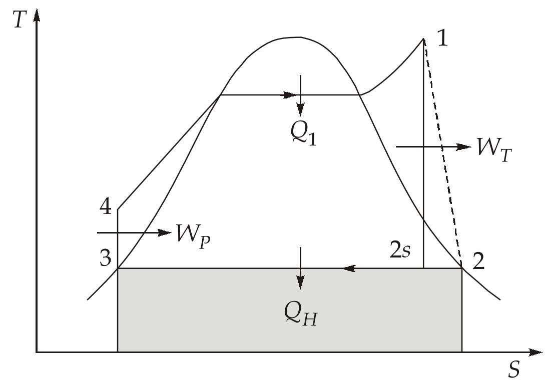


Fig. (b) By-product power cycle with a back pressure turbine

$$W_T \times 3600 = w_s (h_1 - h_2) \text{ and } Q_H = w_s (h_2 - h_3)$$

$\therefore$
$$W_T \times 3600 = \frac{Q_H}{h_2 - h_3}(h_1 - h_2)$$

or,
$$Q_H = \frac{W_T \times 3600 \times (h_2 - h_3)}{h_1 - h_2} \text{ kJ/h}$$

Of the total energy input Q_1 (as heat) to the cogeneration plant, W_T part of it only is converted into shaft work or electricity. The remaining energy ($Q_1 - W_T$), which would otherwise have been a waste, as in the Rankine cycle, by second law, is utilized as process heat.

The cogeneration plant efficiency η_{co} is given by

$$\eta_{co} = \frac{W_T + Q_H}{Q_1}$$

Back pressure turbines are quite small with respect to their power output because they have no great volume of exhaust to cope with, the density being high. They are usually single cylinder and hence, cheap in terms of cost per MW compared to condensing sets of the same power. Besides their use in process industries and petrochemical installations, back pressure turbines are used for desalination of sea- water, district heating, and also for driving compressors and feed pumps.

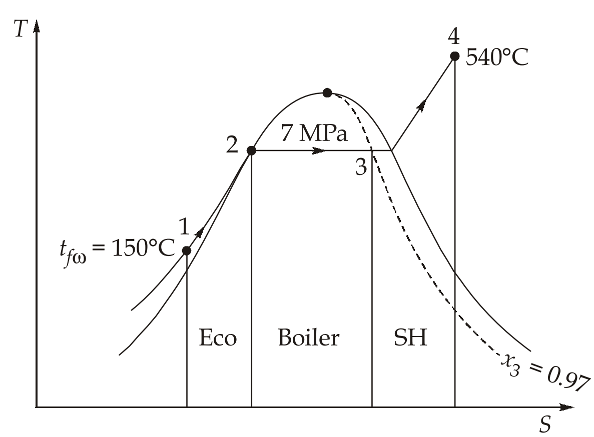
6. (b) (ii)

Swelling Index : Some types of coal during and after release of volatile matter become soft and pasty and form agglomerates. These are called caking coal. In a fixed bed, such as a travelling grate stoker, the coal must not cake as it burns. The consequent agglomeration disturbs greatly the availability of air and so the coal does not completely burn yielding low combustion efficiency. Coal that does not cake is called free-burning coal. It breaks apart during combustion exposing large surface area to the air, thus enhancing the combustion process. Caking coals are used to produce coke by heating in a coke oven in the absence of air, with the volatile matter driven off. Coal devoid of volatile matter is called coke, which is largely needed in steel plants. A qualitative evaluation method, called the swelling index, has been devised to determine the extent of caking of a coal. A free-burning coal has a high value of swelling index, which indicates that it somewhat expands in volume during combustion. When modern pulverized coal burners are used, the swelling property of coal is, however, of less importance.

Grindability : Grindability is often an important criterion for selecting a coal. This property of coal is measured by the standard grindability index, which is inversely proportional to the power required to grind the coal to a specified particle size for burning. Grindability of a standard coal is defined as 100. If the coal selected for use at a power plant has a grindability index of 50, it would require twice the grinding power of the standard coal to produce a specified particle size.

Weatherability: It is a measure of how well coal can be stockpiled for long periods of time without crumbling to pieces. Modern power plants normally stockpile 60 to 90 days' supply of coal in a large pile near the power plant. The coal unloaded from wagons is packed in a long trapezoidal pile. Excessive crumbling or weathering of the coal due to climatic conditions may result in small particles of coal which can be dispersed by wind or rain.

6. (c)



Refer to above figure, $h_1 = 150 \times 4.2 = 630$ kJ/kg

At 7 MPa; $h_f = 1267.7$ kJ/kg; $h_{fg} = 1505.0$ kJ/kg; $h_g = 2772.6$ kJ/kg

At 7 MPa and 540°C; $h_4 = 3507.7$ kJ/kg

$h_3 = (h_f + x_3 h_{fg})_{@7MPa} = 1267.7 + 0.97 \times 1505$

$= 2727.55$ kJ/kg

∴ The efficiency of the steam generator,

$$\eta_{st.gen.} = \frac{\dot{m}_s (h_4 - h_1)}{\dot{m}_f \times CV} = \frac{9 \times (3507.7 - 630)}{1 \times 28.5 \times 10^3} \times 100$$

$= 90.87\%$ **Ans.**

$$\text{Heat transfer in the economiser} = \frac{\dot{m}_s \times (h_2 - h_1)}{\dot{m}_f}$$

$= 9 \times (1267.7 - 630) = 5739.3$ kJ/kg **Ans.**

$$\text{Heat transfer in the boiler} = \frac{\dot{m}_s \times (h_3 - h_2)}{\dot{m}_f}$$

$= 9 \times (2727.55 - 1267.7) = 13138.65$ kJ/kg **Ans.**

$$\text{Heat transfer in air pre-heater} = \frac{\dot{m}_a \times c_{p_a} \times (t_2 - t_1)}{\dot{m}_f}$$

$= 15 \times 1.005 \times (260 - 27) = 3512.48$ kJ/kg **Ans.**

Percentage of total heat absorbed in the economiser

$$= \frac{h_2 - h_1}{h_4 - h_1} \times 100 = \frac{(1267.7 - 630)}{(3507.7 - 630)}$$

$= 0.2216$ or 22.16% **Ans.**

Percentage of total heat absorbed in the boiler

$$= \frac{h_3 - h_2}{h_4 - h_1} \times 100 = \frac{(2727.55 - 1267.7)}{3507.7 - 630} \times 100$$

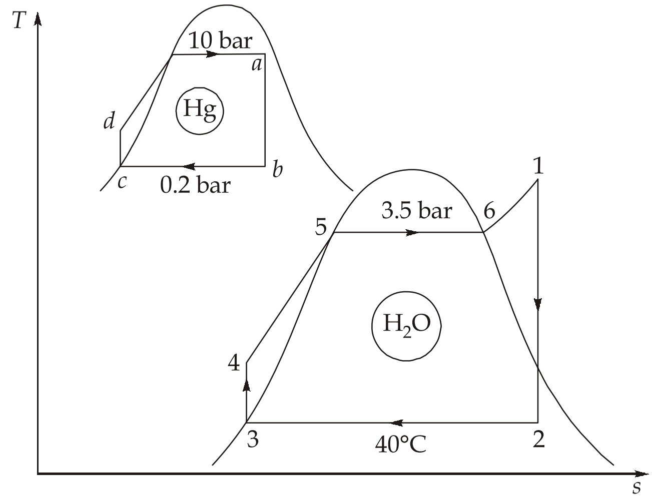
$= 50.73\%$ **Ans.**

Percentage of total heat absorbed in the superheater

$$= \frac{h_4 - h_3}{h_4 - h_1} \times 100 = \frac{(3517.7 - 2726.35)}{3507.7 - 630} \times 100$$

$= 27.11\%$ **Ans.**

7. (a)



For mercury cycle :

$$h_a = (h_f + x_a \times h_{fg})_{@10\text{ bar}} = 72.23 + 0.96 \times (363 - 72.23)$$
$$= 351.37 \text{ kJ/kg}$$
$$s_a = s_b \qquad [\because \text{ isentropic expansion in mercury turbine}]$$
$$\Rightarrow \quad 0.1478 + 0.96 \times (0.5167 - 0.1478) = 0.0967 + x_b \times (0.6385 - 0.0967)$$
$$\Rightarrow \quad x_b = 0.748$$
$$\Rightarrow \quad h_b = (h_f + x_b \times h_{fg})_{@0.2\text{ bar}} = 38.35 + 0.748 \times (336.55 - 38.35)$$
$$= 261.40 \text{ kJ/kg}$$

For steam cycle :

For isentropic expansion in steam cycle process 1 to 2 :

$$s_1 = s_2$$
$$\Rightarrow \quad s_1 = (s_f + x_2 \times s_{fg})_{@40°C}$$
$$\Rightarrow \quad 6.8427 = 0.5724 + x_2 \times (8.2555 - 0.5724)$$
$$\Rightarrow \quad x_2 = 0.816$$
$$\Rightarrow \quad h_2 = (h_f + x_2 \times s_{fg})_{@40°C}$$
$$= 167.53 + 0.816 \times (2573.5 - 167.53)$$
$$= 2130.80 \text{ kJ/kg}$$
$$(w_p)_{H_2O} = v_f \times \Delta P$$
$$= 0.00100789 \times (35 - 0.073849) \times 100 = 3.52 \text{ kJ/kg}$$
$$h_4 = h_3 + (w_p)_{H_2O} = 167.53 + 3.52 = 171.05 \text{ kJ/kg}$$

Let m = mass of mercury circulated per kg of steam.

Then, from energy balance,

$$\dot{m} \times (h_b - h_c) = (h_6 - h_5)$$

$$\Rightarrow \qquad \dot{m} = \frac{2802.6 - 1049.8}{261.40 - 38.35} = 7.86\,\text{kgHg/kg}\,H_2O \qquad \textbf{Ans.}$$

$$Q_{\text{supplied}} = \dot{m}(h_a - h_d) + (h_1 - h_6) + (h_5 - h_4)$$

$$= 7.86 \times (351.37 - 38.35) + (3223.2 - 2802.6) + (1049.8 - 171.05)$$

$$= 3759.69 \text{ kJ/kg}$$

$$W_{\text{net}} = \dot{m}(h_a - h_b) + (h_1 - h_2) - (\omega_p)_{H_2O}$$

$$= 7.86 \times (351.37 - 261.40) + (3223.2 - 2130.80) - 3.52$$

$$= 1796.04 \text{ kJ/kg}$$

$$\eta_{\text{combined}} = \frac{W_{net}}{Q_{\text{supplied}}} = \frac{1796.04}{3759.69}$$

$$= 0.4777 \text{ or } 47.77\% \qquad \textbf{Ans.}$$

7. (b)

(i)

Fire Tube Boilers : In the fire tube boilers, the hot gases (i.e. flue gases) pass through tubes and water surrounds them. The products of combustion (hot gases) leaving the furnace pass through fire tubes which are surrounded by water. Heat from hot flue gases is transferred to water which is converted into steam. The spent flue gases are then discharged to atmosphere through the chimney (stack).

The examples of fire tube boilers are Cochran, Lancashire, Cornish and locomotive boilers.

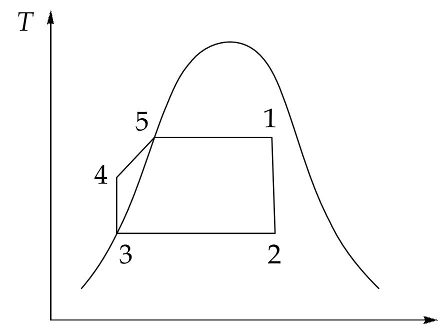
Water Tube Boilers : In water-tube boilers, water flow inside the tubes and the hot flue gases flow outside the tubes. A bank of water tubes containing water is connected with a steam-water drum by means of two sets of headers. The hot flue gases from the furnaces pass over the tubes and are discharged through the chimney. The water thus absorbs heat from the hot gases and evaporates in the form of steam. The steam thus formed gets accumulated in the steam space of drum from where it may be taken into superheater to superheat steam.

The examples of the water-tube boilers are Babcock and Wilcox boiler, sterling boilers, power boilers for utility, etc.

(ii)

Given : $P_1 = P_5 = P_4 = 10$ bar; $T_4 = 37°C$, $x_1 = 0.9$, $\dot{m}_s = 5500$ kg/h; $\dot{m}_f = 700$ kg/h;

C.V. = 30 MJ/kg



Increment in boiler efficiency = 6%

@ 10 bar,

$$h_5 = h_f = 750 \text{ kJ/kg}$$

$$h_{fg} = 2050 \text{ kJ/kg}$$

$$\therefore \quad h_1 = h_f + xh_{fg}$$

$$= 750 + 0.9 \times (2050)$$

$$= 2595 \text{ kJ/kg}$$

$$(h_w)_{35°C} = 145 \text{ kJ/kg}$$

$$(h_w)_{40°C} = 165 \text{ kJ/kg}$$

By linear interpolation,

$$(h_w)_{37°C} = 153 \text{ kJ/kg}$$

Now,

$$\text{Efficiency of boiler, } \eta = \frac{\dot{m}_s \times (h_1 - h_w)}{\dot{m}_f \times C.V.}; \qquad (h_w = (h_w)_{37°C})$$

$$= \frac{5500 \times (2595 - 153)}{700 \times 30 \times 1000} = 0.639$$

$$\simeq 64\%$$

When economiser is used then,

$$\text{New efficiency, } \eta' = (64 + 6)\% = 70\%$$

$$\therefore \quad \eta' = \frac{\dot{m}_s \times (h_1 - h_w)}{\dot{m}_f \times C.V.}; \qquad (h_w = (h_w)_{100°C})$$

$$0.7 = \frac{5000 \times (2595 - 420)}{\dot{m}_f \times 30 \times 1000}$$

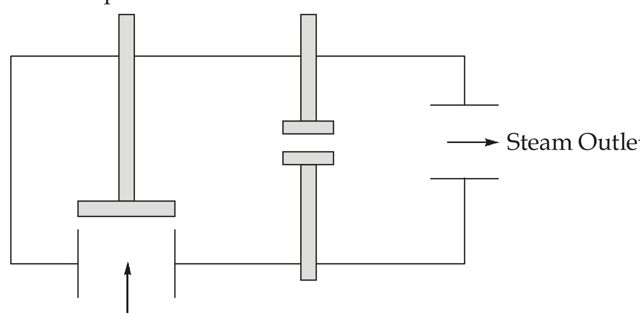
$$\Rightarrow \quad \dot{m}_f = 569.64 \text{ kg/hr}$$

$\therefore$ Saving in coal consumption per hour

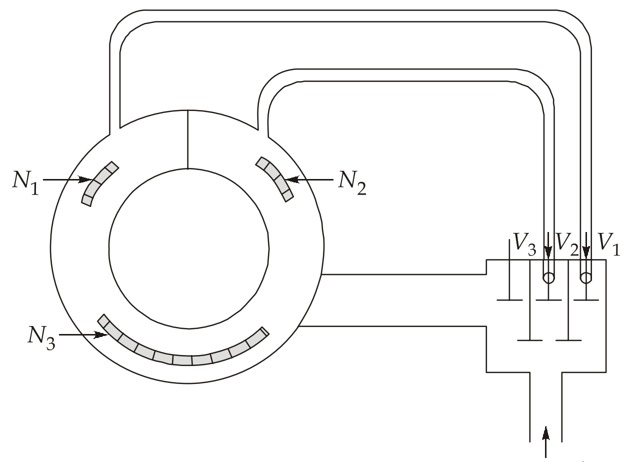
$$= (700 - 569.64) \text{ kg/hr}$$

$$= 130.357 \text{ kg/hr}$$

7. (c) (i)



Steam inlet throttling control valves



Steam turbine governing is to ensure that the turbine speed, remains constant irrespective of steam turbine load conditions. The steam turbine governor controls the steam entry to the turbine to maintain the speed constant. The principle methods of steam turbine governing are as:

1. **Throttle Governing:** Throttle governing is the most widely used method in steam turbine governing for smaller turbines where the steam flow is less. In throttle governing the governor throttles the inlet steam flow through the turbine due to restriction of the passage in the valve. As the load decreases and shaft speed increases, the stop valve is partially closed to admit less steam to the turbine and to produce less power according to the demand.
2. **Nozzle Governing:** If throttle governing is done at low loads, the turbine efficiency is considerably reduced. The nozzle control may then be a better method of governing. The nozzles are made up in sets, each set being controlled by a separate valve. With the decrease of load, the required number of nozzles may be shut off.

3. **By-pass governing:** To produce more power (when on overload), additional steam may be admitted through a by-pass valve to the later stages of the turbine. By-pass regulatory operates in a turbine which is throttle governed,

4. **Emergency Governor:** Every turbine provided with some form of an emergency governor which trips the turbine (closes the stop valve and stops the steam supply) when
   (a) Shaft speed exceeds 110% of its rated value
   (b) Lubrication system fails
   (c) Balancing (static as well as dynamic) of turbine is not proper.
   (d) Condenser becomes hot or vacuum is less.

7. (c) (ii)

Let x moles of propane are reacted by a moles of oxygen supplied. The combustion equation is thus,

$xC_3H_8 + aO_2 + 3.76 \times a \times N_2 \rightarrow 11.4\ CO_2 + 0.8CO + 2.7O_2 + 85.1\ N_2 + bH_2O$

Equating moles for:

Nitrogen : $3.76 \times a = 85.1 \Rightarrow a = 22.63$

Carbon : $3x = 11.4 + 0.8 = 12.2 \Rightarrow x = 4.067$

Oxygen : $22.63 = 11.4 + \frac{0.8}{2} + 2.7 + \frac{b}{2} \Rightarrow b = 16.3$

Hydrogen : $8 \times 4.067 = 32.536$

Therefore, the combustion equation becomes

$4.067C_3H_8 + 22.63O_2 + 85.1N_2 \rightarrow 11.4CO_2 + 0.8CO + 2.7O_2 + 85.1N_2 + 16.3H_2O$

Stoichiometric combustion equation is,

$C_3H_8 + 5O_2 + 5 \times 3.76N_2 \rightarrow 3CO_2 + 4H_2O + 18.8N_2$

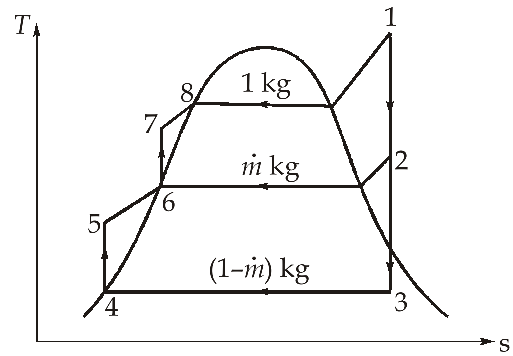
$\therefore$ The excess air supplied $= \frac{5.564 - 5}{5} \times 100 = 11.38\%$ **Ans.**

8. (a)

Since, m kg of steam is extracted from the turbine for each kg of steam entering it to heat the feed water from state 5 to state 6, so that by energy balance.

$$\dot{m}(h_2 - h_6) = (1 - \dot{m})(h_6 - h_5)$$

$$\dot{m} = \frac{h_6 - h_5}{h_2 - h_5} = \frac{h_6 - h_4}{h_2 - h_4} \qquad (\because h_4 = h_5)$$



Therefore, the thermal efficiency of the cycle is

$$\eta = 1 - \frac{(1 - \dot{m})(h_3 - h_4)}{h_1 - h_6}$$

$$= 1 - \frac{\left(1 - \dfrac{h_6 - h_5}{h_2 - h_4}\right)(h_3 - h_4)}{h_1 - h_6}$$

$$= 1 - \frac{(h_2 - h_6)(h_3 - h_4)}{(h_2 - h_4)(h_1 - h_6)} \qquad \text{... (i)}$$

Now, $\beta = h_1 - h_f = h_1 - h_4 = \text{Constant}$

and $\alpha = \text{Total enthalpy rise of feedwater} = h_8 - h_4$

Let the enthalpy rise of feed water in heater $(\gamma) = h_6 - h_4$

Since, $\beta = h - h_f$, which is constant that means β could be, $h_2 - h_6$ or $h_1 - h_8$ or $h_3 - h_4$ also.

Thus, $h_2 - h_4 = h_2 - h_6 + h_6 - h_4 = \beta + \gamma$

and $h_1 - h_6 = h_1 - h_8 + h_8 - h_4 + h_4 - h_6 = \beta + \alpha + \gamma$

Now, equation (i) becomes,

$$\eta = 1 - \frac{(\beta)(\beta)}{(\beta + \gamma)(\beta + \alpha - \gamma)}$$

Here, α and β are fixed and γ is variable, so

For maximum efficiency, $\frac{d\eta}{d\gamma} = 0$

$$\Rightarrow \quad \frac{d\eta}{d\gamma} = \frac{\beta^2[(-\beta-\gamma)+(\alpha+\beta-\gamma)]}{[(\beta+\gamma)(\alpha+\beta-\gamma)]^2} = 0$$

$$\Rightarrow \quad \alpha - 2\gamma = 0$$

$$\Rightarrow \quad \gamma = \frac{\alpha}{2}$$

Thus, the cycle efficiency is maximum when the total enthalpy rise of feedwater ($h_8 - h_4$) from the condenser temperature to the boiler saturation temperature is divided equally between the feedwater heater and the economizer i.e. $h_8 - h_6 = h_6 - h_4$ in a single bleed cycle, so the temperature rise of feedwater in the heater is

$$\Delta t = \frac{1}{2}[t_{\text{boiler saturation}} - t_{\text{condenser}}]$$

and corresponding cycle efficiency is

$$\eta = 1 - \frac{\beta^2}{\left(\beta+\frac{\alpha}{2}\right)\left(\alpha+\beta-\frac{\alpha}{2}\right)} = 1 - \frac{\beta^2}{\left(\beta+\frac{\alpha}{2}\right)\left(\beta+\frac{\alpha}{2}\right)}$$

$$\eta = 1 - \frac{\beta^2}{\left(\beta+\frac{\alpha}{2}\right)^2} = \frac{\alpha^2+4\alpha\beta}{(\alpha+2\beta)^2}$$

8. (b) (i)

To burn pulverized coal successfully, the following two conditions must be satisfied:

1. Large quantities of very fine particles of coal, usually those that would pass a 200-mesh sieve must exist to ensure ready ignition because of their large surface-to-volume ratio.
2. Minimum quantity of coarser particles should be present since these coarser particles cause slagging and reduce combustion efficiency.

Advantages of Pulverized Coal Firing

1. Low excess air requirement
2. Less fan power
3. Ability to use highly preheated air reducing exhaust losses

4. Higher boiler efficiency
5. Ability to burn a wide variety of coals
6. Fast response to load changes
7. Ease of burning alternately with, or in combination with gas and oil
8. Ability to release large amounts of heat enabling it to generate about 2000 t/h of steam or more in one boiler
9. Ability to use fly ash for making bricks etc.
10. Less pressure losses and draught need.

Disadvantages

1. Added investment in coal preparation unit
2. Added power needed for pulverizing coal
3. Investment needed to remove fly ash before ID fan
4. Large volume of furnaces needed to permit desired heat release and to withstand high gas temperature.

8. (b) (ii)

$$\text{Coal burning rate} = \frac{40 \times 10^3}{0.78 \times 26 \times 10^3} = 1.973 \text{ kg/s} = 7102.8 \text{ kg/h}$$

$$\therefore \quad \text{Flow rate of sulphur} = \frac{7102.8 \times 0.036}{32} = 7.99 \text{ kmol/h}$$

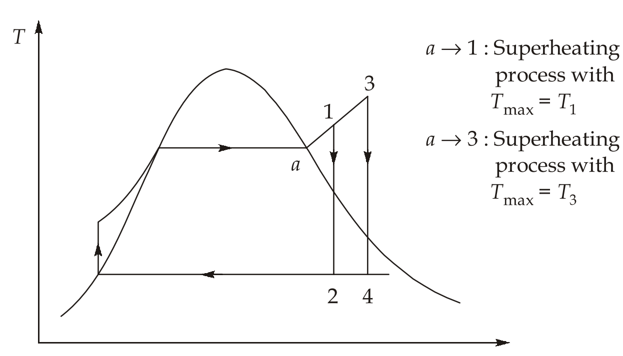
For a Ca : S molar ratio of 3.0, the flow rate of calcium = 7.99 × 3 = 23.973 kmol/h

$\therefore$ Mass flow rate of $CaCO_3$ required = 23.973 × 100

= 2397.3 kg/h (since molecular weight of $CaCO_3$ is 100)

$$\therefore \quad \text{Mass flow of limestone} = \frac{2397.3}{0.85} = 2820.35 \text{ kg/h}$$

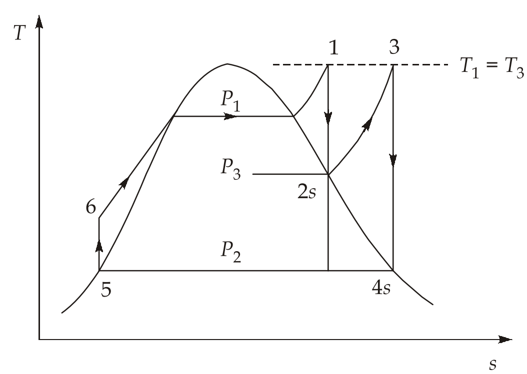
8. (c) (i)



Superheater is a heat exchanger in which heat is transferred to the saturated steam to increase its temperature. Superheaters are commonly classified as either convective superheaters, radiant superheaters or combined superheaters, depending on how heat is transferred from the gases to steam. Convective superheaters are located in the convective zone of the furnace, usually ahead of the economiser. The convective superheaters are often termed as primary superheaters. The pendant superheater is a combined superheater in the sense that it receives heat partly by convection and partly by radiation. The radiant and combined superheaters together are often termed as secondary superheaters.

The effects of steam superheater are:

1. It raises the overall cycle efficiency.
2. It increases the mean temperature of heat addition.
3. It reduces the moisture content in the last stages of the turbine.
4. It increases the turbine internal efficiency.



Reheater: The design considerations for reheater are similar to those for superheaters. In that case, all the steam after partial expansion in the turbine is brought back to the boiler, reheated by combustion gases and then fed back to the turbine for further expansion.

Effects on the performance of plant:

1. It increases the net work output of the plant.
2. It reduces the steam rate for a given output.
3. It keeps the quality of steam at turbine exhaust within a permissible limit.
4. It only gives a small increase in cycle efficiency.

8. (c) (ii)

Theoretically air required for combustion of 1 kg fuel,

$$W_T = 11.5C + 34.5\left(H - \frac{O}{8}\right) + 4.3S$$

$$= 11.5 \times 0.78 + 34.5\left(0.03 - \frac{0.03}{8}\right) + 4.3 \times 0.01$$

$$= 9.9186 \text{ kg air/kg fuel}$$

∴ Actual amount of air supplied for complete combustion of 1 kg fuel,

$$W_A = 1.3 \times W_T = 1.3 \times 9.9186$$

$$= 12.8942 \text{ kg air/kg fuel}$$

$$\nu_{\text{air}} = \frac{RT}{P} = \frac{0.287 \times 300}{101.325} = 0.85 \text{ m}^3/\text{kg}$$

$$\text{FD fan motor capacity} = \frac{W_A \times m_f \times \nu_{air} \times \Delta P}{\eta_{fan}}$$

$$= \frac{12.8942 \times 12 \times 10^3 \times 0.85 \times 0.180 \times 9.81 \times 10^3}{3600 \times 0.75}$$

$$= 86014.63 \text{ W} = 86.01 \text{ kW}$$ **Ans.**

❍❍❍❍