BTD QUESTION BANK

UNIT – 1

THEORY QUESTIONS

1.1 What do you understand by macroscopic and microscopic viewpoints?
1.2 Is thermodynamics a misnomer for the subject?
1.3 How does the subject of thermodynamics differ from the concept of heat transfer?
1.4 What is the scope of classical thermodynamics?
1.5 What is a thermodynamic system?
1.6 What is the difference between a closed system and an open system?
1.7 An open system defined for a fixed region and a control volume are synonymous. Explain.
1.8 Define an isolated system.
1.9 Distinguish between the terms 'change of state', 'path', and 'process'.
1.10 What is a thermodynamic cycle?
1.11 What are intensive and extensive properties?
1.12 What do you mean by homogeneous and heterogeneous systems?
1.13 Explain what you understand by thermodynamic equilibrium.
1.14 Explain mechanical, chemical and thermal equilibrium.
1.15 What is a quasi-static process/ What is its characteristic feature?

2.1 What is the zeroth law of thermodynamics?
2.2 Define thermometric property.
2.3 What is a thermometer?
2.4 What is a fixed point?
2.5 How many fixed points were used prior to 1954? What are these?
2.6 What is the standard fixed point in thermometery? Define it.
2.7 Why is a gas chosen as the standard thermometric substance?
2.8 What is an ideal gas?
2.9 What is the difference between the universal gas constant and a characteristic gas constant?
2.10 What is a constant volume gas thermometer? Why is it preferred to a constant pressure gas thermometer?
2.11 What do you understand by the ideal gas temperature scale?
2.12 How can the ideal gas temperature for the steam point be measured?
2.13 What is the Celsius temperature scale?
2.14 What is the advantage of a thermocouple in temperature measurement?
2.15 How does the resistance thermometer measure temperature?
2.16 What is the need of the international practical temperature scale?

NUMERICALS

2.1 The limiting value of the ratio of the pressure of gas at the steam point and at the triple point of water when the gas is kept at constant volume is found to be 1.36605. What is the ideal gas temperature of the steam point?

2.2 In a constant volume gas thermometer the following pairs of pressures readings were taken at the boiling point of water and the boiling point of sulphur, respectively:

Water b.p.	50.0	100	200	300
Sulphur b.p.	96.4	193	387	582

The numbers are the gas pressures, mm Hg, each pair being taken with the same amount of gas in the thermometer, but the successive pairs being taken with different amounts of gas in the thermometer. Plot the ratio of $S_{b.p.}$: $H_2O_{b.p.}$ against the reading at the water boiling point, and extrapolate the plot to zero pressure at the water boiling point. This gives the ratio of $S_{b.p.}$: $H_2O_{b.p.}$ on a gas thermometer operating at zero gas pressure, i.e., an ideal gas thermometer. What is the boiling point of sulphur on the gas scale, from your plot?

Ans. 445°C

2.3 The resistance of a platinum wire is found to be 11,000 ohms at the ice point, 15.247 ohms at the steam point, and 28.887 ohms at the sulphur point. Find the constants A and B in the equation

$$R = R_0(1 + At + Bt^2)$$

and plot R against t in the range 0 to 660°C.

2.4 When the reference junction of a thermocouple is kept at the ice point and the test junction is the Celsius temperature t, and e.m.f. ε of the thermocouple is given by the equation

$$\varepsilon = at + bt^2$$

where $a = 0.20$ mV/deg, and $b = -50 \times 10^{-4}$ mV/deg^2

(a) Compute the e.m.f. when $t = -100$°C, 200°C, 400°C, and 500°C, and draw graph of ε against t in this range.

(b) Suppose the e.m.f. ε is taken as a thermometric property and that a temperature scale t^* is defined by the linear equation.

$$t^* = a'\varepsilon + b'$$

and that $t^* = 0$ at the ice point and $t^* = 100$ at the steam point. Find the numerical values of a' and b' and draw a graph of ε against t^*.

(c) Find the values of t^* when $t = -100$°C, 200°C, 400°C, and 500°C, and draw a graph of t^* against t.

(d) Compare the Celsius scale with the t^* scale.

2.5 The temperature t on a thermometric scale is defined in terms of a property K by the relation

$$t = a \ln K + b$$

where a and b are constants.

The values of K are found to be 1.83 and 6.78 at the ice point and the steam point, the temperatures of which are assigned the numbers 0 and 100 respectively. Determine the temperature corresponding to a reading of K equal to 2.42 on the thermometer.

Ans. 21.346°C

2.6 The resistance of the windings in a certain motor is found to be 80 ohms at room temperature (25°C). When operating at full load under steady state conditions, the motor is switched off and the resistance of the windings, immediately measured again, is found to be 93 ohms. The windings are made of copper whose resistance at temperature t°C is given by

$$R_t = R_0 [1 + 0.00393\, t]$$

where R_0 is the resistance at 0°C. Find the temperature attained by the coil during full load.

Ans. 70.41°C

UNIT – 2

THEORY QUESTIONS

3.1 How can a closed system and is surroundings interact? What is the effect of such interactions on the system?
3.2 When is work said to be done by a system?
3.3 What are positive and negative work interactions?
3.4 What is displacement work?
3.5 Under what conditions is the work done equal to $\int_1^2 p\,dV$?
3.6 What do you understand by path function and point function? What are exact and inexact differentials?
3.7 Show that work is a path function, and not a property.
3.8 What is an indicator diagram?
3.9 What is mean effective pressure? How is it measured?
3.10 What are the indicated power and the brake power of an engine?
3.11 How does the current flowing through a resistor represent work transfer?
3.12 What do you understand by flow work? Is it different from displacement work?
3.13 Why does free expansion have zero work transfer?
3.14 What is heat transfer? What are its positive and negative directions?
3.15 What are adiabatic and diathermic walls?
3.16 What is an integrating factor?
3.17 Show that heat is a path function and not a property.
3.18 What is the difference between work transfer and heat transfer?
3.19 Does heat transfer inevitably cause a temperature rise?

NUMERICALS

3.1 (a) A pump forces 1 m^3/min of water horizontally from an open well to a closed tank where the pressure is 0.9 MPa. Compute the work the pump must do upon the water in an hour just to force the water into the tank against the pressure. Sketch the system upon which the work is done before and after the process.

Ans. 13.31 kJ

(b) If the work done as above upon the water had been used solely to raise the same amount of water vertically against gravity without change of pressure, how many meters would the water have been elevated?

(c) If the work done in (a) upon the water had been used solely to accelerate the water from zero velocity without change of pressure or elevation, what velocity would the water have reached? If the work had been used to accelerate the water from an initial velocity of 10 m/s, what would the final velocity have been?

3.2 The piston of an oil engine, of area 0.0045 m^2, moves downwards 75 mm, drawing in 0.00028 m^3 of fresh air from the atmosphere. The pressure in the cylinder is uniform during the process at 80 kPa, while the atmospheric pressure is 101.325 kPa, the difference being due to the flow resistance in the induction pipe and the inlet valve. Estimate the displacement work done by the air finally in the cylinder.

Ans. 27 J

3.3 An engine cylinder has a piston of area 0.12 m^2 and contains gas at a pressure of 1.5 MPa. The gas expands according to a process which is represented by a straight line on a pressure-volume diagram. The final pressure is 0.15 MPa. Calculate the work done by the gas on the piston if the stroke is 0.30 m.

Ans. 29.7 kJ.

3.4 A mass of 1.5 kg of air is compressed in a quasi-static process from 0.1 MPa to 0.7 MPa for which pv = constant. The initial density of air is 1.16 kg/m^3. Find the work done by the piston to compress the air.

Ans. 251.62 kJ

3.5 A mass of gas is compressed in a quasi-static process from 80 kPa, 0.1 m^3 to 0.4 MPa, 0.03 m^3. Assuming that the pressure and volume are related by pv^n = constant, find the work done by the gas system.

Ans. – 11.83 kJ

3.6 A single-cylinder, double-acting, reciprocating water pump has an indicator diagram which is a rectangle 0.075 m long and 0.05 m high. The indicator spring constant is 147 MPa per m. The pump runs at 50 rpm. The pump cylinder diameter is 0.15 m and the piston stroke is 0.20 m. Find the rate in kW at which the piston does work on the water.

Ans. 43.3 kW

3.7 A single-cylinder, single-acting, 4 stroke engine of 0.15 m bore develops an indicated power of 4 kW when running at 216 rpm. Calculate the area of the indicator diagram that would be obtained with an indicator having a spring constant of 25×10^6 N/m^3. The length of the indicator diagram is 0.1 times the length of the stroke of the engine.

Ans. 505 mm^2

3.8 A six-cylinder, 4-stroke gasoline engine is run at a speed of 2520 RPM. The area of the indicator card of one cylinder is 2.45×10^3 mm^2 and its length is 58.5 mm. The spring constant is 20×10^6 N/m^3. The bore of the cylinders is 140 mm and the piston stroke is 150 mm. Determine the indicated power, assuming that each cylinder contributes an equal power.

Ans. 243.57 kW

3.9 A closed cylinder of 0.25 m diameter is fitted with a light frictionless piston. The piston is retained in position by a catch in the cylinder wall and the volume on one side of the piston contains air at a pressure of 750 kN/m^2. The volume on the other side of the piston is evacuated. A helical spring is mounted coaxially with the cylinder in this evacuated space to give a force of 120 N on the piston in this position. The catch is released and the piston travels along the cylinder until it comes to rest after a stroke of 1.2 m. The piston is then held in its position of maximum travel by a ratchet mechanism. The spring force increases linearly with the piston displacement to a final value of 5 kN. Calculate the work done by the compressed air on the piston.

Ans. 3.07 kJ

3.10 A steam turbine drives a ship's propeller through an 8 : 1 reduction gear. The average resisting torque imposed by the water on the propeller is 750×10^3 N and the shaft power delivered by the turbine to the reduction gear is 15 MW. The turbine speed is 1450 rpm. Determine (a) the torque developed by the turbine, (b) the power delivered to the propeller shaft, and (c) the net rate of working of the reduction gear.

Ans. (a) T = 98.84 km N, (b) 14.235 MW, (c) 0.765 MW

3.11 A fluid, contained in a horizontal cylinder fitted with a frictionless leakproof piston, is continuously agitated by means of a stirrer passing through the cylinder cover. The cylinder diameter is 0.40 m. During the stirring process lasting 10 minutes, the piston slowly moves out a distance of 0.485m against the atmosphere. The net work done by the fluid during the process is 2 kJ. The speed of the electric motor driving the stirrer is 840 rpm. Determine the torque in the shaft and the power output of the motor.

Ans. 0.08 mN, 6.92 W

3.12 At the beginning of the compression stroke of a two-cylinder internal combustion engine the air is at a pressure of 101.325 kPa. Compression reduces the volume to 1/5 of its original volume, and the law of compression is given by $pv^{1.2}$ = constant. If the bore and stroke of each cylinder is 0.15 m and 0.25 m, respectively, determine the power absorbed in kW by compression strokes when the engine speed is such that each cylinder undergoes 500 compression strokes per minute.

Ans. 17.95 kW

3.13 Determine the total work done by a gas system following an expansion process as shown in Fig. P. 3.13.

Ans. 2952 MJ

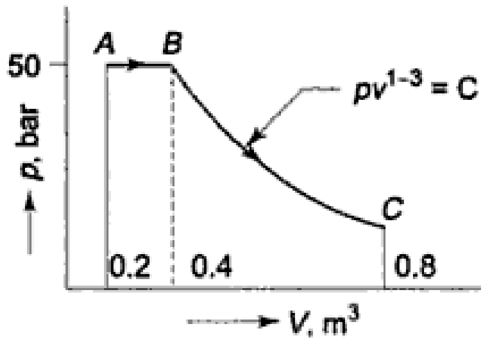

Fig. P. 3.13

3.14 A system of volume V contains a mass m of gas at pressure p and temperature T. The macroscopic properties of the system obey the following relationship:

$$\left(p + \frac{a}{V^2}\right)(V - b) = mRT$$

where a, b, and R are constants.

Obtain an expression for the displacement work done by the system during a constant-temperature expansion from volume V_1 to volume V_2. Calculate the work done by a system which contains 10 kg of this gas expanding from 1 m^3 to 10 m^3 at a temperature of 293 K. Use the values $a = 15.7 \times 10^4$ Nm^4, $b = 1.07 \times 10^{-2}$ m^3, and $R = 0.278$ kJ/kg–K.

Ans. 1742.14 kJ

3.15 If a gas of volume 6000 cm^3 and at a pressure of 100 kPa is compressed quasistatically according to pV^2 = constant until the volume becomes 2000 cm^3, determine the final pressure and the work transfer.

Ans. 900 kPa, 1.2 kJ

3.16 The flow energy of 0.124 m^3/min of a fluid crossing a boundary to a system is 18 kW. Find the pressure at this point.

Ans. 764 kPa

3.17 A milk chilling unit can remove heat from the milk at the rate of 41.87 MJ/h. Heat leaks into the milk from the surroundings at an average rate of 4.187 MJ/h. Find the time required for cooling a batch of 500 kg of milk from 45°C to 5°C. Take the c_p of milk to be 4.187 kJ/kgK.

3.18 680 kg of fish at 5°C are to be frozen and stored at-12°C. The specific heat of fish above freezing point is 3.182, and below freezing point is 1.717 kJ/kgK. The freezing point is – 2°C. and the latent heat of fusion is 234.5 kJ/kg. How much heat must be removed to cool the fish, and what per cent of this is latent heat?

Ans. 186.28 MJ, 85.6%

3.19 A horizontal cylinder fitted with a sliding piston contains 0.1 m^3 of a gas at a pressure of 1 atm. The piston is restrained by a linear spring. In the initial state, the gas pressure inside the cylinder just balances the atmospheric pressure of 1 atm on the outside of the piston and the spring exerts no force on the piston. The gas is then heated reversibly until its volume and pressure become 0.16 m^3 and 2 atm, respectively. (a) Write the equation for the relation between the pressure and volume of the gas. (b) Calculate the work done by the gas. (c) Of the total work done by the gas, how much is done against the atmosphere? How much is done against the spring?

Ans. (a) p (N/m^2) = 2.026×10^6 V – 1.013×10^5
(b) 7,598 J, (c) 5,065 J, 2,533 J

3.20 An elastic sphere initially has a diameter of 1 m and contains a gas at a pressure of 1 atm. Due to heat transfer the diameter of the sphere increases to 1.1 m. During the heating process the gas pressure inside the sphere is proportional to the sphere diameter. Calculate the work done by the gas.

Ans. 18.4 kJ

3.21 A piston-cylinder device contains 0.05 m^3 of a gas initially at 200 kPa. At this state, a linear spring having a spring constant of 150 kN/m is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is 0.25 m^2, determine (a) the final pressure inside the cylinder, (b) the total work done by the gas, and (c) the fraction of this work done against the spring to compress it.

Ans. (a) 320 kPa, (b) 13 kJ, (c) 3 kJ

3.22 A piston-cylinder device, whose piston is resting on a set of stops, initially contains 3 kg of air at 200 kPa and 27°C. The mass of the piston is such that a pressure of 400 kPa is required to move it. Heat is now transferred to the air until its volume doubles. Determine the work done by the air and the total heat transferred to the air.

Ans. 516 kJ, 2674 kJ

UNIT – 3

THEORY QUESTIONS

4.1 State the first law for a closed system undergoing a cycle.
4.2 What was the contribution of J.P. Joule in establishing the first law?
4.3 What is the caloric theory of heat? Why was it rejected?
4.4 Which is the property introduced by the first law?
4.5 State the first law for a closed system undergoing a change of state.
4.6 Show that energy is a property of a system.
4.7 What are the modes in which energy is stored in a system?
4.8 Define internal energy. How is energy stored in molecules and atoms?
4.9 What is the difference between the standard symbols of E and U?
4.10 What is the difference between heat and internal energy?
4.11 Define enthalpy. Why does the enthalpy of an ideal gas depend only on temperature?
4.12 Define the specific heats at constant volume and constant pressure.
4.13 Why should specific heat not be defined in terms of heat transfer?
4.14 Which property of a system increases when heat is transferred: (a) at constant volume, (b) at constant pressure?
4.15 What is a PMM1? Why is it impossible?

5.1 Explain the system approach and the control volume approach in the analysis of a flow process.
5.2 What is a steady flow process? What is steady state?
5.3 Write the steady flow energy equation for a single stream entering and a single stream leaving a control volume and explain the various terms in it.
5.4 Give the differential form of the S.F.E.E.
5.5 Under what conditions does the S.F.E.E. reduce to Euler's equation?
5.6 How does Bernoulli's equation compare with S.F.E.E.?
5.7 What will be the velocity of a fluid leaving a nozzle, if the velocity of approach is very small?
5.8 Show that the enthalpy of a fluid before throttling is equal to that after throttling.
5.9 Write the general energy equation for a variable flow process.
5.10 What is the system technique in a bottle-filling process?
5.11 Explain the control volume technique in a variable flow process.

NUMERICALS

4.1 An engine is tested by means of a water brake at 1000 rpm. The measured torque of the engine is 10000 mN and the water consumption of the brake is 0.5 m^3/s, its inlet temperature being 20°C. Calculate the water temperature at exit, assuming that the whole of the engine power is ultimately transformed into heat which is absorbed by the cooling water.

Ans. 20.5°C

4.2 In a cyclic process, heat transfers are + 14.7 kJ, – 25.2 kJ, – 3.56 kJ and + 31.5 kJ. What is the net work for this cycle process?

Ans. 17.34 kJ

4.3 A slow chemical reaction takes place in a fluid at the constant pressure of 0.1 MPa. The fluid is surrounded by a perfect heat insulator during the reaction which begins at state 1 and ends at state 2. The insulation is then removed and 105 kJ of heat flow to the surroundings as the fluid goes to state 3. The following data are observed for the fluid at states 1, 2 and 3.

State	$V(m^3)$	t(°C)
1	0.003	20
2	0.3	370
3	0.06	20

For the fluid system, calculate E_2 and E_3, if $E_1 = 0$

Ans. $E_2 = -29.7$ kJ, $E_3 = -110.7$ kJ

4.4 During one cycle the working fluid in an engine engages in two work interactions: 15 kJ to the fluid and 44 kJ from the fluid, and three heat interactions, two of which are known: 75 kJ to the fluid and 40 kJ from the fluid. Evaluate the magnitude and direction of the third heat transfer.

Ans. – 6 kJ

4.5 A domestic refrigerator is loaded with food and the door closed. During a certain period the machine consumes 1 kW h of energy and the internal energy of the system drops by 5000 kJ. Find the net heat transfer for the system.

Ans. – 8.6 MJ

4.6 1.5 kg of liquid having a constant specific heat of 2.5 kJ/kg K is stirred in a well-insulated chamber causing the temperature to rise by 15°C. Find ΔE and W for the process.

Ans. $\Delta E = 56.25$ kJ, $W = -56.25$ kJ

4.7 The same liquid as in Problem 4.6 is stirred in a conducting chamber. During the process 1.7 kJ of heat are transferred from the liquid to the surroundings, while the temperature of the liquid is rising by 15°C. Find ΔE and W for the process.

Ans. $\Delta E = 56.25$ kJ, $W = 57.95$ kJ

4.8 The properties of a certain fluid are related as follows

$$u = 196 + 0.718\, t$$
$$pv = 0.287\, (t + 273)$$

where u is the specific internal energy (kJ/kg), t is in °C, p is pressure (kN/m^2), and v is specific volume (m^3/kg).

For this fluid, find c_v and c_p

Ans. 0.718, 1.005 kJ/kg K

4.9 A system composed of 2 kg of the above fluid expands in a frictionless piston and cylinder machine from an initial state of 1 MPa, 100°C to a final temperature of 30°C. If there is no heat transfer, find the net work for the process.

Ans. 100.52 kJ

4.10 If all the work in the expansion of Problem 4.9 is done on the moving piston, show that the equation representing the path of the expansion in the *pv*-plane is given by $pv^{1.4}$ = constant.

4.11 A stationary system consisting of 2 kg of the fluid of Problem 4.8 expands in an adiabatic process according to $pv^{1.2}$ = constant. The initial conditions are 1 MPa and 200°C, and the final pressure is 0.1 MPa. Find W and ΔU for the process.

Why is the work transfer not equal to $\int p dV$?

Ans. $W = 216.83$, $\Delta U = -216.83$ kJ, $\int p dV = 434.4$ kJ

4.12 A mixture of gases expands at constant pressure from 1 MPa, 0.03 m^3 to 0.06 m^3 with 84 kJ positive heat transfer. There is no work other than that done on a piston. Find ΔE for the gaseous mixture.

Ans. 54 kJ

The same mixture expands through the same state path while a stirring device does 21 kJ of work on the system. Find ΔE, W, and Q for the process.

Ans. 54 kJ, – 21 kJ, 33 kJ

4.13 A mass of 8 kg gas expands within a flexible container so that the p–v relationship is of the form $pv^{1.2}$ = const. The initial pressure is 1000 kPa and the initial volume is 1 m^3. The final pressure is 5 kPa. If specific internal energy of the gas decreases by 40 kJ/kg, find the heat transfer in magnitude and direction.

Ans. + 2615 kJ

4.14 A gas of mass 1.5 kg undergoes a quasi-static expansion which follows a relationship $p = a + bV$, where a and b are constants. The initial and final pressures are 1000 kPa and 200 kPa respectively and the corresponding volumes are 0.20 m^3 and 1.20 m^3. The specific internal energy of the gas is given by the relation

$$u = 1.5\, pv - 85 \text{ kJ/kg}$$

where p is in kPa and v is in m^3/kg. Calculate the net heat transfer and the maximum internal energy of the gas attained during expansion.

Ans. 660 kJ, 503.3 kJ

4.15 The heat capacity at constant pressure of a certain system is a function of temperature only and may be expressed as

$$C_p = 2.093 + \frac{41.87}{t + 100} \text{ J/K}$$

where t is the temperature of the system in °C. The system is heated while it is maintained at a pressure of 1 atmosphere until its volume increases from 2000 cm^3 to 2400 cm^3 and its temperature increases from 0°C to 100°C. (a) Find the magnitude of the heat interaction. (b) How much does the internal energy of the system increase?

Ans. (a) 238.32J (b) 197.79 J

4.16 An imaginary engine receives heat and does work on a slowly moving piston at such rates that the cycle of operation of 1 kg of working fluid can be represented as a circle 10 cm in diameter on a p–v diagram on which 1 cm = 300 kPa and 1 cm = 0.1 m^3/kg. (a) How much work is done by each kg of working fluid for each cycle of operation? (b) The thermal efficiency of an engine is defined as the ratio of work done and heat input in a cycle. If the heat rejected by the engine in a cycle is 1000 kJ per kg of working fluid, what would be its thermal efficiency?

Ans. (a) 2356.19 kJ/kg, (b) 0.702

4.17 A gas undergoes a thermodynamic cycle consisting of three processes beginning at an initial state where p_1 = 1 bar, V_1 = 1.5 m^3 and U_1 = 512 kJ. The processes are as follows:

(i) Process 1–2: Compression with pV = constant to p_2 = 2 bar, U_2 = 690 kJ
(ii) Process 2–3: $W_{23} = 0$, Q_{23} = – 150 kJ, and
(iii) Process 3–1: W_{31} = + 50 kJ. Neglecting KE and PE changes, determine the heat interactions Q_{12} and Q_{31}.

Ans. 74 kJ, 22 kJ

4.18 A gas undergoes a thermoynamic cycle consisting of the following processes: (i) Process 1–2: Constant pressure p = 1.4 bar, V_1 = 0.028 m^3, W_{12} = 10.5 kJ, (ii) Process 2–3: Compression with pV = constant, $U_3 = U_2$, (iii) Process 3–1: Constant volume, $U_1 - U_3$ = – 26.4 kJ. There are no significant changes in KE and PE. (a) Sketch the cycle on a p-V diagram. (b) Calculate the net work for the cycle in kJ. (c) Calculate the heat transfer for process 1–2 (d) Show that $\sum_{\text{cycle}} Q = \sum_{\text{cycle}} W$.

Ans. (b) – 8.28 kJ, (c) 36.9 kJ

4.19 A certain gas of mass 4 kg is contained within a piston cylinder assembly. The gas undergoes a process for which $pV^{1.5}$ = constant. The initial state is given by 3 bar, 0.1 m^3. The change in internal energy of the gas in the process is $u_2 - u_1$ = – 4.6 kJ/kg. Find the net heat transfer for the process when the final volume is 0.2 m^3. Neglect the changes in KE and PE.

Ans. – 0.8 kJ

4.20 An electric generator coupled to a windmill produces an average electrical power output of 5 kW. The power is used to charge a storage battery. Heat transfer from the battery to the surroundings occurs at a constant rate of 0.6 kW. Determine the total amount of energy stored in the battery in 8*h* of operation.

Ans. 1.27×10^5 kJ

4.21 A gas in a piston-cylinder assembly undergoes two processes in series. From state 1 to state 2 there is energy transfer by heat to the gas of 500 kJ, and the gas does work on the piston amounting 800 kJ. The second process, from state 2 to state 3, is a constant pressure compression at 400 kPa, during which there is a heat transfer from the gas amounting 450 kJ. The following data are also known: U_1 = 2000 kJ and U_3 = 3500 kJ. Neglecting changes in KE and PE, calculate the change in volume of the gas during process 2–3.

Ans. – 5.625 m^3

4.22 Air is contained in a rigid well-insulated tank with a volume of 0.2 m^3. The tank is fitted with a paddle wheel which transfers energy to the air at a constant rate of 4 W for 20 min. The initial density of the air is 1.2 kg/m^3. If no changes in KE or PE occur, determine (a) the specific volume at the final state, (b) the change in specific internal energy of the air.

Ans. (a) 0.833 m^3/kg, (b) 20 kJ/kg

5.1 A blower handles 1 kg/s of air at 20°C and consumes a power of 15 kW. The inlet and outlet velocities of air are 100 m/s and 150 m/s respectively. Find the exit air temperature, assuming adiabatic conditions. Take c_p of air as 1.005 kJ/kg-K.

Ans. 28.38°C

5.2 A turbine operates under steady flow conditions, receiving steam at the following state: pressure 1.2 MPa, temperature 188°C, enthalpy 2785 kJ/kg, velocity 33.3 m/s and elevation 3 m. The steam leaves the turbine at the following state: pressure 20 kPa, enthalpy 2512 kJ/kg, velocity 100 m/s, and elevation 0 m. Heat is lost to the surroundings at the rate of 0.29 kJ/s. If the rate of steam flow through the turbine is 0.42 kg/s, what is the power output of the turbine in kW?

Ans. 112.51 kW

5.3 A nozzle is a device for increasing the velocity of a steadily flowing stream. At the inlet to a certain nozzle, the enthalpy of the fluid passing is 3000 kJ/kg and the velocity is 60 m/s. At the discharge end, the enthalpy is 2762 kJ/kg. The nozzle is horizontal and there is negligible heat loss from it. (a) Find the velocity at exit from the nozzle. (b) If the inlet area is 0.1 m^2 and the specific volume at inlet is 0.187 m^3/kg, find the mass flow rate. (c) If the specific volume at the nozzle exit is 0.498 m^3/kg, find the exit area of the nozzle.

Ans. (a) 692.5 m/s, (b) 32.08 kg/s (c) 0.023 m^2

5.4 In an oil cooler, oil flows steadily through a bundle of metal tubes submerged in a steady steam of colling water. Under steady flow conditions, the oil enters at 90°C and leaves at 30°C, while the water enters at 25°C and leaves at 70°C. The enthalpy of oil at t°C is given by

$$h = 1.68\, t + 10.5 \times 10^{-4}\, t^2 \text{ kJ/kg}$$

What is the cooling water flow required for cooling 2.78 kg/s of oil?

Ans. 1.473 kg/s

5.5 A thermoelectric generator consists of a series of semiconductor elements (Fig. P. 5.5), heated on one side and cooled on the other. Electric current flow is produced as a result of energy transfer as heat. In a particular experiment the

current was measured to be 0.5 amp and the electrostatic potential at (1) was 0.8 volt above that at (2). Energy transfer as heat to the hot side of the generator was taking place at a rate of 5.5 watts. Determine the rate of energy transfer as heat from the cold side and the energy conversion efficiency.

Ans. Q_2 = 5.1 watts, η = 0.073

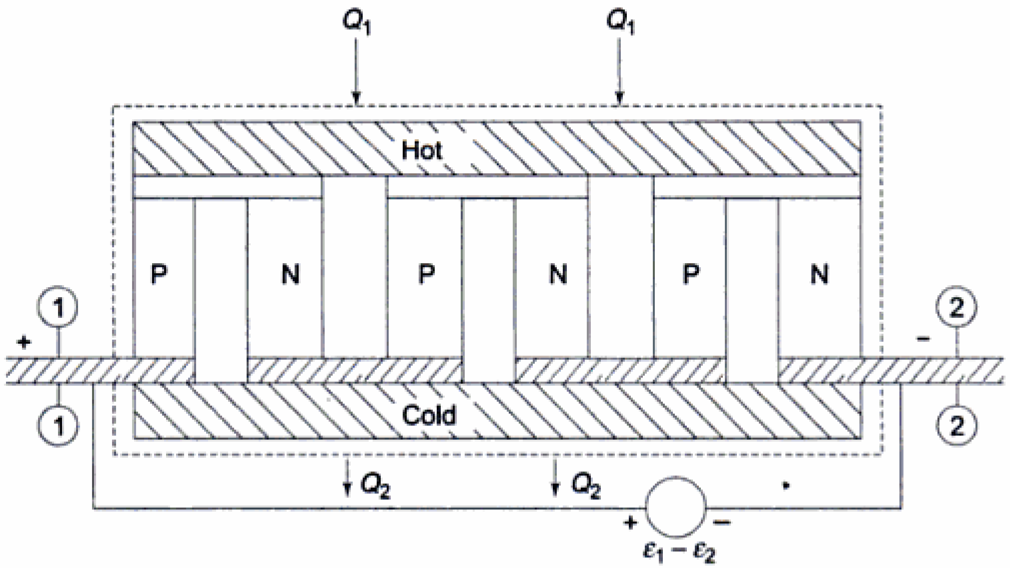

Fig. P.5.5

5.6 A turbocompressor delivers 2.33 m^3/s of air at 0.276 MPa, 43°C which is heated at this pressure to 430°C and finally expanded in a turbine which delivers 1860 kW. During the expansion, there is a heat transfer of 0.09 MJ/s to the surroundings. Calculate the turbine exhaust temperature if changes in kinetic and potential energy are negligible. Take c_p = 1.005 kj/kgK

Ans. 157°C

5.7 A reciprocating air compressor takes in 2 m^3/min at 0.11 MPa, 20°C which it delivers at 1.5 MPa, 111°C to an aftercooler where the air is cooled at constant pressure to 25°C. The power absorbed by the compressor is 4.15 kW. Determine the heat transfer in (a) the compressor, and (b) the cooler. State your assumptions.

Ans. – 0.17 kJ/s, – 3.76 kJ/s.

5.8 In a water cooling tower air enters at a height of 1 m above the ground level and leaves at a height of 7 m. The inlet and outlet velocities are 20 m/s and 30 m/s respectively. Water enters at a height of 8 m and leaves at a height of 0.8 m. The velocity of water at entry and exit are 3 m/s and 1 m/s respectively. Water temperatures are 80°C and 50°C at the entry and exit respectively. Air temperatures are 30°C and 70°C at the entry and exit respectively. The colling tower is well insulated and a fan of 2.25 kW drives the air through the cooler. Find the amount of air per second required for 1 kg/s of water flow. The values of c_p of air and water are 1.005 and 4.187/kg K respectively.

Ans. 3.16 kg

5.9 Air at 101.325 kPa, 20°C is taken into a gas turbine power plant at a velocity of 140 m/s through an opening of 0.15 m^2 cross-sectional area. The air is compressed heated, expanded through a turbine, and exhausted at 0.18 MPa, 150°C through an opening of 0.10 m^2 cross-sectional area. The power output is 375 kW. Calculate the net amount of heat added to the air in kJ/kg. Assume that air obeys the law $pv = 0.287\ (t + 273)$ where p is the pressure in kPa v is the specific volume in m^3/kg, and t is the temperature in °C. Take c_p = 1.005 kJ/kg K.

Ans. 150.23 kj/kg

5.10 A gas flows steadily through a rotary compressor. The gas enters the compressor at a temperature of 16°C, a pressure of 100 kPa, and an enthalpy of 391.2 kJ/kg. The gas leaves the compressor at a temperature of 245°C, a pressure of 0.6 MPa, and an enthalpy of 534.5 kJ/kg. There is no heat transfer to or from the gas as it flows through the compressor. (a) Evaluate the external work done per unit mass of gas assuming the gas velocities at entry and exit to be negligible. (b) Evaluate the external work done per unit mass of gas when the gas velocity at entry is 80 m/s and that at exit is 160 m/s.

Ans. 143.3 kJ/kg, 152.9 kJ/kg

5.11 The steam supply to an engine comprises two streams which mix before entering the engine. One stream is supplied at the rate of 0.01 kg/s with an enthalpy of 2952 kJ/kg and a velocity of 20 m/s. The other stream is supplied at the rate of 0.1 kg/s with an enthalpy of 2569 kJ/kg and a velocity of 120 m/s. At the exit from the engine the fluid leaves as two streams, one of water at the rate of 0.001 kg/s with an enthalpy of 420 kJ/kg and the other of steam; the fluid velocities at the exit are negligible. The engine develops a shaft power of 25 kW. The heat transfer is negligible. Evaluate the enthalpy of the second exit stream.

Ans. 2401 kJ/kg

5.12 The stream of air and gasoline vapour, in the ratio of 14:1 by mass, enters a gasoline engine at a temperature of 30°C and leaves as combustion products at a temperature of 790°C. The engine has a specific fuel consumption of 0.3 kg/kWh. The net heat transfer rate from the fuel-air steam to the jacket cooling water and to the surroundings is 35 kW. The shaft power delivered by the engine is 26 kW. Compute the increase in the specific enthalpy of the fuel-air stream, assuming the changes in kinetic energy and in elevation to be negligible.

Ans. – 1877 kJ/kg mixture

5.13 An air turbine forms part of an aircraft refrigerating plant. Air at a pressure of 295 kPa and a temperature of 58°C flows steadily into the turbine with a velocity of 45 m/s. The air leaves the turbine at a pressure of 115 kPa, a temperature of 2°C, and a velocity of 150 m/s. The shaft work delivered by the turbine is 54 kJ/kg of air. Neglecting changes in elevation, determine the magnitude and sign of the heat transfer per unit mass of air flowing. For air, take c_p = 1.005 kJ/kg K and the enthalpy $h = c_p\, t$.

Ans. + 7.96 kJ/kg

5.14 In a turbomachine handling an incompressible fluid with a density of 1000 kg/m^3 the conditions of the fluid at the rotor entry and exit are as given below

	Inlet	Exit
Pressure	1.15 MPa	0.05 MPa
Velocity	30 m/s	15.5 m/s
Height above datum	10 m	2 m

If the volume flow rate of the fluid is 40 m^3/s, estimate the net energy transfer from the fluid as work.

Ans. 60.3 MW

5.15 A room for four persons has two fans, each consuming 0.18 kW power, and three 100 W lamps. Ventilation air at the rate of 80 kg/h enters with an enthalpy of 84 kJ/kg and leaves with an enthalpy of 59 kJ/kg. If each person puts out heat at the rate of 630 kg/h determine the rate at which heat is to be removed by a room cooler, so that a steady state is maintained in the room.

Ans. 1.92 kW

5.16 Air flows steadily at the rate of 0.4 kg/s through an air compressor, entering at 6 m/s with a pressure of 1 bar and a specific volume of 0.85 m^3/kg, and leaving at 4.5 m/s with a pressure of 6.9 bar and a specific volume of 0.16 m^3/kg. The internal energy of the air leaving is 88 kJ/kg greater than that of the air entering. Cooling water in a jacket, surrounding the cylinder absorbs heat from the air at the rate of 59 W. Calculate the power required to drive the compressor and the inlet and outlet cross-sectional areas.

(*Ans.* 45.4 kW, 0.057 m^2, 0.0142 m^2)

5.17 Steam flowing in a pipeline is at a steady state represented by p_p, t_p, u_p, v_p, h_p and V_p. A small amount of the total flow is led through a small tube to an evacuated chamber which is allowed to fill slowly until the pressure is equal to the pipeline pressure. If there is no heat transfer, derive an expression for the final specific internal energy in the chamber, in terms of the properties in the pipeline.

5.18 The internal energy of air is given, at ordinary temperatures, by

$$u = u_0 + 0.718\, t$$

where u is in kJ/kg, u_0 is any arbitrary value of u at 0°C, kJ/kg, and t is temperature in °C.

Also for air, $pv = 0.287\,(t + 273)$

where p is in kPa and v is in m^3/kg.

(a) An evacuated bottle is fitted with a valve through which air from the atmosphere, at 760 mm Hg and 25°C, is allowed to flow slowly to fill the bottle. If no heat is transferred to or from the air in the bottle, what will its temperature be when the pressure in the bottle reaches 760 mm Hg?

Ans. 144.2°C

(b) If the bottle initially contains 0.03 m^3 of air at 400 mm Hg and 25°C, what will the temperature be when the pressure in the bottle reaches 760 mm Hg?

Ans. 71.6°C

5.19 A pressure cylinder of volume V contains air at pressure p_0 and temperature T_0. It is to be filled from a compressed air line maintained at constant pressure p_1 and temperature T_1. Show that the temperature of the air in the cylinder after it has been charged to the pressure of the line is given by

$$T = \frac{\gamma T_1}{1 + \dfrac{p_0}{p_1}\left(\gamma \dfrac{T_1}{T_0} - 1\right)}$$

5.20 A small reciprocating vacuum pump having the rate of volume displacement V_d is used to evacuate a large vessel of volume V. The air in the vessel is maintained at a constant temperature T by energy transfer as heat. If the initial and final pressures are p_1 and p_2 respectively, find the time taken for the pressure drop and the necessary energy transfer as heat during evacuation. Assume that for air, $pV = mRT$, where m is the mass and R is a constant, and u is a function of T only.

$$\left[Ans.\ t = \frac{V}{V_d} \ln \frac{p_1}{p_2};\ Q = (p_1 - p_2)V \right]$$

[Hint: $dm = -p(V_d \cdot dt)/(RT) = V\,dp/(RT)$].

5.21 A tank containing 45 kg of water initially at 45°C has one inlet and one exit with equal mass flow rates. Liquid water enters at 45°C and a mass flow rate of 270 kg/h. A cooling coil immersed in the water removes energy at a rate of 7.6 kW. The water is well mixed by a paddle wheel with a power input of 0.6 kW. The pressures at inlet and exit are equal. Ignoring changes in KE and PE, find the variation of water temperature with time.

Ans. $T = 318 - 22\,[1 - \exp(-6t)]$

5.22 A rigid tank of volume 0.5 m^3 is initially evacuated. A tiny hole develops in the wall, and air from the surroundings at 1 bar, 21°C leaks in. Eventually, the pressure in the tank reaches 1 bar. The process occurs slowly enough that heat transfer between the tank and the surroundings keeps the temperature of the air inside the tank constant at 21°C. Determine the amount of heat transfer.

Ans. – 50 kJ

UNIT – 4

THEORY QUESTIONS

6.1 What is the qualitative difference between heat and work? Why are heat and work not completely interchangeable forms of energy?
6.2 What is a cyclic heat engine?
6.3 Explain a heat engine cycle performed by a closed system.
6.4 Explain a heat engine cycle performed by a steady flow system.
6.5 Define the thermal efficiency of a heat engine cycle. Can this be 100%?
6.6 Draw a block diagram showing the four energy interactions of a cyclic heat engine.
6.7 What is a thermal energy reservoir? Explain the terms 'source' and 'sink'
6.8 What is a mechanical energy reservoir?
6.9 Why can all processes in a TER or an MER be assumed to be quasi-static?
6.10 Give the Kelvin-Planck statement of the second law.
6.11 To produce net work in a thermodynamic cycle, a heat engine has to exchange heat with two thermal reservoirs. Explain.
6.12 What is a PMM2? Why is it impossible?

6.13 Give the Clausius' statement of the second law.
6.14 Explain the operation of a cyclic refrigerator plant with a block diagram.
6.15 Define the COP of a refrigerator.

6.16 What is a heat pump? How does it differ from a refrigerator?

6.17 Can you use the same plant as a heat pump in winter and as a refrigerator in summer? Explain.

6.18 Show that the COP of a heat pump is greater than the COP of a refrigerator by unity.

6.19 Why is direct heating thermodynamically wasteful?

6.20 How can a heat pump upgrade low grade waste heat?

6.21 Establish the equivalence of Kelvin-Planck and Clausius statements.

6.22 What is a reversible process? A reversible process should not leave any evidence to show that the process had ever occurred. Explain.

6.23 How is a reversible process only a limiting process, never to be attained in practice?

6.24 All spontaneous processes are irreversible. Explain.

6.25 What are the causes of irreversibility of a process?

6.26 Show that heat transfer through a finite temperature difference is irreversible.

6.27 Demonstrate, using the second law, that free expansion is irreversible.

6.28 What do you understand by dissipative effects? When is work said to be dissipated?

6.29 Explain perpetual motion of the third kind.

6.30 Demonstrate using the second law how friction makes a process irreversible.

6.31 When a rotating wheel is brought to rest by applying a brake, show that the molecular internal energy of the system (of the brake and the wheel) increases.

6.32 Show that the dissipation of stirring work to internal energy is irreversible.

6.33 Show by second law that the dissipation of electrical work into internal energy or heat is irreversible.

6.34 What is a Carnot cycle? What are the four processes which constitute the cycle?

6.35 Explain the Carnot heat engine cycle executed by: (a) a stationary system, and (b) a steady flow system.

6.36 What is a reversed heat engine?

6.37 Show that the efficiency of a reversible engine operating between two given constant temperatures is the maximum.

6.38 Show that the efficiency of all reversible heat engines operating between the same temperature levels is the same.

6.39 Show that the efficiency of a reversible engine is independent of the nature or amount of the working substance going through the cycle.

6.40 How does the efficiency of a reversible cycle depend only on the two temperatures at which heat is transferred?

6.41 What is the absolute thermodynamic temperature scale? Why is it called absolute?

6.42 How is the absolute scale indepdent of the working substance?

6.43 How does Q play the role of thermometric property in the Kelvin Scale?

6.44 Show that a definite zero point exists on the absolute temperature scale but that this point cannot be reached without a violation of the second law.
6.45 Give the Fowler-Guggenheim statement of the third law.
6.46 Is the third law an extension of the second law? Is it an independent law of nature? Explain.
6.47 How does the efficiency of a reversible engine vary as the source and sink temperatures are varied? When does the efficiency become 100%?
6.48 For a given T_2, show that the COP of a refrigerator increases as T_1 decreases.
6.49 Explain how the Kelvin temperature can be measured with a gas thermometer.
6.50 Establish the equality of ideal gas temperature and Kelvin temperature.
6.51 What do you understand by internal irreversibility and external irreversibility?
6.52 Explain mechanical, thermal and chemical irreversibilities.
6.53 A Carnot engine with a fuel burning device as source and a heat sink cannot be treated as a reversible plant. Explain.

NUMERICALS

6.1 An inventor claims to have developed an engine that takes in 105 MKJ at a temperature of 400 K, rejects 42 MJ at a temperature of 200 K, and delivers 15 kWh of mechanical work. Would you advise investing money to put this engine in the market?

6.2 If a refrigerator is used for heating purposes in winter so that the atmosphere becomes the cold body and the room to be heated becomes the hot body, how much heat would be available for heating for each kW input to the driving motor? The COP of the refrigerator is 5, and the electromechanical efficiency of the motor is 90%. How does this compare with resistance heating?

Ans. 5.4 kW, 1kW

6.3 Using an engine of 30% thermal efficiency of drive a refrigerator having a COP of 5, what is the heat inpuit into the engine for each MJ removed from the cold body by the refrigerator?

Ans. 666.67 kJ

If this system is used as a heat pump, how many MJ of heat would be available for heating for each MJ of heat input to the engine?

Ans. 1.8 MJ

6.4 An electric storage battery which can exchange heat only with a constant temperature atmosphere goes through a complete cycle of two processes. In process 1–2, 2.8 kWh of electrical work flow into the battery while 732 kJ of heat flow out to the atmosphere. During process 2–1, 2.4 kWh of work flow out of the battery. (a) Find the heat transfer in process 2–1. (b) If the process 1–2 has occurred as above, does the first law or the second law limit the maximum possible work of process 2–1? What is the maximum possible work? (c) If the maximum possible work were obtained in process 2–1, what will be the heat transfer in the process?

(a) – 708 kJ (b) Second law, W_{2-1} = 9348 kJ (c) Q_{2-1} = 0

6.5 A household refrigerator is maintained at a temperature of 2°C. Every time the door is opened, warm material is placed inside, introducing an average of 420 kJ, but making only a small change in the temperature of the refrigerator. The door is opened 20 times a day, and the refrigerator operates at 15% of the ideal COP. The cost of work is 32 paise per kWh. What is the monthly bill for this refrigerator? The atmosphere is at 30°C.

Ans. Rs. 15.20

6.6 A heat pump working on the Carnot cycle takes in heat from a reservoir at 5°C and delivers heat to a reservoir at 60°C. The heat pump is driven by a reversible heat engine which takes in heat from a reservoir at 840°C and rejects heat to a reservoir at 60°C. The reversible heat engine also drives a machine that absorbs 30 kW. If the heat pump extracts 17 kJ/s from the 5°C reservoir, determine (a) the rate of heat supply from the 840°C source, and (b) the rate of heat rejection to the 60°C sink.

Ans. (a) 47.61 kW; (b) 34.61 kW

6.7 A refrigeration plant for a food store operates with a COP which is 40% of the ideal COP of a Carnot of refrigarator. The store is to be maintained at a temperature of –5°C and the heat transfer from the store to the cycle is at the rate of 5 kW. If heat is transferred from the cycle to the atmosphere at a temperature of 25°C, calculate the power required to drive the plant and the heat discharged to the atmosphere.

Ans. 4.4 kW, 6.4 kW

6.8 A heat engine is used to drive a heat pump. The heat transfers from the heat engine and from the heat pump are used to heat the water circulating through the radiators of a building. The efficiency of the heat engine is 27% and the COP of the heat pump is 4. Evaluate the ratio of the heat transfer to the circulating water to the heat transfer to the heat engine.

Ans. 1.81

6.9 If 20 kJ are added to a Carnot cycle at a temperature of 100°C and 14.6 kJ are rejected at 0°C, determine the location of absolute zero on the Celsius scale.

Ans. –270.37°C

6.10 Two reversible heat engines *A* and *B* are arranged in series, *A* rejecting heat directly to *B*. Engine *A* receives 200 kJ at a temperature of 421°C from a hot source, while engine *B* is in communication with a cold sink at a temperature of 4.4°C. If the work output of *A* is twice that of *B*, find (a) the intermediate temperature between *A* and *B*, (b) the efficiency of each engine, and (c) the heat rejected to the cold sink.

Ans. 143.4°C, 40% & 33.5%, 80 kJ

6.11 A heat engine operates between the maximum and minimum temperatures of 671°C and 60°C respectively, with an efficiency of 50% of the appropriate Carnot efficiency. It drives a heat pump which uses river water at 4.4°C to heat a block of flats in which the temperature is to be maintained at 21.1°C. Assuming that a temperature difference of 11.1°C exists between the working fluid and the river water, on the one hand, and the required room temperature on the other, and assuming the heat pump to operate on the reversed Carnot cycle, but with a COP of 50% of the ideal COP, find the heat input to the engine per unit heat output from the heat pump. Why is direct heating thermodynamically more wasteful?

Ans. 0.79 kJ/kJ heat input

6.12 An ice-making plant produces ice at atmospheric pressure and at 0°C from water at 0°C. The mean temperature of the cooling water circulating through the condenser of the refrigerating machine is 18°C. Evaluate the minimum electrical work in kWh required to produce 1 tonne of ice. (The enthalpy of fusion of ice at atmospheric pressure is 333.5 kJ/kg).

Ans. 6.11 kWh

6.13 A reversible engine works between three thermal reservoirs, *A*, *B* and *C*. The engine absorbs an equal amount of heat from the thermal reservoirs *A* and *B* kept at temperatures T_A and T_B respectively, and rejects heat to the thermal reservoir *C* kept at temperature T_C. The efficiency of the engine is α times the efficiency of the reversible engine, which works between the two reservoirs *A* and *C*. Prove that

$$\frac{T_A}{T_B} = (2\alpha - 1) + 2(1 - \alpha)\frac{T_A}{T_C}$$

6.14 A reversible engine operates between temperatures T_1 and $T (T_1 > T)$. The energy rejected from this engine is received by a second reversible engine at the same temperature T. The second engine rejects energy at temperature T_2 $(T_2 < T)$. Show that (a) temperature T is the arithmetic mean of temperatures T_1 and T_2 if the engines produce the same amount of work output, and (b) temperature T is the geometric mean of temperatures T_1 and T_2 if the engines have the same cycle efficiencies.

6.15 Two Carnot engines *A* and *B* are connected in series between two thermal reservoirs maintained at 1000 K and 100 K respectively. Engine *A* receives 1680 kJ of heat from the high-temperature reservoir and rejects heat to the Carnot engine *B*. Engine *B* takes in heat rejected by engine *A* and rejects heat to the low-temperature reservoir. If engines *A* and *B* have equal thermal efficiencies, determine (a) the heat rejected by engine *B*, (b) the temperature at which heat is rejected by engine *A*, and (c) the work done during the process by engines *A* and *B* respectively. If engines *A* and *B* deliver equal work, determine (d) the amount of heat taken in by engine *B*, and (e) the efficiencies of engines *A* and *B*.

Ans. (a) 168 kJ, (b) 316.2 K, (c) 1148.7, 363.3 kJ,
(d) 924 kJ, (e) 45%, 81.8%.

6.16 A heat pump is to be used to heat a house in winter and then reversed to cool the house in summer. The interior temperature is to be maintained at 20°C. Heat transfer through the walls and roof is estimated to be 0.525 kJ/s per degree temperature difference between the inside and outside. (a) If the outside temperature in winter is 5°C, what is the minimum power required to drive the heat pump? (B) If the power output is the same as in part (a), what is the maximum outer temperature for which the inside can be maintained at 20°C?

Ans. (a) 403 W, (b) 35°C.

6.17 Consider an engine in outer space which operates on the Carnot cycle. The only way in which heat can be transferred from the enging is by radiation. The rate at which heat is radiated is proportional to the fourth power of the absolute temperature T_2 and to the area of the radiating surface. Show that for a given power output and a given T_1, the area of the radiator will be a minimum when

$$\frac{T_2}{T_1} = \frac{3}{4}$$

6.18 It takes 10 kW to keep the interior of a certain house at 20°C when the outside temperature is 0°C. This heat flow is usually obtained directly by burning gas or oil. Calculate the power required if the 10 kW heat flow were supplied by operating a reversible heat put with the house as the upper reservoir and the outside surroundings as the lower reservoir.

Ans. 0.6826 kW

6.19 Prove that the COP of a reversible refrigerator operating between two given temperatures is the maximum.

6.20 A house is to be maintained at a temperature of 20°C by means of a heat pump pumping heat from the atmosphere. Heat losses through the walls of the house are estimated at 0.65 kW per unit of temperature difference between the inside of the house and the atmosphere. (a) If the atmospheric temperature is –10°C, what is the minimum power required to drive the pump? (b) It is proposed to use the same heat pump to cool the house in summer. For the same room temperature, the same heat loss rate, and the same power input to the pump, what is the maximum permissible atmospheric temperature?

Ans. 2 kW, 50°C.

6.21 A solar-powered heat pump receives heat from a solar collector at T_h, rejects heat to the atmosphere at T_a, and pumps heat from a cold space at T_c. The three heat transfer rates are Q_h, Q_a, and Q_c respectively. Derive an expression for the minimum ratio Q_h/Q_c, in terms of the three temperatures.
If $T_h = 400$ K, $T_a = 300$ K, $T_c = 200$ K, $Q_c = 12$ kW, what is the minimum Q_h? If the collector captures 0.2 kW/m^2, what is the minimum collector area required?

Ans. 24 kW, 120 m^2

6.22 A heat engine operating between two reservoirs at 1000 K and 300 K is used to drive a heat pump which extracts heat from the reservoir at 300 K at a rate twice that at which the engine rejects heat to it. If the efficiency of the engine is 40% of the maximum possible and the COP of the heat pump is 50% of the maximum possible, what is the temperature of the reservoir to which the heat pump rejects heat? What is the rate of heat rejection from the heat pump if the rate of heat supply to the engine is 50 kW?

Ans. 326.5 K, 86 kW

6.23 A reversible power cycle is used to drive a reversible heat pump cycle. The power cycle takes in Q_1 heat units at T_1 and rejects Q_2 at T_2. The heat pump abstracts Q_4 from the sink at T_4 and discharges Q_3 at T_3. Develop an expression for the ratio Q_4/Q_1 in terms of the four temperatures.

Ans. $\frac{Q_4}{Q_1} = \frac{T_4(T_1 - T_2)}{T_1(T_3 - T_4)}$

6.24 Prove that the following propositions are logically equivalent: (a) A PMM2 is impossible, (b) A weight sliding at constant velocity down a frictional inclined plane executes an irreversible process.

6.25 A heat engine receives half of its heat supply at 1000 K and half at 500 K while rejecting heat to a sink at 300 K. What is the maximum possible thermal efficiency of this heat engine?

Ans. 0.55

6.26 A heat pump provides 3×10^4 kJ/h to maintain a dwelling at 23°C on a day when the outside temperature is 0°C. The power input to the heat pump is 4 kW. Determine the COP of the heat pump and compare it with the COP of a reversible heat pump operating between the reservoirs at the same two temperatures.

Ans. 2.08, 12.87

6.27 A reversible power cycle receiver energy Q_1 from a reservoir at temperature T_1 and rejects Q_2 to a reservoir at temperature T_2. The work developed by the power cycle is used to drive a reversible heat pump that removes energy Q'_2 from a reservoir at temperature T'_2 and rejects energy Q'_1 to a reservoir at temperature T'_1. (a) Determine an expression for the ratio Q'_1/Q_1 in terms of the four temperatures. (b) What must be the relationship of the temperatures T_1, T_2, T'_2 and T'_1 for Q'_1/Q_1 to exceed a value of unity?

Ans. (a) $\frac{Q'_1}{Q_1} = \frac{T'_1(T_1 - T_2)}{T_1(T'_1 - T'_2)}$, (b) $\frac{T_2}{T'_2} < \frac{T_1}{T'_1}$

6.28 When the outside temperature is – 10°C, a residential heat pump must provide 3.5×10^6 kJ per day to a dwelling to maintain its temperature at 20°C. If electricity costs Rs. 2.10 per kWh, find the minimum theoretical operating cost for each day of operation.

Ans. Rs. 208.83

UNIT – 5

THEORY QUESTIONS

7.1 Show that through one point there can pass only one reversible adiabatic.
7.2 State and prove Clausius' Theroem.
7.3 Show that entropy is a property of a system.
7.4 How is the entropy change of a reversible process estimated? Will it be different for an irreversible process between the same end states?
7.5 Why is the Carnot cycle on T–s plot a rectangle?
7.6 State the principle of Caratheodory. How is the existence of entropy function inferred?
7.7 Establish the inequality of Clausius.
7.8 Give the criteria of reversibility, irreversiblility and impossibility of a thermodynamic cycle.
7.9 What do you understand by the entropy principle?
7.10 When the system is at equilibrium, why would any conceivable change in entropy be zero?
7.11 Why is the entropy increase of an isolated system a measure of the extent of irreversibility of the process undergone by the system?
7.12 How did Rudolf Clausius summarize the first and second laws of thermodynamics?
7.13 Show that the transfer of heat through a finite temperature difference is irreversible.
7.14 Show that the a diabatic mixing of two fluids is irreversible.
7.15 What is the maxmium work obtainable from two finite bodies at temperatures T_1 and T_2?
7.16 Determine the maximum work obtainable by using one finite body at temperature T and a thermal energy reservoir at temperature T_0, $T > T_0$.
7.17 What are the causes of entropy increase?
7.18 Why is an isentropic process not necessarily an adiabatic process?
7.19 What is the reversible adiabatic work for a steady flow system when K.E. and P.E. changes are negligibly small? How is it different from that for a closed stationary system?
7.20 Under what conditions is the work done equal to (a) $\int p\, dv$, (b) $-\int v\, dp$?

7.21 Why are the equations

$$TdS = dU + pdV$$
$$TdS = dH - Vdp$$

valid for any process between two equilibrium end states?
7.22 Why is the second law called a directional law of nature?
7.23 How is entropy related to molecular disorder in a system?
7.24 Show that entropy varies logarithmically with the disorder number.
7.25 What do you understand by perfect order?

7.26 Give the Nernst-Simon statement of the third law of thermodynamics.
7.27 Why does entropy remain constant in a reversible adiabatic process?
7.28 What do you understand by the postulatory approach of thermodynamics?
7.29 What do you understand by 'lost work'?

7.30 The amount of entropy generation quantifies the intrinsic irreversiblity of a process. Explain.
7.31 Show that S_{gen} is not a thermodynamic property.
7.32 Give the expression for the entropy generation rate for a control volume of a steady flow system.
7.33 What is the entropy generation in the isothermal dissipation of work?
7.34 What is the entropy generation in the adiabatic dissipation of work?
7.35 What do you understand by entropy transfer? Why is entropy transfer associated with heat transfer and not with work transfer?
7.36 What is the relation between probability and uncertainty of an event? How is entropy defined in communication theory?
7.37 State the five characteristics on which the uncertainty of an event depends. What is the expectation value of uncertainty?
7.38 Define information and explain its relation with entropy. What is Shannon's formula?
7.39 What is bias? State and explain the principle of minimum prejudice.
7.40 Explain the procedure of Jaynes' formalism to prove:

$$S = K\lambda + K\beta <V>$$

7.41 Explain how information theory is applied to a system of particles. What is partition function?
7.42 Explain the relation of information theory and classical thermodynamics.
7.43 How do the heat transfer and the lost work affect changes in p_i and hence the entropy of a system?
7.44 Since information theory considers heat and work as derived quantities, show that for a reversible process:

(a) $đ W_r = -\Sigma p_i \, d\varepsilon_i = p \, dV$

(b) $đ Q + [đ W_r - đ W) = \Sigma \varepsilon_i \, dp_i$

(c) $đ Q_r = T dS$

7.45 Explain how entropy is a fundamental concept in information theory and not a derived function as in classical thermodynamics.

NUMERICALS

7.1 On the basis of the first law fill in the blank spaces in the following table of imaginary heat engine cycles. On the basis of the second law classify each cycle as reversible, irreversible, or impossible.

Cycle	Temperature Source	Temperature Sink	Rate of Heat Flow Supply	Rate of Heat Flow Rejection	Rate of work output	Efficiency
(a)	327°C	27°C	420 kJ/s	230 kJ/s	...kW	
(b)	1000°C	100°C	...kJ/min	4.2 MJ/min	...kW	65%
(c)	750 K	300 K	...kJ/s	...kJ/s	26 kW	60%
(d)	700 K	300 K	3 kW	...kW	2 kW	-

7.2 The latent heat of fusion of water at 0°C is 335 kJ/kg. How much does the entropy of 1 kg of ice change as it melts into water in each of the following ways:

(a) Heat is supplied reversibly to a mixture of ice and water at 0°C. (b) A mixture of ice and water at 0°C is stirred by a paddle wheel.

7.3 Two kg of water at 80°C are mixed adiabatically with 3 kg of water at 30°C in a constant pressure process of 1 atmosphere. Find the increase in the entropy of the total mass of water due to the mixing process (c_p of water = 4.187 kJ/kg K).

Ans. 0.0592 kJ/K

7.4 In a Carnot cycle, heat is supplied at 350°C and rejected at 27°C. The working fluid is water which, while receiving heat, evaporates from liquid at 350°C to steam at 350°C. The associated entropy change is 1.44 kJ/kg K. (a) If the cycle operates on a stationary mass of 1 kg of water, how much is the work done per cycle, and how much is the heat supplied? (b) If the cycle operates in steady flow with a power output of 20kW, what is the steam flow rate?

Ans. (a) 465.12, 897.12 kJ/kg, (b) 0.043 kg/s

7.5 A heat engine receives reversibly 420 kJ/cycle of heat from a source at 327°C, and rejects heat reversibly to sink at 27°C. There are no other heat transfers. For each of the three hypothetical amounts of heat rejected, in (a), (b), and (c) below, compute the cyclic integral of $đQ/T$. From these results show which case is irreversible, which reversible, and which impossible: (a) 210 kJ/cycle rejected, (b) 105 kJ/cycle rejected, (c) 315 kJ/cycle rejected.

Ans. (a) Reversible, (b) Impossible, (c) Irreversible

7.6 In Fig. P.7.6, *abcd* represents a Carnot cycle bounded by two reversible adiabatics and two reversible isotherms at temperatures T_1 and T_2 ($T_1 > T_2$). The oval figure is a reversible cycle, where heat is absorbed at temperatures less than, or equal to, T_1, and rejected at temperatures greater than, or equal to, T_2. Prove that the efficiency of the oval cycle is less than that of the Carnot cycle.

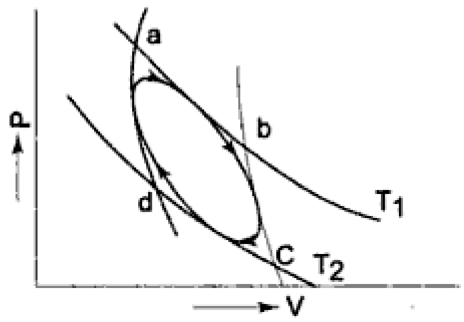

Fig. P. 7.6

7.7 Water is heated at a constant pressure of 0.7 MPa. The boling pointis 164.97°C. The initial temperature of water is 0°C. The latent heat of evaporation is 2066.3 kJ/kg. Find the increase of entropy of water, if the final state is steam.

Ans. 6.6967 kJ/kg K

7.8 One kg of air initially at 0.7 MPa, 20°C changes to 0.35 MPa, 60°C by the three reversible non-flow processes, as shown in Fig. P. 7.8. Process 1-*a*-2 consists of a constant pressure expansion followed by a constant volume cooling, process 1-*b*-2 an isothermal expansion followed by a constant pressure expansion, and process 1-*c*-2 an adiabatic expansion followed by a constant volume heating. Determine the changes of internal energy, enthalpy, and entropy for each process, and find the work transfer and heat transfer for each process. Takes c_p = 1.005 and c_v = 0.718 kJ/kg, K and assume the specific heats to be constant. Also assume for air pv = 0.287 T, where p is the pressure in kPa, v the specific volume in m^3/kg, and T the temperature in K.

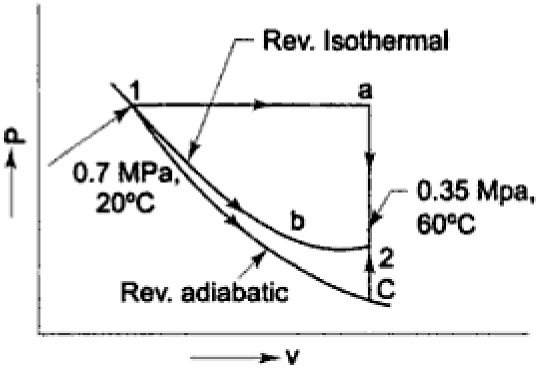

Fig. P. 7.8

7.9 Ten grammes of water at 20°C is converted into ice at –10°C at constant atmospheric pressure. Assuming the specific heat of liquid water to remain constant at 4.2 J/gK and that of ice to be half of this value, and taking the latent heat of fusion of ice at 0°C to be 335 J/g, calculate the total entropy change of the system.

Ans. 16.02 J/K

7.10 Calculate the entropy change of the universe as a result of the following processes:

(a) A copper block of 600 g mass and with C_p of 150 J/K at 100°C is placed in a lake at 8°C.

(b) The same block, at 8°C, is dropped from a height of 100 m into the lake.

(c) Two such blocks, at 100 and 0°C, are joined together.

Ans. (a) 6.63 J/K, (b) 2.095 J/K, (c) 3.64 J/K

7.11 A system maintained at constant volume is initially at temperature T_1, and a heat reservoir at the lower temperature T_0 is available. Show that the maximum work recoverable as the system is cooled to T_0 is

$$W = C_v \left[(T_1 - T_0) - T_0 \ln \frac{T_1}{T_0} \right]$$

7.12 A body of finite mass is originally at temperature T_1 which is higher than that of a reservoir at temperature T_2. Suppose an engine operates in a cycle between the body and the reservoir until it lowers the temperature of the body from T_1 to T_2, thus extracting heat Q from the body. If the engine does work W, then it will reject heat $Q–W$ to the reservoir at T_2. Applying the entropy principle, prove that the maximum work obtainable from the engine is

$$W_{(max)} = Q - T_2(S_1 - S_2)$$

where $S_1 - S_2$ is the entropy decrease of the body.

If the body is maintained at constant volume having constant volume heat capacity C_v = 8.4 kJ/K which is independent of temperature, and if T_1 = 373 K and T_2 = 303 K, determine the maximum work obtainable.

Ans. 58.96 kJ

7.13 Each of three identical bodies satisfies the equation $U = CT$, where C is the heat capacity of each of the bodies. Their initial temperatures are 200 K, 250 K, and 540 K. If C = 8.4 kJ/K, what is the maximum amount of work that can be extracted in a process in which these bodies are brought to a final common temperature?

Ans. 756 kJ

7.14 In the temperature range between 0°C and 100°C a particular system maintained at constant volume has a heat capacity.

$$C_v = A + 2BT$$

with A = 0.014 J/K and $B = 4.2 \times 10^{-4}$ J/K^2.

A heat reservoir at 0°C and a reversible work source are available. What is the maximum amount of work that can be transferred to the reversible work source as the system is cooled from 100°C to the temperature of the reservoir?

Ans. 4.508 J

7.15 A reversible engine, as shown in Fig. P. 7.15, during a cycle of operation draws 5 MJ from the 400 K reservoir and does 840 kJ of work. Find the amount and direction of heat interaction with other reservoirs.

Ans. Q_2 = + 4.98 MJ Q_3 = – 0.82 MJ

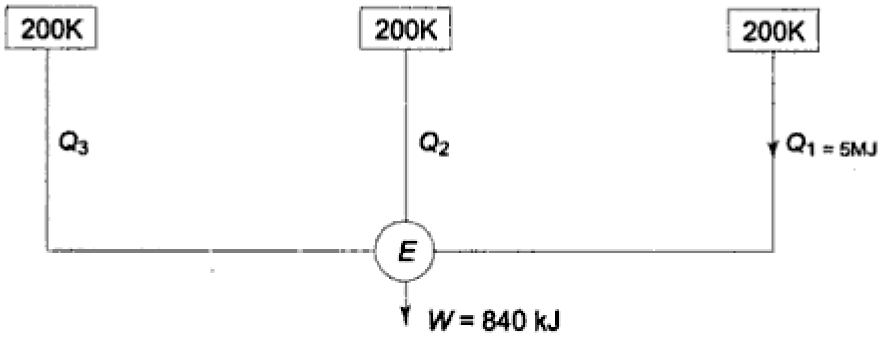

Fig. P. 7.15

7.16 For a fluid for which pv/T is a constant quantity equal to R, show that the change in specific entropy between two states A and B is given by

$$s_B - s_A = \int_{T_A}^{T_B} \frac{c_p}{T} dT - R \ln \frac{p_B}{p_A}$$

A fluid for which R is a constant and equal to 0.287 kJ/kg K, flows steadily through an adiabatic machine, entering and leaving through two adiabatic pipes. In one of these pipes the pressure and temperature are 5 bar and 450 K and in the other pipe the pressure and temperature are 1 bar and 300 K respectively. Determine which pressure and temperature refer to the inlet pipe. For the given temperature range, c_p is given by

$$c_p = a \ln T + b$$

where T is the numerical value of the absolute temperature and $a = 0.026$ kJ/kg K, $b = 0.86$ kJ/kg K.

Ans. $s_B - s_A = 0.0509$ kJ/kg K, A is the inlet pipe

7.17 Two vessels, A and B, each of volume 3 m^3 may be connected by a tube of negligible volume. Vessel A contains air at 0.7 MPa, 95°C, while vessel B contains air at 0.35 MPa, 205°C. Find the change of entropy when A is connected to B by working from the first principles and assuming the mixing to be complete and adiabatic. For air take the relations as given in Examples. 7.8.

Ans. 0.947 kJ/K

7.18 (a) An aluminium block ($c_p = 400$ J/kg K) with a mass of 5 kg is initially at 40°C in room air at 20°C. It is cooled reversibly by transferring heat to a completely reversible cyclic heat engine until the block reaches 20°C. The 20°C room air serves as a constant temperature sink for the engine. Compute (i) the change in entropy for the block, (ii) the change in entropy for the room air, (iii) the work done by the engine.

(b) If the aluminium block is allowed to cool by natural convection to room air, compute (i) the change in entropy for the block, (ii) the change in entropy for the room air (iii) the net change in entropy for the universe.

Ans. (a) – 134.2 J/K, + 132 J/K, 1306 J, (b) – 132 J/K, + 136.5 J/K, 4.5 J/K

7.19 Two bodies of equal heat capacities C and temperatures T_1 and T_2 form an adiabatically closed system. What will the final temperature be if one lets this system come to equilibrium (a) freely? (b) reversibly? (c) What is the maximum work which can be obtained from this system?

7.20 A resistor of 30 ohms is maintained at a constant temperature of 27°C while a current of 10 amperes is allowed to flow for 1 sec. Determine the entropy change of the resistor and the universe.

Ans. $(\Delta S)_{resistor} = 0$, $(\Delta S)_{univ} = 10$ J/K

If the resistor initially at 27°C is now insulated and the same current is passed for the same time, determine the entropy change of the resistor and the universe. The specific heat of the resistor is 0.9 kJ/kg K and the mass of the resistor is 10 g.

Ans. $(\Delta S)_{univ} = 6.72$ J/K

7.21 An adiabatic vessel contains 2 kg of water at 25°C. By paddle-wheel work transfer, the temperature of water is increased to 30°C. If the specific heat of water is assumed constant at 4.187 kJ/kg K, find the entropy change of the universe.

Ans. 0.139 kJ/K

7.22 A copper rod is of length 1 m and diameter 0.01 m. One end of the rod is at 100°C, and the other at 0°C. The rod is perfectly insulated along its length and the thermal conductivity of copper is 380 W/mK. Calculate the rate of heat transfer along the rod and the rate of entropy production due to irreversibility of this heat transfer.

Ans. 2.985 W, 0.00293 W/K

7.23 A body of constant heat capacity C_p and at a temperature T_i is put in contact with a reservoir at a higher temperature T_f. The pressure remains constant while the body comes to equilibrium with the reservoir. Show that the entropy change of the universe is equal to

$$C_p\left[\frac{T_i - T_f}{T_f} - \ln\left(1 + \frac{T_i - T_f}{T_f}\right)\right]$$

Prove that this entropy change is positive.

Given: $$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots -$$

where $x < 1$.

7.24 An insulated 0.75 kg copper calorimeter can containing 0.2 kg water is in equilibrium at a temperature of 20°C. An experimenter now places 0.05 kg of ice at 0°C in the calorimeter and encloses the latter with a heat insulating shield. (a) When all the ice has melted and equilibrium has been reached, what will be the temperature of water and the can? The specific heat of copper is

0.418 kJ/kg K and the latent heat of fusion of ice is 333 kJ/kg. (b) Compute the entropy increase of the universe resulting from the process. (c) What will be the minimum work needed by a stirrer to bring back the temperature of water to 20°C?

Ans. (a) 4.68°C, (b) 0.00276 kJ/K, (c) 20.84 kJ

7.25 Show that if two bodies of thermal capacities C_1 and C_2 at temperatures T_1 and T_2 are brought to the same temperature T by means of a reversible heat engine, then

$$\ln T = \frac{C_1 \ln T_1 + C_2 \ln T_2}{C_1 + C_2}$$

7.26 Two blocks of metal, each having a mass of 10 kg and a specific heat of 0.4 kJ/kg K, are at a temperature of 40°C. A reversible refrigerator receives heat from one block and rejects heat to the other. Calculate the work required to cause a temperature difference of 100°C between the two blocks.

Ans. 32 kJ

7.27 A block of iron weighing 100 kg and having a temperature of 100°C is immersed in 50 kg of water at a temperature of 20°C. What will be the change of entropy of the combined system of iron and water? Specific heats of iron and water are 0.45 and 4.18 kJ/kg K respectively.

Ans. 1.24 kJ/K

7.28 36 g of water at 30°C are converted into steam at 250°C at constant atmospheric pressure. The specific heat of water is assumed constant at 4.2 J/gK and the latent heat of vaporization at 100°C is 2260 J/g. For water vapour, assume $pV = mRT$ where $R = 0.4619$ kJ/kg K, and

$$\frac{c_p}{R} = a + bT + cT^2, \text{ where } a = 3.634,$$

$$b = 1.195 \times 10^{-3}\ \text{K}^{-1} \text{ and } c = 0.135 \times 10^{-6}\ \text{K}^{-2}$$

Calculate the entropy change of the system.

Ans. 273.1 J/K

7.29 A 50 ohm resistor carrying a constant current of 1 A is kept at a constant temperature of 27°C by a stream of cooling water. In a time interval of 1 s, (a) what is the change in entropy of the resistor? (b) What is the change in entropy of the universe?

Ans. (a) 0, (b) 0.167 J/K

7.30 A lump of ice with a mass of 1.5 kg at an initial temperature of 260 K melts at the pressure of 1 bar as a result of heat transfer from the environment. After some time has elapsed the resulting water attains the temperature of the environment, 293 K. Calculate the entropy production associated with this process. The latent heat of fusion of ice is 333.4 kJ/kg, the specific heats of ice and water are 2.07 and 4.2 kJ/kg K respectively, and ice melts at 273.15 K.

Ans. 0.1514 kJ/K

7.31 An ideal gas is compressed reversibly and adiabatically from state a to state b. It is then heated reversibly at constant volume to state c. After expanding reversibly and adiabatically to state d such that $T_b = T_d$, the gas is again reversibly heated at constant pressure to state e such that $T_e = T_c$. Heat is then rejected reversibly from the gas at constant volume till it returns to state a. Express T_a in terms of T_b and T_c. If $T_b = 555$ K and $T_c = 835$ K, estimate T_a. Take $\gamma = 1.4$.

Ans. $T_a = \dfrac{T_b^{\gamma+1}}{T_c^{\gamma}}$, 313.29 K

7.32 Liquid water of mass 10 kg and temperature 20°C is mixed with 2 kg of ice at -5°C till equilibrium is reached at 1 atm pressure. Find the entropy change of the system. Given: c_p of water = 4.18 kJ/kg K, c_p of ice = 2.09 kJ/kg K and latent heat of fusion of ice = 334 kJ/kg.

Ans. 104.9 J/K

7.33 A thermally insulated 50-ohm resistor carries a current of 1 A for 1 s. The initial temperature of the resistor is 10°C. Its mass is 5 g and its specific heat is 0.85 J/g K. (a) What is the change in entropy of the resistor? (b) What is the change in entropy of the universe?

Ans. (a) 0.173 J/K (b) 0.173 J/K

7.34 The value of c_p for a certain substance can be represented by $c_p = a + bT$. (a) Determine the heat absorbed and the increase in entropy of a mass m of the substance when its temperature is increased at constant pressure from T_1 to T_2. (b) Find the increase in the molal specific entropy of copper, when the temperature is increased at constant pressure from 500 to 1200 K. Given for copper: when $T = 500$ K, $c_p = 25.2 \times 10^3$ and when $T = 1200$ K, $c_p = 30.1 \times 10^3$ J/k mol K.

Ans. (a) $m\left[a(T_2 - T_1) + \dfrac{b}{2}(T_2^2 - T_1^2)\right]$ $m\left[a \ln \dfrac{T_2}{T_1} + b(T_2 - T_1)\right]$

(b) 23.9 kJ/k mol K

7.35 An iron block of unknown mass at 85°C is dropped into an insulated tank that contains 0.1m^3 of water at 20°C. At the same time a paddle-wheel driven by a 200 W motor is activated to stir the water. Thermal equilibrium is established after 20 min when the final temperature is 24°C. Determine the mass of the iron block and the entropy generated during the process.

Ans. 52.2 kg, 1.285 kJ/K

7.36 A piston-cylinder device contains 1.2 kg of nitrogen gas at 120 kPa and 27°C. The gas is now compressed slowly in a polytropic process during which $pV^{1.3}$ = constant. The process ends when the volume is reduced by one-half. Determine the entropy change of nitrogen during this process.

Ans. – 0.0615 kJ/K.

7.37 Air enters a compressor at ambient conditions of 96 kPa and 17°C with a low velocity and exits at 1 MPa, 327°C, and 120 m/s. The compressor is cooled by the ambient air at 17°C at a rate of 1500 kJ/min. The power input to the compressor is 300 kW. Determine (a) the mass flow rate of air and (b) the rate of entropy generation.

Ans. (a) 0.851 kg/s, (b) 0.144 kW/K

7.38 A gearbox operating at steady state receives 0.1 kW along the input shaft and delivers 0.095 kW along the output shaft. The outer surface of the gearbox is at 50°C. For the gearbox, determine (a) the rate of heat transfer, (b) the rate at which entropy is produced.

Ans. (a) – 0.005 kW, (b) 1.54×10^{-5} kW/K

7.39 At steady state, an electric motor develops power along its output shaft at the rate of 2 kW while drawing 20 amperes at 120 volts. The outer surface of the motor is at 50°C. For the motor, determine the rate of heat transfer and the rate of entropy generation.

Ans. – 0.4 kW, 1.24×10^{-3} kW/K

7.40 Show that the minimum theoretical work input required by a refrigeration cycle to bring two finite bodies from the same initial temperature to the final temperatures of T_1 and T_2 ($T_2 < T_1$) is given by

$$W_{min} = mc\,[2(T_1T_2)^{1/2} - T_1 - T_2]$$

7.41 A rigid tank contains an ideal gas at 40°C that is being stirred by a paddle wheel. The paddle wheel does 200 kJ of work on the ideal gas. It is observed that the temperature of the ideal gas remains constant during this process as a result of heat transfer between the system and the surroundings at 25°C. Determine (a) the entropy change of the ideal gas and (b) the total entropy generation.

Ans. (a) 0, (b) 0.671 kJ/K

7.42 A cylindrical rod of length L insulated on its lateral surface is initially in contact at one end with a wall at temperature T_1 and at the other end with a wall at a lower temperature T_2. The temperature within the rod initially varies linearly with position x according to:

$$T(x) = T_1 - \frac{T_1 - T_2}{L}x$$

The rod is insulated on its ends and eventually comes to a final equilibrium state where the temperature is T_f. Evaluate T_f and in terms of T_1 and T_2, and show that the amount of entropy generated is:

$$S_{gen} = mc\left[1 + \ln T_f + \frac{T_2}{T_1 - T_2}\ln T_2 - \frac{T_1}{T_1 - T_2}\ln T_1\right]$$

where c is the specific heat of the rod.

Ans. $T_f = [T_1 + T_2]/2$

7.43 Air flowing through a horizontal, insulated duct was studied by students in a laboratory. One student group measured the pressure, temperature, and velocity at a location in the duct as 0.95 bar, 67°C, 75 m/s. At another location the respective values were found to be 0.8 bar, 22°C, 310 m/s. The group neglected to note the direction of flow, however. Using the known data, determine the direction.

Ans. Flow is from right to left

7.44 Nitrogen gas at 6 bar, 21°C enters an insulated control volume operating at steady state for which $W_{C.V.} = 0$. Half of the nitrogen exits the device at 1 bar, 82°C and the other half exits at 1 bar, – 40°C. The effects of KE and PE are negligible. Employing the ideal gas model, decide whether the device can operate as described.

Ans. Yes, the device can operate as described

UNIT – 6

THEORY QUESTIONS

9.1 What is a pure substance?

9.2 What are saturation states?

9.3 What do you understand by triple point?
Give the pressure and temperature of water at its triple point.

9.4 What is the critical state? Explain the terms critical pressure, critical temperature and critical volume of water?

9.5 What is normal boiling point.

9.6 Draw the phase equilibrium diagram on *p–v* coordinates for a substance which shrinks in volume on melting and then for a substance which expands in volume on melting. Indicate thereon the relevant constant property lines.

9.7 Draw the phase equilibrium diagram for a pure substance on *p–T* coordinates. Why does the fusion line for water have negative slope?

9.8 Draw the phase equilibrium diagram for a pure substance on *T–s* plot with relevant constant property lines.

9.9 Draw the phase equilibrium diagram for a pure substance on *h–s* plot with relevant constant property lines.

9.10 Why do the isobars on Mollier diagram diverge from one another?

9.11 Why do isotherms on Mollier diagram become horizontal in the superheated region at low pressures?

9.12 What do you understand by the degree of superheat and the degree of subcooling?

9.13 What is quality of steam? What are the different methods of measurement of quality?

9.14 Why cannot a throttling calorimeter measure the quality if the steam is very wet? How is the quality measured then?

9.15 What is the principle of operation of an electrical calorimeter?

NUMERICALS

9.1 Complete the following table of properties for 1 kg of water (liquid, vapour or mixture).

	p (bar)	*t* (°C)	*v* (m^3/kg)	*x* (%)	*Super-heat* (°C)	*h* (kJ/kg)	*s* (kJ/kg K)
(a)	–	35	25.22	–	–	–	–
(b)	–	–	0.001044	–	–	419.04	–
(c)	–	212.42	–	90	–	–	–
(d)	1	–	–	–	–	–	6.104
(e)	10	320	–	–	–	–	–
(f)	5	–	0.4646	–	–	–	–
(g)	4	–	0.4400	–	–	–	–
(h)	–	500	–	–	–	3445.3	–
(i)	20	–	–	–	50	–	–
(j)	15	–	–	–	–	–	7.2690

9.2 (a) A rigid vessel of volume 0.86 m^3 contains 1 kg of steam at a pressure of 2 bar. Evaluate the specific volume, temperature, dryness fraction, internal energy, enthalpy, and entropy of steam.

(b) The steam is heated to raise its temperature to 150°C. Show the process on a sketch of the *p–v* diagram, and evaluate the pressure, increase in enthalpy, increase in internal energy, increase in entropy of steam, and the heat transfer. Evaluate also the pressure at which the steam becomes dry saturated.

Ans. (a) 0.86 m^3/kg, 120.23°C, 0.97, 2468.54 kJ/kg, 2640.54 kJ/kg, 6.9592 kJ/kg K

(b) 2.3 bar, 126 kJ/kg, 106.6 kJ/kg, 0.2598 kJ/kg K, 106.6 kJ/K

9.3 Ten kg of water at 45°C is heated at a constant pressure of 10 bar until it becomes superheated vapour at 300°C. Find the changes in volume, enthalpy, internal energy and entropy.

Ans. 2.569 m^3, 28627.5 kJ, 26047.6 kJ, 64.842 kJ/K

9.4 Water at 40°C is continuously sprayed into a pipeline carrying 5 tonnes of steam at 5 bar, 300°C per hour. At a section downstream where the pressure is 3 bar, the quality is to be 95%. Find the rate of water spray in kg/h.

Ans. 912.67 kg/h

9.5 A rigid vessel contains 1 kg of a mixture of saturated water and saturated steam at a pressure of 0.15 MPa. When the mixture is heated, the state passes through the critical point. Determine (a) the volume of vessel (b) the mass of liquid and of vapour in the vessel initially, (c) the temperature of the mixture when the pressure has risen to 3 MPa, and (d) the heat transfer required to produce the final state (c).

Ans. (a) 0.003155 m^3, (b) 0.9982 kg, 0.0018 kg, (c) 233.9°C, (d) 581.46 kJ/kg

9.6 A rigid closed tank of volume 3 m^3 contains 5 kg of wet steam at a pressure of 200 kPa. The tank is heated until the steam becomes dry saturated. Determine the final pressure and the heat transfer to the tank.

Ans. 304 kPa, 3346 kJ

9.7 Steam flows through a small turbine at the rate of 5000 kg/h entering at 15 bar, 300°C and leaving at 0.1 bar with 4% moisture. The steam enters at 80 m/s at a point 3 m above the discharge and leaves at 40 m/s. Compute the shaft power assuming that the device is adiabatic but considering kinetic and potential energy changes. How much error would be made if these terms were neglected? Calculate the diameters of the inlet and discharge tubes.

Ans. 765.6 kW, 0.44%, 6.11 cm, 78.9 cm

9.8 A sample of steam from a boiler drum at 3 MPa is put through a throttling calorimeter in which the pressure and temperature are found to be 0.1 MPa, 120°C. Find the quality of the sample taken from the boiler.

Ans. 0.951

9.9 It is desired to measure the quality of wet steam at 0.5 MPa. The quality of steam is expected to be not more than 0.9.

(a) Explain why a throttling calorimeter to atmospheric pressure will not serve the purpose.

(b) Will the use of a separating calorimeter, ahead of the throttling calorimeter, serve the purpose, if at best 5 C degree of superheat is desirable at the end of throttling? What is the minimum dryness fraction required at the exit of the separating calorimeter to satisfy this condition?

9.10 The following observations were recorded in an experiment with a combined separating and throttling calorimeter:
Pressure in the steam main —15 bar
Mass of water drained from the separator —0.55 kg
Mass of steam condensed after passing through the throttle valve —4.20 kg
Pressure and temperature after throttling —1 bar, 120°C
Evaluate the dryness fraction of the steam in the main, and state with reasons, whether the throttling calorimeter alone could have been used for this test.

Ans. 0.85

9.11 Steam from an engine exhaust at 1.25 bar flows steadily through an electric calorimeter and comes out at 1 bar, 130°C. The calorimeter has two 1 kW heaters and the flow is measured to be 3.4 kg in 5 min. Find the quality in the engine exhaust. For the same mass flow and pressures, what is the maximum moisture that can be determined if the outlet temperature is at least 105°C?

Ans. 0.944, 0.921

9.12 Steam expands isentropically in a nozzle from 1 MPa, 250°C to 10 kPa. The steam flow rate is 1 kg/s. Find the velocity of steam at the exit from the nozzle, and the exit area of the nozzle. Neglect the velocity of steam at the inlet to the nozzle.

The exhaust steam from the nozzle flows into a condenser and flows out as saturated water. The cooling water enters the condenser at 25°C and leaves at 35°C. Determine the mass flow rate of cooling water.

Ans. 1224 m/s, 0.0101 m^2, 47.81 kg/s

9.13 A reversible polytropic process, begins with steam at p_1 = 10 bar, t_1 = 200°C, and ends with p_2 = 1 bar. The exponent n has the value 1.15. Find the final specific volume, the final temperature, and the heat transferred per kg of fluid.

9.14 Two streams of steam, one at 2 MPa, 300°C and the other at 2 MPa, 400°C, mix in a steady flow adiabatic process. The rates of flow of the two streams are 3 kg/min and 2 kg/min respectively. Evaluate the final temperature of the emerging stream, if there is no pressure drop due to the mixing process. What would be the rate of increase in the entropy of the universe? This stream with a negligible velocity now expands adiabatically in a nozzle to a pressure of 1 kPa. Determine the exit velocity of the stream and the exit area of the nozzle.

Ans. 340°C, 0.042 kJ/K min, 1530 m/s, 53.77 cm^2

9.15 Boiler steam at 8 bar, 250°C, reaches the engine control valve through a pipeline at 7 bar, 200°C. It is throttled to 5 bar before expanding in the engine to 0.1 bar, 0.9 dry. Determine per kg of steam (a) the heat loss in the pipeline, (b) the temperature drop in passing through the throttle valve, (c) the work output of the engine, (d) the entropy change due to throttling and (e) the entropy change in passing through the engine.

Ans. (a) 105.3 kJ/kg, (b) 5°C, (c) 499.35 kJ/kg, (d) 0.1433 kJ/kg K, (e) 0.3657 kJ/kg K

9.16 Tank *A* (Fig. P 9.16) has a volume of 0.1 m^3 and contains steam at 200°C, 10% liquid and 90% vapour by volume, while tank *B* is evacuated. The valve is then opened, and the tanks eventually come to the same pressure, which is found to be

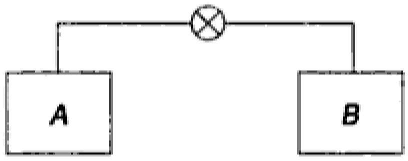

Fig. P 9.16

4 bar. During this process, heat is transferred such that the steam remains at 200°C. What is the volume of tank *B*?

Ans. 4.89 m^3

9.17 Calculate the amount of heat which enters or leaves 1 kg of steam initially at 0.5 MPa and 250°C, when it undergoes the following processes:

(a) It is confined by a piston in a cylinder and is compressed to 1 MPa and 300°C as the piston does 200 kJ of work on the steam.

(b) It passes in steady flow through a device and leaves at 1 MPa and 300°C while, per kg of steam flowing through it, a shaft puts in 200 kJ of work. Changes in K.E. and P.E. are negligible.

(c) It flows into an evacuated rigid container from a large source which is maintained at the initial condition of the steam. Then 200 kJ of shaft work is transferred to the steam, so that its final condition is 1 MPa and 300°C.

Ans. (a) – 130 kJ (b) – 109 kJ, and (c) – 367 kJ

9.18 A sample of wet steam from a steam main flows steadily through a partially open valve into a pipeline in which is fitted an electric coil. The valve and the pipeline are well insulated. The steam mass flow rates 0.008 kg/s while the coil takes 3.91 amperes at 230 volts. The main pressure is 4 bar, and the pressure and temperature of the steam downstream of the coil are 2 bar and 160°C respectively. Steam velocities may be assumed to be negligible.

(a) Evaluate the quality of steam in the main.

(b) State, with reasons, whether an insulated throttling calorimeter could be used for this test.

Ans. (a) 0.97, (b) not suitable

9.19 Two insulated tanks, A and B, are connected by a valve. Tank A has a volume of 0.70 m^3 and contains steam at 1.5 bar, 200°C. Tank B has a volume of 0.35 m^3 and contains steam at 6 bar with a quality of 90%. The valve is then opened, and the two tanks come to a uniform state. If there is no heat transfer during the process, what is the final pressure? Compute the entropy change of the universe.

Ans. 322.6 kPa, 0.1985 kJ/K

9.20 A spherical aluminium vessel has an inside diameter of 0.3 m and a 0.62 cm thick wall. The vessel contains water at 25°C with a quality of 1%. The vessel is then heated until the water inside is saturated vapour. Considering the vessel and water together as a system, calculate the heat transfer during this process. The density of aluminium is 2.7 g/cm^3 and its specific heat is 0.896 kJ/kg K.

Ans. 2682.82 kJ

9.21 Steam at 10 bar, 250°C flowing with negligible velocity at the rate of 3 kg/min mixes adiabatically with steam at 10 Bar, 0.75 quality, flowing also with negligible velocity at the rate of 5 kg/min. The combined stream of steam is throttled to 5 bar and then expanded isentropically in a nozzle to 2 bar. Determine (a) the state of steam after mixing, (b) the steam after throttling, (c) the increase in entropy due to throttling, (d) the velocity of steam at the exit from the nozzle, and (e) the exit area of the nozzle. Neglect the K.E. of steam at the inlet to the nozzle.

Ans. (a) 10 bar, 0.975 dry, (b) 5 bar, 0.894 dry, (c) 0.2669 kJ/kg K, (d) 540 m/s, (e) 1.864 cm^2

9.22 Steam of 65 bar, 400°C leaves the boiler to enter a steam turbine fitted with a throttle governor. At a reduced load, as the governor takes action, the pressure of steam is reduced to 59 bar by throttling before it is admitted to the turbine. Evaluate the availabilities of steam before and after the throttling process and the irreversibility due to it.

9.23 A mass of wet steam at temperature 165°C is expanded at constant quality 0.8 to pressure 3 bar. It is then heated at constant pressure to a degree of superheat of 66.5°C. Find the enthalpy and entropy changes during expansion and during heating. Draw the T–s and h–s diagrams.

Ans. – 59 kJ/kg, 0.163 kJ/kg K during expansion and 676 kJ/kg, 1.588 kJ/kg K during heating

9.24 Steam enters a turbine at a pressure of 100 bar and a temperature of 400°C. At the exit of the turbine the pressure is 1 bar and the entropy is 0.6 J/g K greater than that at inlet. The process is adiabatic and changes in KE and PE may be neglected. Find the work done by the steam in J/g. What is the mass flow rate of steam required to produce a power output of 1 kW?

Ans. 625 J/g, 1.6 kg/s

9.25 One kg of steam in a closed system undergoes a thermodynamic cycle composed the following reversible processes: (1–2) The steam initially at 10 bar, 40% quality is heated at constant volume until the pressure rises to 35 bar; (2–3). It is then expanded isothermally to 10 bar; (3–1) It is finally cooled at constant pressure back to its initial state. Sketch the cycle on *T–s* coordinates, and calculate the work done, the heat transferred, and the change of entropy for each of the three processes. What is the thermal efficiency of the cycle?

Ans. 0; 1364 kJ; 2.781 kJ/K, 367.5 kJ; 404.6 kJ; 0.639 kJ/K; – 209.1 kJ; – 1611 kJ; – 3.419 kJ/K 8.93%

9.26 Determine the exergy per unit mass for the steady flow of each of the following:

(a) steam at 1.5 MPa, 500°C
(b) air at 1.5 MPa, 500°C
(c) water at 4 MPa, 300 K
(d) air at 4 MPa, 300 K
(e) air at 1.5 MPa, 300K

Ans. (a) 1220 kJ/kg, (b) 424 kJ/kg, (c) 3.85 kJ/kg; (d) 316 kJ/kg, (e) 232 kJ/kg

9.27 A liquid (c_p = 6 kJ/kg K) is heated at an approximately constant pressure from 298 K to 90°C by passing it through tubes immersed in a furnace. The mass flow rate is 0.2 kg/s. Determine (a) the heating load in kW, (b) the exergy production rate in kW corresponding to the temperature rise of the fluid.

Ans. (a) 78 kW, (b) 7.44 kW

9.28 A flow of hot water at 80°C is used to heat cold water from 20°C to 45°C in a heat exchanger. The cold water flows at the rate of 2 kg/s. When operated in parallel mode, the exit temperature of hot water stream cannot be less than 55°C, while in the counterflow mode, it can be as low as 30°C. Assuming the surroundings are at 300 K, compare the second law efficiencies for the two modes of operation.

9.29 Water at 90°C is flowing in a pipe. The pressure of the water is 3 bar, the mass flow rate is 10 kg/s, the velocity is 0.5 m/s and the elevation of the pipe is 200 m above the exit plane of the pipeline (ground level). Compute (a) the thermal exergy flux, (b) the pressure exergy flux, (c) the exergy flux from KE, (d) the exergy flux from PE, (e) total exergy flux of the stream.

Ans. (a) 260 kW, (b) 2.07 kW, (c) 1.25×10^{-3} kW, (d) 19.6 kW, (e) 282 kW

9.30 A cylinder fitted with a piston contains 2 kg steam at 500 kPa, 400°C. Find the entropy change and the work done when the steam expands to a final pressure of 200 kPa in each of the following ways: (a) adiabatically and reversibly, (b) adiabatically and irreversibly to an equilibrium temperature of 300°C.

Ans. (a) 0, 386.7 kJ, (b) 0.1976 kJ/K, 309.4 kJ

9.31 Steam expands isentropically in a nozzle from 1 MPa, 250°C to 10 kPa. The steam flow rate is 1 kg/s. Neglecting the KE of steam at inlet to the nozzle, find the velocity of steam at exit from the nozzle and the exit area of the nozzle.

Ans. 1223 m/s, 100 cm^2

9.32 Hot helium gas at 800°C is supplied to a steam generator and is cooled to 450°C while serving as a heat source for the generation of steam. Water enters the steam generator at 200 bar, 250°C and leaves as superheated steam at 200 bar, 500°C. The temperature of the surroundings is 27°C. For 1 kg helium, determine (a) the maximum work that could be produced by the heat removed from helium, (b) the mass of steam generated per kg of helium, (c) the actual work done in the steam cycle per kg of helium, (d) the net change for entropy of the universe, and (e) the irreversibility. Take the average c_p for helium as 5.1926 kJ/kg K and the properties of water at inlet to the steam generator as those of saturated water at 250°C.

Ans. (a) 1202.4 kJ/kg He, (b) 0.844 kg H_2O/kg He (c) 969.9 kJ/kg He, (d) 0.775 kJ/(kg He-K), (e) 232.5 kJ/kg He

UNIT – 7

THEORY QUESTIONS

11.1 What is the condition for exact differential?

11.2 Derive Maxwell's equations.

11.3 Write down the first and second TdS equations, and derive the expression for the difference in heat capacities, C_p and C_v. What does the expression signify?

11.4 Define volume expansivity and isothermal compressibility.

11.5 Show that the slope of an isentrope is greater than that of an isotherm on p–v plot. How is it meaningful for estimating the work of compression?

11.6 What is the energy equation? How does this equation lead to the derivation of the Stefan-Boltzman law of thermal radiation?

11.7 Show that the internal energy and enthalpy of an ideal gas are functions of temperature only.

11.8 Why are $dU = C_v \, dT$ and $dH = C_p \, dT$ true for an ideal gas in any process, whereas these are true for any other substance only at constant volume and at constant pressure respectively?

11.9 Explain Joule-Kelvin effect. What is inversion temperature?

11.10 What is Joule-Thomson coefficient? Why is it zero for an ideal gas?

11.11 Why does the hydrogen gas need to be precooled before being throttled to get the cooling effect?

11.12 Why does the maximum temperature drop occur if the state before throttling lies on the inversion curve?

11.13 Why does the Gibbs function remain constant during phase transition?

11.14 What are the characteristics of the first order phase transition?

11.15 Write down the representative equation for phase transition. Why does the fusion line for water have negative slope on the p–T diagram?

11.16 Why is the slope of the sublimation curve at the triple point on the p–T diagram greater than that of the vaporization curve at the same point?

11.17 Explain how thermodynamic properties are evaluated from an equation of state.

11.18 Illustrate how enthalpy change and entropy change of a gas can be estimated with the help of an equation of state.

11.19 State the important thermodynamic criteria which an equation of state should satisfy.

11.20 Explain how the Boyle temperature is yielded when:

$$\lim_{p \to 0} (\partial Z/\partial p)_T = 0$$

11.21 What is foldback temperature?

11.22 Show that for an inversion curve $(\partial Z/\partial T)_p = 0$.

11.23 Define chemical potential of a component in terms of U, H, F and G.

11.24 What is the use of the Gibbs entropy equation?

11.25 Explain the significance of the Gibbs-Duhem equation.

11.26 State the conditions of equilibrium of a heterogeneous system.

11.27 What do you understand by phase equilibrium?

11.28 Give the Gibbs phase rule for a nonreactive system. Why is the triple point of a substance nonvariant?

11.29 What are the four types of equilibrium? What is stable equilibrium?

11.30 State the conditions of spontaneous change, equilibrium and criterion of stability for: (a) a system having constant U and V (i.e., isolated), and (b) system having constant T and p.

11.31 What do you understand by neutral and unstable equilibrium?

11.32 What is metastable equilibrium?

11.33 Show that for a system to be stable, these conditions are satisfied

(a) $C_v > 0$ (thermal stability)

(b) $\left(\frac{\partial p}{\partial V}\right)_T < 0$ (mechanical stability)

11.34 How is the third law a fundamental law of nature?

11.35 Explain the phenomenon of adiabatic demagnetisation of a paramagnetic salt.

11.36 How are temperatures near absolute zero estimated?

11.37 Give the Fowler-Guggenheim statement of third law. How is it different from the Nernst-Simon statement of third law? Give the third equivalent statement of the third law.

11.38 State some physical and chemical facts which substantiate the third law.

NUMERICALS

11.1 Derive the following equations

(a) $U = F - T\left(\frac{\partial F}{\partial T}\right)_V = -T^2\left(\frac{\partial F/T}{\partial T}\right)_V$

(b) $C_v = -T\left(\frac{\partial^2 F}{\partial T^2}\right)_v$

(c) $H = G - T\left(\frac{\partial G}{\partial T}\right)_p = -T^2\left(\frac{\partial G/T}{\partial T}\right)_p$

(d) $C_p = -T\left(\frac{\partial^2 G}{\partial T^2}\right)_p$

11.2 (a) Derive the equation

$$\left(\frac{\partial c_v}{\partial v}\right)_T = T\left(\frac{\partial^2 p}{\partial T^2}\right)_V$$

(b) Prove that c_v of an ideal gas is a function of T only.

(c) In the case of a gas obeying the equation of state

$$\frac{pv}{RT} = 1 + \frac{B''}{v}$$

where B'' is a function of T only, show that

$$c_v = -\frac{RT}{v}\frac{d^2}{dT^2}(B'' T) + (c_v)_0$$

where $(c_v)_0$ is the value at very large volumes.

11.3 Derive the third TdS equation

$$TdS = C_v\left(\frac{\partial T}{\partial p}\right)_v dp + C_p\left(\frac{\partial T}{\partial V}\right)_p dV$$

and show that the three TdS equations may be written as

(a) $TdS = C_v\, dT + \frac{\beta T}{k} dV$

(b) $TdS = C_p dT - V\beta T dp$

(c) $TdS = \frac{C_v}{\beta} k\, dp + \frac{C_v}{\beta V} dV$

11.4 Derive the equations

(a) $C_p = T\left(\frac{\partial V}{\partial T}\right)_p\left(\frac{\partial p}{\partial T}\right)_s$

(b) $\left(\frac{\partial p}{\partial T}\right)_s = \frac{C_p}{V\beta T}$

(c) $\frac{(\partial p/\partial T)_s}{(\partial p/\partial T)_v} = \frac{\gamma}{\gamma - 1}$

11.5 Derive the equations

(a) $C_v = -T\left(\frac{\partial p}{\partial T}\right)_v \left(\frac{\partial V}{\partial T}\right)_s$

(b) $\left(\frac{\partial V}{\partial T}\right)_s = -\frac{C_v k}{\beta T}$

(c) $\frac{(\partial V/\partial T)_s}{(\partial V/\partial T)_p} = \frac{1}{1-\gamma}$

11.6 (a) Prove that the slope of a curve on a Mollier diagram representing a reversible isothermal process is equal to

$$T - \frac{1}{\beta}$$

(b) Prove that the slope of a curve on a Mollier diagram representing a reversible isochoric process is equal to

$$T + \frac{\gamma - 1}{\beta}$$

11.7 (a) Show that

$$\mu_J c_p = T^2\left(\frac{\partial V/T}{\partial T}\right)_p$$

For 1 mole of a gas, in the region of moderate pressures, the equation of state may be written as

$$\frac{p\bar{v}}{\bar{R}T} = 1 + B'p + C'p^2$$

where B' and C' are functions of temperature only.

(b) Show that as $p \to 0$

$$\mu_J c_p \to \bar{R}T^2 \frac{dB'}{dT}$$

(c) Show that the equation of the inversion curve is

$$p = -\frac{dB'/dT}{dC'/dT}$$

11.8 Prove the following functional relationship of the reduced properties for the inversion curve of a van der Waals' gas

$$T_r = \frac{3(3v_r - 1)^2}{4v_r^2} \text{ and } p_r = \frac{9(2v_r - 1)}{v_r^2}$$

Hence, show that

$$\frac{\text{Maximum inversion temperature}}{\text{Critical temperature}} = 6.75$$

and

$$\frac{\text{Minimum inversion temperature}}{\text{Critical temperature}} = 0.75$$

11.9 Estimate the maximum inversion temperature of hydrogen if it is assumed to obey the equation of state

$$pV = RT + B_1 p + B_2 p^2 + B_3 p^3 + \dots$$

For hydrogen, $B_1 \times 10^5 = a + 10^{-2}\, bT + 10^2\, c/T$

where $a = 166$, $b = -7.66$, $c = -172.33$

11.10 The vapour pressure of mercury at 399 K and 401 K is found to be 0.988 mm and 1.084 mm of mercury respectively. Calculate the latent heat of vaporization of liquid mercury at 400 K.

Ans. 61,634.96 kJ/kg mol

11.11 In the vicinity of the triple point, the vapour pressure of liquid ammonia (in atmospheres) is represented by

$$\ln p = 15.16 - \frac{3063}{T}$$

This is the equation of the liquid-vapour boundary curve in a p–T diagram. Similarly, the vapour pressure of solid ammonia is

$$\ln p = 18.70 - \frac{3754}{T}$$

(a) What is the temperature and pressure at the triple point?
(b) What are the latent heats of sublimation and vaporization?
(c) What is the latent heat of fusion at the triple point?

Ans. 195.2 K, 0.585 atm., 1498 kJ/kg, 1836 kJ/kg, 338 kJ/kg

11.12 It is found that a certain liquid boils at a temperature of 95°C at the top of a hill, whereas it boils at a temperature of 105°C at the bottom. The latent heat is 4.187 kJ/g mole. What is the approximate height of the hill? Assume $T_0 = 300$ K.

Ans. 394 m

11.13 Show that for an ideal gas in a mixture of ideal gases

$$d\mu_k = \frac{\mu_k - h_k}{T}\, dT + v_k\, dp + RTd \ln x_k$$

11.14 Compute μ_j for a gas whose equation of state is

$$p\,(v - b) = RT$$

Ans. $\mu_J = -\,b/c_p$

11.15 Show that

(a) $$\left(\frac{\partial \beta}{\partial p}\right)_T = -\left(\frac{\partial k}{\partial T}\right)_p$$

(b) $$\left(\frac{\partial u}{\partial p}\right)_T = -T\left(\frac{\partial v}{\partial T}\right)_p - p\left(\frac{\partial v}{\partial p}\right)_T$$

11.16 Two particular systems have the following equations of state

$$\frac{1}{T^{(1)}} = \frac{3}{2}\bar{R}\frac{N^{(1)}}{U^{(1)}} \text{ and } \frac{1}{T^{(2)}} = \frac{5}{2}\bar{R}\frac{N^{(2)}}{U^{(2)}}$$

where $\bar{R} = 8.3143$ kJ/kg mol K. The mole number of the first system is $N^{(1)} = 2$, and that of the second is $N^{(2)} = 3$. The two systems are separated by a diathermal wall, and the total energy in the composite system is 25.120 kJ. What is the internal energy of each system in equilibrium?

Ans. 7.2 kJ, 17.92 kJ

11.17 Two systems with the equations of state given in Problem 11.16 are separated by a diathermal wall. The respective mole numbers are $N^{(1)} = 2$ and $N^{(2)} = 3$. The initial temperatures are $T^{(1)} = 250$ K and $T^{(2)} = 350$ K. What are the values of $U^{(1)}$ and $U^{(2)}$ after equilibrium has been established? What is the equilibrium temperature?

Ans. 8.02 kJ, 20.04 kJ, 321.4 K

11.18 Show that the change in latent heat L with temperature is given by the following relation

$$\left(\frac{dL}{dT}\right) = (C_p''' - C_p'') + \frac{L}{T} - \frac{v'''\beta''' - v''\beta''}{v''' - v''} L$$

11.19 Show that for a van der Waals' gas, the Joule-Thomson coefficient is given by

$$\mu_j = \frac{v}{c_p}\left[\frac{2a(v-b)^2 - RTbv^2}{RTv^3 - 2a(v-b)^2}\right]$$

11.20 At 273.15 K the specific volumes of water and ice are 0.001 and 0.001091 m^3/kg and the latent heat of fusion of ice is 334 kJ/kg. Determine the melting point increase due to increase of pressure by 1 atm (101.325 kPa).

Ans. – 0.00753 K

11.21 Calculate the latent heat of vaporization of steam formed by boiling water under a pressure of 101.325 kPa. At a pressure near this, a rise of temperature of 1 K causes an increase of vapour pressure of 3.62 kPa.

Ans. 2257 kJ/kg

11.22 It is known that radiation exerts a pressure $p = 1/3\ u$, where u is the energy per unit volume.

(a) Show that

$$du = T ds + \frac{1}{V}\left(Ts - \frac{4}{3}u\right)dV$$

where s is the entropy per unit volume.

(b) Assuming u and s as functions of temperature only, show that

(i) $u = As^{4/3}$

(ii) $s = \frac{4}{3}aT^3$

(iii) $u = aT^4$

where A is the constant of integration and $a = 81/256\ A^3$.

(c) Show that the average time radiation remains in a spherical enclosure of radius r is given by

$$t = \frac{4r}{3c}$$

where c is the speed of radiation.

(d) If E_B is the energy emitted per unit area of spherical surface per unit time, show that

$$E_B = \sigma T^4$$

where $\sigma = ac/4$ and T is the temperature of the surface.

11.23 Show that the inversion temperature of a van der Waals' gas is given by $T_i = 2a/bR$.

11.24 Show that:

(a) $$\left(\frac{\partial u}{\partial v}\right)_T = T^2\left(\frac{\partial (p/T)}{\partial T}\right)_v$$

(b) $$\left(\frac{\partial h}{\partial p}\right)_T = -T^2\left(\frac{\partial (v/T)}{\partial T}\right)_p$$

11.25 Show that for a van der Waals' gas at low pressures, a Joule-Thomson expansion from pressure p_1 to p_2 produces a temperature change which can be found from the solution of

$$p_1 - p_2 = \frac{c_p}{b}(T_1 - T_2) + T_i \ln \frac{T_2 - T_i}{T_1 - T_i}$$

where T_i is the inversion temperature.

11.26 Using the Redlich-Kwong equation of state, develop expressions for the changes in entropy and internal energy of a gas in an isothermal process.

Ans. $$(s_2 - s_1)_T = R \ln \frac{v_2 - b}{v_1 - b} + \frac{a}{2bT^{3/2}} \ln\left[\frac{v_2(v_1 + b)}{v_1(v_2 + b)}\right]$$

$$(u_2 - u_1)_T = \frac{a}{2bT^{1/2}} \ln\left[\frac{v_2(v_1 + b)}{v_1(v_2 + b)}\right]$$

11.27 Find the change of entropy of a gas following Clausius equation of state at constant temperature

$$p(v - b) = RT$$

Ans. $R \ln \frac{v_2 - b}{v_1 - b}$

11.28 (a) Show that for a van der Waals' gas

$$\beta = \frac{Rv^2(v-b)}{RTv^3 - 2a(v-b)^2}$$

$$k_T = \frac{v^2(v-b)^2}{RTv^3 - 2a(v-b)^2}$$

(b) What is the value of k_T/β expressed in its simplest form?

(c) What do the above relations become when $a = 0$, $b = 0$ (ideal gas)?

11.29 (a)Show that

(i) $\left(\frac{\partial u}{\partial p}\right)_v = \frac{k}{\beta}\cdot c_v$

(ii) $\left(\frac{\partial u}{\partial v}\right)_p = \frac{c_p}{v_\beta} - p$

(b) Hence show that the slope of a reversible adiabatic process on p–v coordinates is

$$\frac{dp}{dv} = -\frac{\gamma}{kv}$$

where k is the isothermal compressibility.

11.30 According to Berthelot, the temperature effect of the second virial coefficient is given by

$$B'(T) = \frac{b}{T} - \frac{a}{T^3}$$

where a and b are constants. Show that according to Berthelot,

$$T_{inv}/T_B = \sqrt{3}$$

11.31 The following expressions for the equation of state and the specific heat c_p are obeyed by a certain gas:

$$v = \frac{RT}{p} + \alpha T^2 \text{ and } c_p = A + BT + Cp$$

where α, A, B, C are constants. Obtain an expression for (a) the Joule-Thomson coefficient, and (b) the specific heat c_v.

Ans. (a) $\mu_J = \frac{\alpha T^2}{A + BT + Cp}$ (b) $C_v = A + BT + \frac{CRT}{v - \alpha T^2} - R\left(\frac{v + \alpha T^2}{v - \alpha T^2}\right)$

11.32 Determine the maximum Joule-Thomson inversion temperature in terms of the critical temperature T_c predicted by the

(a) van der Waals equation

(b) Redlich-Kwong equation

(c) Dieterici equation

Ans. (a) 6.75 T_c, (b) 5.34 T_c (c) 8T_c

11.33 From the virial form of the equation of state of a gas

$$v = \frac{RT}{p} + RTB'(T) + RTC'(T)_p + \ldots$$

show that the Joule-Thomson coefficient is

$$\mu_J = \frac{RT^2}{c_p}\left[\frac{dB'}{dT} + \frac{dC'}{dT}p + \cdots\right]$$

(b) For a van der Waals gas

$$B'(T) = \frac{bRT - a}{R^2T^2}$$

Show that the limiting value of μ_J at low pressures is

$$\mu_J = \frac{1}{c_p}\left(\frac{2a}{RT} - b\right)$$

11.34 Show that $k_T - k_s = \dfrac{Tv\beta^2}{c_p}$

11.35 For a simple compressible system, show that

(a) $\left[\dfrac{\partial u}{\partial v}\right]_T = T^2\left[\dfrac{\partial p/T}{\partial T}\right]_v$

(b) $\left[\dfrac{\partial h}{\partial p}\right]_T = -T^2\left[\dfrac{\partial v/T}{\partial T}\right]_p$

11.36 The liquid-vapour equilibrium curve for nitrogen over the range from the triple point to the normal boiling point may be expressed by the relation:

$$\log p = A - BT - \frac{C}{T}$$

where p is the vapour pressure in mm Hg, T is the temperature in K, and $A = 7.782$, $B = 0.006265$, and $C = 341.6$.

(a) Derive an expression for the enthalpy of vaporization h_{fg} in terms of A, B, C, T and v_{fg}.

(b) Calculate h_{fg} for nitrogen at 71.9 K with $v_{fg} = 11{,}530$ cm^3/gmol.

Ans. 5,790 J/gmol

11.37 For a gas obeying the van der Waals equation of state, show that:

(a) $c_p - c_v = \dfrac{R}{1 - 2a(v-b)^2/RTv^3}$

(b) $\left[\dfrac{\partial c_v}{\partial v}\right]_T = T\left[\dfrac{\partial^2 p}{\partial T^2}\right]_v = 0$ to prove that c_v is a function of temperature only.

(c) $\left[\dfrac{\partial c_p}{\partial p}\right]_T = -T\left[\dfrac{\partial^2 v}{\partial T^2}\right]_p$

$$= R^2T\left[\frac{2av^{-3} - 6abv^{-4}}{(p - av^{-2} + 2abv^{-3})^3}\right]$$

to prove that c_p for a van der Waals gas is not a function of temperature only.

(d) The relation between T and v is given by:

$T(v-b)^{R/c_v} = \text{constant}$

(e) The relation between p and v is given by:

$$\left[p+\frac{a}{v^2}\right](v-b)^{1+R/c_v} = \text{constant.}$$

11.38 Nitrogen at a pressure of 250 atm and a temperature of 400 K expands reversibly and adiabatically in a turbine to an exhaust pressure of 5 atm. The flow rate is 1 kg/s. Calculate the power output if nitrogen obeys the Redlich-Kwong equation of state. For nitrogen at 1 atm take,

$$c_p = 6.903 - 0.3753 \times 10^{-3}T + 1.930 \times 10^{-6}T^2 - 6.861 \times 10^{-9}T^3$$

where c_p is in cal/gmol-K and T is in K.

For nitrogen, $T_c = 126.2$ K,

$p_c = 33.5$ atm. *Ans.* 272 kW

Hints: See Fig. P-11.34

$h_1 - h_2 = (h_1 - h_4) + (h_4 - h_3) + (h_3 - h_2)$ and

$s_1 - s_2 = 0 = (s_1 - s_4) + (s_4 - s_3) + (s_3 - s_2)$

$a = 15.4 \times 10^6$ atm/K$^{1/2}$ cm^6/(gmol)^2, $b = 26.8$ cm^3/gmol

By trial-and-error, $v_1 = 143$ cm^3/gmol, $v_4 = 32{,}800$ cm^3/gmol

$T_2 = 124$ K, $h_1 - h_2 = 7.61$ kJ/gmol.

UNIT – 8

THEORY QUESTIONS

10.1 What is a mole?

10.2 What is Avogadro's law?

10.3 What is an equation of state?

10.4 What is the fundamental property of gases with respect to the product pv?

10.5 What is universal gas constant?

10.6 Define an ideal gas.

10.7 What is the characteristic gas constant?

10.8 What is Boltzmann constant?

10.9 Why do the specific heats of an ideal gas depend only on the atomic structure of the gas?

10.10 Show that for an ideal gas the internal energy depends only on its temperature.

10.11 Show that the enthalpy of an ideal gas is a function of temperature only.

10.12 Why is there no temperature change when an ideal gas is throttled?

10.13 Show that for an ideal gas, $c_p - c_v = R$.

10.14 Derive the equations used for computing the entropy change of an ideal gas.

10.15 Show that for a reversible adiabatic process executed by an ideal gas, the following relations hold good: (i) pv^γ = constant, (ii) $Tv^{\gamma-1}$ = constant, and (iii) $Tp^{(1-\gamma)/\gamma}$ = constant.

10.16 Express the changes in internal energy and enthalpy of an ideal gas in a reversible adiabatic process in terms of the pressure ratio.

10.17 Derive the expression of work transfer for an ideal gas in a reversible isothermal process.

10.18 What is a polytropic process? What are the relations among p, v and T of an ideal gas in a polytropic process?

10.19 Show that the entropy change between states 1 and 2 in a polytropic process, pv^n = constant, is given by the following relations:

(i) $s_2 - s_1 = \frac{n-\gamma}{(\gamma-1)(n-1)} R \ln \frac{T_2}{T_1}$

(ii) $s_2 - s_1 = \frac{n-\gamma}{n(\gamma-1)} R \ln \frac{p_2}{p_1}$

(iii) $s_2 - s_1 = -\frac{n-\gamma}{\gamma-1} R \ln \frac{v_2}{v_1}$

10.20 What are the expressions of work transfer for an ideal gas in a polytropic process, if the gas is: (i) a closed system, and (ii) a steady flow system?

10.21 Derive the expression of heat transfer for an ideal gas in a polytropic process. What is the polytropic specific heat? What would be the direction of heat transfer if (a) $n > \gamma$, and (b) $n < \gamma$?

10.22 Why is the external work supplied to a compressor equal to $-\int_{p_1}^{p_2} v\,dp$?

10.23 Why does isothermal compression need minimum work and adiabatic compression maximum work?

10.24 What is the advantage of staging the compression process?

10.25 What is meant by perfect intercooling?

10.26 Show that the optimum intermediate pressure of a two-stage reciprocating compressor for minimum work is the geometric mean of the suction and discharge pressures.

10.27 Explain how the use of intermediate pressure for minimum work results in equal pressure ratios in the two stages of compression, equal discharge temperatures, and equal work for the two stages.

10.28 What is the isothermal efficiency of a compressor?

10.29 Define volumetric efficiency of a compressor.

10.30 Why does the volumetric efficiency of a compressor decrease: (a) as the clearance increases for the given pressure ratio, (b) as the pressure ratio increases for the given clearance?

10.31 Write down the van der Waals equation of state. How does it differ from the ideal gas equation of state. What is force of cohesion? What is co-volume?

10.32 What are the two-constant equations of state?

10.33 Give the virial expansions for pv in terms of p and v.

10.34 What are virial coefficients? When do they become zero?

10.35 What is the compressibility factor?
10.36 What are reduced properties?
10.37 What is the generalized compressibility chart?
10.38 What is the law of corresponding states?
10.39 Express the van der Waals constants in terms of critical properties.
10.40 Draw the diagram representing the law of corresponding states in reduced coordinates indicating the isotherms and the liquid and vapour phases.
10.41 Define Boyle temperature? How is it computed?
10.42 State Dalton's law of partial pressures.

10.43 How is the partial pressure in a gas mixture related to the mole fraction?
10.44 How are the characteristic gas constant and the molecular weight of a gas mixture computed?

NUMERICALS

10.1 What is the mass of air contained in a room 6 m × 9 m × 4 m if the pressure is 101.325 kPa and the temperature is 25°C?

Ans. 256 kg

10.2 The usual cooking gas (mostly methane) cyclinder is about 25 cm in diameter and 80 cm in height. It is charged to 12 MPa at room temperature (27°C). (a) Assuming the ideal gas law, find the mass of gas filled in the cyclinder. (b) Explain how the actual cyclinder contains nearly 15 kg of gas. (c) If the cylinder is to be protected against excessive pressure by means of a fusible plug, at what temperature should the plug melt to limit the maximum pressure to 15 MPa?

10.3 A certain gas has $c_p = 0.913$ and $c_v = 0.653$ kJ/kg K. Find the molecular weight and the gas constant R of the gas.

10.4 From an experimental determination the specific heat ratio for acetylene (C_2H_2) is found to 1.26. Find the two specific heats.

10.5 Find the molal specific heats of monatomic, diatomic, and polyatomic gases, if their specific heat ratios are respectively 5/3, 7/5 and 4/3.

10.6 A supply of natural gas is required on a site 800 m above storage level. The gas at – 150°C, 1.1 bar from storage is pumped steadily to a point on the site where its pressure is 1.2 bar, its temperature 15°C, and its flow rate 1000 m^3/hr. If the work transfer to the gas at the pump is 15 kW, find the heat transfer to the gas between the two points. Neglect the change in K.E. and assume that the gas has the properties of methane (CH_4) which may be treated as an ideal gas having $\gamma = 1.33$ ($g = 9.75$ m/s^2).

Ans. 63.9 kW

10.7 A constant volume chamber of 0.3 m^3 capacity contains 1 kg of air at 5°C. Heat is transferred to the air until the temperature is 100°C. Find the work done, the heat transferred, and the changes in internal energy, enthalpy and entropy.

10.8 One kg of air in a closed system, initially at 5°C and occupying 0.3 m^3 volume, undergoes a constant pressure heating process to 100°C. There is no work other than pdv work. Find (a) the work done during the process, (b) the heat transferred, and (c) the entropy change of the gas.

10.9 0.1 m^3 of hydrogen initially at 1.2 MPa, 200°C undergoes a reversible isothermal expansion to 0.1 MPa. Find (a) the work done during the process, (b) the heat transferred, and (c) the entropy change of the gas.

10.10 Air in a closed stationary system expands in a reversible adiabatic process from 0.5 MPA, 15°C to 0.2 MPa. Find the final temperature, and per kg of air, the change in enthalpy, the heat transferred, and the work done.

10.11 If the above process occurs in an open steady from system, find the final temperature, and per kg of air, the change in internal energy, the heat transferred, and the shaft work. Neglect velocity and elevation changes.

10.12 The indicator diagram for a certain water-cooled cyclinder and piston air compressor shows that during compression $pv^{1.3}$ = constant. The compression starts at 100 kPa, 25°C and ends at 600 kPa. If the process is reversible, how much heat is transferred per kg of air?

10.13 An ideal gas of molecular weight 30 and $\gamma = 1.3$ occupies a volume of 1.5 m^3 at 100 kPa and 77°C. The gas is compressed according to the law $pv^{1.25}$ = constant to a pressure of 3 MPa. Calculate the volume and temperature at the end of compression and heating, work done, heat transferred, and the total change of entropy.

10.14 Calculate the change of entropy when 1 kg of air changes from a temperature of 330 K and a volume of 0.15 m^3 to a temperature of 550 K and a volume of 0.6 m^3. If the air expands according to the law, pv^n = constant, between the same end states, calculate the heat given to, or extracted from, the air during the expansion, and show that it is approximately equal to the change of entropy multiplied by the mean absolute temperature.

10.15 0.5 kg of air, initially at 25°C, is heated reversibly at constant pressure until the volume is doubled, and is then heated reversibly at constant volume until the pressure is doubled. For the total path, find the work transfer, the heat transfer, and the change of entropy.

10.16 An ideal gas cycle of three processes uses Argon (Mol. wt. 40) as a working substance. Process 1–2 is a reversible adiabatic expansion from 0.014 m^3, 700 kPa, 280°C to 0.056 m^3. Process 2–3 is a reversible isothermal process. Process 3–1 is a constant pressure process in which heat transfer is zero. Sketch the cycle in the p–v and T–s planes, and find (a) the work transfer in process 1–2, (b) the work transfer in process 2–3, and (c) the net work of the cycle. Take $\gamma = 1.67$.

Ans. (a) 8.85 kJ (b) 8.96 kJ (c) 5.82 kJ

10.17 A gas occupies 0.024 m^3 at 700 kPa and 95°C. It is expanded in the non-flow process according to the law $pv^{1.2}$ = constant to a pressure of 70 kPa after which it is heated at constant pressure back to its original temperature. Sketch the process on the p–v and T–s diagrams, and calculate for the whole process the work done, the heat transferred, and the change of entropy. Take $C_p = 1.047$ and $c_v = 0.775$ kJ/kg K for the gas.

10.18 0.5 kg of air at 600 kPa receives an addition of heat at constant volume so that its temperature rises from 110°C to 650°C. It then expands in a cyclinder polytropically to its original temperature and the index of expansion is 1.32. Finally, it is compressed isothermaly to its original volume. Calculate (a) the change of entropy during each of the three stages, (b) the pressures at the end of constant volume heat addition and at the end of expansion. Sketch the processes on the *p–v* and *T–s* diagrams.

10.19 0.5 kg of helium and 0.5 kg of nitrogen are mixed at 20°C and at a total pressure of 100 kPa. Find (a) the volume of the mixture, (b) the partial volumes of the components, (c) the partial pressures of the components, (d) the mole fractions of the components, (e) the specific heats c_p and c_v of the mixture, and (f) the gas constant of the mixture.

Ans. (a) 3.481 m^3 (b) 3.045, 0.436 m^3 (c) 87.5, 12.5 kPa (d) 0.875, 0.125 (e) 3.11, 1.921 kJ/k (f) 1.189 kJ/kgK.

10.20 A gaseous mixture consists of 1 kg of oxygen and 2 kg of nitrogen at a pressure of 150 kPa and a temperature of 20°C. Determine the changes in internal energy, enthalpy and entropy of the mixture when the mixture is heated to a temperature of 100°C (a) at constant volume, and (b) at constant pressure.

10.21 A closed rigid cyclinder is divided by a diaphragm into two equal compartments, each of volume 0.1 m^3. Each compartment contains air at a temperature of 20°C. The pressure in one compartment is 2.5 MPa and in the other compartment is 1 MPa. The diaphragm is ruptured so that the air in both the compartments mixes to bring the pressure to a uniform value throughout the cylinder which is insulated. Find the net change of entropy for the mixing process.

10.22 A vessel is divided into three compartments (a), (b), and (c) by two partitions. Part (a) contains oxygen and has a volume of 0.1 m^3, (b) has a volume of 0.2 m^3 and contains nitrogen, while (c) is 0.05 m^3 and holds CO_2. All three parts are at a pressure of 2 bar and a temperature of 13°C. When the partitions are removed and the gases mix, determine the change of entropy of each constituent, the final pressure in the vessel and the partial pressure of each gas. The vessel may be taken as being completely isolated from its surroundings.

Ans. 0.0875, 0.0783, 0.0680 kJ/K; 2 bar; 0.5714, 1.1329, 0.2857 bar.