MECHANICAL ENGINEERING

Paper I

(Conventional)

Time Allowed : Three Hours *Maximum Marks : 200*

INSTRUCTIONS

Please read each of the following instructions carefully before attempting the questions :

There are SEVEN questions in the paper.

Candidates are required to attempt FIVE questions in all.

Question no. ***1*** *is* **compulsory**.

Out of the remaining SIX questions, attempt any FOUR questions.

The number of marks carried by a question/part is indicated against it.

Unless otherwise mentioned, symbols and notations have their usual standard meanings.

Assume suitable data, if necessary and indicate the same clearly.

Neat sketches are to be drawn to illustrate answers, wherever required.

All parts and sub-parts of a question are to be attempted together in the answer book.

Attempts of questions shall be counted in sequential order. Unless struck off, attempt of a question shall be counted even if attempted partly.

Answers must be written in ENGLISH only.

Any page or portion of the page left blank in the answer book must be clearly struck off.

Values of constants which may be needed :

Universal gas constant $R = 8{\cdot}314$ *kJ/kg mole-K.*

For air $R = 0{\cdot}287$ *kJ/kg-K,* $C_p = 1{\cdot}005$ *kJ/kg-K,*

$\gamma = 1{\cdot}4$, $M = 28{\cdot}97$ *kg/kg-mole*

1. (a) A rigid tank whose volume is 0·75 m^3 developed a small hole on its wall. Air from the surroundings at 1 bar 25°C leaked in and finally the pressure in the tank reached 1 bar. The process occurred slowly so that heat transfer between the tank and the surroundings kept the temperature of the air inside the tank constant at 25°C. Determine the heat transfer involved in the process :

(i) if initially the tank was evacuated,

(ii) if it contained air at 0·7 bar and 25°C. *10*

(b) (i) Distinguish between skin friction drag and pressure drag. Does the total drag acting on a body necessarily decrease as a result of streamlining ? Explain. *5*

(ii) With a neat sketch explain the principle and working of a pitot tube. *5*

(c) (i) Two concentric spheres have diameters of 0·3 m and 0·8 m and are maintained at uniform temperatures of 700 K and 400 K respectively. The inner and outer spheres have emissivities of 0·5 and 0·7 respectively. The emissivity of the outer surface is 0·35. The surrounding medium and surrounding surfaces are at a temperature of 30°C. Determine the net radiation heat transfer between the two spheres. Also determine the convective heat transfer coefficient at the outer surface. *5*

(ii) Stainless steel ball bearings having diameter of 1·2 cm are to be quenched in water. The balls leave the oven at 900°C and are exposed to air at 30°C for a while before they are dropped in water. If the temperature of the balls is not to fall below 850°C prior to quenching and the heat transfer coefficient in the air is 125 W/m^2 K, determine how long they can stand in the air before being dropped into the water. Following properties of stainless steel may be used :

$$\rho = 8085 \text{ kg/m}^3, \quad k = 15{\cdot}1 \ \frac{W}{mK},$$

$$c_p = 0{\cdot}480 \ \frac{kJ}{kg\ K}, \ \alpha = 3{\cdot}91 \times 10^{-6} \text{ m}^2/\text{s}$$ 5

(d) A horizontal cylinder is separated into two compartments by an adiabatic frictionless piston. One side contains 0·2 m^3 of nitrogen and the other side contains 0·1 kg of helium both initially at 20°C and 95 kPa. The sides of the cylinder and the helium end are insulated. Now heat is added to the nitrogen side from a reservoir at 500°C until the pressure of the helium rises to 120 kPa. Determine (i) the final temperature of helium, (ii) the final volume of nitrogen, (iii) the heat transferred to nitrogen, and (iv) entropy generated during the process.

Following properties of nitrogen and helium are given :

Nitrogen : $R = 0{\cdot}2968 \ \frac{kJ}{kg\ K}$, $c_p = 1{\cdot}039 \ \frac{kJ}{kg\ K}$,

$c_v = 0{\cdot}743 \ \frac{kJ}{kg\ K}$, $\gamma = 1{\cdot}4$

Helium : $R = 2{\cdot}0769 \ \frac{kJ}{kg\ K}$, $c_p = 5{\cdot}1926 \ \frac{kJ}{kg\ K}$,

$c_v = 3{\cdot}1156 \ \frac{kJ}{kg\ K}$, $\gamma = 1{\cdot}667$ *10*

(e) (i) What is 'dry bulb' temperature and 'wet bulb' temperature ? Explain the principle of a sling psychrometer. *5*

(ii) How does a natural draft wet cooling tower work ? What is a spray pond ? How does its performance compare to that of a wet cooling tower ? *5*

(f) (i) A long water trough of triangular cross-section is formed from two rectangular planks. A gap of 3 mm is maintained at the junction of the two planks. If the water depth initially was 0·6 m, how long does it take for the water depth to reduce to 0·3 m ? *5*

(ii) Obtain an expression for the reversible work transfer associated with an internally reversible process in a steady flow device in terms of thermodynamic properties of the system. Deduce Bernoulli's equation from it. *5*

(g) (i) A two-dimensional incompressible flow of a Newtonian fluid has the following velocity field :

$$u = -2xy,\ v = y^2 - x^2,\ w = 0.$$

Show that it represents a possible flow field. Find the pressure field p(x, y), if the pressure at point (x = 0, y = 0) is equal to p_a. *5*

(ii) A 5 cm diameter horizontal jet of water, with a velocity of 30 m/s, strikes the tip of a horizontal cone which deflects the water by 45° from its original direction. How much force is required to hold the cone against the water stream ? *5*

(h) (i) A centrifugal pump having an impeller diameter of 1 m is to be constructed so that it will supply a head rise of 200 m at a flow rate of water when operating at a speed of 1200 rpm. To study the characteristics of this pump, a geometrically similar model operated at the same speed is to be tested in the laboratory. Determine the required model discharge and head rise. Assume that both model and prototype operate with the same efficiency. *5*

(ii) What is cavitation in hydraulic machines ? Explain the significance of Thoma cavitation factor. *5*

2. (a) A simple steam power cycle uses solar energy for heat input. Water in the cycle enters the pump as saturated liquid at 40°C and is pumped to 2 bar. The water at this pressure evaporates in the steam generator and enters the turbine as saturated vapour. At the exit of the turbine, the condition of steam is 40°C with dryness fraction of 0·9. The flow rate is 150 $\frac{kg}{h}$. The instantaneous solar input is 0·58 $\frac{kW}{m^2}$ at a specified time. Obtain the isentropic efficiency of the turbine, network output, cycle efficiency and the area of the solar collector needed based on the given solar input.

Following properties of steam are given : *10*

p (bar)	T (°C)	h_f	h_{fg} (kJ/kg)	h_g	s_f (kJ/kg K)	s_{fg}	s_g
0·07375	40	167·53	2405·97	2573·5	0·572	7·686	8·258
2	120·2	504·7	2201·6	2706·3	1·530	5·597	7·127

(b) Liquid nitrogen is stored in a spherical thin walled metallic container at 77 K temperature. The container is of 1·0 metre diameter and is covered with evacuated silica powder. The insulation is 20 mm thick and the outer surface is exposed to the surrounding air at 300 K. The convective heat transfer coefficient of the exposed surface is 25 W/m^2 K. The density and latent heat of vaporization of the liquid nitrogen are 804 kg/m^3 and 2×10^5 J/kg respectively. Determine the rate of heat transfer to the liquid nitrogen and the rate of liquid boil-off. The thermal conductivity (k) of evacuated silica powder is 0·0017 W/m.K. Neglect the thermal resistance of the metallic container. *10*

(c) (i) Explain how draft tubes are advantageous when installed at the exit of Francis and Kaplan turbines. *3*

(ii) A sphere of diameter D and density ρ_s falls at a steady rate through a liquid of density ρ and viscosity μ. If the Reynolds number is less than 1, show that the viscosity can be determined from $\mu = \dfrac{g D^2 (\rho_s - \rho)}{18U}$ where the Reynolds number is evaluated as $\dfrac{\rho D U}{\mu}$. *7*

3. (a) (i) Compare the governing mechanism of a Pelton turbine with that of a Francis turbine. *4*

(ii) Water to run a Pelton wheel is supplied by a penstock of length l and diameter D with a friction factor f. If the only losses associated with the flow in the penstock are due to pipe friction, show that the maximum power output of the turbine occurs when the nozzle diameter D_1 is given by $D_1 = \frac{D}{\left(\frac{2fl}{D}\right)^{1/4}}$. *6*

(b) A runner of a Francis turbine having 1·5 m outer diameter and 0·75 m inner diameter operates under a head of 150 m with a specific speed of 120 and generates 14 MW power. If the water enters the wheel at an angle of 11°20′ and leaves the blade radially with no velocity of whirl, what will be the value of inlet and outlet blade angles ? Assume the hydraulic efficiency of the turbine as 92 percent. *10*

(c) A room is provided with a sliding glass door (patio door) with a height of 1·8 m and width of 1 m. On a cold winter day, the window glass on the patio door has a uniform temperature of 0°C and the room wall and air temperatures are 15°C. The emissivity of the glass surface is 0·94. A frost line was observed at the base of the window glass. (i) Explain why the window developed a frost layer at the base and not at the top. (ii) Estimate the heat loss through the window due to free convection and radiation. (iii) If the room is provided with an electric heater, estimate the corresponding daily cost of the window heat loss for an electricity cost of ₹ 5/kWh. Assume the following properties of air at 280 K : $\nu = 14{\cdot}11 \times 10^{-6}\ \frac{m^2}{s}$,

$k = 0{\cdot}0247\ \frac{W}{mK}$, $\alpha = 1{\cdot}986 \times 10^{-5}\ \frac{m^2}{s}$,

$Pr = 0{\cdot}710$

The following empirical correlation may be useful :

$$Nu_L = \frac{h_L L}{k} = \left\{0{\cdot}825 + \frac{0{\cdot}387\, Ra_L^{1/6}}{\left[1 + (0{\cdot}492/Pr)^{9/16}\right]^{8/27}}\right\}^2$$

where, Ra_L is the Rayleigh number. *10*

4. (a) (i) A ship with a hull length of 140 metres has to travel with 7·6 m/s velocity. Compute the Froude number. For dynamic similarity, at what velocity should a 1 : 30 scale down model flow through water ? *5*

(ii) Illustrate the head vs discharge curves for three dissimilar pumps in series and three such pumps in parallel. *5*

(b) Carbon dioxide enters an adiabatic nozzle at 1200 K with a velocity of 50 $\frac{m}{s}$ and leaves at 400 K. Determine the Mach number (i) at the inlet of the nozzle, and (ii) at the exit of the nozzle. For CO_2, $R = 0{\cdot}1889 \ \frac{kJ}{kg\,K}$,

$c_p = 0{\cdot}8439 \ \frac{kJ}{kg\,K}$, $\gamma = 1{\cdot}288$. *10*

(c) On the basis of a cold-air-standard analysis, show that the thermal efficiency of an ideal regenerative gas turbine can be expressed as

$$\eta = 1 - \left(\frac{T_1}{T_3}\right)(\gamma)^{\left(\frac{k-1}{k}\right)},$$

where, γ is the compressor pressure ratio and T_1, T_3 denote the temperatures at the compressor and turbine inlets respectively. *10*

5. (a) The impeller of a centrifugal pump has a diameter of 0·2 m and axial width at outlet of 20 mm. There are 18 blades swept backwards and inclined at 25° to the tangent to the periphery. The flow rate through the impeller is $8{\cdot}5 \dfrac{m^3}{h}$ when it rotates at 750 rpm. Calculate the head developed by the pump when handling water and assuming one-dimensional ideal flow theory. How can a more realistic estimation of the head developed be carried out ? *10*

(b) Hot oil is to be cooled in a multi-pass shell and tube heat exchanger by water. The oil flows through the shell with a heat transfer coefficient of $h = 35 \dfrac{W}{m^2K}$ and the water flows through the tube with an average velocity of 3 m/s. The tube is made of brass $\left(k = 110 \dfrac{W}{mK}\right)$ with internal and external diameters of 1·3 cm and 1·5 cm respectively. Determine the overall heat transfer coefficient of this heat exchanger based on the inner surface. Properties of water at 25°C : $k = 0{\cdot}607 \dfrac{W}{mK}$,

$\nu = 0{\cdot}894 \times 10^{-6} \dfrac{m^2}{s}$, Pr = 6·14.

Given $Nu = 0{\cdot}023\, Re^{0{\cdot}8}\, Pr^{0{\cdot}4}$. *10*

(c) A gas turbine engine with regeneration operates with two stages of compression and two stages of expansion. The pressure ratio across each stage of the compressor and turbine is 3·5. The air enters each stage of the compressor at 300 K and each stage of the turbine at 1200 K. The compressor and turbine efficiencies are 78% and 86% respectively and the effectiveness of the regenerator is 72%. Determine the back work ratio and the thermal efficiency of the cycle, assuming constant specific heats for air at room temperature. *10*

6. (a) (i) Consider a conical enclosure of height h and base diameter D. Determine the view factor from the conical side surface to a hole of diameter d located at the centre of the base. *5*

(ii) Sketch the typical boiling curve for water at 1 atm clearly indicating the salient regimes of boiling. *5*

(b) Air at 27°C with a free stream velocity of 10 m/s is used to cool electronic devices mounted on a printed circuit board. Each device, 4 mm × 4 mm dissipates 40 mW which is removed from the top surface. A turbulator is located at the leading edge of the board. Estimate the surface temperature of the fourth device located at 15 mm from the leading edge of the board. The following relation may be used :

$Nu_x = 0{\cdot}0296 \ Re_x^{4/5} \, Pr^{1/3}$.

For air at 315 K and 1 atm, $k = 0{\cdot}0274 \ \dfrac{W}{mK}$,

$\nu = 17{\cdot}4 \times 10^{-6} \ \dfrac{m^2}{s}$, $\alpha = 24{\cdot}7 \times 10^{-6} \ \dfrac{m^2}{s}$,

$Pr = 0{\cdot}705$. *10*

(c) An air-conditioner with refrigerant R134a as the working fluid is used to keep a room at 26°C by rejecting the waste heat to the outside air at 34°C. The room is gaining heat through the walls and the windows at a rate of $250 \frac{kJ}{min}$ while the heat generated by the appliances in the room amounts to 900 W. An unknown amount of heat is also generated by the people in the room. The condenser and evaporator pressures are 1200 kPa and 500 kPa respectively. The refrigerant is saturated liquid at the condenser exit and saturated vapour at the compressor inlet. If the refrigerant enters the compressor at a rate of $100 \frac{L}{min}$ and the isentropic efficiency of the compressor is 75%, determine the (i) temperature of the refrigerant at the compressor exit, (ii) rate of heat generation by the people in the room, (iii) COP of the air-conditioner, and (iv) minimum volume flow rate of the refrigerant at the compressor inlet for the same compressor inlet and exit conditions.

Properties of R134a :

At 500 kPa : $h_g = 259{\cdot}3 \frac{kJ}{kg}$, $v_g = 0{\cdot}4112 \frac{m^3}{kg}$

$$s_g = 0{\cdot}924 \frac{kJ}{kg}$$

At 1200 kPa : $h_f = 117{\cdot}77 \frac{kJ}{kg}$ *10*

7. (a) Show that the enthalpy of an ideal gas is a function of temperature only and that for an incompressible substance it also depends on pressure, using thermodynamic property relations. *10*

(b) A house built on a riverside is to be cooled in summer by utilizing the cool water of the river which flows at an average temperature of 15°C. A 15 m long section of a circular duct of 20 cm diameter passes through the water. Air enters the underwater section of the duct at 25°C at a velocity of 3 m/s. Assuming the surface of the duct is at the temperature of water, determine the outlet temperature of air as it leaves the underwater portion of the duct. Also, for an overall fan efficiency of 55%, determine the fan power input needed to overcome the flow resistance in this section of the duct. The properties of air at 20°C and 1 atm :

$\rho = 1{\cdot}204\ \text{kg/m}^3,\ k = 0{\cdot}02514\ \dfrac{\text{W}}{\text{mK}},$

$\nu = 1{\cdot}516 \times 10^{-5}\ \dfrac{\text{m}^2}{\text{s}},\ c_p = 1{\cdot}007\ \dfrac{\text{kJ}}{\text{kg K}},$

$\text{Pr} = 0{\cdot}7309.$

For fully developed turbulent flow in smooth pipes : $f = (0{\cdot}790\ ln\ \text{Re} - 1{\cdot}64)^{-2}$, where f is the friction factor. *10*

(c) A two-cylinder single-acting air compressor is to deliver 20 kg/minute of free air from atmospheric conditions (100 kPa, 20°C). The delivery pressure is 7 bar, clearance is 4% of the stroke and the index for both compression and expansion is 1·3. The compressor is directly coupled to a four-cylinder, four-stroke petrol engine running at 2000 rpm. The BMEP of the engine is 5 bar. Assuming stroke-to-bore ratio of 1·1 for both engine and compressor and mechanical efficiency of 80% for the compressor, calculate the cylinder dimensions for the compressor. *10*