(*xvii*) A heat exchanger, with heat transfer surface area A and overall heat transfer coefficient U, handles two fluids of heat capacities C_{max} and C_{min}. The number of transfer units (NTU) used in the analysis of heat exchanger is specified as

(*a*) $A \times C_{min} / U$

(*b*) $U / A \times C_{min}$

(*c*) $A \times UC_{min}$

(*d*) $A \times U/C_{min}$

(*xviii*) The emissivity for a black body is

(*a*) 0

(*b*) 0.5

(*c*) 0.75

(*d*) 1

(*xix*) Which one of the following statement is *correct* ?

(*a*) A grey body is one which absorbs all radiations incident on it.

(*b*) At thermal equilibrium, the emissivity and absorptivity are same.

(*c*) The energy absorbed by a body to the total energy falling on it is called emissivity.

(*d*) A perfect body is one which is black in colour.

(*xx*) When α is absorptivity ; ρ, the reflectivity ; and τ, the transmittivity, then for a diathermanous body,

(*a*) $\alpha = 1, \ \rho = 0$ and $\tau = 0$.

(*b*) $\alpha = 0, \ \rho = 1$ and $\tau = 0$.

(*c*) $\alpha = 0, \ \rho = 0$ and $\tau = 1$.

(*d*) $\alpha + \rho = 1$ and $\tau = 0$.

W'11:6 AN:MC 405 (1498)

THERMAL SCIENCE AND ENGINEERING

Time : Three hours

Maximum Marks : 100

Answer FIVE *questions, taking* ANY TWO *from* **Group A,** ANY TWO *from* **Group B** and ALL *from* **Group C.**

All parts of a question (a, b, etc.) should be answered at one place.

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Any missing or wrong data may be assumed suitably giving proper justification

Figures on the right-hand side margin indicate full marks.

Group A

1. (*a*) Define the thermodynamic system. Differentiate between open system, closed system and isolated system. 8

(*b*) 3 kg of an ideal gas is expanded from a pressure 7 bar and volume 1.5 m^3 to a pressure 1.4 bar and volume 4.5 m^3. The change in internal energy is 525 kJ. The specific heat at constant volume for the gas is 1.047 kJ/kg-K. Calculate (*i*) gas constant ; (*ii*) change in enthalpy ; and (*iii*) initial and final temperatures. 3×4

2. (*a*) Derive an expression for the efficiency of a reversible heat engine. 8

(*b*) The law of the expansion curve of a gas engine indicator is found to be $pv^{1.3}$ = constant and the ratio of specific heat of the mixture is 1.40. If the expansion ratio is 5.2 and the pressure and temperature before expansion are 8.5 bar, 330 °C, respectively and pressure after expansion is 1 bar, what is the rate of heat transfer per kg of gas ? 12

3. (*a*) Derive the general energy equation for steady flow system and simplify it for the compressor. 10

(*b*) In an air compressor, air flows steadily at the rate of 15 kg/min. The air enters the compressor at 5 m/s with a pressure of 1 bar and a specific volume of 0.5 m^3/kg. It leaves the compressor at 7.5 m/s with a pressure of 7 bar and a specific volume of 0.15 m^3/kg. The internal energy of the air leaving the compressor is 165 kJ/kg greater than that of the air entering. The cooling water in the compressor jackets absorbs heat from the air at the rate of 500 kJ/s. Find (*i*) power required to drive the compressor ; and (*ii*) ratio of the inlet pipe diameter to outlet pipe diameter. 10

4. (*a*) Derive an expression for the efficiency of diesel cycle. 10

(*b*) Two engines are to operate on Otto and diesel cycles with the following data : Maximum temperature = 1500 K ; exhaust temperature = 700 K ; ambient conditions = 1 bar and 300 K. Compare the compression ratios, maximum pressures, and efficiencies of two engines. 10

Group B

5. (*a*) Prove that, for a cyclindrical body as shown in Fig. 1, the heat transfer by conduction is given by 10

$$q = \frac{2\pi l (T_1 - T_2)}{\frac{\log (r_2/r_1)}{K_A} + \frac{\log (r_3/r_2)}{K_B} + \frac{\log (r_4/r_3)}{K_C}}$$

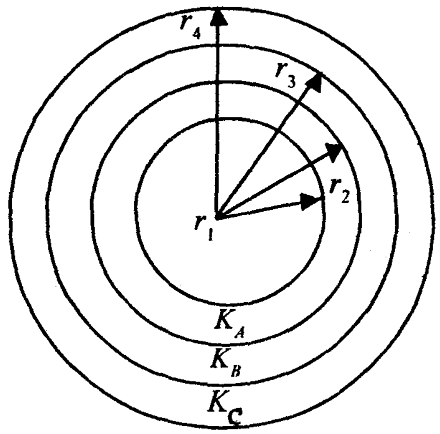

Fig. 1

(*b*) An insulated steam pipe, having outside diameter of 30 mm, is to be covered with two layers of insulation, each having thickness of 20 mm. The thermal conductivity of one material is 5 times that of the other. Assuming that the inner and outer surface temperature of insulation is fixed, how much will heat transfer be increased when better insulation material is next to the pipe that it is outer layer ? 10

6. (*a*) Derive the momentum equation for laminar boundary layer over a flate plate. What are the assumptions involved in the derivation of this equation ? 10

(*b*) A plate of length 750 mm and width 250 mm has been placed longitudinally in a stream of crude oil which flows with a velocity of 5 m/s. If the oil has a specific gravity of 0.8 and kinematic viscosity of 1 stoke, calculate the following : 3 + 3 + 4

(*i*) Boundary layer thickness at the middle of plate.

(*ii*) Shear stress at the middle of plate.

(*iii*) Friction drag on one side of the plate.

7. (*a*) Derive an expression for the effectiveness of a parallel flow heat exchanger in terms of NTU. 8

(*b*) Oil (C_p = 3.6 kJ/kg °C) at 100 °C flows at the rate of 30,000 kg/h and enters into a parallel flow heat exchanger. Cooling water (C_p = 4.2 kJ/kg °C) enters the heat exchanger at 10 °C) at the rate of 50,000 kg/h. The heat transfer area is 10 m^2 and U = 1000 W/m^2 °C). Calculate the following: 6 + 6

(*i*) Outlet temperature of oil and water.

(*ii*) Maximum possible outlet temperature of water.

8. (*a*) Define the flowing terms : 3 + 3 + 4

(*i*) Total intensity of radiation

(*ii*) Shape factor

(*iii*) Stefan-Boltzmann law

(*b*) Calculate the following for an industrial furnace in the form of a black body and emitting radiation at 2500 °C. 5 × 2

(*i*) Monochromatic emissive power at 1.2 μm length.

(*ii*) Wavelength at which the emission is maximum.

(*iii*) Maximum emissive power.

(*iv*) Total emissive power.

(*v*) Total emissive power of the furnace, if it is assumed as a real surface with emissivity equal to 9.0.

Group C

9. Choose the *correct* answer for the following : 20 × 1

(*i*) The value of one bar (in SI unit) is equal to

(*a*) 1 × 10^2 N/m^2
(*b*) 1 × 10^3 N/m^2
(*c*) 1 × 10^4 N/m^2
(*d*) 1 × 10^5 N/m^2

(*ii*) Which one of the following statemet is *correct* ?

(*a*) The heat and work are boundary phenomena.
(*b*) The heat and work represent the energy crossing the boundary of the system.
(*c*) The heat and work are path functions.
(*d*) All of the above.

(*iii*) Kelvin-Planck's statement deals with

(*a*) conservation of work.

(*b*) conservation of heat.

(*c*) conversion of heat into work.

(*d*) conversion of work into heat.

(*iv*) When the gas is heated at constant volume, the heat supplied

(*a*) increases the internal energy of the gas.

(*b*) increases the temperature of the gas.

(*c*) does some external work during expansion.

(*d*) Both (*a*) and (*b*) above.

(*v*) The heat absorbed/rejected by the working substance is given by

(*a*) $\delta Q = T.ds$

(*b*) $\delta Q = T/ds$

(*c*) $\delta Q = ds/T$

(*d*) None of the above.

where ds = increase/decrease of entropy ; T = absolute temperature ; and δQ = heat absorbed/ rejected.

(*vi*) For the same maximum pressure and temperature,

(*a*) Otto cycle is more efficient than diesel cycle.

(*b*) diesel cycle is more efficient than Otto cycle.

(*c*) dual cycle is more efficient than Otto and diesel cycles.

(*d*) dual cycle is less efficient than Otto and diesel cycles.

(*vii*) Which one of the following is the *correct* statement ?

(*a*) For a given compression ratio, both Otto and diesel cycles have the same efficiency.

(*b*) For a given compression ratio, Otto cycle is more efficient than diesel cycle.

(*c*) For a given compression ratio, diesel cycle is more efficient than Otto cycle.

(*d*) The efficiency of Otto or diesel cycle has nothing to do with compression ratio.

(*viii*) Which one of the following is the *correct* statement ?

(*a*) All the reversible engines have the same efficiency.

(*b*) All the reversible and irreversible engines have the same efficiency.

(*c*) Irreversible engines have maximum efficiency.

(*d*) None of the above.

(*ix*) The thermal efficiency of an ideal gas turbine plant is given by

(*a*) r^{y-1}

(*b*) $1 - r^{y-1}$

(*c*) $1 - (1/r)^{y/y-1}$

(*d*) $1 - (1/r)^{(y-1)/y}$

where r = pressure ratio.

(*x*) The condition for an irreversible cyclic process is

(*a*) $\oint \frac{\delta Q}{T} = 0$

(*b*) $\oint \frac{\delta Q}{T} < 0$

(*c*) $\oint \frac{\delta Q}{T} > 0$

(*d*) None of the above.

(*xi*) The average value of thermal conductivity for water at 20 °C saturate is about 0.51.

(*a*) True

(*b*) False

(*xii*) A composite slab has two layers of different materials with thermal conductivities k_1 and k_2. If each layer has the same thickness, then the equivalent thermal conductivity of the slab will be

(*a*) $k_1 \ k_2$

(*b*) $k_1 + k_2$

(*c*) $k_1 + k_2 / k_1 \ k_2$

(*d*) $2 \ k_1 \ k_2 / k_1 + k_2$

(*xiii*) The logarithmic mean temperature difference (t_m) is given by

(*a*) $t_m = \Delta t_1 - \Delta t_2 / \ln \ (\Delta t_1 / \Delta t_2)$

(*b*) $t_m = \ln \ (\Delta t_1 / \Delta t_2) = (\Delta t_1 - \Delta t_2)$

(*c*) $t_m = (\Delta t_1 - \Delta t_2) / \ln \ (\Delta t_1 / \Delta t_2)$

(*d*) $t_m = \ln \ (\Delta t_1 / \Delta t_2) / (\Delta t_1 / \Delta t_2)$

(*xiv*) In counter-current flow heat exchangers,

(*a*) both the fluids at inlet are in their hottest state.

(*b*) both the fluids at inlet are in their coldest state.

(*c*) both the fluids at exit are in their hottest rate.

(*d*) one fluid is coldest and the other is hottest at inlet.

(*xv*) When t_{C_1} and t_{C_2} are the temperatures of cold fluid at entry and exit, respectively and t_{h_1} and t_{h_2} are the temperatures of hot fluid at entry and exit point, and cold fluid has lower heat capacity rate as compared to hot fluid, then effectiveness of the heat exchanger is given by

(*a*) $(t_{C_1} - t_{C_2}) / (t_{h_1} - t_{C_1})$

(*b*) $(t_{h_2} - t_{h_1}) / (t_{C_2} - t_{h_1})$

(*c*) $(t_{h_1} - t_{h_2}) / (t_{h_1} - t_{C_1})$

(*d*) $(t_{C_2} - t_{C1}) / (t_{h_1} - t_{C_1})$

(*xvi*) In free convection heat transfer, transition from laminar to turbulent flow is governed by the critical value of the

(*a*) Reynold's number.

(*b*) Grashoff's number.

(*c*) Reynold's number, Grashoff's number.

(*d*) Prandtl number, Grashoff's number,

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Group A

1. (*a*) (*i*) What does the state postulate say and what is the necessity of this postulate ? 2

(*ii*) State the zeroth law of thermodynamics and prove that this law is the basis for all temperature measurements. 2

(*b*) It is proposed to compress air (ideal gas) reversibly from an initial state of 100 kPa and 27 °C to a final state of 500 kPa and 27 °C. Compare the work required for the following processes : (*i*) Heating at constant volume followed by cooling at constant pressure, (*ii*) isothermal compression, (*iii*) adiabatic compression followed by cooling at constant volume. For air, C_v = 20.93 J/molK and C_p = 29.302 J/mol K. 8

(*c*) A pressure vessel is connected to a gas maintained at 1.4 MPa and 85 °C through a valve. The valve is opened and 2.7 kg of gas is allowed into the vessel which was at vacuum initially. When the valve is closed, the gas in the vessel stabilizes at 700 kPa and 60 °C. Determine the heat transfer associated with the filling process. Also, determine the volume of the pressure vessel and the initial volume of the gas allowed into the vessel. Assume C_p = 0.88 kJ/(kg-K), C_v = 0.67 kJ/(kg-K) and neglect the velocity of gas in the main. 8

2. (*a*) (*i*) Show that the transfer of heat through a finite temperature difference is irreversible.

(*ii*) A room is maintained at 27 °C while the surroundings are at 2 °C. The temperature of inner and outer surfaces of the wall (k = 0.71 W/mK) are measured to be 21 °C and 6 °C, respectively. Heat flows steadily through the wall 5 m × 7 m in cross-section and 0.32 m in thickness. Determine the (*i*) rate of heat transfer through the wall, (*ii*) rate of entropy generation in the wall, and (*iii*) rate of total entropy generation with this heat transfer process. 8

(*b*) Establish the equivalence of Kelvin-Planck and Clausius statements of the second law of thermodynamics. 6

(*c*) The lowest temperature which has been achieved till date is 0.0014 K. Suppose a sample is to be maintained at that temperature. The energy losses as heat from the sample are estimated at 50 J/s and the ambient temperature is 35 °C. Suppose a reversible heat engine which uses a source at 400 °C and the ambient atmosphere as the sink to drive a reversible heat pump in order to maintain the sample at the required temperature. Determine the power required to operate the heat pump and the ratio of energy absorbed by the heat engine from the source to the energy absorbed by the heat pump from the sample. 6

3. (*a*) What are the availability functions for a closed system and for a steady flow system ? 2 kg of air at 500 kPa, 80 °C expands adiabatically in a closed system until its volume is doubled and its temperature becomes equal to that of the surroundings which is at 100 kPa, 5 °C. For this process, determine the (*i*) maximum work, (*ii*) change in availability, and (*iii*) irreversibility. For air, take, C_v = 0.718 kJ/kgK, $u = C_v T$, where C_v is constant, and $pV = mRT$, where p is pressure (in kPa) ; V = volume (in m^3) ; m = mass (in kg) ; R = a constant equal to 0.287 kJ/kg-K and T = temperature (in K). 8

(*b*) Explain the working of an actual gas turbine with the help of p–V and T–s diagrams. 4

(*c*) Explain Joule–Thomson coefficient. What is inversion temperature ? 4

(*d*) Explain the vapour compression cycle of refrigeration with the help of T–s and p–h diagrams. 4

4. (*a*) A rigid and insulated tank of volume $10 m^3$ is divided into two equal compartments by a partition. One compartment is filled with nitrogen at 10 bar and 500K while the other compartment is filled with helium at 2 bar and 300K. The partition is removed and the gases are allowed to mix. Calculate the (*i*) final temperature and pressure of the mixture; (*ii*) molar composition of the mixture; and (*iii*) entropy change associated with the mixing process. Molar heat capacities of gases are:

C_v (for N_2) = 20.8641 kJ/molK

C_v (for He) = 12.4717 kJ/molK

$C_{p_{N_2}}$ = 29.1783 kJ/molK

$C_{p_{He}}$ = 20.7860 kJ/molK 8

(*b*) The efficiency of a Carnot engine can be increased either by decreasing the sink temperature while keeping the source temperature constant or by increasing the source temperature while keeping the sink temperature constant. Which one of the above two possibilities is more effective? 6

(*c*) Why is Carnot cycle not practicable for a steam power plant? Name the real being adopted. Draw the schematic diagram, p–V and T–s diagrams of this cycle. 4

(*d*) What is adiabatic saturation? 2

Group B

5. (*a*) Show that the temperature variation for heat conduction through a cylindrical wall having uniform K is logarithmic.

A hollow cylinder, with inner radius 30mm and outer radius 50mm, is heated at the inner surface at the rate of $10^5 W/m^2$ and dissipates heat by convection from the outer surface into a fluid at temperature 100°C with a heat transfer coefficient of 400 W/m^2K. There is no energy generation and the thermal conductivity of the solid is assumed to be constant at 15 W/mK. Calculate the temperatures of inside and outside surfaces of the cylinder. 8

(*b*) What is meant by transient heat conduction? What is lumped capacity? An aluminium sphere, weighing 5.5 kg and initially at a temperature of 290°C, is suddenly immersed in a fluid at 15°C. The convective heat transfer coefficient is 58 W/m^2K. Estimate the time required to cool the aluminium sphere to 95°C, using the lumped capacity method of analysis. Take the properties of aluminium as follows: 8

ρ (density) = 2700 kg/m^3
C (specific heat) = 900 J/kgK
K (conductivity) = 205 W/mk.

(*c*) What do you mean by critical radius of insulation? Show that it is given by k_i/h_a, where k_i is the thermal conductivity of insulation and h_a, the heat transfer coefficient. 4

6. (*a*) Atmospheric air at $T_\infty = 275$ K and a free stream velocity $u_\infty = 20$ m/s flows over a flat plate $L = 1.5$ m long and is maintained at a uniform temperature $T_w = 325$ K.

(*i*) Calculate the average heat transfer coefficient, h_m, over the region, where the boundary layer is laminar. 4

(*ii*) Find the average heat transfer coefficient over the entier length $L = 1.5$ m of the plate. 4

(*iii*) Calculate the total heat transfer rate Q from the plate to the air over the length $L = 1.5$ m and width $w = 1$ m. Assume transition occurs at $\mathrm{Re}_X = 2 \times 10^5$. 4

The physical properties of atmospheric air are taken as follows at $(T_w + T_\infty)/2 = 300\ K$

$K = 0.026$ W/mK

$\Pr = 0.708$

$\nu = 16.8 \times 10^{-6}\ \mathrm{m^2/s}$

$\mu_\infty = 1.98 \times 10^{-5}$ kg/(m-s).

Also, take the average heat transfer coefficient for the laminar layer (neglecting the viscosity correction) from the relation

$$h_m = 0.664\,(k/x_e)\,\Pr^{1/3}\,\mathrm{Re}_X^{1/2}$$

The average heat transfer coefficient (neglecting viscosity correction) over $L = 1.5$ m is to be taken from the relation

$$h_m = 0.036\,(k/L)\,\Pr^{0.43}\,[(\mathrm{Re}_L)^{0.8} - 9200].$$

(*b*) Explain the Colburn analogy in detail. 4

(*c*) Sketch temperature and velocity profiles in free-convection on a vertical wall. Why an analytical solution of a free convection heat transfer problem more difficult than that of a forced convection problem? 4

7. (*a*) Consider a cross-flow heat exchanger with hot and cold fluids entering at uniform temperature. Illustrate, with sketches, the exit temperature distribution for the following cases: 4

(*i*) Both fluids are unmixed

(*ii*) Cold fluid is unmixed and hot fluid is mixed.

(*b*) A heat exchanger is to be designed to cool $m_h = 8.7$ kg/s in an ethyl alcohol solution [$C_{ph} = 3840$ J/kg-K] from $T_1 = 75$°C to $T_2 = 45$°C with cooling water [$C_{p_c} = 4180$ J/kg-K] entering the tube side at $t_1 = 10$°C at a rate of $m_c = 9.6$ kg/s. The overall heat transfer coefficient based on the outer tube surface is $U_0 = 500\ \mathrm{W/m^2K}$. Calculate the heat transfer area for (*i*) parallel flow, shell and tube, and (*ii*) counter flow, shell and tube. 6

(*c*) If the local heat transfer coefficient for the thermal boundary layer over a flat plate has a power-law dependent on $x\,b_x = Cx^n$, where C is a constant, then show that the quantity averaged from $x = 0$ to x (in this case $h_{x,\,ave}$) is simply $h_{x_{ave}} = h_x/(1+n)$. Apply this to show that, for the laminar thermal boundary layer over a flat plate, the average heat transfer coefficient over a distance x is twice its local value. 5

(*d*) Discuss various regimes in boiling heat transfer. 5

8. (*a*) What is shape factor ? Show that

$$A_1 F_{12} = \frac{1}{\pi} \int_{A_1} \int_{A_2} \frac{\cos\phi_1 \cos\phi_2}{r^2} \, dA_1 \, dA_2 .$$ 6

(*b*) Explain the electrical analogy for radiative heat transfer in a black enclosure. Draw the equivalent electrical network for radiative flux between four walls of a black enclosure. 6

(*c*) Define/explain *any four* of the following: 4×2

(*i*) Gray body

(*ii*) Kirchhoff's law

(*iii*) Monocromatic emissive power of a body.

(*iv*) Transmissivity of a surface

(*v*) Wien's displacement law

(*vi*) Solid angle.

Group C

9. Explain/answer the following in brief: 10×2

(*i*) How can a heat pump upgrade low grade waste heat ?

(*ii*) All spontaneous processes are irreversible. Explain.

(*iii*) What is the absolute thermodynamic temperature scale ? Why is it called absolute ?

(*iv*) What is the difference between heat and internal energy ?

(*v*) The amount of entropy generation quantifies the intrinsic irreversibility of a process. Explain.

(*vi*) In a gas-to-liquid heat exchanger, why are fins provided on the gas side ?

(*vii*) Explain why the condenser tubes are usually horizontal.

(*viii*) What is a black body and opaque body ?

(*ix*) What is the range of wavelength for visible radiation, i.e., light ?

(*x*) What do you mean by a non-conducting and re-radiating wall ?