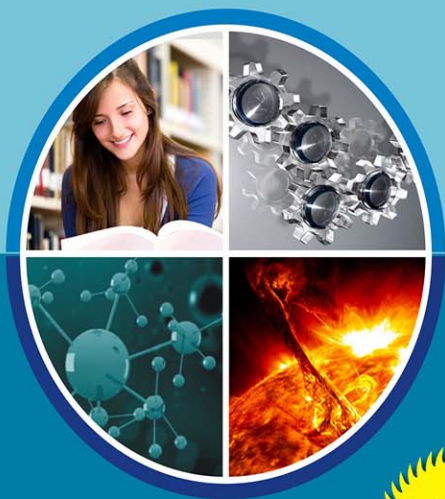


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**Thermodynamics**

**By**

**Sanjay Kumar**



**QUANTUM PAGE PVT. LTD.**  
**Ghaziabad ■ New Delhi**

**PUBLISHED BY :**            **Apram Singh**  
                                      **Quantum Page Pvt. Ltd.**  
                                      Plot No. 59/2/7, Site - 4, Industrial Area,  
                                      Sahibabad, Ghaziabad-201 010

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## RME 302 : THERMODYNAMICS

### **UNIT - 1 : INTRODUCTION**

**(1-1 C to 1-42 C)**

Introduction- Basic Concepts: System, Control Volume, Surrounding, Boundaries, Universe, Types of Systems, Macroscopic and Microscopic viewpoints, Concept of Continuum, Thermodynamic Equilibrium, State, Property, Process, Exact & Inexact Differentials, Cycle Reversibility Quasi-static Process, Irreversible Process, Causes of Irreversibility Energy and its forms, Work and heat (sign convention), Gas laws, Ideal gas, Real gas, Law of corresponding states, Dalton's law, Amagat's law, Property of mixture of gases. Zeroth law of thermodynamics: Concept of Temperature and its' measurement, Temperature scales.

First law of thermodynamics: Thermodynamic definition of work, Displacement work and flow work, Displacement work for various non flow processes, Joules' experiment, First law analysis for closed system (non flow processes), Internal energy and enthalpy. Limitations of first law of thermodynamics, PMM-I. Steady flow systems and their analysis, Steady flow energy equation, Boilers, Condensers, Turbine, Throttling process, Pumps etc. Analysis of unsteady processes such as filling and evacuation of vessels with and without heat transfer.

### **UNIT - 2 : SECOND LAW OF THERMODYNAMICS**

**(2-1 C to 2-47 C)**

Thermal reservoirs, Energy conversion, Heat engines, Efficiency, Reversed heat engine, Heat pump, Refrigerator, Coefficient of Performance, Kelvin Planck and Clausius statement of second law of thermodynamics, Equivalence of the two statements. Reversible and irreversible processes, Carnot cycle and Carnot engine, Carnot theorem and its' corollaries, Thermodynamic Temperature Scale, PMM-II.

Entropy : Clausius inequality, Concept of Entropy, Entropy change of pure substance in different thermodynamic processes, Tds equation, Principle of entropy increase, T-s diagram, Statement of the third law of thermodynamics.

### **UNIT - 3 : AVAILABILITY & IRREVERSIBILITY**

**(3-1 C to 3-23 C)**

Availability and Irreversibility: Available and unavailable energy, Availability and Irreversibility, Second law efficiency, Helmholtz & Gibbs' function.

Thermodynamic relations: Conditions for exact differentials. Maxwell relations, Clapeyron equation, Joule-Thompson coefficient and Inversion curve. Coefficient of volume expansion, Adiabatic and Isothermal compressibility.

### **UNIT - 4 : STEAM & RANKINE CYCLE**

**(4-1 C to 4-41 C)**

Pure substance, Property of Pure Substance (steam), Triple point, Critical point, Saturation states, Sub-cooled liquid state, Superheated vapour state, Phase transformation process of water, Graphical representation of pressure, volume and temperature, P-T, P-V and P-h diagrams, T-S and H-S diagrams, use of property diagram, Steam-Tables & Mollier chart, Dryness factor and its' measurement, processes involving steam in closed and open systems. Simple Rankine cycle.

Psychometric terms and their definitions, Psychometric chart, Different Psychometric processes and their representation on Psychometric chart.

### **UNIT - 5 : REFRIGERATION CYCLES**

**(5-1 C to 5-31 C)**

Reversed Carnot Cycle for gas and vapour. Refrigeration capacity, unit of refrigeration. Air Refrigeration cycles; Reversed Brayton Cycle and Bell Coleman Cycle. Vapour compression refrigeration cycle; simple saturated cycle and actual vapour compression refrigeration cycle. Analysis of cycles, effect of superheating, sub-cooling and change in evaporator and condenser pressure on performance of vapour compression refrigeration cycle. Refrigerants; their classification and desirable properties. Vapour absorption refrigeration system.

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## SEMESTER-III

### THERMODYNAMICS

L-T-P  
3-1-0

#### Objectives:

- To learn about work and heat interactions, and balance of energy between system and its surroundings.
- To learn about application of I law to various energy conversion devices.
- To evaluate the changes in properties of substances in various processes.
- To understand the difference between high grade and low-grade energies and II law limitations on energy conversion.

#### UNIT I

##### Review of Fundamental Concepts and Definitions:

Introduction- Basic Concepts: System, Control Volume, Surrounding, Boundaries, Universe, Types of Systems, Macroscopic and Microscopic viewpoints, Concept of Continuum, Thermodynamic Equilibrium, State, Property, Process, Exact & Inexact Differentials, Cycle Reversibility Quasi – static Process, Irreversible Process, Causes of Irreversibility Energy and its forms, Work and heat (sign convention), Gas laws, Ideal gas, Real gas, Law of corresponding states, Property of mixture of gases, electrical, magnetic, gravitational, spring and shaft work.

**Zeroth law of thermodynamics:** Concept of Temperature and its measurement, Temperature scales.

##### First law of thermodynamics:

First Law for Flow Processes - Derivation of general energy equation for a control volume; Steady state steady flow processes including throttling; Examples of steady flow devices; Unsteady processes; examples of steady and unsteady I law applications for system and control volume. Limitations of first law of thermodynamics, PMM-I. Steady flow systems and their analysis, Steady flow energy equation, Boilers, Condensers, Turbine, Throttling process, Pumps etc.

#### UNIT II

##### Second law of thermodynamics:

Thermal reservoirs, Energy conversion, Heat engines, Efficiency, Reversed heat engine, Heat pump, Refrigerator, Coefficient of Performance, Kelvin Planck and Clausius statement of second law of thermodynamics, Equivalence of the two statements. Reversible and irreversible processes, Carnot cycle and Carnot engine, Carnot theorem and its corollaries, Thermodynamic Temperature Scale, PMM-II.

**Entropy:** Clausius inequality, Concept of Entropy, Entropy change of pure substance in different thermodynamic processes, Tds equation, Principle of entropy increase, T-S diagram, Statement of the third law of thermodynamics.

#### UNIT III

##### Availability and Irreversibility:

Available and unavailable energy, Availability and Irreversibility, Second law efficiency, Helmholtz & Gibbs's function.

##### Thermodynamic relations:

Conditions for exact differentials. Maxwell relations, Clapeyron equation, Joule-Thompson coefficient and Inversion curve. Coefficient of volume expansion, Adiabatic and Isothermal compressibility.

#### UNIT IV

**Properties of steam and Rankine cycle:**

Pure substance, Property of Pure Substance (steam), Triple point, Critical point, Saturation states, Sub-cooled liquid state, Superheated vapour state, Phase transformation process of water, Graphical representation of pressure, volume and temperature, P-T, P-V and P-h diagrams, T-S and H-S diagrams, use of property diagram, Steam-Tables & Mollier chart, Dryness factor and its measurement, processes involving steam in closed and open systems. Simple Rankine cycle.

**Air-water vapour mixture and Psychrometry:** Psychrometric terms and their definitions, Psychrometric chart, Different Psychrometric processes and their representation on Psychrometric chart.

**UNIT V**

**Refrigeration Cycles:**

Reversed Carnot Cycle for gas and vapour. Refrigeration capacity, unit of refrigeration. Air Refrigeration cycles; Reversed Brayton Cycle and Bell Coleman Cycle. Vapour compression refrigeration cycle; simple saturated cycle and actual vapour compression refrigeration cycle. Analysis of cycles, effect of superheating, sub-cooling and change in evaporator and condenser pressure on performance of vapour compression refrigeration cycle. Refrigerants; their classification and desirable properties. Vapour absorption refrigeration system.

**Course Outcomes:**

- After completing this course, the students will be able to apply energy balance to systems and control volumes, in situations involving heat and work interactions.
- Students can evaluate changes in thermodynamic properties of substances.
- The students will be able to evaluate the performance of energy conversion devices.
- The students will be able to differentiate between high grade and low-grade energies.

**Books and References:**

1. Basic and Applied Thermodynamics by PK Nag, MCGRAW HILL INDIA.
2. Thermodynamics for Engineers by Kroos & Potter, Cengage Learning.
3. Thermodynamics by Shavit and Gutfinger, CRC Press.
4. Thermodynamics- An Engineering Approach by Cengel, MCGRAW HILL INDIA.
5. Basic Engineering Thermodynamics, Joel, Pearson.
6. Fundamentals of Engineering Thermodynamics by Rathakrishnan, PHI.
7. Engineering Thermodynamics by Dhar, Elsevier.
8. Engineering Thermodynamics by Onkar Singh, New Age International.
9. Engineering Thermodynamics by CP Arora.
10. Engineering Thermodynamics by Rogers, Pearson.
11. Fundamentals of Engineering Thermodynamics by Moran, Shapiro, Boettner, & Bailey, John Wiley.
12. Engineering Thermodynamics by Mishra, Cengage Learning.
13. Refrigeration and Air Conditioning by C P Arora, MCGRAW HILL INDIA.

## 1

## UNIT

## Introduction

**Part-1 ..... (1-2C to 1-12C)**

- *System*
- *Surrounding*
- *Concept of Continuum*
- *Energy and its Forms*
- *Work and Heat*

A. *Concept Outline : Part-1* ..... 1-2CB. *Long and Medium Answer Type Questions* ..... 1-2C**Part-2 ..... (1-12C to 1-17C)**

- *Gas Laws*
- *Ideal Gas*
- *Property of Mixture of Gases*
- *Real Gas*
- *Dalton's Law*

A. *Concept Outline : Part-2* ..... 1-13CB. *Long and Medium Answer Type Questions* ..... 1-13C**Part-3 ..... (1-18C to 1-21C)**

- *Concept of Temperature and its Measurement*
- *Temperature Scales*

A. *Concept Outline : Part-3* ..... 1-18CB. *Long and Medium Answer Type Questions* ..... 1-18C**Part-4 ..... (1-22C to 1-32C)**

- *Displacement Work and Flow Work*
- *Joule's Experiment*
- *Limitations of First Law of Thermodynamics*

A. *Concept Outline : Part-4* ..... 1-22CB. *Long and Medium Answer Type Questions* ..... 1-22C**Part-5 ..... (1-32C to 1-41C)**

- *Steady State Flow*
- *Steady Flow Energy Equation and its Application*
- *Analysis of Unsteady Flow*

A. *Concept Outline : Part-5* ..... 1-32CB. *Long and Medium Answer Type Questions* ..... 1-32C



**PART- 1**

*Introduction, Basic Concepts : System, Control Volume, Surroundings, Universe, Types of Systems, Macroscopic and Microscopic View Points, Concept of Continuum, Thermodynamic Equilibrium, State, Property, Process, Exact and Inexact Differentials, Cycle Reversibility, Quasi-Static Process, Irreversible Process, Causes of Irreversibility, Energy and its forms, and Work and Heat.*

**CONCEPT OUTLINE : PART-1**

**Microscopic and Macroscopic Approaches :** A thermodynamic study can be conducted at the atomic or molecular level is called microscopic approaches. In contrast, a thermodynamic study on a large assemblage of atoms or molecules is referred to as a macroscopic approach.

**Quasi-Static Process :** Quasi means 'almost'. A quasi-static process is also called a reversible process. This process is a succession of equilibrium states and infinite slowness is its characteristics feature.

**Concept of Continuum :** For a macroscopic analysis, we are concerned with a large number of molecules disregarding the behaviour of an individual molecule and as such matter is here treated as continuous to enable us to investigate the bulk behaviour of a substance.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions**

**Que 1.1.** Write a short note on following :

- System,
- Boundary, and
- Surroundings.

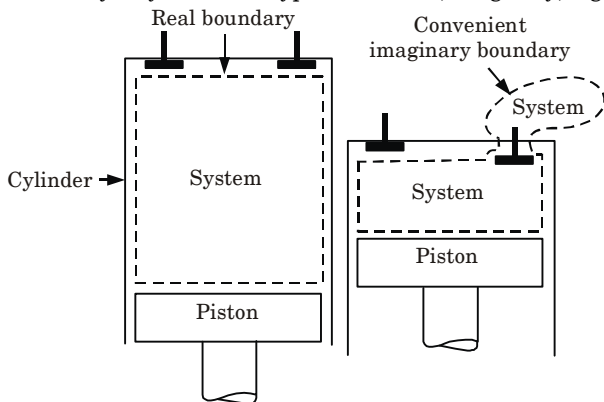
**Answer**

- System :** A system is a finite quantity of matter, or a prescribed region of space, which is under the thermodynamic study.
  - Closed System :** If the system boundary is impervious to the mass flow, it is called a closed system. No mass can flow in or out of the system. Energy, both in form of heat and work can cross the boundary.
  - Open System :** An open system is the one that allows both mass and energy interactions with the surroundings.

**iii. Isolated System :** An isolated system is that system which exchanges neither energy nor mass with the surroundings.

**b. Boundary :**

1. The actual or hypothetical envelope enclosing a system is the boundary of the system.
2. The boundary may be real or hypothetical (*i.e.*, imaginary, Fig. 1.1.1).



**Fig. 1.1.1.** A system boundary may be real or imaginary.

3. It may be rigid or it may move (e.g., as and when a system containing a gas is compressed or expanded).
- c. Surroundings :** Anything outside the system boundary is termed as surroundings.

$$\text{Universe} = \text{Systems} + \text{Surroundings}$$

**Que 1.2.** What do you mean by control volume ? Also discuss about macroscopic and microscopic approaches.

**Answer**

**A. Control Volume :**

1. If the volume of a system under study remains constant, then the volume is called the control volume (CV). The control volume is bounded by the control surface (CS).
2. Various masses and energies can be investigated as they cross the control surface into, or out of, the control volume.
3. Thus the control volume is similar in concept to the open system. Hence, the boundary of the open system is known as the control volume.

**B. Macroscopic and Microscopic Approaches :**

1. A thermodynamic study can be conducted at the atomic or molecular level. For example, we can consider fusion of four hydrogen nuclei (protons) into a helium nucleus. This is a microscopic approach.

2. In contrast, a thermodynamic study on a large assemblage of atoms or molecules is referred to as a macroscopic approach.

**Que 1.3. Distinguish between microscopic and macroscopic approaches of thermodynamics.**

**AKTU 2013-14, Marks 10**

**Answer**

S. No.	Macroscopic Approach	Microscopic Approach
1.	It is used in classical thermodynamics.	It is used in statistical thermodynamics.
2.	System is considered as continuum. <i>i.e.</i> , continuous distribution of matter without cavities or voids.	System is considered to contain a large number of molecules moving randomly.
3.	Properties of system are their average values. Changes can be sensed by human. <i>e.g.</i> , pressure, temperature etc.	Properties are defined for each molecule individually. (Properties like velocity, momentum, kinetic energy which describe a molecule) changes in it cannot be sensed by human.
4.	Few properties are required to describe the system.	Large number of variables is required to describe the system.

**Que 1.4. Describe thermodynamic equilibrium of a system.**

**AKTU 2011-12, Marks 3.5**

**Answer**

**A. Thermodynamic Equilibrium :**

- A system is said to exist in a state of thermodynamic equilibrium when no spontaneous change in any macroscopic property is registered, if the system is isolated from its surroundings.  
“If the system exists in equilibrium state, there can be no spontaneous change in any macroscopic property of the system”.
- A system will be in thermodynamic equilibrium, if following three types of equilibrium are satisfied.

**a. Mechanical Equilibrium :**

- System is in mechanical equilibrium if there is no unbalanced force (pressure forces) within the system and also between system and its surroundings.

**b. Chemical Equilibrium :**

1. If there is no chemical reaction, or transfer of matter from one part of system to another, (such as diffusion or solution), system is in chemical equilibrium.

**c. Thermal Equilibrium :**

1. Condition or state in which the temperature of system is uniform.

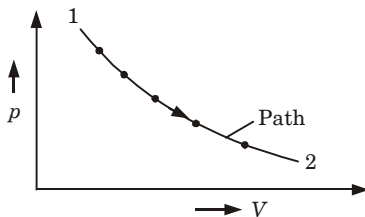
**Que 1.5.** Define the following : thermodynamic properties, path, process, open system, continuum.

**AKTU 2011-12, Marks 3.5**

**Answer****A. Thermodynamic Properties :**

1. Every system has certain characteristics by which its physical condition may be described e.g., volume, temperature, pressure etc. Such characteristics are called properties of the system. They are macroscopic in nature.
2. In other words, "properties are the coordinates to describe the state of a system".
3. There are two types of thermodynamic properties :
  - a. Intensive Property :** These are independent of mass and size of system. e.g., pressure, density, temperature.
  - b. Extensive Property :** These properties depend on mass and size of system. e.g., volume, energy, entropy.

**B. Path :** Succession of states passed through during a change of state is called 'path' of the change of state.



**Fig. 1.5.1.**

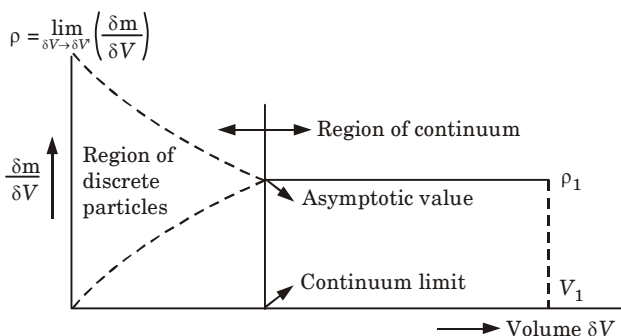
**C. Process :**

1. When the path is completely specified, the change of state is called 'process'.
2. In other words, "A process is the cause of change of state of a system". e.g. Isothermal expansion, Isochoric, Isobaric etc.

**D. Open System :** Refer Q. 1.1, Page 1-2C, Unit-1.

**E. Concept of Continuum :**

1. According to this concept, there is a minimum limit of volume upto which properties of the systems will remain in continuum. But below this volume, there is an abrupt change in the value of property.
2. Such a region where properties remain in continuum is known as “region of continuum” and region in which properties change abruptly is called “region of discrete particles”.
3. Limiting volume upto which continuum properties are maintained is called “continuum limit”.
4. According to “concept of continuum” density can be defined as

**Fig. 1.5.2.**

**Que 1.6.** Explain the reversible and irreversible processes.

**AKTU 2014-15, Marks 03**

**Answer**

**A. Reversible Process :**

1. A process is called reversible if after the conclusion of reversed process the initial states of system and surroundings are restored without any extraordinary changes either in the system or surroundings.
2. A reversible process is a quasi-static process, a process carried out infinitely slowly with infinitesimal gradient with the system passing through a series of equilibrium states.
3. Consider a process in which the system undergoes a change of state 1 to state 2 and during the process, system does work ‘W’ and it transfers heat ‘Q’ to the surroundings.
4. If at the completion of its reverse process, *i.e.*, from state ‘2’ to state ‘1’ and the system is restored to its initial state then the work ‘W’ must be done on the system and the heat Q must be transferred from the

surroundings to the system so that there may be no outstanding changes either in the system or in the surroundings.

5. After the completion of reversed process no traces will be left in the universe and such a process is referred to as reversible process.

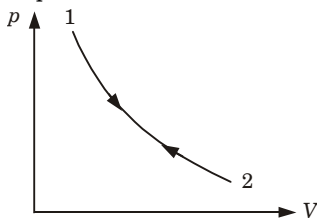


Fig. 1.6.1. Reversible process.

### B. Irreversible Process :

1. A process is called irreversible if the initial state of the system cannot be restored without any changes either in the system or surroundings.
2. It can be observed from the consequence of second law of thermodynamics that all the natural processes are irreversible because the available work energy either of the system or the surroundings is converted into heat energy at the completion of reversed process which is an undesirable or outstanding change from the view point of second law of thermodynamics.

a. **Types of Irreversibility :** Followings are various types of irreversibility :

#### i. External Irreversibility :

1. It is due to dissipative effects like mechanical friction, viscosity, surface tension, magnetism etc.
2. It is due to finite temperature difference.

ii. **Internal Irreversibility :** It is related with dissipative effects within the working substance, e.g., free expansion, throttling etc.

**Que 1.7.**

**What do you understand by cyclic and quasi-static process ? Differentiate between point functions and path functions.**

**AKTU 2012-13, Marks 05**

**Answer**

### A. Cyclic Process :

1. A thermodynamic cycle is defined as a series of state changes such that the final state is identical with the initial state.
2. The processes through which the system has passed can be shown on a state diagram, but a complete section of the path requires in addition a statement of the heat and work crossing the boundary of the system.

3. Fig. 1.7.1, shows such a cycle in which a system commencing at condition '1' changes in pressure and volume through a path 1-3-2 and returns to its initial condition '1'.

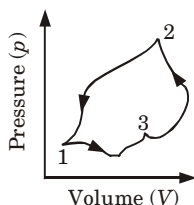


Fig. 1.7.1.

### B. Quasi-Static Process :

1. It is a succession of equilibrium states, "A process is called quasi-static if it is carried out in such a way that at every instant the system departs only infinitesimally from previous thermodynamic equilibrium state".
2. Only a quasi-static process can be reversible and can be represented on a thermodynamic plane.

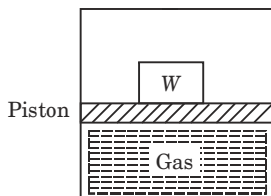


Fig. 1.7.2.

3. Consider a gas contained in piston-cylinder assembly. System is initially in equilibrium state  $(p_1, V_1, T_1)$ .

**Case I :** Whole weight is removed in one step. In this case, intermediate states passed through by system are non-equilibrium states.

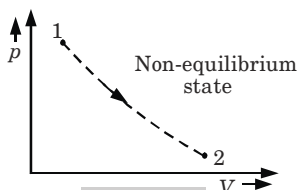


Fig. 1.7.3.

**Case II :** Weight is removed in steps. Now every state passed by system will be an equilibrium state as shown on  $p$ - $V$  coordinate.

"Such a process which is locus of all equilibrium points passed through by system is called quasi-state process".

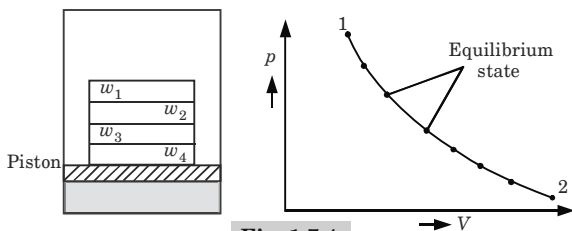


Fig. 1.7.4.

### C. Difference between Point Function and Path Function :

S.No.	Point Function	Path Function
1.	Point function are those function which depend upon the initial and final point of the curve. If their path is changed keeping the initial and final point same, their value will not change.	Path function are those functions whose value depends upon the path traced by them. If their path is changed keeping the initial and final point same, their value will change.
2.	<b>Example :</b> Pressure, temperature, volume etc.	<b>Example :</b> Heat, work etc.
3.	These are exact differentials <i>i.e.</i> , $\int_1^2 dV = V_2 - V_1$	These are not exact differentials <i>i.e.</i> , $\int_1^2 \delta W \neq W_2 - W_1$

**Que 1.8.** Explain point function and path function.

**Answer**

#### A. Point (state) Function :

1. Thermodynamic properties are the point functions for a given state where there is one and only one value for each property.
2. As such, any two thermodynamic properties locate a point on the graph as and when a change of state is represented graphically by means of any two thermodynamic parameters.
3. When a change of state occurs, thermodynamic properties of a system undergo change and their values depend only on the initial and final states of the system.
4. For example



$$\int_1^2 dV = V_2 - V_1$$

$$\int_1^2 dP = P_2 - P_1$$

$$\int_1^2 dT = T_2 - T_1$$

Point functions are also called as state functions.

5. They are exact differentials.

$$\text{If } z = f(x, y), \text{ then } dz = \left[ \frac{\partial z}{\partial x} \right] dx + \left[ \frac{\partial z}{\partial y} \right] dy$$

Now, if  $z$  is an exact (*i.e.*, perfect) differential, then

$$\frac{\partial^2 z}{\partial x \partial y} = \frac{\partial^2 z}{\partial y \partial x}$$

### B. Path Function :

1. There are certain quantities which cannot be located on a graph by a point but are given by the area under the graph. Such quantities are called path functions. Examples of path functions are heat and work.
2. They are inexact differentials because their change cannot be written as the difference of their values at the end states.

3. That is,  $\int_1^2 \delta Q \neq Q_2 - Q_1$ , but  ${}_1Q_2$  or  $Q_{1-2}$

$$\int_1^2 \delta W \neq W_2 - W_1, \text{ but } {}_1W_2 \text{ or } W_{1-2}$$

which indicated the change in  $Q$  or  $W$  as and when path 1 – 2 has been followed.

4. The operator  $\delta$  has been used to denote inexact differentials, while the operator  $d$  is used to denote exact differentials.
5.  $\delta W$  is an inexact differential, but  $\int_{V_1}^{V_2} PdV$  is an exact differential. So if you divide  $\delta W$  by  $P$ , then it will become a perfect differential.

$$dV = \left[ \frac{1}{P} \right] \delta W$$

**Que 1.9.** Define thermodynamic equilibrium and also show that energy is a property of a system.

**AKTU 2015-16, Marks 10**

**Answer**

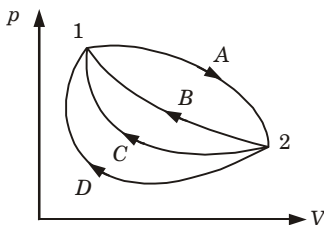
**A. Thermodynamic Equilibrium :** Refer Q. 1.4, Page 1–4C, Unit-1.

**B. Energy is a Property of System :**

- Let's consider a closed system which changes its state from 1 to 2 by path A and comes back to its original state '1' by any of the following paths :
  - Along the path 2-B-1.
  - Along the path 2-C-1.
  - Along the path 2-D-1.
- For the cyclic process 1-A-2-B-1,

Apply first law,  $\oint \delta Q = \oint \delta W$  or  $\oint (\delta Q - \delta W) = 0$

$$\therefore \int_{1, \text{Via A}}^2 (\delta Q - \delta W) + \int_{2, \text{Via B}}^1 (\delta Q - \delta W) = 0 \quad \dots(1.9.1)$$



**Fig. 1.9.1.** Standard energy in a point function.

- Similarly for the cyclic process 1-A-2-C-1,

$$\int_{1, \text{Via A}}^2 (\delta Q - \delta W) + \int_{2, \text{Via C}}^1 (\delta Q - \delta W) = 0 \quad \dots(1.9.2)$$

and for the cyclic process 1-A-2-D-1

$$\int_{1, \text{Via A}}^2 (\delta Q - \delta W) + \int_{2, \text{Via D}}^1 (\delta Q - \delta W) = 0 \quad \dots(1.9.3)$$

- Comparing eq. (1.9.1), (1.9.2) and (1.9.3), we have

$$\int_{2, \text{Via B}}^1 (\delta Q - \delta W) = \int_{2, \text{Via C}}^1 (\delta Q - \delta W) = \int_{2, \text{Via D}}^1 (\delta Q - \delta W)$$

- Since B, C and D indicate arbitrary paths between states 1 and 2, it can be concluded that the expression  $\int_2^1 (\delta Q - \delta W)$  remains the same irrespective of the path along which the system is proceeding solely depends on the initial and final states of the system. Therefore energy is a point function and hence a property of the system.

- The integral  $\int_2^1 (\delta Q - \delta W)$  is called energy of the system and is denoted by  $dU$ .

Therefore for a process,  $dU = \delta Q - \delta W$

$$\text{or} \quad \delta Q = dU + \delta W$$

**Que 1.10.** Define work and heat with their sign convention.

**Answer**

**A. Work :**

1. Work reflects the effect of a force on the system boundary.
2. When there occurs a physical displacement of a system boundary due to the action of an unbalanced force across the system boundary, then work is done by or on the system.
3. If a part or whole of a system boundary undergoes displacement under the action of an unbalanced force, then work done

$$W = \text{Force} \times \text{Displacement}$$

4. If work is done by a system on the surroundings, *i.e.*, a residual unbalanced force acting within the system pushes the system boundary against the surroundings, the work is said to be positive.
5. Imagine a gas contained in a cylinder enclosed by a piston expands by pushing the piston up in the same direction in which the residual unbalanced force acts. Hence, work of the system is positive :

$$\text{Work output} = + W$$

6. In this case, work is done on a system by the surroundings, *e.g.*, when the piston compresses a gas, the work is said to be negative,

$$\text{Work input to system} = - W$$

That is, all work input to the system is negative.

**B. Heat :**

1. Heat is thermal energy that crosses a system boundary when there is a temperature gradient across the boundary, *i.e.*, a net temperature difference between the system and the surroundings is a must for heat transfer. If there is no temperature difference, then there is no heat transfer. This implies that heat is a transient quantity.
2. For heat inflow into the system,  $Q$  is positive. For heat outflow from the system to the surroundings,  $Q$  is negative.

$$\therefore \text{Heat received by the system} = + Q$$

$$\text{Heat rejected by the system} = - Q$$

**PART-2**

*Gas Laws, Ideal Gas, Real Gas, Law of Corresponding States, Dalton's Law, Amagat's Law, and Property of Mixture of Gases.*

**CONCEPT OUTLINE : PART-2**

**Avogadro's Law :** Equal volumes of all gases, at a specified temperature and pressure, contain equal number of molecules.

**Boyle's Law :** The volume of a given mass of a gas is inversely related to the pressure exerted on it at a given temperature and given number of moles.

**Charle's Law :** For a given mass of an ideal gas at constant pressure, the volume is directly proportional to its absolute temperature.

**Dalton's Law :** The pressure of a mixture of gases simply is the sum of the partial pressure of the individual components.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions**

**Que 1.11.** Write short note on following :

- Avogadro's law,
- Boyle's law, and
- Charle's law.

**Answer**

**a. Avogadro's Law :**

- Equal volumes of all gases, at a specified temperature and pressure, contain equal numbers of molecules.
- Avogadro's law states that the volume occupied by an ideal gas is directly proportional to the number of molecules of the gas present in the container.
- The relation is given by

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

Where,  $n$  is equal to number of molecules of gas.

**b. Boyle's Law :**

- According to this law, volume of a given mass of a perfect gas varies inversely with absolute pressure when temperature is kept constant.
- Product of absolute pressure and volume of a given quantity of gas is constant when the temperature is kept constant *i.e.*,

$$V \propto \frac{1}{P} \quad \text{or} \quad PV = \text{Constant.}$$

**c. Charle's Law :**

1. According to this law, the volume of a given mass of a perfect gas varies directly with its absolute temperature when pressure is kept constant *i.e.*,

$$\frac{V}{T} = \text{Constant.} \quad (\text{At constant pressure})$$

2. Charle's law can also be defined as "The absolute pressure of a perfect gas varies directly with absolute temperature if the volume of the gas is kept constant during the process."

$$\frac{P}{T} = \text{Constant} \quad (\text{At constant volume})$$

**Que 1.12.** An insulated tank is divided in two equal parts by a thin membrane. Air at 1 bar pressure and 300 °C is contained in one half of the tank and other half is completely evacuated. Membrane gets punctured and fills the entire volume. Calculate the final pressure and temperature of air in the vessel. **AKTU 2011-12, Marks 3.5**

**Answer**

**Given :**  $p_1 = 1 \text{ bar}$ ,  $T_1 = 300 + 273 = 573 \text{ K}$ ,  $V_1 = V/2$ ,  $V_2 = V$

**To Find :** Final pressure and temperature of air in the vessel.

1. We know that

$$p_1 V_1 = p_2 V_2$$

$$p_2 = \frac{p_1 V_1}{V_2} = \frac{1 \times V / 2}{V} = 0.5 \text{ bar}$$

$$2. \quad \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

$$\frac{V / 2}{573} = \frac{V}{T_2}$$

$$T_2 = 573 \times 2 = 1146 \text{ K}$$

$$T_2 = 873 \text{ } ^\circ\text{C}$$

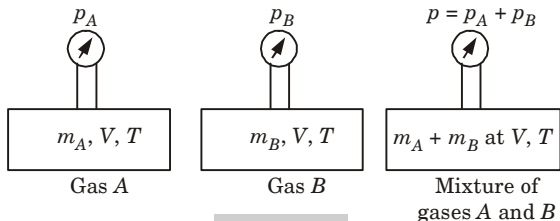
**Que 1.13.** Define Dalton's law and Amagat's law.

**Answer****A. Dalton's Law of Partial Pressure :**

1. According to this law, "The total pressure exerted by a mixture of gases is the algebraic sum of partial pressures exerted by the individual constituents when they occupy the same volume and temperature of the mixture".

2. Consider two individual gases A and B which occupy volume  $V$  at temperature  $T$  are mixed together and kept in a third container of volume  $V$  and temperature  $T$ .

$$\begin{aligned}\text{Volume of gas A} &= \text{Volume of gas B} \\ &= \text{Volume of mixture (A + B)}\end{aligned}$$



**Fig. 1.13.1.**

From mass balance equation,

$$m = m_A + m_B$$

From Dalton's law of partial pressure,

$$(p)_{V,T} = (p_A)_{V,T} + (p_B)_{V,T}$$

Above equations can be extended for any number of non-reactive gases.

$$p = p_A + p_B + \dots = \sum p_i$$

### B. Gibbs Dalton's Law :

1. According to this law, "The internal energy, enthalpy and entropy of mixture of gases are equal to the algebraic sum of internal energies, enthalpies and entropies of individual gases where they occupy the same volume and temperature of mixture of gases."
2. From this law, following relations can be written

$$mu = m_A u_A + m_B u_B + m_C u_C + \dots = \sum m_i u_i$$

$$mh = m_A h_A + m_B h_B + m_C h_C + \dots = \sum m_i h_i$$

$$ms = m_A s_A + m_B s_B + m_C s_C + \dots = \sum m_i s_i$$

3. Although Gibbs Dalton's law is applicable to perfect gases, it can be applied to real gases for approximate engineering calculations involving mixture of gases at lower pressure.

### C. Amagat's Law :

1. According to this law, "The total volume occupied by a mixture of gases is equal to the sum of volumes which would be occupied by each constituent, when they are at the same pressure and temperature as that of the mixture".
2. It follows that

$$(V)_{p,T} = (V_A)_{p,T} + (V_B)_{p,T} + (V_C)_{p,T} + \dots = \sum (V_i)_{p,T}$$

#### Que 1.14.

**Explain Van der Waal's equation of state.**

**Answer**

1. Real gases differ from ideal gas because of presence of intermolecular forces and also due to finite molecular volumes. Van der Waal's equation of state has been established by incorporating the following two corrections in the equations of state,  $pV = RT$ .

**Correction 1 :**

- i. Let equation of state  $pV = RT$  be represented in the form  $V = \frac{RT}{p}$ .

When pressure increases, volumes decreases

- ii. But in case of real gases, molecules occupy a finite volume and an allowance is to be made for the volume of voids existing between the molecules.
- iii. Thus the free volume available for molecular motion will be equal to  $[V - b]$  where  $b = V_{\text{molecule}} + V_{\text{void}}$ ; where 'b' represents the smallest volume upto which the gas can be compressed.

**Correction 2 :**

- i. Because of intermolecular forces in real gases, some impacts will be there on the walls of vessel. It is due to the fact that molecules positioned at the walls are attracted by adjacent molecules inside the vessel.
- ii. As a result, when compared to an ideal gas, the pressure exerted by a real gas will be smaller by an amount equal to  $\Delta p$ .
- iii. This decrease in pressure is directly proportional to the number of molecules affected by molecular interaction or directly proportional to the square of density of gas as given by the expression.

$$\Delta p = a\rho^2 \text{ or } \frac{a}{V^2}$$

Where  $a$  is the constant of proportionality which has a definite numerical value for each gas.

2. When the above two corrections are introduced, we get the Van der Waal's equation of state

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

3. In the above equation,  $a/V^2$  is known as force of cohesion and 'b' is known as co-volume.

**Que 1.15. Derive the relation of Van der Waal's equation in terms of critical properties. Explain compressibility factor.**

**Answer****A. Relation of Van der Waal's Equation in Terms of Critical Properties :**

1. Van der Waal's equation is given as  

$$(p + a/V^2)(V - b) = RT$$
2. This equation can be also written as  

$$pV^3 - (pb + RT)V^2 + aV - ab = 0$$
3. This equation will give the three roots with following characteristics :
  - i. The three roots are real and positive for a certain range of pressure at low temperature.
  - ii. With rise in temperature, three roots approach each other and become equal at critical point.
  - iii. Above critical temperature, there is only one real root for all values of pressure.
4. Now,  $p_C$ ,  $V_C$  and  $T_C$  denote the symbol at critical point. So at critical point, Van der Waal's equation can be written as

$$p_C = \frac{RT_C}{V_C - b} - \frac{a}{V_C^2} \quad \dots(1.15.1)$$

5. Now, at critical point isotherm has zero slope therefore

$$\left(\frac{\partial p}{\partial V}\right)_C = \frac{-RT_C}{(V_C - b)^2} + \frac{2a}{V_C^3} = 0$$

$$\left(\frac{\partial^2 p}{\partial V^2}\right)_C = \frac{2RT_C}{(V_C - b)^3} - \frac{6a}{V_C^4} = 0$$

6. After solving these two equations, we get

$$V_C = 3b, T_C = \frac{8a}{27bR}$$

7. Put these values in eq. (1.15.1), we get

$$p_C = \frac{a}{27b^2}$$

**B. Compressibility Factor :**

1. The compressibility factor is defined as the ratio of actual volume  $V$  of the gas to the value predicted by the ideal gas equation at same temperature and pressure.
2. It is denoted by  $Z$ .

$$Z = \frac{\text{Actual volume of gas}}{\text{Volume as predicted by ideal gas equation}}$$

$$= \frac{V}{RT/p} = \frac{pV}{RT}$$



**PART-3***Concept of Temperature and It's Measurement, and Temperature Scales.***CONCEPT OUTLINE : PART-3**

**Zerorth Law of Thermodynamics :** This law gives the basis for measuring the thermodynamic property called temperature. A reference system known as thermometer is brought in contact separately with two systems, and if the thermometer shows the same readings in both the cases, the two systems are at same temperature.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions**

**Que 1.16.** State Zeroth law of thermodynamics. Explain how the Zeroth law of thermodynamics can be used for temperature measurement.

**AKTU 2014-15, Marks 05****Answer****A. Zeroth Law of Thermodynamics :**

1. When a body *A* is in thermal equilibrium with a body *B*, and also separately with a body *C*, then *B* and *C* will be in thermal equilibrium with each other. This is known as the zeroth law of thermodynamics.

**B. Temperature Measurement :**

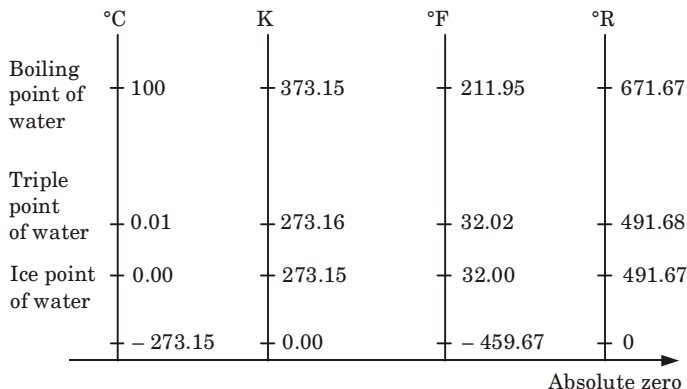
1. Zeroth law forms the basis of temperature measurement. The temperature of a body can be determined by bringing another body (say a thermometer) in contact with the first body and allowing the thermal equilibrium to be attained.
2. The value of temperature is found out by measuring some temperature dependent property of the thermometer. Such a property of thermometer is known as thermometric property which can be volume of gases, pressure of gases, electrical resistance of solids, magnetic effects etc.
3. To give a numerical value to the thermal state of a body, it is imperative to establish a temperature scale on which temperature of a body or system can be read.

4. It needs selection of basic unit and a reference state. For this purpose, generally two fixed points are used :
- Ice point :** Ice point is the equilibrium temperature of ice with air saturated water at standard atmospheric pressure.
  - Steam point :** This is the equilibrium temperature of pure water with its own vapour at standard atmospheric pressure.

**Que 1.17.** What do you understand by temperature scales ?

**Answer**

1. The following diagram represents comparison of reference on various scales :



**Fig. 1.17.1.**

**A. Relation between Centigrade and Fahrenheit Scales :**

- Let ice point be represented as  $t_i$  and steam point be represented as  $t_s$ .
- Let corresponding thermometric properties be represented as  $x_i$  and  $x_s$  respectively.
- Considering linear correlation
 
$$t = ax + b \quad \dots(1.17.1)$$
 between temperature ' $t$ ' and thermometric property  $x$ .  
 At ice point  $t_i = ax_i + b \quad \dots(1.17.2)$   
 At steam point  $t_s = ax_s + b \quad \dots(1.17.3)$
- Solving eq. (1.17.2) and eq. (1.17.3) we have

$$a = \frac{t_s - t_i}{x_s - x_i}$$

and

$$b = t_i - \left( \frac{t_s - t_i}{x_s - x_i} \right) x_i$$

5. Put ' $a$ ' and ' $b$ ' in eq. (1.17.1)

$$t = \frac{t_s - t_i}{x_s - x_i} x + t_i - \left( \frac{t_s - t_i}{x_s - x_i} \right) x_i$$

$$t = t_i + (t_s - t_i) \left[ \frac{x - x_i}{x_s - x_i} \right] \quad \dots(1.17.4)$$

6. At ice point for centigrade scale,  $t_i = 0^\circ\text{C}$  and at steam point for centigrade scale,  $t_s = 100^\circ\text{C}$

$$\therefore t^\circ\text{C} = 0 + (100 - 0) \left( \frac{x - x_i}{x_s - x_i} \right)$$

$$t^\circ\text{C} = 100 \times \left( \frac{x - x_i}{x_s - x_i} \right) \Rightarrow \frac{t^\circ\text{C}}{100} = \frac{x - x_i}{x_s - x_i} \quad \dots(1.17.5)$$

At ice point for Fahrenheit scale,  $t_i = 32^\circ\text{F}$

At steam point for Fahrenheit scale,  $t_s = 212^\circ\text{F}$

7. From eq. (1.17.4),

$$t^\circ\text{F} = 32 + (212 - 32) \left( \frac{x - x_i}{x_s - x_i} \right)$$

$$\text{or} \quad \frac{t^\circ\text{F} - 32}{180} = \frac{x - x_i}{x_s - x_i} \quad \dots(1.17.6)$$

Equating eq. (1.17.5) and eq. (1.17.6), we get

$$\frac{t^\circ\text{C}}{100} = \frac{t^\circ\text{F} - 32}{180} \quad \text{or} \quad \frac{^\circ\text{C}}{5} = \frac{^\circ\text{F} - 32}{9}$$

8. Similarly relation between other temperature scales can be obtained. e.g., relation between  $^\circ\text{C}$  and  $^\circ\text{R}$ .

$$\frac{t^\circ\text{C}}{100} = \frac{t^\circ\text{R} - 491.67}{180} \quad \text{or} \quad \frac{C}{5} = \frac{R - 491.67}{9}$$

$$\text{and} \quad \frac{t^\circ\text{C}}{100} = \frac{t^\circ\text{K} - 273.15}{100} \quad \text{or} \quad t^\circ\text{C} = t^\circ\text{K} - 273.15$$

$$\text{or} \quad K = ^\circ\text{C} + 273.15$$

**Que 1.18.** Explain how the zeroth law of thermodynamics can be used for temperature measurement. In an unknown temperature scale freezing point of water is  $0^\circ\text{X}$  and boiling point of water is  $1000^\circ\text{X}$ . Obtain a conversion relation between degrees X and degree celsius. Also determine the absolute zero in degree X.

**AKTU 2011-12, Marks 3.5**

### Answer

**A. Zeroth Law of Thermodynamics :** Refer Q. 1.16, Page 1-18C, Unit-1.

**B. Relation between  $^\circ\text{X}$  and  $^\circ\text{C}$  :**

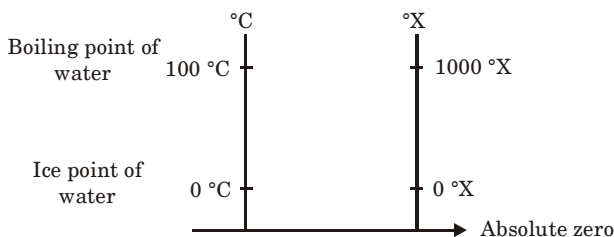
1. As temperature has a linear relationship i.e.,

$$t = ax + b$$

$$\text{For } ^\circ\text{C, at ice point, } t_i = ax_i + b \quad \dots(1.18.1)$$

$$\text{At boiling point, } t_s = ax_s + b \quad \dots(1.18.2)$$

2. Here,  $x$  = Thermodynamic property of water.

**Fig. 1.18.1.**

3. Solving eq. (1.18.1) and eq. (1.18.2) we have,

$$a = \frac{t_s - t_i}{x_s - x_i} \text{ and } b = t_i - \left( \frac{t_s - t_i}{x_s - x_i} \right) x_i$$

4. Now,

$$t = ax + b$$

$$t = \left( \frac{t_s - t_i}{x_s - x_i} \right) x + t_i - \left( \frac{t_s - t_i}{x_s - x_i} \right) x_i$$

$$t = t_i + (t_s - t_i) \left( \frac{x - x_i}{x_s - x_i} \right)$$

5. Now put

$$t_i = 0^\circ\text{C} \text{ and } t_s = 100^\circ\text{C} \Rightarrow t = 100 \left( \frac{x - x_i}{x_s - x_i} \right)$$

$$\frac{t^\circ\text{C}}{100} = \frac{x - x_i}{x_s - x_i} \quad \dots(1.18.3)$$

6. For X° scale,  $t^\circ\text{X} = t_i + (t_s - t_i) \left( \frac{x - x_i}{x_s - x_i} \right)$

Put  $t_i = 0^\circ\text{X} \text{ and } t_s = 1000^\circ\text{X}$

$$t^\circ\text{X} = 0 + 1000 \left( \frac{x - x_i}{x_s - x_i} \right)$$

$$\frac{t^\circ\text{X}}{1000} = \left( \frac{x - x_i}{x_s - x_i} \right) \quad \dots(1.18.4)$$

7. From eq. (1.18.3) and eq. (1.18.4) we have,

$$\frac{t^\circ\text{C}}{100} = \frac{t^\circ\text{X}}{1000}$$

$$t^\circ\text{C} = \frac{t^\circ\text{X}}{10}$$

8. Now absolute zero in °C = -273.15

$$\text{So absolute zero in } ^\circ\text{X} = -273.15 \times 10^\circ\text{X} = -2731.5^\circ\text{X}$$

**PART-4**

*Thermodynamic Definition of Work, Displacement Work and Flow Work, Displacement Work for Various Non Flow Process, Joule's Experiment, First Law Analysis Energy and Enthalpy, Limitations of First Law of Thermodynamics and PMM-I.*

**CONCEPT OUTLINE : PART-4**

**First Law of Thermodynamics :** Whenever a system undergoes a cyclic change, the algebraic sum of work transfers is proportional to the algebraic sum of heat transfer or work and heat are mutually convertible one into the other.

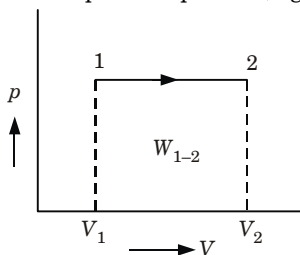
**Thermodynamic Processes :** A process occurs when the system undergoes a change in a state or an energy transfer at a steady state. A process may be non-flow in which a fixed mass within the defined boundary is undergoing a change of state, e.g., closed systems undergo non-flow processes. A process may be a flow process in which mass is entering and leaving through the boundary of an open system.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions**

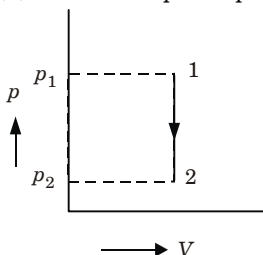
**Que 1.19.** Derive the expression of workdone for various non-flow processes.

**Answer**

1. Constant pressure process (Fig. 1.19.1) (isobaric or isopiestic process)



**Fig. 1.19.1.** Constant pressure process.



**Fig. 1.19.2.** Constant volume process.

$$W_{1-2} = \int_{V_1}^{V_2} p dV = p(V_2 - V_1) \quad \dots(1.19.1)$$

2. Constant volume process (Fig. 1.19.2) (isochoric process)

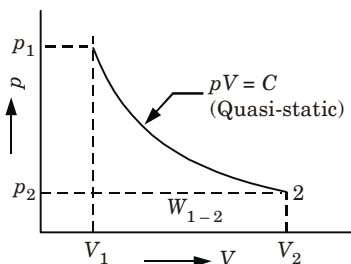
$$W_{1-2} = \int p dV = 0 \quad \dots(1.19.2)$$

3. Constant temperature process (Isothermal process) ( $pV = C$ ) (Fig. 1.19.3)

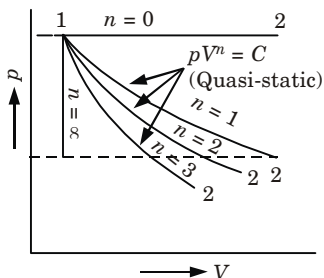
$$\therefore W_{1-2} = \int_{V_1}^{V_2} p dV$$

$$\therefore pV = p_1 V_1 = C, \text{ putting } p = \frac{p_1 V_1}{V}$$

$$\begin{aligned} W_{1-2} &= p_1 V_1 \int_{V_1}^{V_2} \frac{dV}{V} = p_1 V_1 \ln \frac{V_2}{V_1} \\ &= p_1 V_1 \ln \frac{p_1}{p_2} \quad \dots(1.19.3) \end{aligned}$$



**Fig. 1.19.3.** Process in which  $pV = \text{Constant}$ .



**Fig. 1.19.4.** Process in which  $pV^n = \text{Constant}$ .

4. Polytropic process ( $pV^n = C$ ), where  $n$  is a constant (Fig. 1.19.4).

$$pV^n = p_1 V_1^n = p_2 V_2^n = C$$

$$\therefore p = \frac{(p_1 V_1^n)}{V^n}$$

$$\begin{aligned} \therefore W_{1-2} &= \int_{V_1}^{V_2} p dV = \int_{V_1}^{V_2} \frac{p_1 V_1^n}{V^n} \cdot dV = (p_1 V_1^n) \left[ \frac{V^{-n+1}}{-n+1} \right]_{V_1}^{V_2} \\ &= \frac{p_1 V_1^n}{1-n} (V_2^{1-n} - V_1^{1-n}) \\ &= \frac{p_2 V_2^n \times V_2^{1-n} - p_1 V_1^n \times V_1^{1-n}}{1-n} \\ &= \frac{p_1 V_1 - p_2 V_2}{n-1} = \frac{p_1 V_1}{n-1} \left[ 1 - \left( \frac{p_2}{p_1} \right)^{n-1/n} \right] \quad \dots(1.19.4) \end{aligned}$$

5. Reversible adiabatic process (Isentropic process) ( $pV^\gamma = c$ ), where  $\gamma = c_p/c_v$ ,

$$W_{1-2} = \frac{p_1 V_1}{n-1} \left[ 1 - \left( \frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \right] \quad \dots(1.19.5)$$

**Que 1.20.** An inelastic flexible balloon is inflated from initial empty state to a volume of  $0.4 \text{ m}^3$  with  $\text{H}_2$  available from hydrogen cylinder. For atmospheric pressure of  $1.0313 \text{ bar}$  determine the amount of work done by balloon upon atmosphere and work done by atmosphere.

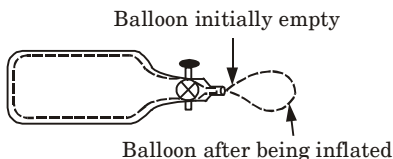
**AKTU 2014-15, Marks 05**

**Answer**

**Given :**  $V = 0.4 \text{ m}^3, p = 1.0313 \text{ bar}$

**To Find :** Work done by balloon and by atmosphere.

- Here let us assume that the pressure is always equal to atmospheric pressure as balloon is flexible, inelastic and unstressed and no work is done for stretching balloon during its filling.
- Fig. 1.20.1 shows the boundary of system before and after filling balloon by firm line and dotted line respectively.



**Fig. 1.20.1.**

- Displacement work,  $W = \int_{\text{cylinder}} p dV + \int_{\text{balloon}} p dV$   
 $\int p dV = 0$  as cylinder shall be rigid.  
 $= 0 + p \Delta V$   
 $= 0 + 1.0313 \times 10^5 \times 0.4 = 41.25 \text{ kJ}$
- Work done by system upon atmosphere =  $41.25 \text{ kJ}$
- Work done by atmosphere =  $-41.25 \text{ kJ}$

**Que 1.21.**  $3 \text{ kg}$  of air at  $1.5 \text{ bar}$  pressure and  $77^\circ \text{C}$  temperature at state 1 is compressed polytropically to state 2 at pressure  $7.5 \text{ bar}$ , index of compression being  $1.2$ . It is then cooled at constant temperature to its original state 1. Find the net work done and heat transferred.

**AKTU 2016-17, Marks 10**

**Answer**

**Given :**  $m = 3 \text{ kg}$ ,  $P_1 = 1.5 \text{ bar}$ ,  $T_1 = 77^\circ \text{C}$ ,  $P_2 = 7.5 \text{ bar}$ ,  $n = 1.2$

**To Find :** Net work done and heat transferred.

1. **For polytropic compression :**

$$PV^{1.2} = C$$

Since,

$$P_1 V_1^{1.2} = P_2 V_2^{1.2}$$

$$\left(\frac{V_1}{V_2}\right)^{1.2} = \left(\frac{P_2}{P_1}\right) \quad \dots(1.21.1)$$

$$P_1 V_1 = mRT_1$$

$$1.5 V_1 = 3 \times 0.287 \times 350$$

$$V_1 = 200.9 \text{ m}^3$$

2. From eq. (1.21.1)

$$V_2^{1.2} = \frac{P_1}{P_2} V_1^{1.2}$$

$$= \frac{1.5 \times (200.9)^{1.2}}{7.5} = \frac{1.5 \times 580.197}{7.5}$$

$$V_2^{1.2} = 116.039, V_2 = 52.54 \text{ m}^3$$

3. Work done during process 1 - 2;

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n - 1} = \frac{1.5 \times 200.9 - 7.5 \times 52.54}{1.2 - 1}$$

$$W_{1-2} = -\frac{92.713}{0.2} = -463.565$$

4. Work done during process 2 - 1;

$$W_{2-1} = P_1 V_1 \ln \frac{P_2}{P_1}$$

$$= 1.5 \times 200.9 \times \ln \left(\frac{7.5}{1.5}\right) = 485.00 \text{ J}$$

5. Hence, net work done =  $W_{1-2} + W_{2-1}$

$$\delta W = -463.565 + 485.00 = 21.435 \text{ J}$$

6. From first law of thermodynamics;

$$\delta Q = du + \delta W$$

7. Process is cyclic, therefore

$$du = 0$$

Hence, heat transfer during process;

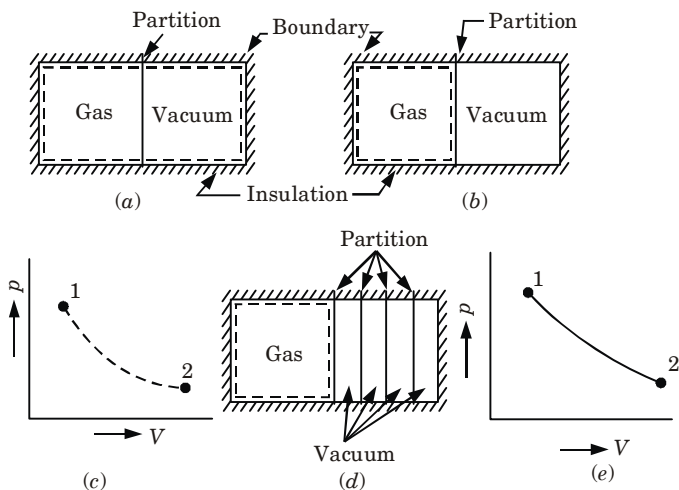
$$\delta Q = \delta W = 21.435 \text{ J}.$$

**Que 1.22. Explain free expansion phenomenon.**



**Answer**

1. Work transfer is identified only at the boundaries of a system. It is a boundary phenomenon, and a form of energy in transit crossing the boundary.
2. Let us consider a gas separated from the vacuum by a partition (Fig. 1.22.1).

**Fig. 1.22.1. Free expansion.**

3. Let the partition be removed. The gas rushes to fill the entire volume.
4. The expansion of a gas against vacuum is called free expansion.
5. If we neglect the work associated with the removal of partition, and consider the gas and vacuum together as our system (Fig. 1.22.1(a)), there is no work transfer involved here, since no work crosses the system boundary and hence

$$\int_1^2 \delta W = 0, \quad \text{although} \quad \int_1^2 p dV \neq 0$$

6. If only the gas is taken as the system (Fig. 1.22.1(b)), when the partition is removed there is a change in the volume of the gas, and one is tempted to calculate the work from the expression  $\int_1^2 p dV$ . However, this is not a quasi-static process, although the initial and final end states are equilibrium. Therefore, the work cannot be calculated from this relation.
7. The two end states can be located on the p-V diagram and these are joined by a dotted line (Fig. 1.22.1(c)) to indicate that the process had occurred.

8. However, if the vacuum space is divided into a large number of small volumes by partitions and the partitions are removed one by one slowly (Fig. 1.22.1(d)), then every state passed through by the system is an equilibrium state and the work done can be estimated from the relation  $\int_1^2 p dV$  (Fig. 1.22.1(e)).
9. Yet, in free expansion of a gas, there is no resistance to the fluid at the system boundary as the volume of the gas increases to fill up the vacuum space. Work is done by a system to overcome resistance. Since vacuum does not offer any resistance, there is no work transfer involved in free expansion.

**Que 1.23.** Two insulated tanks are connected through a pipe with closed valve in between. Initially one tank having volume of  $1.8 \text{ m}^3$  has argon gas at 12 bar,  $40^\circ\text{C}$  and other tank having volume of  $3.6 \text{ m}^3$  is completely empty. Subsequently valve is opened and the argon pressure gets equalized in two tanks. Determine, (a) the final pressure and temperature (b) the change of enthalpy and (c) the work done considering argon as perfect gas and gas constant as  $0.208 \text{ kJ/kg}\cdot\text{K}$ .

**AKTU 2014-15, Marks 10**

**Answer**

**Given :** Volume,  $V_1 = 1.8 \text{ m}^3$ ,  $V_2 = 3.6 \text{ m}^3$

Pressure,  $p_1 = 12 \text{ bar} = 12 \times 10^2 \text{ kPa}$ , Temperature,  $T_1 = 40^\circ\text{C} = 313 \text{ K}$

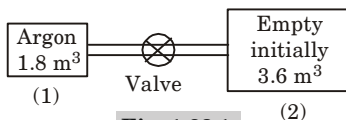
Total volume,  $V = V_1 + V_2 = 5.4 \text{ m}^3$

**To Find :**

- The final pressure and temperature,
- the change of enthalpy, and
- Work done.

1. By perfect gas law,  $p_1 V_1 = m R T_1$   
 $12 \times 10^2 \times 1.8 = m \times 0.208 \times 313$   
 $m = 33.18 \text{ kg}$

2. By gas law for initial and final state,  
 $p_1 V_1 = p_{\text{final}} \times V_{\text{final}}$   
 $12 \times 10^2 \times 1.8 = p_{\text{final}} \times 5.4$



**Fig. 1.23.1.**

3. Final pressure,  $p_{\text{final}} = 400 \text{ kPa}$  or 4 bar
4. Since it is insulated system and it has no heat transfer so, there will be no change in internal energy.

5. Final temperature = 313 K.

$$\delta q = du + \delta w \Rightarrow du = 0$$

i.e.,  $T_{\text{initial}} = T_{\text{final}}$

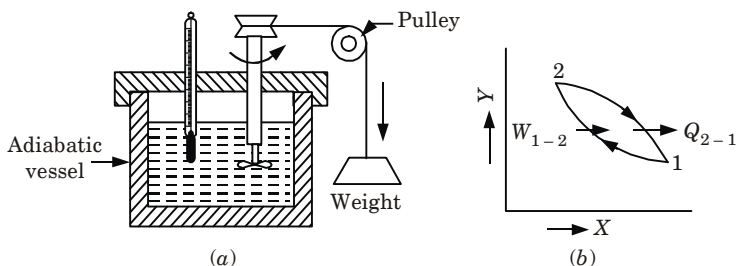
Change in enthalpy = 0

Work done = 0

**Que 1.24.** Write a short note on Joule's experiment.

**Answer**

1. Let us consider a closed system which consists of a known mass of water contained in an adiabatic vessel having a thermometer and a paddle wheel, as shown in Fig. 1.24.1(a).



**Fig. 1.24.1.** (a) Adiabatic work, (b) Cycle completed by a system with two energy interactions : Adiabatic work transfer  $W_{1-2}$  followed by heat transfer  $Q_{2-1}$ .

- Let a certain amount of work  $W_{1-2}$  be done upon the system by the paddle wheel.
- The quantity of work can be measured by the fall of weight which drives the paddle wheel through a pulley.
- The system was initially at temperature  $t_1$ , same as that of atmosphere, and after work transfer let the temperature rise to  $t_2$ .
- The pressure is always 1 atm. The process 1-2 undergone by the system is shown in Fig. 1.24.1 in generalized thermodynamic co-ordinates X, Y.
- Let the insulation now be removed. The system and the surroundings interact by heat transfer till the system returns to the original temperature  $t_1$ , attaining the condition of thermal equilibrium with the atmosphere.
- The amount of heat transfer  $Q_{2-1}$  from the system during the process 2-1, shown in Fig. 1.24.1(b), can be estimated.
- The system thus executes a cycle, which consists of a definite amount of work input  $W_{1-2}$  to the system followed by the transfer of an amount of heat  $Q_{2-1}$  from the system.

9. It has been found that this  $W_{1-2}$  is always proportional to the heat  $Q_{1-2}$ , and the constant of proportionality is called the Joule's equivalent or the mechanical equivalent of heat.
10. In the simple example given here, there are only two energy transfer quantities as the system performs a thermodynamic cycle.
11. If the cycle involves many more heat and work quantities, the same result will be found and can be expressed algebraically.

$$(\Sigma W)_{\text{cycle}} = J (\Sigma Q)_{\text{cycle}}$$

Where  $J$  is the Joule's equivalent. This is also expressed in the form

$$\oint \delta W = J \oint \delta Q$$

Where the symbol  $\oint$  denote the cyclic integral for the closed path.

This is the first law for a closed system undergoing a cycle.

**Que 1.25.** A piston and cylinder machine containing a fluid system

has a stirring device in the cylinder. The piston is frictionless and it is held against the fluid due to the atmospheric pressure of 101.325 kPa. The stirring device is turned 10,000 revolutions with an average torque against the fluid 1.275 N-m. Meanwhile the piston of 0.6 m diameter moves out 0.80 m. Find the net work transfer from the system.

**AKTU 2013-14, Marks 10**

**Answer**

**Given :** Pressure,  $p = 101.325$  kPa, RPM,  $N = 10,000$ ,

Torque,  $T = 1.275$  N-m, Diameter,  $d = 0.6$  m, Stroke,  $L = 0.80$  m

**To Find :** Net work transfer from the system.

1. Workdone by the stirring device upon the system is given as :

$$W_1 = 2\pi TN = 2\pi \times 1.275 \times 10,000 = 80 \text{ kJ}$$

2. This work will be negative. So

$$W_1 = -80 \text{ kJ}$$

3. Workdone by the system upon the surrounding

$$W_2 = (pA)L$$

Where

$$p = 101.325 \text{ kPa} = 101.325 \text{ kN/m}^2$$

$$A = \frac{\pi}{4} d^2 = \frac{\pi}{4} (0.6)^2 = 0.2827 \text{ m}^2$$

$$L = 0.80 \text{ m}$$

$$\therefore W_2 = (pA)L = 101.325 \times 0.2827 \times 0.8 = 22.9 \text{ kJ}$$

4. This work will be positive.

$$W_2 = +22.9 \text{ kJ}$$

5. Net work transfer from the system

$$W = W_1 + W_2 = -80 + 22.9 = -57.1 \text{ kJ}$$

**Que 1.26. State first law of thermodynamics with its limitations.**

**Answer**

1. First law of thermodynamics is related with principle of conservation of energy according to which the total energy of an isolated system is conserved.
2. It can be concluded that all forms of energies are equivalent and convertible. If one form of energy disappears, it must appear in an equivalent amount of some other form of energy.
3. Thus first law stipulates that when a thermodynamic process is carried out, energy is neither gained nor lost.
4. Energy is only transformed from one form into another and the energy balance is maintained.
5. First law fails to state the conditions under which energy conversion takes place.
6. The limitations of 1<sup>st</sup> law of thermodynamics can be explained with the help of following illustrations :
  - a. Temperature of liquid contained in a vessel increases when it is churned by paddle work. But paddle work can not be restored on cooling the liquid to its initial state.
  - b. When a block slides down a rough place, it gets warmer. However, the reverse process when the block slides up the plane and becomes cooler is not true even if the first law of thermodynamics still holds good.
  - c. Electrical current flowing through a resistor produces heat according to equation,

$$H = i^2 R t.$$

Current once dissipated as heat cannot be converted back into electricity.

- d. Fuel (solid or liquid) burns with air and gets converted into products of combustion. Fuel once burnt cannot be restored back to its original form.
- e. Work is easily converted into heat. However there is a maximum limit up to which the conversion of heat is possible in a heat engine. Work is superior to heat, and a complete transformation of low grade energy (heat) into high grade energy (work) is not possible.

**Que 1.27. Define the first law of thermodynamics. How the first law of thermodynamics is applied to a closed system undergoing a non-cycle process ?**

**Answer**

1. The expression  $(\Sigma W)_{\text{cycle}} = (\Sigma Q)_{\text{cycle}}$  applies only to systems undergoing cycles, and the algebraic summation of all energy transfer across system boundaries is zero.
2. But if a system undergoes a change of state during which both heat transfer and work transfer are involved, the net energy transfer will be stored for accumulated within the system.
3. If  $Q$  is the amount of heat transferred to the system and  $W$  is the amount of work transferred from the system during the process (Fig. 1.27.1), the net energy transfer  $(Q - W)$  will be stored in the system.
4. Energy in storage is neither heat nor work, and is given the name internal energy or simply, the energy of the system.

Therefore,  $Q - W = \Delta E$

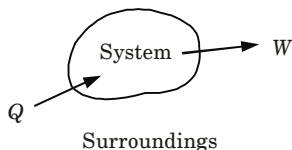
Where  $\Delta E$  is the increase in the energy of the system

or  $Q = \Delta E + W$

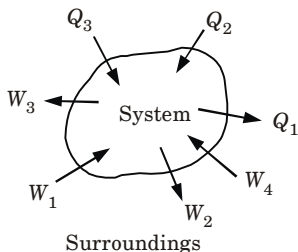
Here  $Q$ ,  $W$ , and  $\Delta E$  are all expressed in the same units (in joules).

5. If there are more energy transfer quantities involved in the process, as shown in Fig. 1.27.2, the first law gives

$$(Q_2 + Q_3 - Q_1) = \Delta E + (W_2 + W_3 - W_1 - W_4)$$



**Fig. 1.27.1.** Heat and work interaction of a system with its surroundings in a process.



**Fig. 1.27.2.** System-surroundings interaction in a process involving many energy fluxes.

6. Energy is thus conserved in the operation. The first law is a particular formulation of the principle of the conservation of energy.
7. This definition does not give an absolute value of energy  $E$ , but only the change of energy  $\Delta E$  for the process.

**Que 1.28.** Explain PMM-1.

**Answer**

1. The first law states the general principle of the conservation of energy. Energy is neither created nor destroyed, but only gets transformed from one form to another.

- There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously (Fig. 1.28.1).
- Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM1. A PMM1 is thus impossible.
- The converse of the above statement is also true, *i.e.*, there can be no machine which would continuously consume work without some other form of energy appearing simultaneously (Fig. 1.28.2).

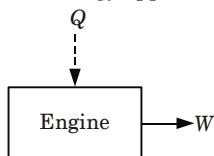


Fig. 1.28.1. A PMM1.

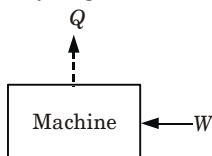


Fig. 1.28.2. The converse of PMM1.

### PART-5

*Steady Flow System, Steady Flow Energy Equation and its Application, Analysis of Unsteady Process.*

### CONCEPT OUTLINE : PART-5

**Steady Flow Process :** Steady flow means that the rates of flow of mass and energy across the control surface are constant. At the steady state of a system, any thermodynamic property will have a fixed value at a particular location, and will not alter with time.

**Steady Flow Energy Equation :**

$$h_1 + \frac{C_1^2}{2} + Z_1 g + \frac{dQ}{dm} = h_2 + \frac{C_2^2}{2} + Z_2 g + \frac{dW}{dm}$$

**Unsteady Flow Process :** In the case of unsteady flow process, the rate of energy and mass transfer into and out of the control volume are not same.

### Questions-Answers

#### Long Answer Type and Medium Answer Type Questions

**Que 1.29.** What is steady flow energy equation (SFEE) ? What are the assumptions made for it.

OR

What are the assumptions for steady flow process ? Write the general energy equation for steady flow process.

**Answer****A. Assumptions Made in the Analysis of SFEE :**

1. There is no accumulation or decrease of mass in the control volume at any time *i.e.*, there is no other source or sink of mass in the control volume.
2. Rate of mass flow in and out of the control volume is equal and constant with respect to time.
3. State, velocity and elevation of fluid mass entering and leaving the surface do not change with time.
4. Rate of heat and work transfers across the control volume is constant.

**B. General Energy Equation For Steady Flow Processes :**

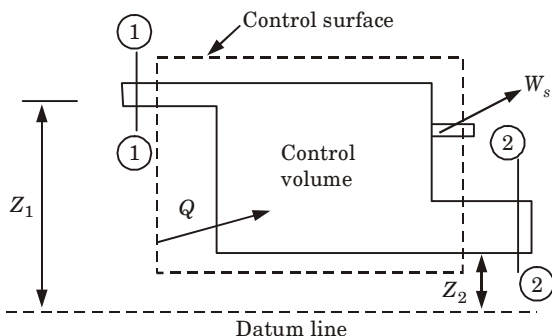
1. Let's consider the flow of a fluid through a control volume as shown in Fig. 1.29.1. In the time interval " $dt$ ", there occurs a flow (or flux) of mass and energy into the control volume.
2. Section 1-1 is the inlet side and section 2-2 is the outlet side.
3. At the inlet side (section 1-1) to control volume following are the fluid parameters :

Average velocity =  $C_1$

Pressure =  $p_1$

Specific volume =  $v_1$

Internal energy =  $u_1$



**Fig. 1.29.1.**

4. At the outlet (section 2-2), following are fluid parameters :

Velocity =  $C_2$

Pressure =  $p_2$

Specific volume =  $v_2$

Internal energy =  $u_2$

5. During the flow of fluid through the control volume, heat ' $Q$ ' and mechanical work ' $W_s$ ' are also supposed to cross the control surface. While writing the energy balance equation on the sides of the control volume, following energies are taken into consideration :



- a. Internal energy stored in the fluid.
  - b. Potential energy and kinetic energy.
  - c. Flow energy (or flow work) required to push the fluid in or out of control volume.
  - d. Heat and shaft (mechanical) work which may cross the control volume.
6. Since the energy is conserved therefore energy balance for the control volume mentioned above can be written in the following form
- $$m_1 \left[ u_1 + p_1 v_1 + \frac{C_1^2}{2} + gZ_1 \right] + Q = m_2 \left[ u_2 + p_2 v_2 + \frac{C_2^2}{2} + gZ_2 \right] + W_s \dots (1.29.1)$$
7. The eq. (1.29.1) is a general energy equation and can be applied to all fluids compressible or incompressible, ideal or real fluids, liquids and gases.

**Que 1.30. What are the applications of SFEE ?**

**Answer**

**A. Application of SFEE to Engineering Devices :**

**a. Nozzle and Diffuser :**

1. The flow through a nozzle is characterized by following features :
  - i. Shaft work is zero *i.e.*,  $W_s = 0$
  - ii. If the flow is reversible adiabatic manner, then  $Q = 0$ .
  - iii. If the nozzle is horizontal, change in elevation, *i.e.*,  $dZ$  will be zero
$$\therefore Z_1 = Z_2.$$
2. Under these features, SFEE for a nozzle / diffuser is reduced to

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$

$$\text{or} \quad h_1 - h_2 = \frac{C_2^2}{2} - \frac{C_1^2}{2}$$

3. For a nozzle  
Enthalpy drop = Increase in kinetic energy
4. For a diffuser,  
Rise in enthalpy = decrease in kinetic energy.

**b. Boiler :**

1. A boiler has following features :
  - i. Shaft work is zero,  $W_s = 0$ .
  - ii. Change in kinetic energy is negligible,  $\frac{C_2^2 - C_1^2}{2} = 0$ .
  - iii. Change in elevation between inlet and outlet point is negligible,

$$Z_1 = Z_2.$$

2. Therefore SFEE is reduced to

$$mh_1 + Q = mh_2 \Rightarrow Q = m(h_2 - h_1)$$

**c. Turbine :**

1. A steam or gas turbine has following features :

- $\Delta KE$  or  $d$  (kinetic energy) = 0
- $\Delta PE$  or  $d$  (potential energy) = 0
- $Q = 0$  since walls are insulated.

2. Therefore, SFEE for a turbine is reduced to

$$mh_1 = mh_2 + W_s$$

$$\text{or } W_s = m(h_1 - h_2)$$

Obviously the work is done by the turbine at the expense of enthalpy.

**d. Compressor :**

1. A compressor is characterized by following features :

- Shaft work is negative  
i.e.,  $W_s = \text{negative}$   
(Since work is done on the system and working fluid is compressed.)
- Change in potential energy is negligible  
i.e.,  $d(PE) = 0$
- Generally heat is lost to surroundings,  $Q$  is negative.

2. Therefore SFEE for a compressor is reduced to

$$m\left(h_1 + \frac{C_1^2}{2}\right) - Q = m\left(h_2 + \frac{C_2^2}{2}\right) - W_s$$

**e. Centrifugal Water Pump :**

1. For a pump,  $Q = 0$ ,  $dU = 0$

(Since there is no change in the temperature of water)

- Work is negative since it is done on the system.
- SFEE for a pump is reduced to

$$m\left[p_1v_1 + \frac{C_1^2}{2} + gZ_1\right] = m\left[p_2v_2 + \frac{C_2^2}{2} + gZ_2\right] - W$$

**f. Heat Exchanger :**

1. A heat exchanger is characterized by the following features :

- Shaft work is zero,  $W_s = 0$
- Change in KE = 0
- Change in PE = 0
- It is a perfectly insulated system i.e., no external heat interaction.

2. From energy balance equation, we can write,  
Energy given by fluid A = Energy gained by fluid B

**Que 1.31.** In a nozzle air at 627 °C and twice atmospheric pressure enters with negligible velocity of air at entrance. Find velocity of air at exit, assuming no heat loss and nozzle being horizontal. Take  $C_p = 1.005 \text{ kJ/kg-K}$  for air.

AKTU 2014-15, Marks 3.5

### Answer

**Given :** Inlet temperature,  $T_1 = 627^\circ\text{C} = 627 + 273 = 900 \text{ K}$

Outlet temperature,  $T_2 = 27^\circ\text{C} = 27 + 273 = 300 \text{ K}$

Negligible inlet velocity,  $C_1 \approx 0$

**To Find :** Velocity at exit.

1. Applying steady flow energy equation with inlet and exit states as 1, 2 with no heat and work interaction and no change in potential energy.

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$

$$C_2 = \sqrt{2(h_1 - h_2)}$$

2. Exit velocity,  $C_2 = \sqrt{2C_p(T_1 - T_2)}$

$$C_2 = \sqrt{2 \times 1.005 \times 10^3 \times (900 - 300)}$$

$$C_2 = 1098.2 \text{ m/s}$$

**Que 1.32.** A nozzle is a device for increasing the velocity of a steadily flowing steam. 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.

- Find the velocity at exits from the nozzle.
- If the inlet area is  $0.1 \text{ m}^2$  and the specific volume at inlet is  $0.187 \text{ m}^3/\text{kg}$ , find the mass flow rate.
- If the specific volume at the nozzle exit is  $0.498 \text{ m}^3/\text{kg}$ , find the exit area of the nozzle.

AKTU 2015-16, Marks 10

### Answer

**Given :** At the inlet, Enthalpy,  $h_1 = 3000 \text{ kJ/kg}$ , Velocity,  $C_1 = 60 \text{ m/s}$

At the discharge end, Enthalpy  $h_2 = 2762 \text{ kJ/kg}$

**To Find :**

- Velocity at exit.
- Mass flow rate.
- Exit area.

1. At the discharge end,

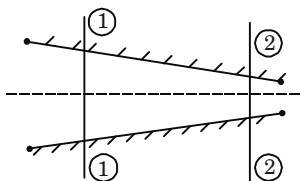


Fig. 1.32.1.

Enthalpy,  $h_2 = 2762 \text{ kJ/kg}$

It is given that nozzle is horizontal and there is negligible heat loss from it.

2. Applying SFEE, between section (1) and section (2),

$$h_1 + \frac{1}{2000} C_1^2 + \frac{gZ_1}{1000} + \dot{Q} = h_2 + \frac{1}{2000} C_2^2 + \frac{gZ_2}{1000} + \dot{w} \quad \dots(1.32.1)$$

3. Since,  $Z_1 = Z_2$

And assuming, there is no heat transfer and work transfer.

Then from eq. (1.32.1),

$$h_1 + \frac{1}{2000} C_1^2 = h_2 + \frac{1}{2000} C_2^2$$

4. On putting given values,

$$3000 + \frac{1}{2000} \times (60)^2 = 2762 + \frac{1}{2000} C_2^2$$

$$C_2^2 = 479600$$

$$C_2 = 692.53 \text{ m/s}$$

Hence, the velocity at exit from the nozzle,

$$C_2 = 692.53 \text{ m/s}$$

5. Inlet area,  $a_1 = 0.1 \text{ m}^2$

Specific volume,  $v_1 = 0.187 \text{ m}^3/\text{kg}$

6. Now from continuity equation, at inlet

$$\dot{m} v_1 = a_1 C_1$$

$$\dot{m} \times 0.187 = 0.1 \times 60$$

$$\dot{m} = 32.08 \text{ kg/s}$$

Hence, the mass flow rate,  $\dot{m} = 32.08 \text{ kg/s}$ .

7. Specific volume at exit  $= v_2$

$$v_2 = 0.498 \text{ m}^3/\text{kg}$$

8. Then, from continuity equation at exit,

$$a_2 C_2 = \dot{m} v_2$$

$$a_2 \times 692.53 = 32.08 \times 0.498$$

$$a_2 = 0.02307 \text{ m}^2$$

Hence, the exit area of the nozzle,

$$a_2 = 0.02307 \text{ m}^2$$

**Que 1.33.** In a gas turbine unit, the gases flow through the turbine is 15 kg/s and the power developed by the turbine is 12000 kW. The enthalpies of gases at the inlet and outlet are 1260 kJ/kg and 400 kJ/kg respectively, and the velocity of gases at the inlet and outlet are 50 m/s and 110 m/s respectively. Calculate :

- The rate at which heat is rejected to the turbine, and
- The area of the inlet pipe given that the specific volume of the gases at the inlet is  $0.45 \text{ m}^3/\text{kg}$ .

**AKTU 2016-17, Marks 10**

### Answer

**Given :**  $\dot{m} = 15 \text{ kg/sec}$ , Power developed  $W_s = 12000 \text{ kW}$ ,  
Enthalpy at inlet,  $h_1 = 1260 \text{ kJ/kg}$ , Enthalpy at outlet,  $h_2 = 400 \text{ kJ/kg}$ ,  
Velocity at inlet  $C_1 = 50 \text{ m/s}$ , Velocity at outlet  $v_2 = 110 \text{ m/s}$

**To Find :** i. Rate of heat rejected.  
ii. Area of the inlet pipe.

$$\begin{aligned}
 1. \quad Q - W_s &= \Delta KE + \Delta PE + \Delta H \\
 &= \frac{1}{2} \times 15 \times ((110)^2 - 50^2) + 0 + (400 - 1260) \times 15 \\
 &= \frac{1}{2} \times 15 \times 9600 + (-860) \times 15 \\
 &= \frac{1}{2} \times 144000 - 860 \times 15 \\
 Q - 12000 \times 10^3 &= 72000 - 860 \times 15 \times 10^3 \\
 Q - 12000 \times 10^3 &= 72 \times 10^3 - 860 \times 10^3 \times 15 \\
 Q &= -828 \times 10^3 \text{ J/s} \\
 Q &= -828 \text{ kJ/s}
 \end{aligned}$$

Hence, the rate at which heat is rejected to the turbine = 828 kJ/s

$$\begin{aligned}
 2. \quad \dot{m} &= \frac{A_1 C_1}{v_1} = \frac{A_2 C_2}{v_2} \\
 \text{Specific volume of the gases at inlet } v_1 &= 0.45 \text{ m}^3/\text{kg} \\
 15 &= \frac{A_1 \times 50}{0.45} \\
 A_1 &= \frac{6.75}{50} = 0.135 \text{ m}^2 \\
 A_1 &= 0.135 \text{ m}^2
 \end{aligned}$$

**Que 1.34.** What is unsteady flow processes ? Explain filling and

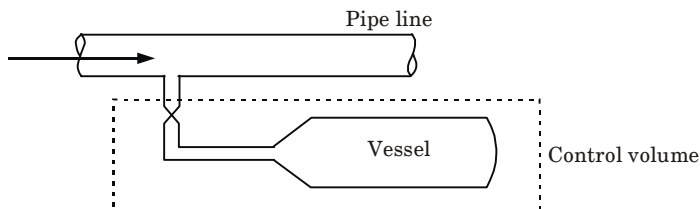
evacuation process of a vessel.

**AKTU 2013-14, Marks 10**

**Answer**

**A. Unsteady Process :**

1. A flow process is called unsteady when the fluid parameters vary with respect to time.
2. Unsteady flow process refers to changing fluid parameters with the passage of time at a position in the control volume.
3. An unsteady flow process is represented as  $\frac{\partial P}{\partial t} \neq 0$
4. Consider, a vessel initially contains fluid having mass  $m_1$  at the state  $p_1$ ,  $V_1$  and  $T_1$ . The corresponding values after filling operation are  $m_2$ ,  $p_2$ ,  $V_2$  and  $T_2$ .
5. There may be heat and work interaction with the surrounding due to change in volume of the bottle or by internal electrical/mechanical devices.



**Fig. 1.34.1.**

**B. Vessel Filling Process :**

1. Mass of fluid entering =  $m_2 - m_1$
2. Energy balance equation given as
 
$$(m_2 - m_1) c_p + Q = (m_2 u_2 - m_1 u_1) + W \quad \dots(1.34.1)$$

$u$  is the specific internal energy.
3. In filling process of a bottle from large reservoir, the properties of the entering fluid stream are taken as constant.
4. So, energy of entering fluid  $c_p$

$$c_p = u_p + p_p v_p + \frac{v_p^2}{2} = h_p + \frac{v_p^2}{2}$$

( $v_p$  = velocity of entering fluid)

5. From eq. (1.34.1),

$$(m_2 - m_1) \left( h_p + \frac{v_p^2}{2} \right) + Q = (m_2 u_2 - m_1 u_1) + W$$

6. If work transfer zero,  $W = 0$

$$(m_2 - m_1) \left( h_p + \frac{v_p^2}{2} \right) + Q = (m_2 u_2 - m_1 u_1)$$

7. If kinetic energy of entering fluid is neglect,  $v_p = 0$

$$(m_2 - m_1) h_p = m_2 u_2 - m_1 u_1$$

8. If the bottle is initially empty,  $m_1 = 0$

$$m_2 h_p = m_2 u_2$$

$$h_p = u_2$$

9. Therefore, specific internal energy of fluid charged into empty insulated bottle is equal to the specific enthalpy of the filling fluid in the charging pipe line.

### C. Vessel Evacuation Process :

1. Vessel evacuation process is just reverse of filling process.

2. Therefore analogous to filling process,

$$(m_1 - m_2) \left( h_p + \frac{v_p^2}{2} \right) + Q = m_1 u_1 - m_2 u_2$$

3. If  $Q = 0$ ,  $v_p = 0$

$$(m_1 - m_2) (h_p) = m_1 u_1 - m_2 u_2$$

4. If vessel is fully empty,  $m_2 = 0$

$$m_1 h_p = m_1 u_1$$

$$h_p = u_1$$

**Que 1.35.** 0.8 kg/s of air flows through a compressor under steady state conditions. The properties of air at entry are, pressure 1 bar, velocity 10 m/s, specific volume 0.95 m<sup>3</sup>/kg and internal energy 30 kJ/kg. The corresponding values at exit are 8 bar, 6 m/s, 0.2 m<sup>3</sup>/kg, 124 kJ/kg. Neglecting the change in potential energy, determine the power input and pipe diameter at entry and exit.

**AKTU 2013-14, Marks 10**

### Answer

#### Given : Properties of Air at Entry :

Pressure,  $p_1 = 1 \text{ bar} = 10^2 \text{ kN/m}^2$ , Velocity,  $C_1 = 10 \text{ m/s}$ ,

Specific volume,  $v_1 = 0.95 \text{ m}^3/\text{kg}$ , Internal energy,  $u_1 = 30 \text{ kJ/kg}$

**Properties of Air at Exit :** Pressure,  $p_2 = 8 \text{ bar} = 8 \times 10^2 \text{ kN/m}^2$ ,

Velocity,  $C_2 = 6 \text{ m/s}$ , Specific volume,  $v_2 = 0.2 \text{ m}^3/\text{kg}$ ,

Internal energy,  $u_2 = 124 \text{ kJ/kg}$

**To Find :** The power input and pipe diameter at entry and exit.

1. Using the steady flow energy equation

$$u_1 + \frac{C_1^2}{2} + p_1 \cdot v_1 + Q = u_2 + \frac{C_2^2}{2} + p_2 \cdot v_2 + W$$

2. Here  $Q = 0$

$$\begin{aligned} \text{So } 30 \times 10^3 + \frac{(10)^2}{2} + 10^2 \times 10^3 \times 0.95 + 0 \\ = 124 \times 10^3 + \frac{(6)^2}{2} + 8 \times 10^2 \times 10^3 \times 0.2 + W \\ 125050 = 284018 + W \\ W = -158968 \text{ J/kg} \end{aligned}$$

3. Work input required = 158968 J/kg = 158.968 kJ/kg

$$W \approx 159 \text{ kJ/kg}$$

4. For mass flow rate of 0.8 kg/s the input power required  
 $= W \times 0.8 = 159 \times 0.8 \text{ kW} = 127.2 \text{ kW}$

5. Using the continuity equation.

- i. Pipe diameter at entry,

$$\begin{aligned} \dot{m} &= \frac{C_1 A_1}{v} \\ 0.8 &= \frac{C_1 A_1}{v_1} \\ A_1 &= \frac{0.8 \times 0.95}{10} = 0.076 \text{ m}^2 \\ \frac{\pi}{4} d_i^2 &= 0.076 \Rightarrow d_i = 0.311 \text{ m} = 311 \text{ mm} \end{aligned}$$

- ii. Pipe diameter at exit,

$$\begin{aligned} \dot{m} &= \frac{C_2 A_2}{v_2} \\ 0.8 &= \frac{6 \times A_2}{0.2} \\ A_2 &= \frac{0.8 \times 0.2}{6} = 0.02667 \text{ m}^2 \\ \frac{\pi}{4} d_o^2 &= 0.02667 \Rightarrow d_o = 0.1843 \text{ m} = 184.3 \text{ mm} \end{aligned}$$

### VERY IMPORTANT QUESTIONS

***Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.***



**Q. 1. Write short notes on following :**

- a. System
- b. Surrounding
- c. Boundary
- d. Macroscopic and microscopic approaches.

**Ans.** Refer Q. 1.1, and Refer Q. 1.2; Unit-1.

**Q. 2. Describe thermodynamic equilibrium of system.**

**Ans.** Refer Q. 1.4, Unit-1.

**Q. 3. What do you understand by cyclic and quasi-static process ?**

**Ans.** Refer Q. 1.7, Unit-1.

**Q. 4. Define Dalton's Law and Amagat's Law.**

**Ans.** Refer Q. 1.13, Unit-1.

**Q. 5. Write down zeroth law of thermodynamics. Explain how it can be used for temperature measurement.**

**Ans.** Refer Q. 1.16, Unit-1.

**Q. 6. Derive the expression of work done for various non-flow processes.**

**Ans.** Refer Q. 1.19, Unit-1.

**Q. 7. Explain free expansion phenomenon.**

**Ans.** Refer Q. 1.22, Unit-1.

**Q. 8. Write short note on Joule's experiment and explain PMM-1.**

**Ans.** **Joule's Experiment :** Refer Q. 1.24, Unit-1.

**PMM-1 :** Refer Q. 1.28, Unit-1.

**Q. 9. What are the applications of SFEE ?**

**Ans.** Refer Q. 1.30, Unit-1.

**Q. 10. In a nozzle air at 627 °C and twice atmospheric pressure enters with negligible velocity of air at entrance. Find velocity of air at exit, assuming no heat loss and nozzle being horizontal. Take  $C_p = 1.005 \text{ kJ/kg-K}$  for air.**

**Ans.** Refer Q. 1.31, Unit-1.

**Q. 11. What is unsteady flow process ? Explain filling and evacuation process of a vessel.**

**Ans.** Refer Q. 1.34, Unit-1.



# 2

## UNIT

# Second Law of Thermodynamics

### Part-1 ..... (2-2C to 2-27C)

- *Thermal Reservoir*
- *Heat Engine*
- *Second Law of Thermodynamics*
- *Reversible and Irreversible Process*
- *Carnot Cycle and Engine*
- *PPM-II*

A. *Concept Outline : Part-1* ..... 2-2C

B. *Long and Medium Answer Type Questions* ..... 2-2C

### Part-2 ..... (2-27C to 2-46C)

- *Clausius Inequality*
- *Concept of Entropy*
- *TdS Equations*
- *Third Law of Thermodynamics*

A. *Concept Outline : Part-2* ..... 2-27C

B. *Long and Medium Answer Type Questions* ..... 2-28C

**PART-1**

*Thermal Reservoirs, Heat Engine, Second Law of Thermodynamics, Reversible and Irreversible Process, Carnot Cycle and Engine, PMM-II.*

**CONCEPT OUTLINE : PART-1**

**Thermal Reservoirs :** Thermal reservoir is defined as a large body of infinite heat capacity, which is capable of absorbing or rejecting an unlimited quantity of heat without suffering appreciable changes in its thermodynamic coordinates.

**Kelvin-Planck Statement :** It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

**Clausius Statement :** It is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a cooler to a hotter body.

**Carnot Theorem :** It states that of all heat engine operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions**

**Que 2.1.** What is heat reservoir ? Also discuss about heat engine.

**Answer****A. Heat Reservoir :**

1. A heat reservoir is a body with a very large heat capacity to which, and from which, heat can be transferred without any change in its temperature.
2. Such a body at high temperature is referred to as a high temperature reservoir.
3. If heat is transferred from it, then it is considered as a heat source.
4. A body at low temperature is referred to as a low temperature reservoir.
5. If heat is transferred to it, then it is considered as a heat sink.

6. By definition, a heat reservoir is a closed system with no work interaction.
7. The environment constitutes the largest heat reservoir operating without any change in temperature usually employed as a heat sink, and sometimes as a heat source.
8. The mediums in the environment which are used as such are generally the following :
  - a. Atmosphere air,
  - b. Ocean, river or well water, and
  - c. Ground.
9. The characteristic which remains constant for a heat reservoir is its temperature. Hence, a heat reservoir is characterised by its temperature.

**B. Heat Engine :**

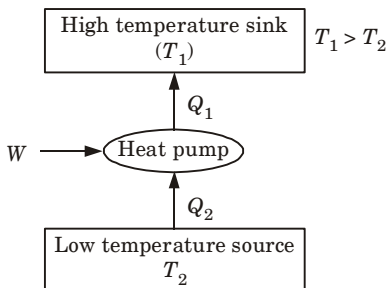
1. A heat engine is a thermodynamic system operating in a cycle to which net positive amount of heat is added, and from which net positive amount of work is obtained.

**Que 2.2.** Write short note on the following :

- a. Heat pump, and
- b. Refrigerator.

**Answer****A. Heat Pump :**

1. A heat pump is a reversed heat engine. It receives heat from a low temperature reservoir (source) and rejects it to a high temperature reservoir (sink).
2. This transfer of heat from a low temperature body to a high temperature one is essentially a non-spontaneous process. And that calls for the help of an external work which is supplied to the heat pump (Fig. 2.2.1).



**Fig. 2.2.1.** A schematic diagram of a heat pump.

3. A heat pump extracts  $Q_2$  amount of heat from the low temperature ( $T_2$ ) source and delivers  $Q_1$  amount of heat to the high temperature ( $T_1$ ) sink by consuming  $W$  amount of external work.
4. Now, the first law of efficiency of a heat pump cycle is usually called the coefficient of performance.
5. It is the desired effect upon the external work supplied for obtaining that desired effect,

$$\text{COP} = \frac{\text{Desired effect}}{\text{Work input}} \quad \dots(2.2.1)$$

6. Now, the desired effect for a heat pump is to supply heat  $Q_1$  to the hot body. Therefore,

$$\text{COP}_{\text{HP}} = \frac{Q_1}{W} \quad \dots(2.2.2)$$

Again,  $\sum_{\text{cycle}} Q = \sum_{\text{cycle}} W$  (the first law of thermodynamics)

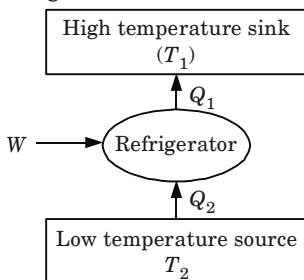
$$\therefore Q_1 - Q_2 = W$$

Hence, eq. (2.2.2) becomes

$$\text{COP}_{\text{HP}} = \frac{Q_1}{Q_1 - Q_2} \quad \dots(2.2.3)$$

### B. Refrigerator :

1. A refrigerator is similar to a heat pump.
2. It operates as a reversed heat engine.
3. Its duty is to extract heat as much as possible from the cold body/space and deliver the same to high temperature body/surroundings.
4. The desired effect of a refrigerator, under a steady state, is to pump out the heat in the same rate as is infiltrating into the system ( $Q_2$ ). And in order to do so, the refrigerator or an air conditioner takes up  $W$  amount of external work (Fig. 2.2.2).



**Fig. 2.2.2.** The working principle into the cold space of the refrigerator.

5. The desired effect of a refrigerator is to remove  $Q_2$  heat infiltrating into the cold space.
6. By using the external work, it rejects  $Q_1$  heat to the high temperature reservoir (surroundings). Therefore,

$$\text{COP}_{\text{ref}} = \frac{\text{Desired effect}}{\text{Work input}} = \frac{Q_2}{W} \quad \dots(2.2.4)$$

Again,  $\sum_{\text{cycle}} Q = \sum_{\text{cycle}} W$  (The first law of thermodynamics)

$$\therefore Q_1 - Q_2 = W$$

Hence, eq. (2.2.4) becomes

$$\text{COP}_{\text{ref}} = \frac{Q_2}{Q_1 - Q_2} \quad \dots(2.2.5)$$

$Q_2$  is the heat infiltrating into the cold space of the refrigerator.

**Que 2.3. Define second law of thermodynamics.**

**Answer**

1. On the basis of limitations of first law of thermodynamics, we have two statements of second law of thermodynamics which are as follows :
  - A. Kelvin-Planck Statement :** According to this statement, "It is impossible to construct a heat engine that operates in a cycle and produces no effect other than work output and exchange of heat with a single heat reservoir."
  - B. Clausius Statement :** According to this statement "It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a region of low temperature to another system at high temperature."
2. The Clausius statement implies that the heat itself cannot flow from a region of low temperature to a region of high temperature without the aid of external work.
3. Kelvin-Planck statement is applied to heat engines while Clausius statement is concerned with heat pumps and refrigerators. Both the statements of second law of thermodynamics are negative statements, they do not have any mathematical proofs.

**Que 2.4. Write Kelvin Planck and Clausius statements. Establish**

**the equivalence of above statements.**

**AKTU 2013-14, Marks 10**

**Answer**

**A. Statements :** Refer Q. 2.3, Page 2-5C, Unit-2.

**B. Equivalence of Kelvin-Planck and Clausius Statements :**

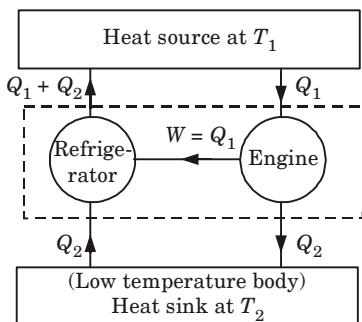
- Both Kelvin Planck and Clausius statements appear to be different but both are interlinked and are complementary to each other.
- Equivalence of these two statements can be proved by showing that violating one statement leads to the violation of other statement and vice-versa.

**a. Violating Kelvin Planck Statement Leads to Violation of Clausius Statement :**

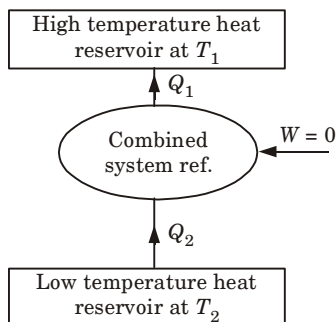
- Let's consider a heat engine which violates Kelvin Planck statement by absorbing heat from source at  $T_1$  and converts it completely into work.

$$\therefore W = Q_1$$

- Now let's introduce a refrigerator which gets work input from the engine.
- The refrigerator extracts  $Q_2$  from the low temperature heat reservoir and rejects heat  $Q_1 + Q_2$  to the high temperature heat reservoir.
- Combining the engine the refrigerator into one system working between same temperature limits, we observe that the sole effect of combined system is to transfer  $Q_2$  from low temperature heat reservoir  $T_2$  to high temperature heat reservoir without any work input thus violating the Clausius statement Fig. 2.4.1.



**Fig. 2.4.1.**



**Fig. 2.4.2. Combined system (refrigerator) violates Clausius statement.**

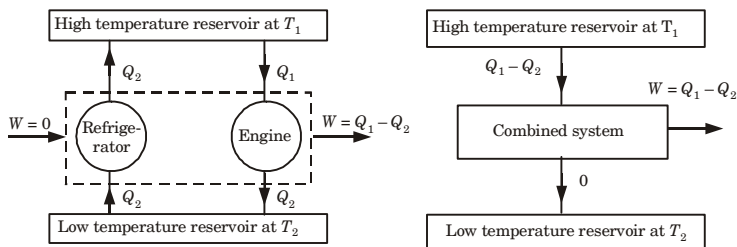
**b. Violation of Clausius Statement Leads to Violation of Kelvin Planck Statement :**

- Let's consider a refrigerator which violates Clausius statement as shown in the Fig. 2.4.3(a).

- Refrigerator absorbs heat  $Q_2$  from low temperature heat reservoir and rejects the same to the high temperature reservoir without the aid of any external work *i.e.*,  $W = 0$ .
- Let's introduce a heat engine which receives heat  $Q_1$  ( $Q_1 > Q_2$ ) from the high temperature reservoir and rejects heat  $Q_2$  and produces work,

$$W = Q_1 - Q_2.$$

- Now combining the refrigerator and heat engine into one system. We observe that the combined system operates as a heat engine, which receives heat from a single high temperature reservoir as  $Q_1 - Q_2$  and converts the same into equal amount of work energy without any heat rejection.



(a) Violation of Clausius statement.

(b) Combined system (engine) violates Kelvin Planck statement.

Fig. 2.4.3.

- This violates the Kelvin Planck statement of second law of thermodynamics.

**Que 2.5.**

**Shows that efficiency of an irreversible engine is always less than the efficiency of reversible engine operating between same temperature limit.**

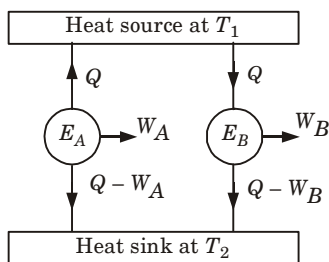
**AKTU 2011-12, Marks 10**

**Answer**

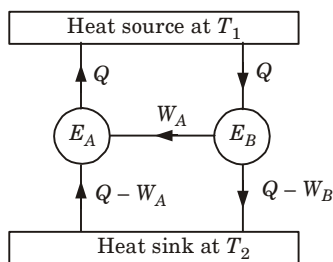
- According to Carnot's theorem, "No heat engine operating in a cycle between two given heat reservoirs, with fixed temperatures, can be more efficient than a reversible engine operating between the same temperature limits (or same heat reservoirs)."
- Let us consider a reversible engine  $E_A$  and an irreversible engine  $E_B$  operating between the same heat reservoirs at temperatures  $T_1$  and  $T_2$ .
- For the same quantity of heat withdrawn from the high temperature reservoir, the work output from these engines is  $W_A$  and  $W_B$  respectively.



4. Therefore heat rejected by reversible engine will be  $Q - W_A$  and by irreversible engine will be  $Q - W_B$ .
5. Let us assume that irreversible engine  $E_B$  is more efficient than the reversible engine  $E_A$ .
6. Then it follows that  $\frac{W_B}{Q} > \frac{W_A}{Q}$  or  $W_B > W_A$ .
7. That is to say that the output of the irreversible engine is more than that of reversible engine.



(a)



(b)

**Fig. 2.5.1.**

8. Now let the reversible engine operates as a refrigerator and the irreversible engine ( $E_B$ ) still continues to act as an engine. Since the engine  $E_A$  is reversible, amount of heat and work interactions will remain the same but their directions will be reversed. Work input to drive the refrigerator may be received from the irreversible engine through direct coupling between the two.
9. The Fig. 2.5.1(b) represents heat and work interactions for the composite system constituted by the reversible engine (which is now operating as refrigerator) and the irreversible engine.
10. The net effect is
  - a. No net interaction with the heat source at  $T_1$ , because it supplies and recovers back the same magnitude of heat.
  - b. The composite system withdraws  $(Q - W_A) - (Q - W_B) = W_B - W_A$  units of heat from the heat sink at  $T_2$  and converts the same into an equal amount of work output.
11. Therefore the combination of the two constitutes a perpetual motion machine of 2<sup>nd</sup> kind violating second law of thermodynamics. Thus the assumption that the irreversible engine is more efficient than a reversible engine is wrong.
12. Therefore an irreversible engine cannot be more efficient than a reversible engine operating between the same heat reservoirs.

**Que 2.6.** A reversible heat engine operates between two reservoirs at temperature of 600 °C and 40 °C. The engine drives a reversible refrigerator which operates between reservoirs at temperature of 40 °C and - 20 °C. The heat transfer to the engine is 2 MJ and the net work output of the combined engine and refrigerator plant is 360 kJ. Find the heat transfer to the refrigerant and the net heat transfer to the reservoir at 40 °C. Also find these values if the efficiency of the heat engine and COP of the refrigerator are each 40 % of their maximum possible values.

AKTU 2011-12, Marks 06

**Answer**

**Given :** Heat reservoirs temperature for heat engine,

$$T_1 = 600\text{ }^{\circ}\text{C}, T_2 = 40\text{ }^{\circ}\text{C}$$

Heat reservoirs temperature for refrigerator,

$$T_2 = 40\text{ }^{\circ}\text{C}, T_3 = -20\text{ }^{\circ}\text{C},$$

$$Q_1 = 2000\text{ kJ}, W = 360\text{ kJ}, \text{COP}_{\text{ref}} = 40\text{ \% of maximum value.}$$

**To Find :** Heat transfer to the refrigerant, Net heat transfer to the reservoir and Efficiency of heat engine.

1. Efficiency of heat engine,

$$\eta_{\text{HE}} = 1 - \frac{T_2}{T_1} = 1 - \frac{(273 + 40)}{(273 + 600)} = 0.642$$

2. Efficiency is also given as

$$\eta_{\text{HE}} = \frac{W_1}{Q_1}$$

$$0.642 = \frac{W_1}{2000}$$

$$W_1 = 1284\text{ kJ}$$

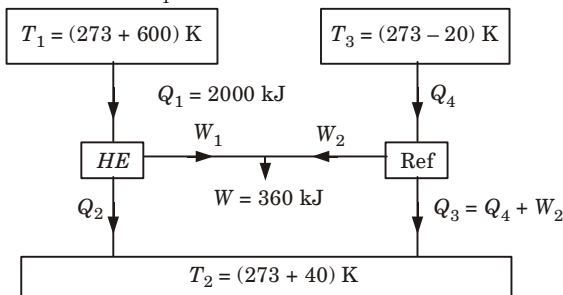


Fig. 2.6.1.

3. COP of refrigeration cycle

$$\text{COP} = \frac{T_3}{T_2 - T_3} = \frac{(273 - 20)}{(273 + 40) - (273 - 20)} = 4.22$$

4. COP also given as

$$\text{COP} = \frac{Q_4}{W_2} = 4.22$$

5. Since total output of system is
- $W$
- .

$$\therefore W = W_1 - W_2$$

$$360 = 1284 - W_2$$

$$W_2 = 924 \text{ kJ}$$

6. So,

$$Q_4 = 4.22 \times W_2$$

$$= 4.22 \times 924 = 3899 \text{ kJ}$$

- 7.

$$Q_3 = Q_4 + W_2$$

$$= 3899 + 924 = 4823 \text{ kJ}$$

- 8.

$$Q_2 = Q_1 - W_1$$

$$= 2000 - 1284 = 716 \text{ kJ}$$

- 9.

Heat rejected to the  $40^\circ\text{C}$  reservoir  $= Q_2 + Q_3$ 

$$= 716 + 4823 = 5539 \text{ kJ}$$

10. Efficiency of actual heat engine is 40 %.

$$\therefore \eta' = 0.4 \times \eta_o = 0.4 \times 0.642$$

$$W_1 = 0.4 \times 0.642 \times 2000 = 513.6 \text{ kJ}$$

$$W_2 = 513.6 - 360 = 153.6 \text{ kJ}$$

11. COP of the actual refrigerator

$$\text{COP} = \frac{Q_4}{W_2}$$

$$0.4 \times 4.22 = \frac{Q_4}{W_2}$$

So,

$$Q_4 = 1.69 \times 153.6 = 259.6 \text{ kJ}$$

$$Q_3 = 259.6 + 153.6 = 413.2 \text{ kJ}$$

$$Q_2 = Q_1 - W_1$$

$$= 2000 - 513.6 = 1486.4 \text{ kJ}$$

12. Heat rejected to the
- $40^\circ\text{C}$
- reservoir
- $= Q_2 + Q_3$

$$= 413.2 + 1486.4 = 1899.6 \text{ kJ}$$

**Que 2.7.**

**All reversible engines working between the two constant temperature reservoirs have the same efficiency.**

**Comment.****AKTU 2012-13, Marks 05****Answer**

1. "The efficiency of all reversible heat engines operating between the same temperature levels is the same".

2. From Fig. 2.7.1, let both the heat engines  $HE_A$  and  $HE_B$  be reversible and  $\eta_A > \eta_B$ . Let the rates of working of the engines be such that

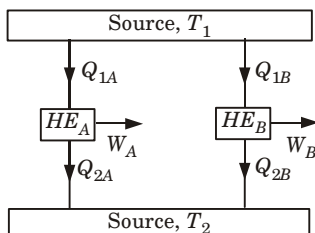
$$Q_{1A} = Q_{1B} = Q_1$$

3. Since

$$\eta_A > \eta_B$$

$$\frac{W_A}{Q_{1A}} > \frac{W_B}{Q_{1B}}$$

$$W_A > W_B$$



**Fig. 2.7.1.** The cyclic heat engines  $HE_A$  and  $HE_B$  operating between the same source and sink.

4. If  $HE_B$  is reversed to run say, as a heat pump using some part of the work output ( $W_A$ ) of engine  $HE_A$ , we see that the combined system of heat pump  $HE_B$  and engine  $HE_A$ , becomes a PMM2.
5. So  $\eta_A$  cannot be greater than  $\eta_B$ . Similarly, if we assume  $\eta_B > \eta_A$  and reverse the engine  $HE_A$ , we observe that  $\eta_B$  cannot be greater than  $\eta_A$ ,  
 $\therefore \eta_A = \eta_B$
6. Since the efficiencies of all reversible engines operating between the same heat reservoirs are the same, the efficiency of a reversible engine is independent of the nature or amount of the working substance undergoing the cycle.

**Que 2.8.**

A temperature of  $-5^\circ\text{C}$  is maintained by steadily circulating a refrigerant at low temperature through passages in the walls of the freezer compartment of a refrigerator. The air surrounding the refrigerator is at  $27.1^\circ\text{C}$ . The power input required to operate the refrigerator is  $3316.5\text{ kJ/h}$  and the rate of heat transfer from the freezer compartment to the refrigerant is  $8140.5\text{ kJ/h}$ . Draw the system and find the coefficient of performance of the refrigerator and compare with the coefficient of performance of a reversible refrigeration cycle operating between the reservoirs at the same temperature limits. Comment on the results.

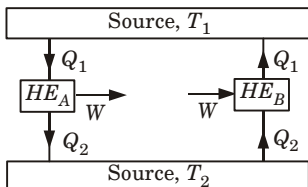
**Answer**

**Given :**  $T_2 = -5^\circ\text{C} = -5 + 273 = 268\text{ K}$ ,

$T_1 = 27.1^\circ\text{C} = 27.1 + 273 = 300.1\text{ K}$ ,  $Q = 8140.5\text{ kJ/h}$ ,

$W = 3316.5\text{ kJ/h}$

**To Find :** COP of refrigerator.



**Fig. 2.8.1.**

- Since,  $(\text{COP})_{\text{ref}} = \frac{Q_2}{Q_1 - Q_2}$   
 $Q_2 = Q_1 - W = 8140.5 - 3316.5 = 4824\text{ kJ/h}$   
 $\therefore (\text{COP})_{\text{ref}} = \frac{4824}{8140.5 - 4824} = 1.45$
- Now for reversible refrigerator,  

$$[(\text{COP})_{\text{ref}}]_{\text{rev}} = \frac{T_2}{T_1 - T_2} = \frac{268}{300.1 - 268} = 8.35$$
  
 $\therefore [(\text{COP})_{\text{ref}}]_{\text{rev}} \gg (\text{COP})_{\text{ref}}$

**Que 2.9. Discuss the irreversibility due to :**

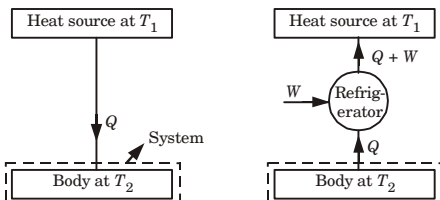
- Heat transfer through a finite temperature difference, and
- Free expansion process.

**AKTU 2012-13, Marks 05**

**Answer**

**A. Irreversibility due to Finite Temperature Difference :**

- Consider a heat source at  $T_1$  and a body at  $T_2$  as shown in the adjoining Fig. 2.9.1 ( $T_1 > T_2$ ).

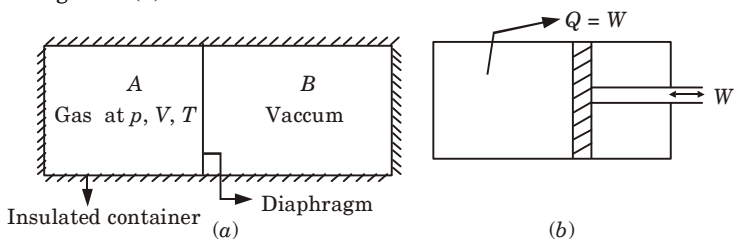


**Fig. 2.9.1.**

- Heat  $Q$  can be transferred from heat source to the body by bringing them in contact due to finite temperature difference.
- If the process is to be reversed in order to restore the temperature of the body, it requires a Carnot refrigerator (or heat pump) which would transfer heat  $Q$  from the body at the expense of external work  $W$  and reject  $(Q + W)$  to the heat source at  $T_1$ .
- On the completion of reversed process it is observed that work energy of surroundings has been transformed into heat energy.
- This transformation of work energy into heat energy is undesirable from the view point of second law of thermodynamics.
- Thus it can be concluded that all the processes in which heat transfer is due to finite temperature difference are irreversible.

### B. Free Expansion Process :

- Let us consider an insulated container divided in two compartments A and B separated by means of a diaphragm as shown in the Fig. 2.9.2(a).



**Fig. 2.9.2.**

- Compartment A has a gas system maintained at  $p$ ,  $V$  and  $T$ . In compartment B, vacuum is maintained.
- If the diaphragm is removed, gas in the compartment A expands into B until an equilibrium state is established.
- During this expansion process;  
heat  $Q = 0$  (since the system is insulated)  
and work  $W = 0$  (i.e., no external work transfer)
- From the first law of thermodynamics,  
For a closed system,  $\delta Q = dU + \delta W$   
Here  $\delta Q$  and  $\delta W$  are zero.
- Change in internal energy,  $dU = 0 \Rightarrow U_1 = U_2$
- Only pressure and volume of the gas are changed. Now if the process has to be reversed so that it may attain its initial state, it requires an isothermal compression process in which work ' $W$ ' is supplied to the system from the surroundings with equivalent amount of heat to be rejected from the system to the surroundings even if the process is carried out in the absence of friction.

8. The sole effect of the process is the transformation of work energy of the surroundings into the heat energy.
9. That's why free expansion process is highly irreversible.

**Que 2.10.** A reversible heat engine operates between two reservoirs at  $827^{\circ}\text{C}$  and  $27^{\circ}\text{C}$ . Engine drives a Carnot refrigerator maintaining  $-13^{\circ}\text{C}$  and rejecting heat to reservoir at  $27^{\circ}\text{C}$ . Heat input to the engine is  $2000\text{ kJ}$  and the net work available is  $300\text{ kJ}$ . Determine the heat transferred to refrigerator and total heat rejected to reservoir at  $27^{\circ}\text{C}$ .

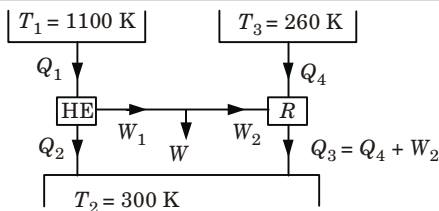
**AKTU 2013-14, Marks 10**

**Answer**

**Given :**  $T_1 = 827 + 273 = 1100\text{ K}$ ,  $W = 300\text{ kJ}$ ,

$T_2 = 27 + 273 = 300\text{ K}$ ,  $Q_1 = 2000\text{ kJ}$ ,  $T_3 = -13 + 273 = 260\text{ K}$

**To Find :** Heat transfer and total heat rejected.



**Fig. 2.10.1.**

1. Efficiency of heat engine,

$$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{1100} = 0.7272$$

2. Again  $\frac{W_1}{Q_1} = 0.7272$

$$\begin{aligned} W_1 &= 0.7272 \times Q_1 \\ &= 0.7272 \times 2000 = 1454.4\text{ kJ} \end{aligned}$$

3. Again, at junction,

$$\begin{aligned} W_1 - W_2 &= W \\ W_2 &= W_1 - W \\ &= 1454.4 - 300 = 1154.4\text{ kJ} \end{aligned}$$

4. COP of refrigeration,

$$\begin{aligned} \text{COP} &= \frac{T_3}{T_2 - T_3} = \frac{Q_4}{W_2} \\ \frac{260}{300 - 260} &= \frac{Q_4}{1154.4} \\ Q_4 &= 7503.6\text{ kJ} \end{aligned}$$

5. Now  $Q_3 = Q_4 + W_2$   
 $= 7503.6 + 1154.4 = 8658 \text{ kJ}$
6.  $Q_2 = Q_1 - W_1 = 2000 - 1454.4 = 545.6 \text{ kJ}$
7. Heat rejected to the  $27^\circ\text{C}$  reservoir  
 $= Q_2 + Q_3 = 545.6 + 8658 = 9203.6 \text{ kJ}$

**Que 2.11.** A heat engine operating between two reservoirs at  $1000 \text{ K}$  and  $300 \text{ K}$  is used to drive a heat pump which extracts heat from the reservoir at  $300 \text{ K}$  at a rate twice that at which the engine ejects 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 ejects heat? What is the rate of heat ejection from the heat pump if the rate of heat supply to the engine is  $50 \text{ kW}$ ?

AKTU 2015-16, Marks 10

**Answer**

**Given :**  $T_1 = 1000 \text{ K}$ ,  $T_2 = 300 \text{ K}$ ,  $T_3 = 300 \text{ K}$ ,  $\eta_{HE} = 0.4 (\eta_{HE})_{\max}$   
 $\text{COP}_{HP} = 0.5 \times (\text{COP}_{HP})_{\max}$ ,  $Q_1 = 50 \text{ kW}$ ,  $Q_3 = 2 Q_2$

**To Find :** Temperature of reservoir, Rate of heat rejected.

1. Since,  $(\eta_{HE})_{\max} = 1 - \frac{T_2}{T_1}$   
 $= 1 - \frac{300}{1000} = 0.7$
- So,  $\eta_{HE} = 0.4 \times 0.7 = 0.28$

2. But  $\eta_{HE} = \frac{W}{Q_1}$

then,  $W = 0.28 \times 50 = 14 \text{ kW}$

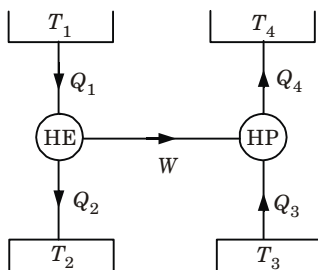


Fig. 2.11.1.

3. Since,  $(\text{COP}_{HP})_{\max} = \frac{T_4}{T_4 - T_3} = \frac{T_4}{T_4 - 300}$



So, 
$$\text{COP}_{HP} = 0.5 \times \frac{T_4}{T_4 - 300} \quad \dots(2.11.1)$$

4. For heat engine,

$$Q_2 = Q_1 - W = 50 - 14$$

$$Q_2 = 36 \text{ kW}$$

Since,  $Q_3 = 2Q_2 = 2 \times 36 = 72 \text{ kW}$

5. Now, for heat pump,

$$Q_4 = W + Q_3$$

$$= 14 + 72 = 86 \text{ kW} \quad \dots(2.11.2)$$

6. Since, we know that,

$$\text{COP}_{HP} = \frac{Q_4}{W}$$

7. Now from eq. (2.11.1),

$$\frac{86}{14} = \frac{0.5 T_4}{T_4 - 300}$$

$$T_4 - 300 = 0.08139 T_4$$

$$T_4 = 326.58 \text{ K} \quad \dots(2.11.3)$$

8. Hence from eq. (2.11.2) and eq. (2.11.3), the temperature of the reservoir to which the heat pump rejects heat = 326.58 K, and the rate of heat rejection from the heat pump = 86 kW

**Que 2.12. Explain working of Carnot and reversed Carnot Cycle.**

**AKTU 2013-14, Marks 10**

**Answer**

**A. Carnot Cycle Operations (Processes) :**

1. The system inside the cylinder has an initial volume and initial pressure as indicated by the state point '1' on  $p$ - $V$  diagram.
2. Let  $Q_1$  be the heat supplied to the system at  $T_1$  (source temperature). Since the heat supply (addition) takes place at constant temperature, the system volume increases at constant temperature thus performing an isothermal expansion.

**a. Process 1-2 : (Isothermal Heat Addition Process)**

1. During this process, the working substance (air) expands isothermally from state '1' to state '2'.
2. At point '2' heat supply is cut off and cylinder head is brought in contact with an insulator or adiabatic cover.

**b. Process 2-3 : (Reversible Adiabatic Expansion)**

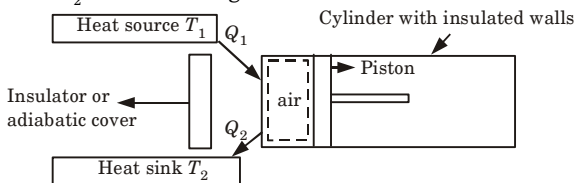
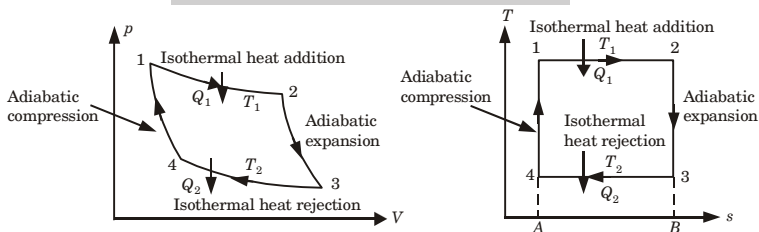
1. Adiabatic cover is brought in contact with the cylinder head and during this process, the working substance is allowed to expand adiabatically so that its temperature becomes  $T_2$ .

**c. Process 3-4 : (Reversible Isothermal Heat Rejection)**

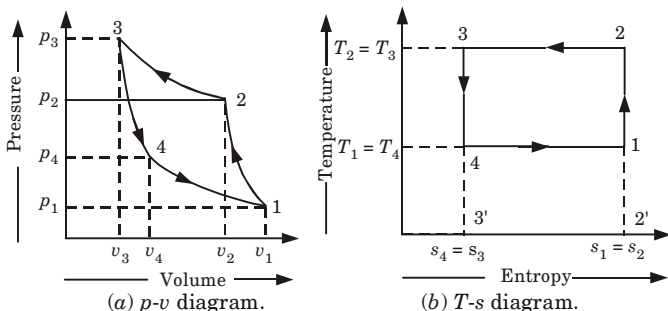
1. Adiabatic cover is removed and heat sink is brought in contact with the cylinder head.
2. The working substance is compressed isothermally thus transferring heat  $Q_2$  to the heat sink at  $T_2$ .

**d. Process 4-1 : (Reversible Adiabatic Compression)**

1. The adiabatic cover is again brought in contact with the cylinder head and the system is compressed adiabatically.
2. During this process the temperature of system is raised to  $T_1$  from  $T_2$  and it is brought to its initial state.

**Fig. 2.12.1.** Operation is Carnot cycle.**Fig. 2.12.2.** Carnot cycle on  $p$ - and  $T$ - $s$  diagram.**B. Reversed Carnot Cycle :**

1. A reversed Carnot cycle, using air as working medium (or refrigerant) is shown on  $p$ - $v$  and  $T$ - $s$  diagrams in Fig. 2.12.3(a) and 2.12.3(b) respectively.

**Fig. 2.12.3.** Reversed Carnot cycle.

2. At point 1, let  $p_1, v_1, T_1$  be the pressure, volume and temperature of air respectively.
3. The four processes of the cycle are as follows :

**a. Isentropic Compression Process :**

1. The air is compressed isentropically as shown by the curve 1-2 on  $p-v$  and  $T-s$  diagrams.
2. During this process, the pressure of air increases from  $p_1$  to  $p_2$ , specific volume decreases from  $v_1$  to  $v_2$  and temperature increases from  $T_1$  to  $T_2$ .
3. We know that during isentropic compression, no heat is absorbed or rejected by the air.

**b. Isothermal Heat Rejection Process :**

1. The air is now compressed isothermally (*i.e.*, at constant temperature,  $T_2 = T_3$ ) as shown by the curve 2-3 on  $p-v$  and  $T-s$  diagrams.
2. During this process, the pressure of air increases from  $p_2$  to  $p_3$  and specific volume decreases from  $v_2$  to  $v_3$ .
3. We know that the heat rejected by the air during isothermal compression per kg of air,

$$\begin{aligned} q_R = q_{2-3} &= \text{Area } 2-3-3'-2' \\ &= T_3(s_2 - s_3) = T_2(s_2 - s_3) \end{aligned}$$

**c. Isentropic Expansion Process :**

1. The air is now expanded isentropically as shown by the curve 3-4 on  $p-v$  and  $T-s$  diagrams.
2. The pressure of air decreases from  $p_3$  to  $p_4$ , specific volume increases from  $v_3$  to  $v_4$  and the temperature decreases from  $T_3$  to  $T_4$ .
3. We know that during isentropic expansion, no heat is absorbed or rejected by the air.

**d. Isothermal Heat Addition Process :**

1. The air is now expanded isothermally (*i.e.*, at constant temperature,  $T_4 = T_1$ ) as shown by the curve 4-1 on  $p-v$  and  $T-s$  diagrams.
2. The pressure of air decreases from  $p_4$  to  $p_1$ , and specific volume increases from  $v_4$  to  $v_1$ .
3. We know that the heat absorbed by the air (or heat extracted from the cold body) during isothermal expansion per kg of air,

$$\begin{aligned} q_A = q_{4-1} &= \text{Area } 4-1-2'-3' \\ &= T_4(s_1 - s_4) = T_4(s_2 - s_3) = T_1(s_2 - s_3) \end{aligned}$$

4. We know that work done during the cycle per kg of air

$$w_R = \text{Heat rejected} - \text{Heat absorbed}$$

$$= q_R - q_A = q_{2-3} - q_{4-1}$$

$$= T_2(s_2 - s_3) - T_1(s_2 - s_3) = (T_2 - T_1)(s_2 - s_3)$$

5. Coefficient of performance of the refrigeration system working on reversed Carnot cycle,

$$\begin{aligned} (\text{COP})_R &= \frac{\text{Heat absorbed}}{\text{Work done}} = \frac{q_A}{q_R - q_A} = \frac{q_{4-1}}{q_{2-3} - q_{4-1}} \\ &= \frac{T_1(s_2 - s_3)}{(T_2 - T_1)(s_2 - s_3)} = \frac{T_1}{T_2 - T_1} \end{aligned}$$

6. Though the reversed Carnot cycle is the most efficient between the fixed temperature limits, yet no refrigerator has been made using this cycle.
7. This is due to the reason that the isentropic processes of the cycle require high speed while the isothermal processes require an extremely low speed.
8. This variation in speed of air is not practicable.

**Que 2.13.** Why Carnot cycle is a theoretical cycle ? Explain. Three

reversible engines of Carnot type are operating in series between the limiting temperatures of 1100 K and 300 K. If the work output from engines is in proportion of 3 : 2 : 1, determine the intermediate temperature.

**AKTU 2011-12, Marks 10**

**Answer**

**A. Carnot Cycle is a Theoretical Cycle :** Carnot cycle cannot be used in a practical engine because of following reasons :

1. An isothermal (expansion or compression) process can be achieved only if the piston moves very slowly to allow time for heat transfer so that the temperature remains constant.
2. Adiabatic process can be achieved only if the piston moves very fast so that heat transfer between the system and the surrounding is negligible due to short time available. In a Carnot cycle, isothermal and adiabatic processes take place during the same stroke and therefore the piston has to move very slowly for part of stroke and has to move very fast during the remaining part of the stroke. This kind of variation of piston movement during the same stroke is not possible from kinematic viewpoint.
3. It is impossible to achieve a frictionless process.
4. It is not possible to transfer heat without finite difference of temperature (according to second law of thermodynamics).

- Real process can never be reversible process.
- The atmosphere can be considered an infinitely large sink at constant temperature but it is never possible to produce a large heat source that will supply heat without change in the temperature.
- The above reasons describe that a Carnot cycle cannot be used in a practical engine.

**B. Given :**  $W_1 : W_2 : W_3 = 3 : 2 : 1$

**To Find :** The intermediate temperature.

- Efficiency of heat engine 1 :

$$\eta_1 = \frac{W_1}{Q_1} = \frac{T_1 - T_2}{T_1}$$

Since,

$$W_1 = Q_1 - Q_2$$

$$Q_1 = W_1 + Q_2$$

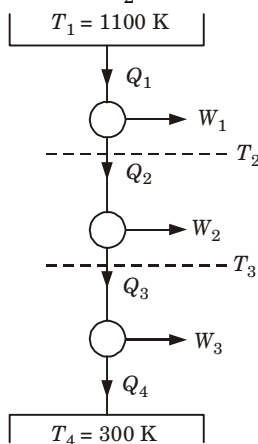
So, 
$$\frac{W_1}{W_1 + Q_2} = \frac{T_1 - T_2}{T_1} \quad \text{or} \quad \frac{W_1 + Q_2}{W_1} = \frac{T_1}{T_1 - T_2}$$

$$1 + \frac{Q_2}{W_1} = \frac{T_1}{T_1 - T_2} \quad \text{or} \quad \frac{Q_2}{W_1} = \frac{T_1}{T_1 - T_2} - 1$$

$$\frac{Q_2}{W_1} = \frac{T_1 - (T_1 - T_2)}{T_1 - T_2} = \frac{T_2}{T_1 - T_2}$$

Hence,

$$W_1 = Q_2 \left( \frac{T_1 - T_2}{T_2} \right) \quad \dots(2.13.1)$$



**Fig. 2.13.1.**

- For heat engine 2 :

$$\eta_2 = \frac{W_2}{Q_2} = \frac{T_2 - T_3}{T_2}$$

$$W_2 = Q_2 \left( \frac{T_2 - T_3}{T_2} \right) \quad \dots(2.13.2)$$

Since,

$$W_2 = Q_2 - Q_3 = W_2 + Q_3$$

So,

$$\frac{W_2}{W_2 + Q_3} = \frac{T_2 - T_3}{T_2} \quad \text{or} \quad \frac{T_2}{T_2 - T_3} = \frac{W_2 + Q_3}{W_2}$$

$$1 + \frac{Q_3}{W_2} = \frac{T_2}{T_2 - T_3} \quad \text{or} \quad \frac{Q_3}{W_2} = \frac{T_2}{T_2 - T_3} - 1$$

$$\frac{Q_3}{W_2} = \frac{T_2 - (T_2 - T_3)}{T_2 - T_3} = \frac{T_3}{T_2 - T_3}$$

$$W_2 = Q_3 \left( \frac{T_2 - T_3}{T_3} \right) \quad \dots(2.13.3)$$

3. For heat engine 3 :

$$\eta_3 = \frac{W_3}{Q_3} = \frac{T_3 - T_4}{T_3}$$

$$W_3 = Q_3 \left( \frac{T_3 - T_4}{T_3} \right) \quad \dots(2.13.4)$$

Now

$$\frac{W_1}{W_2} = \frac{3}{2}$$

4. Put the value of  $W_1$  and  $W_2$  from eq. (2.13.1) and eq. (2.13.2).

$$\frac{Q_2 \left( \frac{T_1 - T_2}{T_2} \right)}{Q_2 \left( \frac{T_2 - T_3}{T_2} \right)} = \frac{3}{2}$$

$$2(T_1 - T_2) = 3(T_2 - T_3)$$

$$5T_2 - 3T_3 = 2T_1$$

$$T_1 = 1100 \text{ K}$$

$$5T_2 - 3T_3 = 2200 \text{ K}$$

$$\dots(2.13.5)$$

5. Ratio of  $W_2$  and  $W_3$

$$\frac{W_2}{W_3} = \frac{2}{1}$$

6. Put the value of  $W_2$  and  $W_3$  from eq. (2.13.3) and eq. (2.13.4),

$$\frac{Q_3 \left( \frac{T_2 - T_3}{T_3} \right)}{Q_3 \left( \frac{T_3 - T_4}{T_3} \right)} = \frac{2}{1}$$

$$2(T_3 - T_4) = T_2 - T_3$$

$$T_2 = 3T_3 - 2T_4$$

$$T_4 = 300 \text{ K}$$

$$T_2 = 3T_3 - 600$$

...(2.13.6)

7. Put the value of  $T_2$  into eq. (2.13.5),

$$5(3T_3 - 600) - 3T_3 = 2200$$

$$12T_3 = 5200$$

$$T_3 = \frac{5200}{12} = 433.33 \text{ K}$$

8. Put the value of  $T_3$  in eq. (2.13.6),

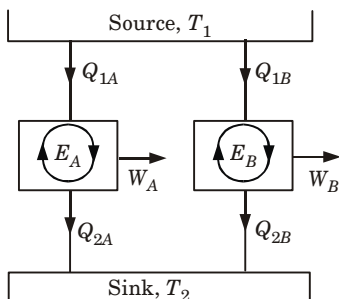
$$T_2 = 3 \times 433.33 - 600 \approx 700 \text{ K}$$

**Que 2.14.** Explain Carnot's theorem. Also explain its corollary.

**Answer**

**A. Carnot's Theorem :**

1. It states that of all heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.



**Fig. 2.14.1.** The cyclic heat engines  $E_A$  and  $E_B$  operating between the same source and sink of which  $E_B$  is reversible.

- Let two heat engines  $E_A$  and  $E_B$  operate between the given source at temperature  $T_1$  and given sink at temperature  $T_2$  as shown in Fig. 2.14.1.
- Let  $E_A$  be any heat engine and  $E_B$  be any reversible heat engine. We have to prove that the efficiency of  $E_B$  is more than that of  $E_A$ .
- Let us assume that this is not true and  $\eta_A > \eta_B$ .
- Let the rates of working of the engines be such that

$$Q_{1A} = Q_{1B} = Q_1$$

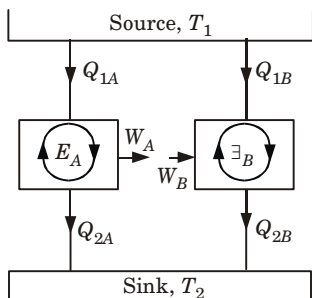
Since

$$\eta_A > \eta_B$$

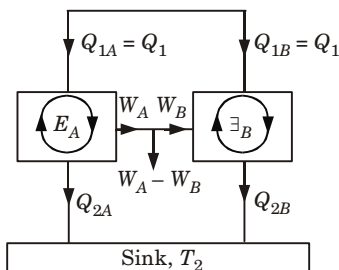
$$\frac{W_A}{Q_{1A}} > \frac{W_B}{Q_{1B}}$$

$$\therefore W_A > W_B$$

6. Now, let  $E_B$  be reversed. Since  $E_B$  is a reversible heat engine, the magnitude of heat and work transfer quantities will remain the same, but their directions will be reversed, as shown in Fig. 2.14.2.



**Fig. 2.14.2.**  $E_A$  is reversed.



**Fig. 2.14.3.**  $E_A$  and  $E_B$  together violate the Kelvin-Planck statement.

7. Since  $W_A > W_B$ , some part of  $W_A$  (equal to  $W_B$ ) may be fed to drive the reversed heat engine  $E_B$ .
8. Since  $Q_{1A} = Q_{1B} = Q_1$ , the heat discharged by  $E_B$  may be supplied to  $E_A$ .
9. The source may, therefore, be eliminated (Fig. 2.14.3). The net result is that  $E_A$  and  $E_B$  together constitute a heat engine which, operating in a cycle, produces net work  $W_A - W_B$ , while exchanging heat with a single reservoir at  $T_2$ . Violates the Kelvin-Planck statement of the second law. Hence the assumption that  $\eta_A > \eta_B$  is wrong.

Therefore  $\eta_B \geq \eta_A$

### B. Corollary of Carnot' Theorem :

1. The efficiency of all reversible heat engines operating between the same temperature levels is the same.
2. Let both the heat engines  $E_A$  and  $E_B$  (Fig. 2.14.2) be reversible.
3. Let us assume  $\eta_A > \eta_B$ .
4. Similar if  $E_B$  is reversed to run, say as a heat pump using some part of the work output ( $W_A$ ) of engine  $E_A$ , we see that the combined system of heat pump  $E_B$  and engine  $E_A$ , becomes a PMM2.
5. So  $\eta_A$  cannot be greater than  $\eta_B$ .
6. Similarly, if  $\eta_B > \eta_A$  and reverse the engine  $E_A$ , then  $\eta_B$  can not be greater than  $\eta_A$ .
7. Therefore  $\eta_A = \eta_B$



8. Since the efficiencies of all reversible heat engines operating between the same heat reservoirs are the same, the efficiency of a reversible engine is independent of the nature or amount of the working substance undergoing the cycle.

**Que 2.15.** A Carnot engine operates between temperatures  $T_1$  and  $T_2$  with efficiency  $\eta_1$  and other Carnot engine operates between temperatures  $T_2$  and  $T_3$  with efficiency  $\eta_2$ . Show that the Carnot engine operating between temperatures  $T_1$  and  $T_3$  will have efficiency given as  $(\eta_1 + \eta_2 - \eta_1\eta_2)$ .

**Answer**

**Given :** Carnot engine with efficiency,  $\eta_1$  between  $T_1$  and  $T_2$ .

Other Carnot engine with efficiency,  $\eta_2$  between  $T_2$  and  $T_3$ .

**To Find :** Show that, efficiency between  $T_1$  and  $T_3 = (\eta_1 + \eta_2 - \eta_1\eta_2)$ .

1. Efficiency for temperature  $T_1$  and  $T_3$  is

$$\eta_3 = 1 - \frac{T_3}{T_1} \quad \dots(2.15.1)$$

2. Efficiency for temperature  $T_1$  and  $T_2$  is

$$\eta_1 = 1 - \frac{T_2}{T_1} \quad \dots(2.15.2)$$

3. Efficiency for temperature  $T_2$  and  $T_3$  is

$$\eta_2 = 1 - \frac{T_3}{T_2} \quad \dots(2.15.3)$$

4. From eq. (2.15.2),  $\eta_1 T_1 = T_1 - T_2$

$$T_1 - \eta_1 T_1 = T_2$$

$$T_1 (1 - \eta_1) = T_2$$

5. Put the value of  $T_2$  in eq. (2.15.3),

$$\eta_2 = 1 - \frac{T_3}{T_1(1 - \eta_1)}$$

$$\frac{T_3}{T_1(1 - \eta_1)} = 1 - \eta_2$$

$$\frac{T_3}{T_1} = (1 - \eta_2)(1 - \eta_1) = 1 - \eta_1 - \eta_2 + \eta_1\eta_2$$

6. Putting value of  $\frac{T_3}{T_1}$  in eq. (2.15.1), we get

$$\eta_3 = 1 - \frac{T_3}{T_1}$$

$$\eta_3 = 1 - [1 - \eta_1 - \eta_2 + \eta_1\eta_2]$$

$$\eta_3 = 1 - 1 + \eta_1 + \eta_2 - \eta_1\eta_2 = \eta_1 + \eta_2 - \eta_1\eta_2$$

**Que 2.16.** What is perpetual motion machine of second type ? 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  $0.20 \text{ m}^3$  and  $1.20 \text{ m}^3$ . The specific internal energy of the gas is given by the relation.

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

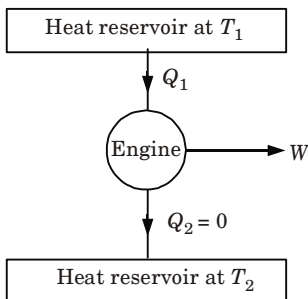
Where  $p$  is in kPa and  $v$  is in  $\text{m}^3/\text{kg}$ . Calculate the net heat transfer and the maximum internal energy of the gas attained during expansion.

**AKTU 2015-16, Marks 10**

### Answer

**A. Perpetual Motion Machine of Second Kind (PMM-2) :**

1. A device or machine which violates the second law of thermodynamics is known as perpetual motion machine of second kind (PMM-2).
2. A PMM-2 will exchange heat from a single thermal (or heat) reservoir and produce equal amount of work energy.



**Fig. 2.16.1.**

3. If heat rejection  $Q_2$  to the heat reservoir at  $T_2$  is zero, then

$$Q_1 = W$$

$$\text{i.e.,} \quad \eta_E = \frac{W}{Q_1} = \frac{W}{W} = 100 \%$$

i.e., engine is 100 % efficient.

4. This is a violation of Kelvin-Planck statement of second law of thermodynamics. So it is impossible to construct a perpetual motion machine of second kind.

**B. Numerical :**

**Given :**  $m = 1.5 \text{ kg}$ ,  $p_1 = 1000 \text{ kPa}$ ,  $p_2 = 200 \text{ kPa}$ ,  $V_1 = 0.20 \text{ m}^3$ ,  $V_2 = 1.20 \text{ m}^3$ ,  $p = a + bV$ , Assume,  $\gamma = 1.20$ .

**To Find :** Net heat transfer and maximum internal energy.

1. Specific internal energy,

$$u = 1.5 pv - 85 \text{ kJ/kg} \quad \dots(2.16.1)$$

2. On plotting the
- $p$
- 
- $V$
- curve,

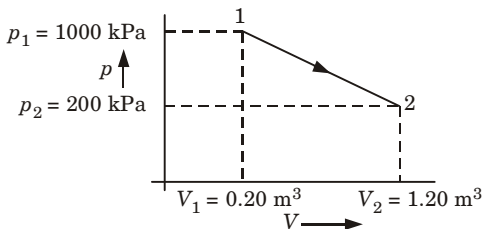


Fig. 2.16.2.

3. Net work done, from Fig. 2.16.2.

$$\begin{aligned} W_{1-2} &= \text{Area of } (1-V_1-V_2-2) \\ &= \frac{1}{2} \times (1.20 - 0.20) \times (1000 - 200) + 200 \times (1.20 - 0.20) \\ &= 400 + 200 = 600 \text{ kJ} \quad \dots(2.16.2) \end{aligned}$$

4. Now from eq. (2.16.1),

Change in internal energy =  $\Delta u$ 

$$\begin{aligned} \Delta u &= u_2 - u_1 \\ &= 1.5(p_2 v_2 - p_1 v_1) \quad \left( \because v = \frac{V}{m} \right) \\ &= 1.5 \left( 200 \times \frac{1.20}{1.5} - 1000 \times \frac{0.2}{1.5} \right) \end{aligned}$$

$$\Delta u = 40 \text{ kJ/kg}$$

$$\Delta U = 40 \times 1.5 \text{ kJ}$$

$$\Delta U = 60 \text{ kJ}$$

5. Net heat transfer,

$$\begin{aligned} \delta Q &= dU + \delta W \\ &= 60 + 600 \\ \delta Q &= 660 \text{ kJ} \end{aligned}$$

6. For maximum internal energy,

$$\frac{du}{dv} = 0$$

$$\text{then } \frac{d}{dv} (1.5pv - 85) = 0$$

$$\frac{d}{dv} [1.5(a + bV)v - 85] = 0 \quad (\because p = a + bV)$$

$$\frac{d}{dv} [1.5(a + bmv)v - 85] = 0 \quad \left[ \because v = \frac{V}{m} \right]$$

$$a + 2bmv = 0$$

$$\Rightarrow \quad v = \frac{-a}{2bm} \quad \dots(2.16.3)$$

$\therefore$  It is given that

$$p = a + bV$$

7. Now putting the given values,

$$1000 = a + b \times 0.20 \quad \dots(2.16.4)$$

$$200 = a + b \times 1.20 \quad \dots(2.16.5)$$

8. After solving eq. (2.16.4) and eq. (2.16.5),

$$a = 1160$$

$$b = -800$$

9. Putting these values in eq. (2.16.3),

$$v = \frac{-1160}{2 \times (-800) \times 1.5}$$

$$v = 0.4833 \text{ m}^3/\text{kg}$$

10. Since,

$$u = 1.5(a + bV)v - 85$$

$$= 1.5[(a + bmv)v] - 85$$

11. Now putting the values of  $a$ ,  $b$  and  $v$  for maximum internal energy,

$$u_{\max} = 1.5[1160 + (-800) \times 1.5 \times 0.4833] \times 0.4833 - 85$$

$$u_{\max} = 335.499 \text{ kJ/kg}$$

$$U_{\max} = 1.5 \times 335.499 \text{ kJ}$$

$$U_{\max} = 503.25 \text{ kJ}$$

## PART-2

*Clausius Inequality, Concept of Entropy, Entropy Change of Pure Substance in Different Thermodynamic Process, TdS Equation, Principle of Entropy Increase, T-S Diagram, Statement of the Third Law of Thermodynamics.*

### CONCEPT OUTLINE : PART-2

**Clausius Inequality :** The cyclic integral of  $\frac{\delta Q}{T}$  for a reversible cycle is equal to zero.

$$\oint \frac{\delta Q}{T} = 0$$

**Entropy :** Entropy is a function of quantity of heat which shows the possibility of conversion of that heat into work. The increase in entropy is small when heat is added at a high temperature and is greater when heat addition is made at a lower temperature. Thus for maximum entropy, there is minimum availability for conversion into work and for minimum entropy there is maximum availability for conversion into work.

**Third Law of Thermodynamics :** The third law of thermodynamics states, "The entropy of all perfect crystalline solid is zero at absolute zero temperature." The third law of thermodynamics, often referred to as Nernst law, provides the basis for the calculation of absolute entropies of substances.

### Questions-Answers

#### Long Answer Type and Medium Answer Type Questions

**Que 2.17.** What is Clausius inequality ? Explain it with  $T$ - $V$  diagram.

#### Answer

##### A. Clausius Inequality :

1. Clausius inequality states that, for a system undergoing a cycle

$$\oint \frac{\delta Q}{T} \leq 0 \text{ or } \left[ \oint \frac{\delta Q}{T} + I = 0 \right]$$

2. Consider a cycle  $LMNO$ . Let  $LM$  be a general process (which may be reversible or irreversible); while other processes of cycle are reversible.
3. Let the cycle be divided into a number of elementary cycles as shown in Fig. 2.17.1.

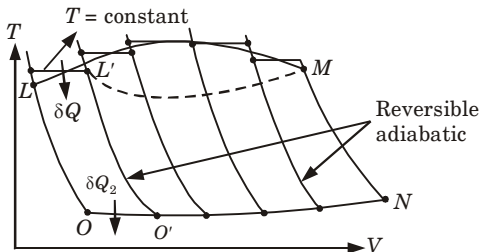


Fig. 2.17.1.

4. Let  $\delta Q$  – Heat supplied at  $T$  and  $\delta Q_2$  – Heat rejected at  $T_2$

5. For one elementary cycle  $LL'O'O$ ,  
Efficiency of the cycle

$$\eta = 1 - \frac{\delta Q_2}{\delta Q}$$

6. Since efficiency of a general cycle  $\leq$  efficiency of a reversible cycle

$$\text{Therefore } \eta_{\text{gen}} \leq \eta_{\text{rev}} \Rightarrow \left(1 - \frac{\delta Q_2}{\delta Q}\right) \leq \left(1 - \frac{\delta Q_2}{\delta Q}\right)_{\text{rev}}$$

$$\text{or } \frac{\delta Q_2}{\delta Q} \geq \left(\frac{\delta Q_2}{\delta Q}\right)_{\text{rev}} \Rightarrow \frac{\delta Q}{\delta Q_2} \leq \left(\frac{\delta Q}{\delta Q_2}\right)_{\text{rev}}$$

7. But for a reversible cycle,  $\left(\frac{\delta Q}{\delta Q_2}\right)_{\text{rev}} = \frac{T}{T_2}$

8. Therefore  $\frac{\delta Q}{\delta Q_2} \leq \frac{T}{T_2}$  or  $\frac{\delta Q}{T} \leq \frac{\delta Q_2}{T_2}$  for any process either reversible or irreversible and for a cycle,  $\oint \frac{\delta Q}{T} \leq \oint \frac{\delta Q_2}{T_2}$

9. But for reversible cycle,  $\oint \frac{\delta Q_2}{T_2} = 0$

$$\left[ \because \oint \frac{\delta Q_2}{T_2} = dS, \text{ which is zero for reversible cycle} \right]$$

10.  $\oint \frac{\delta Q}{T} \leq 0$ ; This is known as Clausius inequality.

**Que 2.18.** What is Clausius theorem? Explain it with  $p$ - $V$  diagram.

**Answer**

**A. Clausius Theorem :**

1. Consider a smooth closed curve representing a reversible cycle.
2. Let the cycle be divided in large number of strips by reversible adiabatic and each strip be closed at top and bottom by reversible isotherms.
3. For the elemental cycle  $ABCD$ ,

Let  $\delta Q_1$  is absorbed at  $T_1$  and  $\delta Q_2$  is rejected at  $T_2$

$$\therefore \frac{\delta Q_1}{T_1} = \frac{\delta Q_2}{T_2}$$

4. If heat supply is taken as positive and heat rejection as negative.

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} = 0 \text{ (for cycle } ABCD)$$

5. Similarly for elemental cycle  $EFGH$

$$\frac{\delta Q_3}{T_3} + \frac{\delta Q_4}{T_4} = 0$$

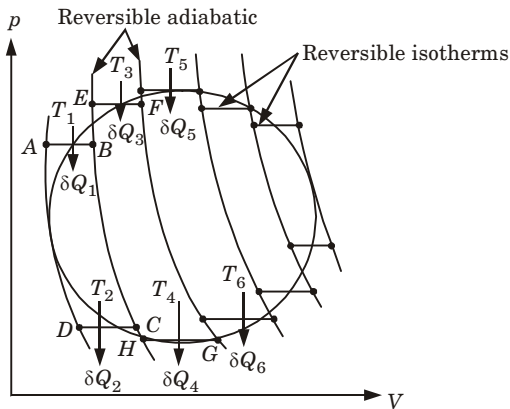


Fig. 2.18.1.

Hence for the entire original reversible cycle

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} + \frac{\delta Q_3}{T_3} + \frac{\delta Q_4}{T_4} + \dots = 0$$

$$\therefore \oint \frac{\delta Q}{T} = 0$$

6. Cyclic integral of  $\frac{\delta Q}{T}$  for reversible cycle is equal to zero. This is known as Clausius theorem.

**Que 2.19.** Define entropy. Prove that entropy is a point function.

**Answer**

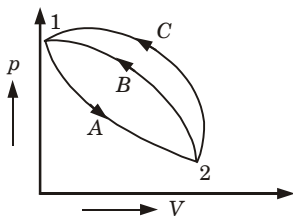
**A. Entropy :**

- From Clausius theorem, cyclic integral of  $\frac{\delta Q}{T}$  for a reversible process is zero. It suggests that  $\frac{\delta Q}{T}$  is a point function and hence a property of system. The term  $\frac{\delta Q}{T}$  is called entropy and its change from state 1 to state 2 during reversible process as
 
$$\int_1^2 \left( \frac{\delta Q}{T} \right)_{rev} = \int_1^2 dS = S_2 - S_1$$
- Entropy is a measure of degree of randomness of molecules comprising a system. Higher the disorderness, greater is the increase in entropy.
- In other words, entropy is the function of quantity of heat which shows the possibility of conversion of that heat into work. On heat addition entropy of system increases and on heat rejection, it decreases.

**B. Entropy is a point function :**

1. Consider a system taken from state '1' to '2' via A and is brought back to initial state '1' via B and via C.
2. From Clausius theorem, for cycle 1 – A – 2 – B – 1

$$\int_1^2 \text{via A} \frac{\delta Q}{T} + \int_2^1 \text{via B} \frac{\delta Q}{T} = 0 \quad \dots(2.19.1)$$

**Fig. 2.19.1.**

3. For cycle 1 – A – 2 – C – 1

$$\int_1^2 \text{via A} \frac{\delta Q}{T} + \int_2^1 \text{via C} \frac{\delta Q}{T} = 0 \quad \dots(2.19.2)$$

4. From eq. (2.19.1) and eq. (2.19.2),

$$\int_{2,B}^1 \frac{\delta Q}{T} = \int_{2,C}^1 \frac{\delta Q}{T} = \int_{2,D}^1 \frac{\delta Q}{T} = \dots dS$$

5. Integral of  $\left(\frac{\delta Q}{T}\right)_{rev}$  is path independent and depends on end states hence it is a point function.

**Que 2.20.** Establish the following relations :

- a.  $\Delta s = c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$
- b.  $\Delta s = c_p \ln \frac{T_2}{T_1} + R \ln \frac{p_1}{p_2}$
- c.  $\Delta s = c_v \ln \frac{p_2}{p_1} + c_p \ln \frac{V_2}{V_1}$

**Answer**

**A. Entropy Change During a Process :**

1. Change of entropy for  $m$  kg of perfect gas during heating from state 1 ( $p_1, V_1, T_1$ ) to state 2 ( $p_2, V_2, T_2$ ) can be found as follows :
- a. **In terms of volume and temperature ( $V$  and  $T$ ) :**
  1. From first law of thermodynamics



$$\delta Q = W + dU \text{ (for } m \text{ kg of gas)}$$

$$\delta q = \delta w + du \text{ (for per kg of gas)}$$

2. Divide both sides by  $T$ ,

$$\frac{\delta q}{T} = \frac{du}{T} + \frac{\delta w}{T}$$

$$ds = \frac{c_v dT}{T} + \frac{pdV}{T} \quad [\because \delta w = pdV]$$

$$\int_1^2 ds = \int_1^2 c_v \frac{dT}{T} + \int_1^2 R \frac{dV}{V} \quad \left[ \because pV = RT, \frac{p}{T} = \frac{R}{V} \right]$$

$$s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

$$\Delta s = c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \text{ [per kg]} \quad \dots(2.20.1)$$

### b. In terms of $p$ and $T$ :

1. From equation of state  $\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$

$$\frac{V_2}{V_1} = \frac{p_1}{p_2} \frac{T_2}{T_1}$$

2. Put  $\frac{V_2}{V_1}$  in eq. (2.20.1),

$$\begin{aligned} \Delta s &= c_v \ln \frac{T_2}{T_1} + R \ln \left( \frac{p_1}{p_2} \frac{T_2}{T_1} \right) \\ &= c_v \ln \frac{T_2}{T_1} + [c_p - c_v] \left( \ln \frac{p_1}{p_2} + \ln \frac{T_2}{T_1} \right) \\ &= c_v \ln \frac{T_2}{T_1} + c_p \ln \frac{p_1}{p_2} + c_p \ln \frac{T_2}{T_1} - c_v \ln \frac{p_1}{p_2} - c_v \ln \frac{T_2}{T_1} \\ &= c_p \ln \frac{T_2}{T_1} + (c_p - c_v) \ln \frac{p_1}{p_2} \end{aligned}$$

$$\Delta s = c_p \ln \frac{T_2}{T_1} + R \ln \frac{p_1}{p_2} \quad \dots(2.20.2)$$

### c. In terms of $p$ and $V$ :

1. From  $\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \Rightarrow \frac{T_2}{T_1} = \frac{p_2}{p_1} \frac{V_2}{V_1}$

2. Put  $\frac{T_2}{T_1}$  in eq. (2.20.1),

$$\Delta s = c_v \ln \left\{ \frac{p_2}{p_1} \frac{V_2}{V_1} \right\} + R \ln \frac{V_2}{V_1}$$

$$\begin{aligned}
 &= c_v \ln \frac{p_2}{p_1} + c_v \ln \frac{V_2}{V_1} + (c_p - c_v) \ln \frac{V_2}{V_1} \\
 &= c_v \ln \frac{p_2}{p_1} + c_v \ln \frac{V_2}{V_1} + c_p \ln \frac{V_2}{V_1} - c_v \ln \frac{V_2}{V_1} \\
 \Delta s &= c_v \ln \frac{p_2}{p_1} + c_p \ln \frac{V_2}{V_1} \quad \dots(2.20.3)
 \end{aligned}$$

**Que 2.21.** Derive the following  $Tds$  equation :

$$Tds = c_v dT + \frac{T\beta}{K} dv$$

**Answer**

1. As we know that,  $s = f(T, v)$

$$i.e., \quad ds = \left( \frac{\partial s}{\partial T} \right)_v dT + \left( \frac{\partial s}{\partial v} \right)_T dv$$

$$or \quad Tds = T \left( \frac{\partial s}{\partial T} \right)_v dT + T \left( \frac{\partial s}{\partial v} \right)_T dv \quad \dots(2.21.1)$$

2. But for reversible constant volume change,

$$dq = c_v (dT)_v = T(ds)_v$$

$$or \quad c_v = T \left( \frac{\partial s}{\partial T} \right)_v \quad \dots(2.21.2)$$

$$We \text{ know, } \left( \frac{\partial s}{\partial v} \right)_T = \left( \frac{\partial p}{\partial T} \right)_v \text{ [Maxwell's equation]}$$

3. Substituting in eq. (2.21.1), we get

$$Tds = c_v dT + T \left( \frac{\partial p}{\partial T} \right)_v dv \quad \dots(2.21.3)$$

$$4. \text{ Now, } \left( \frac{\partial p}{\partial T} \right)_v \left( \frac{\partial T}{\partial v} \right)_p \left( \frac{\partial v}{\partial p} \right)_T = -1$$

$$\therefore \left( \frac{\partial p}{\partial T} \right)_v = - \left( \frac{\partial v}{\partial T} \right)_p \left( \frac{\partial p}{\partial v} \right)_T = \frac{\beta v}{Kv} = \frac{\beta}{K} \quad \dots(2.21.4)$$

5. From eq. (2.21.3) and eq. (2.21.4), we get

$$Tds = c_v dT + \frac{T\beta}{K} dv$$

**Que 2.22.** Explain the entropy principle and apply it to a closed system.

**AKTU 2016-17, Marks 10**

**Answer****A. Entropy Principle :**

1. According to this principle, "Entropy of an isolated system either increases, or in the limit, remains constant."
2. An isolated system does not undergo any energy interaction (*i.e.*, work or heat energy) with its surroundings, and the total energy of all the possible states remains constant. Therefore for an isolated system,

$$\delta Q = 0$$

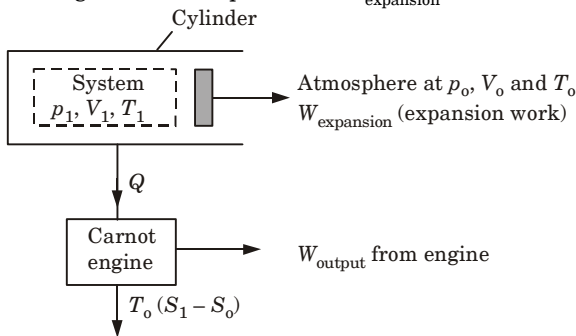
$$\therefore (dS)_{\text{Isolated}} \geq 0$$

If the process is reversible,  $(dS)_{\text{Isolated}} = 0$  and if the process is irreversible,  $(dS)_{\text{Isolated}} > 0$ .

3. From above we see that the entropy of an isolated system can never decrease. It always increases with every irreversible process and remains constant during a reversible process. This is called "Principle of entropy increase".

**B. Entropy Principle for a Closed System :**

1. Let's consider a piston cylinder arrangement substance at  $p_1, T_1$  and  $V_1$  is expanded reversibly to close state at  $p_o, V_o$  and  $T_o$ . The working substance expands and  $W_{\text{expansion}}$  is obtained.

**Fig. 2.22.2.**

2. From the law of conservation of energy,

$$Q = dU + W$$

$$-Q = W_{\text{expansion}} + (U_o - U_1)$$

(Heat interaction is negative because it leaves the system.)

$$\text{Therefore } W_{\text{expansion}} = (U_1 - U_o) - Q$$

3. This heat rejected from the piston-cylinder arrangement can be used to run a reversible heat engine. Work output of the reversible engine is equal to

$$W_{\text{engine}} = Q - Q \frac{T_o}{T} = Q \left[ 1 - \frac{T_o}{T} \right]$$

$$\therefore W_{\text{engine}} = Q - T_o (S_1 - S_o)$$

4. Maximum work obtained from the cylinder piston assembly is the sum of  $W_{\text{expansion}}$  and  $W_{\text{engine}}$ .

$$\begin{aligned} W_{\text{max}} &= W_{\text{expansion}} + W_{\text{engine}} \\ &= [(U_1 - U_o) - Q + Q - T_o (S_1 - S_o)] \\ &= (U_1 - U_o) - T_o (S_1 - S_o) \end{aligned}$$

And surrounding work,  $W_{\text{surrounding}} = p_o (V_o - V_1)$

(This is the work which the piston, while moving outwards, has to spend in pushing the atmosphere against its own pressure.)

5. Therefore maximum available useful net work,

$$\begin{aligned} W_{\text{net}} &= W_{\text{max}} - W_{\text{surrounding}} \\ &= (U_1 - U_o) - T_o (S_1 - S_o) - p_o (V_o - V_1) \\ &= (U_1 + p_o V_1 - T_o S_1) - (U_o + p_o V_o - T_o S_o) = A_1 - A_o \end{aligned}$$

Where  $A = U + p_o V - T_o S$  is called non-flow availability function. This is a composite property of the system and surrounding because it consists of extensive properties (internal energy  $U$ , volume  $V$  and entropy  $S$ ) and intensive property of the environment (pressure  $p_o$  and temperature  $T_o$ ).

Thus availability is a function of properties of the surrounding and also of end states of the closed system.

6. Entropy change for a closed system can be calculated from the relation,

$$\begin{aligned} \delta Q &= dU + \delta W \\ TdS &= m c_v dT + p dV \\ dS &= \frac{m c_v dT}{T} + \frac{p dV}{T} \\ \left[ dS &= \frac{\delta Q}{T}, dU = m c_v dT \text{ and } \delta W = p dV \right] \end{aligned}$$

7. Integrating between initial and final states, we have

$$\begin{aligned} \int_1^2 dS &= \int_1^2 \frac{m c_v dT}{T} + \int_1^2 \frac{m R dV}{V} \\ &\left[ \because pV = mRT, \therefore \frac{p}{T} = \frac{mR}{V} \right] \\ S_2 - S_1 &= m c_v \ln \frac{T_2}{T_1} + m R \ln \frac{V_2}{V_1} \end{aligned}$$

**Que 2.23.** Calculate the change in entropy when  $0.2 \text{ m}^3$  of air at 1 bar and  $59.9^\circ \text{C}$  is compressed to  $0.051 \text{ m}^3$  according to the law  $pV^{1.29} = \text{constant}$ . Take  $R = 0.287 \text{ kJ/kg-K}$  and adiabatic index is 1.4.

Draw the  $p$ - $V$  and  $T$ - $s$  diagrams also.

AKTU 2012-13, Marks 05

**Answer**

**Given :**  $V_1 = 0.2 \text{ m}^3$ ,  $p_1 = 1 \text{ bar}$ ,  $T_1 = 59.9^\circ\text{C} = 59.9 + 273 = 332.9 \text{ K}$ ,

$V_2 = 0.051 \text{ m}^3$ ,  $pV^{1.29} = \text{Constant}$ ,  $R = 0.287 \text{ kJ/kg-K} = c_p - c_v$ ,

$$\gamma = 1.4 = \frac{c_p}{c_v} \Rightarrow c_p = 1.4c_v$$

**To Find :** Change in entropy.

$$1. \quad p_1(V_1)^{1.29} = p_2(V_2)^{1.29}$$

$$p_2 = p_1 \left( \frac{V_1}{V_2} \right)^{1.29} = 1 \left( \frac{0.2}{0.051} \right)^{1.29} = 5.83 \text{ bar}$$

2. For a polytropic process,

$$\frac{V_2}{V_1} = \left( \frac{T_1}{T_2} \right)^{\frac{1}{n-1}}$$

$$\left( \frac{0.051}{0.2} \right) = \left( \frac{332.9}{T_2} \right)^{\frac{1}{1.29-1}}$$

$$0.255 = \left( \frac{332.9}{T_2} \right)^{3.45}$$

$$T_2 = \frac{332.9}{(0.255)^{1/3.45}} = 494.68 \text{ K}$$

3. Now change in entropy,

$$s_2 - s_1 = c_v \left( \frac{n - \gamma}{n - 1} \right) \ln \frac{T_2}{T_1} \text{ per kg of air}$$

4. Now,

$$c_p - c_v = 0.287$$

$$1.4c_v - c_v = 0.287$$

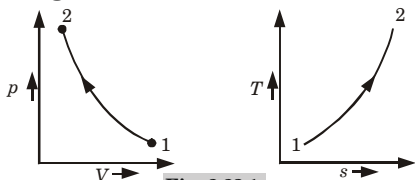
$$c_v = 0.7175 \text{ kJ/kg-K}$$

$$\therefore s_2 - s_1 = 0.7175 \left( \frac{1.29 - 1.4}{1.29 - 1} \right) \ln \left( \frac{494.68}{332.9} \right)$$

$$= -0.107 \text{ kJ/kg-K}$$

Negative sign shows compression process.

***p-V and T-s diagrams :***

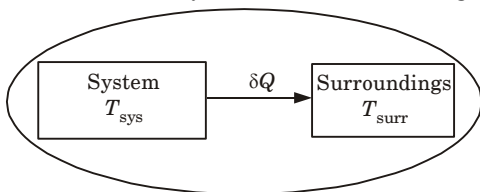


**Fig. 2.23.1.**

**Que 2.24. Prove : Entropy of an isolated system always increases.**

**Answer**

1. Let's consider an isolated system as shown in the Fig. 2.24.1.



**Fig. 2.24.1.**

2. Let  $\delta Q$  be an irreversible heat transfer from the system to the surroundings,

$$(dS)_{\text{system}} = -\frac{\delta Q}{T_{\text{system}}} \quad (\text{negative sign due to heat loss})$$

and  $(dS)_{\text{surrounding}} = \frac{\delta Q}{T_{\text{surrounding}}} \quad (\text{positive sign due to heat gain})$

3. Therefore, entropy change for the isolated system or surrounding is given by :

$$(dS)_{\text{isolated}} = (dS)_{\text{system}} + (dS)_{\text{surrounding}} = -\frac{\delta Q}{T_{\text{system}}} + \frac{\delta Q}{T_{\text{surrounding}}}$$

$$(dS)_{\text{isolated}} = \delta Q \left[ \frac{1}{T_{\text{surrounding}}} - \frac{1}{T_{\text{system}}} \right] > 0$$

i.e., the entropy of an isolated system gets increased if the isolated system undergoes an irreversible process.

4. If  $T_{\text{system}} = T_{\text{surroundings}}$ , the process will take place in a reversible manner and the entropy will remain constant.
5. Thus it can be calculated that  $dS \geq 0$  for an isolated system.

**Que 2.25. Deduce two  $T$ - $dS$  relations. A metal block of 5 kg and 200 °C is cooled in a surrounding of air which is at 30 °C. If the specific heat of metal is 0.4 kJ/kg-K, calculate :**

- Entropy change of block.
- Entropy change of universe surrounding.
- Entropy change of universe.

**AKTU 2013-14, Marks 10**

**Answer**

**A.  $T$ - $dS$  Relations :**

1. From first law of thermodynamics as applied to closed system process,

$$\begin{aligned}\delta Q &= \delta W + dU \\ \delta Q &= pdV + dU \quad (\because \delta W = pdV) \quad \dots(2.25.1)\end{aligned}$$

2. From second law of thermodynamics,

$$dS = \left( \frac{\delta Q}{T} \right)_{\text{rev}} \quad \text{i.e., } \delta Q = T.dS \quad \dots(2.25.2)$$

3. From eq. (2.25.1) and eq. (2.25.2)

$$TdS = pdV + dU \quad \dots(2.25.3)$$

This is the first  $T$ - $dS$  relation.

4. Since Enthalpy,  $H = U + pV$  ...(2.25.4)

5. Putting in differential form

$$\begin{aligned}dH &= d(U + pV) \\ dH &= dU + pdV + Vdp \quad \dots(2.25.5)\end{aligned}$$

$$\therefore TdS = pdV + dU \quad (\text{From eq. (2.25.3)})$$

$$\therefore dU = TdS - pdV$$

$$\text{put } dU = TdS - pdV \text{ in eq. (2.25.5)}$$

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

$$dH = TdS + Vdp$$

$$\text{or } T.dS = dH - Vdp \quad \dots(2.25.6)$$

This is second  $T$ - $dS$  relation.

## B. Numerical :

**Given :**  $m = 5 \text{ kg}$ ,  $T_1 = 200 + 273 = 473 \text{ K}$ ,

$T_2 = 30 + 273 = 303 \text{ K}$ ,  $c = 0.4 \text{ kJ/kg-K}$

**To Find :** Entropy of change of block, entropy change of universe surrounding and entropy change of universe.

1. Entropy change of block :

$$\begin{aligned}(\Delta S)_1 &= mc \ln \frac{T_2}{T_1} \\ &= 5 \times 0.4 \times \ln \frac{303}{473} = -0.89 \text{ kJ/K}\end{aligned}$$

2. Entropy change of surrounding :

$$\begin{aligned}(\Delta S)_2 &= \frac{\Delta Q}{T_2} = \frac{mc(T_1 - T_2)}{T_2} \\ &= \frac{5 \times 0.4(473 - 303)}{303} = 1.12 \text{ kJ/K}\end{aligned}$$

3. Entropy change of universe :

$$\begin{aligned}(\Delta S) &= (\Delta S)_1 + (\Delta S)_2 \\ &= -0.89 + 1.12 = 0.23 \text{ kJ/K}\end{aligned}$$

**Que 2.26.** Show that the entropy change for a polytropic process is given by the following expressions :

- a.  $ds = (c_p - nc_v) \ln \frac{V_2}{V_1}$  (in terms of volume ratio)
- b.  $ds = \frac{c_p - n c_v}{n} \ln \frac{p_1}{p_2}$  (in terms of pressure ratio)
- c.  $ds = \left( \frac{\gamma - n}{n - 1} \right) c_v \ln \frac{T_1}{T_2}$  (in terms of temperature ratio)

### Answer

#### a. In Terms of Volume Ratio :

1. For a polytropic process, changes in entropy can be represented as

$$ds = \frac{\delta q}{T} = \frac{\gamma - n}{\gamma - 1} \cdot \frac{\delta w}{T}$$

$$\left[ \because \delta q = \frac{\gamma - n}{\gamma - 1} \delta w \text{ for polytropic process and } ds = \frac{\delta q}{T} \right]$$

$$ds = \frac{\gamma - n}{\gamma - 1} \frac{pdV}{T} \quad (\because \delta w = pdV)$$

$$ds = \frac{\gamma - n}{\gamma - 1} \frac{RdV}{V} \quad \left( \because pV = RT \Rightarrow \frac{p}{T} = \frac{R}{V} \right)$$

2. Integrating between state 1 and 2,

$$\int_1^2 ds = \int_1^2 \frac{\gamma - n}{\gamma - 1} R \frac{dV}{V}$$

$$s_2 - s_1 = \frac{\gamma - n}{\gamma - 1} R \ln \frac{V_2}{V_1}$$

$$\Delta s = (\gamma - n) \left( \frac{R}{\gamma - 1} \right) \ln \frac{V_2}{V_1} \quad \left( \because c_v = \frac{R}{\gamma - 1} \right)$$

$$\Delta s = (\gamma - n) c_v \ln \frac{V_2}{V_1}$$

$$= \left( \frac{c_p}{c_v} - n \right) c_v \ln \frac{V_2}{V_1} \quad \left( \because \gamma = \frac{c_p}{c_v} \right)$$

$$= \frac{(c_p - n c_v)}{c_v} c_v \ln \frac{V_2}{V_1}$$

$$\Delta s = (c_p - n c_v) \ln \frac{V_2}{V_1} \quad \dots(2.26.1)$$

The above expression represents an entropy change in terms of volume ratio.

#### b. In Terms of Pressure Ratio :

1. Now from polytropic law,  
 $pV^n = C$



We obtain,  $p_1 V_1^n = p_2 V_2^n$

$$\text{or} \quad \frac{p_1}{p_2} = \left( \frac{V_2}{V_1} \right)^n \Rightarrow \frac{V_2}{V_1} = \left( \frac{p_1}{p_2} \right)^{\frac{1}{n}} \quad \dots(2.26.2)$$

2. Put this volume ratio  $\frac{V_2}{V_1}$  in eq. (2.26.1),

$$\Delta s = (c_p - n c_v) \ln \left( \frac{p_1}{p_2} \right)^{\frac{1}{n}} \quad \left( \because \frac{V_2}{V_1} = \left( \frac{p_1}{p_2} \right)^{\frac{1}{n}} \right)$$

$$\Delta s = \frac{(c_p - n c_v)}{n} \ln \frac{p_1}{p_2} \quad \left[ \because \ln \left( \frac{p_1}{p_2} \right)^{\frac{1}{n}} = \frac{1}{n} \ln \left( \frac{p_1}{p_2} \right) \right] \quad \dots(2.26.3)$$

The above expression for change in entropy is in terms of pressure ratio.

### c. In Terms of Temperature Ratio :

1. Again from polytropic law,

$$\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}}$$

$$\text{or} \quad \left( \frac{p_2}{p_1} \right) = \left( \frac{T_2}{T_1} \right)^{\frac{n}{n-1}}$$

$$\text{or} \quad \frac{p_1}{p_2} = \left( \frac{T_2}{T_1} \right)^{-\left( \frac{n}{n-1} \right)} \quad \dots(2.26.4)$$

2. From eq. (2.26.4) put  $\frac{p_1}{p_2}$  in eq. (2.26.3) we get

$$\begin{aligned} \Delta s &= \frac{(c_p - n c_v)}{n} \ln \left( \frac{T_2}{T_1} \right)^{-\frac{n}{n-1}} \\ &= \frac{(c_p - n c_v)}{n} \times \left( -\frac{n}{n-1} \right) \ln \frac{T_2}{T_1} = -\frac{(c_p - n c_v)}{n-1} \ln \frac{T_2}{T_1} \\ &= -\frac{(\gamma c_v - n c_v)}{n-1} \ln \frac{T_2}{T_1} \quad \left( \because \frac{c_p}{c_v} = \gamma, \therefore c_p = \gamma c_v \right) \\ \Delta s &= -\frac{c_v(\gamma - n)}{n-1} \ln \frac{T_2}{T_1} \\ \therefore \Delta s &= \frac{c_v(\gamma - n)}{n-1} \ln \frac{T_1}{T_2} \quad \dots(2.26.5) \end{aligned}$$

The above expression represents entropy change in terms of temperature ratio.

**Que 2.27.** Explain why the slope of constant volume line is more than the slope of constant pressure line.

AKTU 2011-12, Marks 06

**Answer**

1. For ideal gas

$$\begin{aligned} Tds &= du + pdV \\ &= c_v dT + pdV \end{aligned}$$

2. At constant volume

$$Tds = c_v dT$$

$$\left(\frac{dT}{ds}\right)_v = \frac{T}{c_v} \quad \dots(2.27.1)$$

Again,

$$\begin{aligned} Tds &= dh - Vdp \\ Tds &= c_p dT - Vdp \end{aligned}$$

3. At constant pressure

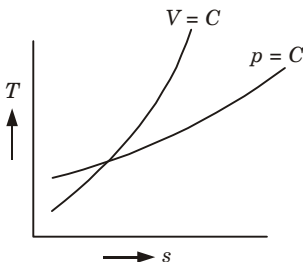


Fig. 2.27.1.

$$\left(\frac{dT}{ds}\right)_p = \frac{T}{c_p} \quad \dots(2.27.2)$$

4. Since

$$c_p > c_v$$

So

$$\frac{T}{c_v} > \frac{T}{c_p}$$

and

$$\left(\frac{dT}{ds}\right)_v > \left(\frac{dT}{ds}\right)_p$$

Now we can say that slope of constant volume line is greater than slope of constant pressure line.

**Que 2.28.** One kg of air occupies  $0.084 \text{ m}^3$  at 12.5 bar and  $537^\circ\text{C}$ . It is expanded at constant temperature to a final volume of  $0.336 \text{ m}^3$ . Calculate :

- a. Pressure at the end of expansion.

- b. Work done during expansion.  
 c. Heat absorbed by the air.  
 d. Change of entropy.

AKTU 2011-12, Marks 06

**Answer****Given :**  $p_1 = 12.5 \text{ bar}$ ,  $T_1 = 537^\circ \text{C}$ ,  $V_1 = 0.084 \text{ m}^3$ ,  $V_2 = 0.336 \text{ m}^3$ **To Find :** Pressure at the end of expansion, work done during expansion, heat absorbed by the air and change of entropy.

- a. Pressure at the end of expansion :

$$p_1 V_1 = p_2 V_2$$

$$12.5 \times 0.084 = p_2 \times 0.336$$

$$p_2 = 3.125 \text{ bar}$$

- b. Work done :
- $W = p_1 V_1 \ln \frac{p_1}{p_2} = 12.5 \times 0.084 \ln \frac{12.5}{3.125} = 1.45 \text{ kW}$

- c. Heat absorbed by the air :

$$Q = W = 1.45 \text{ kW}$$

- d. Entropy change :

$$S_2 - S_1 = mR \ln \frac{p_1}{p_2} = 1 \times 0.287 \times \ln \frac{12.5}{3.125} = 0.397 \text{ kJ/K}$$

**Que 2.29. Find the change in entropy of steam generated at**

**400 °C from 5 kg of water at 27 °C and atmospheric pressure. Take specific heat of water to be 4.2 kJ/kg-K, heat of vapourization at 100 °C as 2260 kJ/kg and specific heat for steam given by;**

$$c_p = R (3.5 + 1.2T + 0.14T^2) \text{ J/kg-K}$$

AKTU 2014-15, Marks 05

**Answer****Given :**  $m = 5 \text{ kg}$ ,  $C = 4.2 \text{ kJ/kg-K}$ ,  $T_2 = 100^\circ \text{C}$ ,  $T_2 = 27^\circ \text{C}$  $T_3 = 400^\circ \text{C}$ , heat of vapourization = 2260 kJ/kg**To Find :** Change in entropy of steam generated at 400 °C.

1. Total entropy change = Entropy change during water temperature rise ( $\Delta S_1$ ) + Entropy change during water to steam change ( $\Delta S_2$ ) + Entropy change during steam temperature rise ( $\Delta S_3$ )  
 2. Heat added for increasing water temperature from 27 °C to 100 °C.

where,  $Q_1 = mc_p \Delta T = 5 \times 4.2 \times (100 - 27) = 1533 \text{ kJ}$ 

$$\Delta S_1 = \frac{Q_1}{T_1}$$

Therefore,  $\Delta S_1 = \frac{1533}{300} = 5.11 \text{ kJ/K}$

3. Entropy change during water to steam change

$$\Delta S_2 = \frac{Q_2}{T_2}$$

Heat of vapourization  $Q_2 = 5 \times 2260 = 11300 \text{ kJ}$

Entropy change,  $\Delta S_2 = \frac{11300}{373.15} = 30.28 \text{ kJ/K}$ .

4. Entropy change during steam temperature rise :

$$\Delta S_3 = \int_{373.15}^{673.15} \frac{\delta Q}{T}$$

$dQ = mc_p \cdot dT$ ; for steam,  $R = \frac{8.314}{18} = 0.462 \text{ kJ/kg-K}$

Therefore,  $c_p$  for steam  $= 0.462 (3.5 + 1.2 T + 0.14 T^2) \times 10^{-3}$   
 $= (1.617 + 0.5544 T + 0.065 T^2) \times 10^{-3}$

$$\Delta S_3 = \int_{373.15}^{673.15} 5 \times 10^{-3} \times \left( \frac{1.617}{T} + 0.5544 + 0.065 T \right) dT$$

$$= 51843.49 \times 10^{-3} \text{ kJ/K}$$

$$\Delta S_3 = 51.84 \text{ kJ/K}$$

5. Total entropy change

$$= 5.11 + 30.28 + 51.84 = 87.23 \text{ kJ/K}$$

**Que 2.30.** 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  $C = 8.4 \text{ kJ/K}$ , 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 ?

**AKTU 2015-16, Marks 10**

**Answer**

**Given :**  $T_1 = 540 \text{ K}$ ,  $T_2 = 250 \text{ K}$ ,  $T_3 = 200 \text{ K}$ ,  $C = 8.41 \text{ kJ/K}$

**To Find :** Maximum amount of work.

1. Assuming final temperature of three bodies  $= T_F$ .
2. According to entropy principle for maximum work output,

$$(\Delta S)_{\text{universe}} = 0$$

$$(\Delta S)_1 + (\Delta S)_2 + (\Delta S)_3 = 0$$

$$C \ln \left( \frac{T_F}{540} \right) + C \ln \left( \frac{T_F}{250} \right) + C \ln \left( \frac{T_F}{200} \right) = 0$$

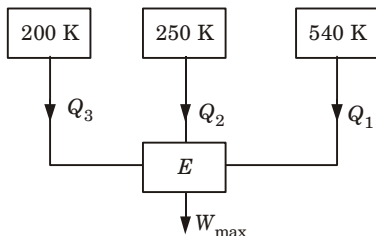


Fig. 2.30.1.

$$\Rightarrow \ln \left( \frac{T_F^3}{540 \times 250 \times 200} \right) = 0$$

$$\Rightarrow \frac{T_F^3}{540 \times 250 \times 200} = e^0 = 1$$

$$T_F = 300 \text{ K}$$

3. According to first law of thermodynamics,

$$\delta q = du + \delta w$$

4. For maximum work,  $dq = 0$  ;

$$(dw)_{\max} = -du = u_1 - u_2$$

$\therefore$  It is given that  $u = CT$

$$\text{So, } (w_1)_{\max} = 8.4 (540 - 300) \quad (\text{where, } C = 8.4 \text{ kJ/K})$$

$$= 2016 \text{ kJ}$$

$$(w_2)_{\max} = 8.4 (250 - 300) = -420 \text{ kJ}$$

$$(w_3)_{\max} = 8.4 (200 - 300) = -840 \text{ kJ}$$

$$5. \quad (w_{\text{net}})_{\max} = (w_1)_{\max} + (w_2)_{\max} + (w_3)_{\max}$$

$$= 2016 - 420 - 840 = 756 \text{ kJ.}$$

**Que 2.31.** Explain Third law of Thermodynamics.

**Answer**

- According to the third law of thermodynamics, "Entropy of all homogeneous crystalline substances in equilibrium state is zero at absolute zero temperature."
- The degree of atomic or molecular activity of a substance depends on its temperature. As the absolute zero temperature is approached, the randomness of molecules tends to decrease and at absolute zero temperature the entropy becomes zero.
- It suggests that the entropy ceases to be a function of state at absolute zero temperature.

Mathematically,  $\lim_{T \rightarrow 0} S = 0$

4. But for many substances like alloys, amorphous bodies, chemical compounds such as carbon mono oxide, NO, etc; entropy does not tend to zero as  $T \rightarrow 0$  but takes some finite positive value at absolute zero temperature. The reason being that these substances are not found in equilibrium state.
5. The third law of thermodynamics provides absolute base which helps in measuring the entropy of each substance. The third law is also helpful in measuring the chemical affinity (*i.e.*, action of chemical forces of reacting substances), explaining behaviour of solids at low temperature and analyzing the chemical and phase equilibrium.

**Que 2.32. Discuss the significance of Clausius inequality and**

**third law of thermodynamics.**

**AKTU 2014-15, Marks 05**

**Answer**

**A. Significance of Clausius Inequality :**

1. In case of a reversible engine for which

$$\sum_{\text{cycle}} \left( \frac{\delta Q}{T} \right) \leq 0,$$

reverse the engine and for the reversible heat pump obtained it is possible to develop the expression,

$$- \sum_{\text{cycle}} \left( \frac{\delta Q}{T} \right) \leq 0$$

2. The negative sign indicates that the heat transfers have all reversed in direction when the engine was reversed. This means that for the same machine we have two relations which are only satisfied in the reversible case,

$$\sum_{\text{cycle}} \left( \frac{\delta Q}{T} \right) \leq 0$$

3. For a reversible case, as the number of reservoirs used tends to infinity, the limiting value of the summation will be

$$\sum_{\text{cycle}} \left( \frac{\delta Q}{T} \right) \leq 0$$

4. In other words the Clausius inequality may be expressed as follows : When a system performs a reversible cycle, then

$$\sum_{\text{cycle}} \left( \frac{\delta Q}{T} \right) = 0$$

but when the cycle is not reversible

$$\sum_{\text{cycle}} \left( \frac{\delta Q}{T} \right) < 0.$$

### B. Significance of Third law of Thermodynamics :

1. The third law of thermodynamics is stated as follow :

“The entropy of all perfect crystalline solids is zero at absolute zero temperature”.

2. The third law of thermodynamics, often referred to as Nernst Law, provides the basis for the calculation of absolute entropies of substances.

According to this law, if the entropy is zero at  $T = 0$  the absolute entropy  $s_{ab}$  of a substance at any temperature  $T$  and pressure  $p$  is expressed by the expression.

$$s_{ab} = \int_0^{T_s = T_{f1}} c_{ps} \frac{dT}{T} + \frac{h_{sf}}{T_s} + \int_{T_s}^{T_{f2} = T_g} c_{pf} \frac{dT}{T} + \frac{h_{fg}}{T_g} + \int_{T_g}^T c_{pg} \frac{dT}{T} \quad \dots(2.32.1)$$

Where

$$T = T_{f1} = T_{sf} = T_{sat}$$

... for fusion,

$$T_{f2} = T_g = T_{fg} = T_{sat}$$

... for vapourization

$c_{ps}, c_{pf}, c_{pg}$  = Constant pressure specific heats for solids, liquids and gas,

$h_{sf}, h_{fg}$  = Latent heats of fusion and vapourization.

3. Thus by putting  $s = 0$  at  $T = 0$ , one may integrate zero Kelvin and standard state of 298.15 K and 1 atm., and find the entropy difference. Further, it can be shown that the entropy of a crystalline substance at  $T = 0$  is not a function of pressure, viz.,

$$\left( \frac{\partial s}{\partial p} \right)_{T=0} = 0$$

4. However, at temperatures above absolute zero, the entropy is a function of pressure also. The absolute entropy of a substance at 1 atm pressure can be calculated using eq. (2.32.1); for pressure difference from 1 atm, necessary corrections have to be applied.

### VERY IMPORTANT QUESTIONS

**Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.**

**Q. 1. Define second law of thermodynamics.**

**Ans.** Refer Q. 2.3, Unit-2.

**Q. 2. Write Kelvin Planck and Clausius statements. Establish the equivalence of above statements.**

**Ans.** Refer Q. 2.4, Unit-2.

**Q. 3. Discuss the irreversibility due to :**

- Heat transfer through a finite temperature difference, and
- Free expansion process.

**Ans.** Refer Q. 2.9, Unit-2.

**Q. 4. Explain working of Carnot and reversed Carnot cycle.**

**Ans.** Refer Q. 2.12, Unit-2.

**Q. 5. Why Carnot cycle is a theoretical cycle ? Explain. Three reversible engines of Carnot type are operating in series between the limiting temperatures of 1100 K and 300 K. If the work output from engines is in proportion of 3 : 2 : 1, determine the intermediate temperature.**

**Ans.** Refer Q. 2.13, Unit-2.

**Q. 6. Explain Carnot's theorem. Also explain its corollary.**

**Ans.** Refer Q. 2.14, Unit-2.

**Q. 7. What is Clausius inequality ? Explain it with  $T-v$  diagram.**

**Ans.** Refer Q. 2.17, Unit-2.

**Q. 8. Explain the entropy principle and apply it to a closed system.**

**Ans.** Refer Q. 2.22, Unit-2.

**Q. 9. Prove : Entropy of an isolated system always increase.**

**Ans.** Refer Q. 2.24, Unit-2.

**Q. 10. Discuss the significance of Clausius inequality and third law of thermodynamics.**

**Ans.** Refer Q. 2.32, Unit-2.





# 3

## UNIT

# Availability and Irreversibility

### Part-1 ..... (3-2C to 3-15C)

- *Available and Unavailable Energy*
- *Second Law Efficiency*
- *Helmholtz and Gibb's Function*

A. *Concept Outline : Part-1* ..... 3-2C

B. *Long and Medium Answer Type Questions* ..... 3-2C

### Part-2 ..... (3-15C to 3-22C)

- *Maxwell's Equations*
- *Clapeyron's Equation*

A. *Concept Outline : Part-2* ..... 3-15C

B. *Long and Medium Answer Type Questions* ..... 3-16C

**PART-1**

*Available and Unavailable Energy, Availability and Irreversibility, Second Law Efficiency, Helmholtz and Gibb's Function.*

**CONCEPT OUTLINE : PART-1**

**Available and Unavailable Energy :** The maximum work output obtained from a certain heat input in a cyclic heat engine is called the available energy, or the available part of the energy supplied. The minimum energy that has to be rejected to the sink by the second law is called the unavailable energy or the unavailable part of the energy supplied.

**Availability :** The availability of a given system is defined as the maximum useful work (total work minus  $p dv$  work) that is obtainable in a process in which the system comes to equilibrium with its surroundings. Availability is thus a composite property depending on the state of both the system and surroundings.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions**

**Que 3.1.** What is available and unavailable energy ?

**Answer****A. Available and Unavailable Energy :**

1. The part of heat energy input in a cyclic heat engine which gets converted into mechanical work is known as available energy.
2. That part of heat energy which is not utilizable and is to be rejected to the surroundings is known as 'unavailable energy'.
3. The term 'exergy' is synonymous with available energy and the term 'anergy' is synonymous with unavailable energy. Therefore,  $\text{Energy} = \text{exergy} + \text{anergy}$ .
4. The concept of availability is related to the maximum amount of theoretical work (without dissipative effects) which can be obtained from a system at a given state upto in dead state.
5. Maximum useful work obtained under such ideal conditions is known as available energy of the system and the part of energy rejected is known as unavailable energy.

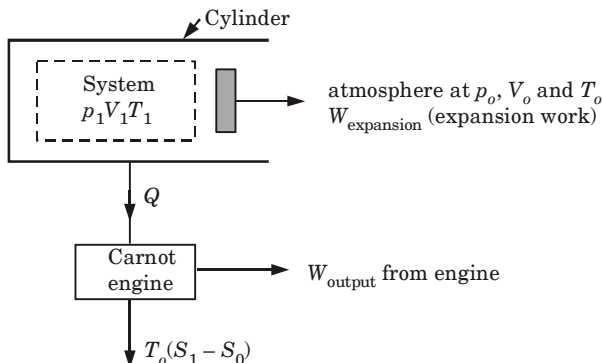
6. It is worthwhile to note that when the system reaches its dead state, the transfer of energy ceases, though the system contains internal energy but this energy cannot be referred to as available energy.

**Que 3.2.** Explain the availability of a closed system.

**Answer**

**A. Availability of a Closed System :**

- Let's consider a piston cylinder arrangement substance at  $p_1, T_1$  and  $V_1$  is expanded reversibly to close state at  $p_o, V_o$  and  $T_o$ .
- The working substance expands and  $W_{\text{expansion}}$  is obtained.



**Fig. 3.2.1.**

3. From the law of conservation of energy,

$$Q = dU + W$$

$$-Q = W_{\text{expansion}} + (U_o - U_1)$$

(Heat interaction is negative because it leaves the system.)

Therefore,  $W_{\text{expansion}} = (U_1 - U_o) - Q$

4. This heat rejected from the piston-cylinder arrangement can be used to run a reversible heat engine. Work output of the reversible engine is equal to

$$W_{\text{engine}} = Q - Q \frac{T_o}{T} = Q \left[ 1 - \frac{T_o}{T} \right]$$

$$\therefore W_{\text{engine}} = Q - T_o (S_1 - S_o)$$

5. Maximum work obtained from the cylinder piston assembly is the sum of  $W_{\text{expansion}}$  and  $W_{\text{engine}}$ .

$$W_{\text{max}} = W_{\text{expansion}} + W_{\text{engine}}$$

$$= [(U_1 - U_o) - Q] + [Q - T_o (S_1 - S_o)]$$

$$= (U_1 - U_o) - T_o (S_1 - S_o)$$

6. Surrounding work,  $W_{\text{surrounding}} = p_0 (V_0 - V_1)$

This is the work which the piston, while moving outwards, has to spend in pushing the atmosphere against its own pressure.

7. Therefore maximum available useful network,

$$\begin{aligned} W_{\text{net}} &= W_{\text{max}} - W_{\text{surrounding}} \\ &= (U_1 - U_0) - T_0 (S_1 - S_0) - p_0 (V_0 - V_1) \\ &= (U_1 + p_0 V_1 - T_0 S_1) - (U_0 + p_0 V_0 - T_0 S_0) \\ &= A_1 - A_0 \end{aligned}$$

Where  $A = U + p_0 V - T_0 S$  is called non-flow availability function.

8. This is a composite property of the system and surroundings because it consists of extensive properties (internal energy  $U$ , volume  $V$  and entropy  $S$ ) and intensive property environment pressure  $p_0$  and temperature  $T_0$ . Thus availability is a function of properties of the surroundings and also of end states of the closed system.

9. Entropy change for a closed system can be calculated from the relation;

$$\begin{aligned} \delta Q &= dU + \delta W \\ TdS &= m c_v dT + pdV \\ dS &= \frac{mc_v dT}{T} + \frac{pdV}{T} \end{aligned}$$

$$\left[ dS = \frac{\delta Q}{T}, dU = mc_v dT \text{ and } \delta W = pdV \right]$$

10. Integrating between initial and final states, we have

$$\begin{aligned} \int_1^2 dS &= \int_1^2 \frac{mc_v dT}{T} + \int_1^2 \frac{mRdV}{V} \quad \left[ \because pV = mRT, \therefore \frac{p}{T} = \frac{mR}{V} \right] \\ S_2 - S_1 &= mc_v \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1} \end{aligned}$$

**Que 3.3.** Explain the availability of open system.

**Answer**

#### A. Availability of an Open System :

1. Let's consider a steady flow system and let the working substance has following parameters :

$u$  — Specific internal energy

$v$  — Specific volume

$h$  — Specific enthalpy

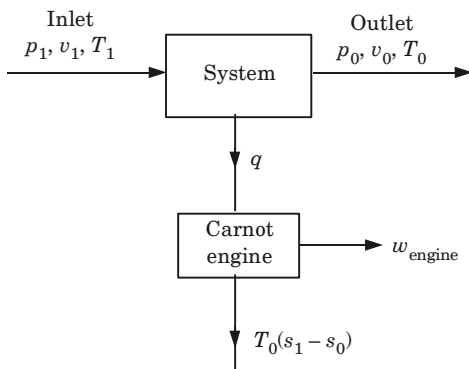
$p$  — Pressure

$C$  — Velocity

$Z$  — Elevation

- When the working substance flows through a system, its properties will change.
- At the inlet of a system let fluid properties and characteristics be written as  $u_1, v_1, h_1, p_1, C_1$  and  $Z_1$ .
- At the outlet the corresponding values will be  $u_0, v_0, h_0, p_0, C_0$  and  $Z_0$ .
- Let  $Q$  be the heat rejected by the system and  $W$  be the work done by the system.
- The SFEE can be written as

$$u_1 + p_1 v_1 + \frac{C_1^2}{2} + gZ_1 - q = u_0 + p_0 v_0 + \frac{C_0^2}{2} + gZ_0 + w$$



**Fig. 3.3.1.** Availability of a steady flow system.

- Let changes in kinetic and potential energies be negligible *i.e.*,

$$\Delta KE = 0 \text{ and } \Delta PE = 0$$

- The SFEE is reduced to

$$u_1 + p_1 v_1 - q = u_0 + p_0 v_0 + w$$

But enthalpy  $h = u + pv$

$$\therefore h_1 - q = h_0 + w$$

$$\text{or } w = (h_1 - h_0) - q \quad (w \text{ is the shaft work})$$

- The output of this engine,

$$\begin{aligned} w_{\text{engine}} &= q - q \frac{T_0}{T_1} \\ &= q \left( 1 - \frac{T_0}{T_1} \right) = q - T_0 (s_1 - s_0) \end{aligned}$$

- Therefore, maximum available net work

$$\begin{aligned} w_{\text{net}} &= w + w_{\text{engine}} = (h_1 - h_0) - q + q - T_0 (s_1 - s_0) \\ &= (H_1 - T_0 S_1) - (H_0 - T_0 S_0) \\ &= B_1 - B_0 \end{aligned}$$

Where,  $B = h - T_0 s$  is called steady flow availability function. It is also a composite property of system and surroundings.

11. Entropy change can be found from the property and relation,

$$Tds = dh - vdp \Rightarrow ds = \frac{dh}{T} - \frac{vdp}{T}$$

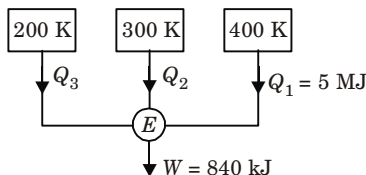
12. Integrating between initial and final states

$$\int_1^2 ds = \int_1^2 \frac{C_p dT}{T} - \int_1^2 R \frac{dp}{p} \quad \left[ \because pv = RT, \therefore \frac{v}{T} = \frac{R}{p} \right]$$

$$s_2 - s_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

13.  $S_2 - S_1 = mc_p \ln \frac{T_2}{T_1} - mR \ln \frac{p_2}{p_1}$  therefore, for mass  $m_1$

**Que 3.4.** Discuss exergy destruction. A reversible engine, as shown in Fig. 3.4.1, during a cycle of operations 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.



**Fig. 3.4.1.**

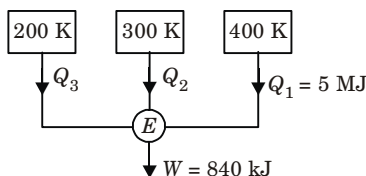
### Answer

#### A. Exergy Destruction :

1. In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir.
2. When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment.
3. Exergy is the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero.
4. Determining exergy was also the first goal of thermodynamics.
5. Exergy is never destroyed during a process, it changes from one form to another. In contrast, exergy accounts for the irreversibility of a process due to increase in entropy.
6. Exergy is always destroyed when a process involves a temperature change. This destruction is proportional to the entropy increase of the system together with its surroundings. The destroyed exergy has been called anergy.

**B. Numerical :**

1. Assuming the positive direction of  $Q_1$ ,  $Q_2$  and  $Q_3$  as shown in Fig. 3.4.2.

**Fig. 3.4.2.**

2. Then, according to first law of thermodynamics,

$$Q_1 + Q_2 + Q_3 = W$$

$$Q_2 + Q_3 = 0.840 - 5$$

$$Q_2 + Q_3 = -4.16 \text{ MJ} \quad \dots(3.4.1)$$

3. Now, according to Clausius inequality principle,

$$\frac{Q_1}{400} + \frac{Q_2}{300} + \frac{Q_3}{200} = 0$$

$$\frac{Q_2}{3} + \frac{Q_3}{2} = \frac{-5}{4} \quad \text{or} \quad 2Q_2 + 3Q_3 = -7.5 \quad \dots(3.4.2)$$

4. On solving eq. (3.4.1) and eq. (3.4.2),

$$Q_2 = -4.98 \text{ MJ}, Q_3 = +0.82 \text{ MJ}$$

**Que 3.5.**

**What is meant by irreversibility and effectiveness of systems ?**

**Answer**

1. Maximum useful work (or net work), from a system corresponds to a reversible process in which the system has heat interaction with the environments. Since the processes in real practice are irreversible, the actual work done by the system for the given change of state is always less than reversible work.

2. Therefore, irreversibility of a process is defined as the difference of reversible work and the actual work.

3. In mathematical form,

$$\text{Irreversibility, } I = W_{\text{rev}} - W_{\text{useful}}$$

$$\begin{aligned} I &= (U_1 - T_o S_1) - (U_2 - T_o S_2) - [-Q - (U_2 - U_1)] \\ &= Q + T_o (S_2 - S_1) \end{aligned}$$

4. Change in entropy of surroundings due to heat addition at constant atmospheric temperature,  $T_o$  is

$$(dS)_{\text{surrounding}} = \frac{Q}{T_o}$$

or

$$Q = T_o (dS)_{\text{surrounding}}$$

Therefore, irreversibility,  $I = T_o (dS)_{\text{system}} + T_o (dS)_{\text{surrounding}}$

$$I = T_o (dS)_{\text{universe}}$$

- From the above expression irreversibility equals the product of entropy production and surroundings temperature.
- The expression  $T_o (dS)_{\text{universe}}$  also represents an increase in the unavailable part of energy (or Anergy) and therefore it can be stated that irreversibility causes an increase in Anergy.

**Que 3.6.** What is the importance of availability, effectiveness and irreversibility ?

**Answer**

- First law of thermodynamics has given the concept of efficiency which can be applied to cycles only, while the concept of availability, irreversibility and effectiveness have been derived from second law of thermodynamics and these concepts are applicable to both processes and cycles.
- These concepts also help in analyzing the processes since they show the deviation of actual processes from ideal processes; therefore, these concepts suggest the improvement in thermodynamic cycles.
- The derived concepts of availability, irreversibility and effectiveness are particularly useful in heat transfer processes between two fluids while first law of thermodynamics does not show any irreversibility during the process.

**Que 3.7.** Two tanks A and B contain 1 kg of air at 1 bar, 50 °C and 3 bar, 50 °C when atmosphere is at 1 bar, 15 °C. Identify the tank in which stored energy is more. Also find the availability of air in each tank.

**AKTU 2014-15, Marks 05**

**Answer**

**Given :**  $p_o = 1 \text{ bar}$ ,  $T_o = 15 + 273, = 288 \text{ K}$ ,

For air  $c_p = 1.005 \text{ kJ/kg-K}$ ,  $c_v = 0.71 \text{ kJ/kg-K}$ ,  $R = 0.287 \text{ kJ/kg-K}$

**To Find :** The tank in which stored energy is more and availability of air in each tank

$$\begin{aligned} p_1 &= 1 \text{ bar} \\ T_1 &= 50 + 273 \\ &= 323 \text{ K} \\ m_1 &= 1 \text{ kg} \end{aligned}$$

Tank A

$$\begin{aligned} p_2 &= 3 \text{ bar} \\ T_2 &= 50 + 273 \\ &= 323 \text{ K} \\ m_2 &= 1 \text{ kg} \end{aligned}$$

Tank B

- For tank A, availability is expressed as per unit mass,



$$\begin{aligned}
 W_{\max} &= (u_1 - u_o) + p_o(V_1 - V_o) - T_o(s_1 - s_o) \\
 &= c_v(T_1 - T_o) + p_o R \left( \frac{T_1}{p_1} - \frac{T_o}{p_o} \right) - T_o \left( c_p \ln \frac{T_1}{T_o} - R \ln \frac{p_1}{p_o} \right) \\
 &= 0.71(323 - 288) + 1 \times 0.287 \left( \frac{323}{1} - \frac{288}{1} \right) \\
 &\quad - 288 \left( 1.005 \times \ln \frac{323}{288} - 0.287 \ln \frac{1}{1} \right) \\
 &= 24.85 + 10.045 - 33.19 = 1.705 \text{ kJ/kg}
 \end{aligned}$$

2. For tank B,

$$\begin{aligned}
 W_{\max} &= c_v(T_2 - T_o) + p_o R \left( \frac{T_2}{p_2} - \frac{T_o}{p_o} \right) - T_o \left( c_p \ln \frac{T_2}{T_o} - R \ln \frac{p_2}{p_o} \right) \\
 &= 0.71(323 - 288) + 1 \times 0.287 \left( \frac{323}{3} - \frac{288}{1} \right) \\
 &\quad - 288 \left( 1.005 \times \ln \frac{323}{288} - 0.287 \ln \frac{3}{1} \right) \\
 &= 24.85 - 51.75 + 57.6 = 30.7 \text{ kJ/kg}
 \end{aligned}$$

Hence stored energy in tank B is more than that of tank A.

### Que 3.8.

An air preheater is used to heat up the air used for combustion by cooling the outgoing products of combustion from a furnace. The rate of flow of the products is 10 kg/s, and the products are cooled from 300 °C to 200 °C, and for the products at this temperature  $c_p = 1.09 \text{ kJ/kgK}$ . The rate of air flow is 9 kg/s, the initial air temperature is 40 °C, and for the air  $c_p = 1.005 \text{ kJ/kgK}$ .

- What is the initial and final availability of the product ?
- What is the irreversibility for this process ?
- If the heat transfer from the products were to take place reversibly through heat engines, what would be the final temperature of the air ?

**AKTU 2015-16, Marks 10**

### Answer

**Given :**  $\dot{m}_g = 10 \text{ kg/s}$ ,

$T_{g1} = 300 + 273 = 573 \text{ K}$ ,  $T_{g2} = 200 + 273 = 473 \text{ K}$ ,  $c_{pg} = 1.09 \text{ kJ/kgK}$ ,

$\dot{m}_a = 9 \text{ kg/s}$ ,  $T_{a1} = 40 + 273 = 313 \text{ K}$ ,

$c_{pa} = 1.005 \text{ kJ/kgK}$

**To Find :** Initial and final availability of product Irreversibility of the process and final temperature of air.

**Data Assume :** Let,  $T_o = 300 \text{ K}$  (atmospheric temperature)

**a. Initial and Final Availability :**

1. Initial availability of the product,

$$\psi_1 = (h_1 - h_0) - T_0 (S_1 - S_0)$$

$$\psi_1 = c_{pg} (T_{g1} - T_0) - T_0 c_{pg} \ln \left( \frac{T_{g1}}{T_0} \right)$$

$$= 1.09 (573 - 300) - 300 \times 1.09 \ln \left( \frac{573}{300} \right)$$

$$\psi_1 = 297.57 - 211.6$$

$$\psi_1 = 85.97 \text{ kJ/kg}$$

2. Final availability of the product,

$$\psi_2 = (h_2 - h_0) - T_0 (S_2 - S_0)$$

$$= 1.09 (473 - 300) - 300 \times 1.09 \ln \left( \frac{473}{300} \right)$$

$$= 188.57 - 148.89$$

$$\psi_2 = 39.68 \text{ kJ/kg}$$

**b. Irreversibility :**

1. Decrease in availability of the products =
- $\psi_1 - \psi_2$

$$= 85.97 - 39.68 = 46.29 \text{ kJ/kg}$$

2. By making an energy balance for the air preheater,

$$\dot{m}_g c_{pg} (T_{g1} - T_{g2}) = \dot{m}_a c_{pa} (T_{a2} - T_{a1})$$

$$10 \times 1.09 (573 - 473) = 9 \times 1.005 [T_{a2} - 313]$$

$$T_{a2} = \frac{1090}{9.045} + 313$$

$$T_{a2} = 433.508 \text{ K}$$

3. Now, increase in availability of the air

$$= \psi_2 - \psi_1 = (h_2 - h_1) - T_0 (S_2 - S_1)$$

$$= c_{pa} (T_{a2} - T_{a1}) - T_0 c_{pa} \ln \left( \frac{T_{a2}}{T_{a1}} \right)$$

$$= 1.005 (433.508 - 313) - 300 \times 1.005 \ln \left( \frac{433.508}{313} \right)$$

$$= 121.1105 - 98.2006 = 22.9099 \text{ kJ/kg}$$

4. Hence the irreversibility of the process

$$= 10 \times 46.29 - 9 \times 22.9099$$

$$= 462.9 - 206.1891 = 256.7109 \text{ kW.}$$

**c. For reversible Heat Transfer :**

$$\Delta \dot{S}_{\text{univ}} = 0$$

$$\Delta \dot{S}_{\text{sys}} + \Delta \dot{S}_{\text{surr}} = 0$$

$$\Delta \dot{S}_{\text{product}} + \Delta \dot{S}_{\text{air}} = 0$$

$$\Delta \dot{S}_{\text{product}} = -\Delta \dot{S}_{\text{air}}$$

$$\dot{m}_g c_{pg} \ln \frac{T_{g2}}{T_{g1}} = -\dot{m}_a c_{pa} \ln \frac{T_{a2}}{T_{a1}}$$

$$10 \times 1.09 \ln \left( \frac{473}{573} \right) = -9 \times 1.005 \ln \left( \frac{T_{a2}}{313} \right)$$

$$\Rightarrow T_{a2} = 394.38 \text{ K}$$

Hence the final temperature of air = 394.38 K.

**Que 3.9.** Define dead state and second law efficiency.

**AKTU 2012-13, Marks 05**

**Answer**

**A. Dead State :**

1. Dead state refers to the state at which system and environment are at chemical, thermal and mechanical equilibrium.
2. Thus neither there can be any spontaneous change within the system or within the environment, nor any spontaneous interaction between the two. Dead state being a limiting state is also called 'restricted dead state'.
3. At dead state the system is at same temperature and pressure as that of its surroundings and shall have no kinetic energy or potential energy relative to surroundings.
4. Thus, a system shall have zero availability at dead state and yield maximum possible work only when it follows a reversible process from its state to the state of its surroundings (dead state).

**B. Second Law Efficiency :**

1. The second law efficiency ' $\eta_{II}$ ' of a process is defined as the ratio of the minimum available energy which must be consumed to do a work divided by the actual amount of available energy consumed in performing the work.

$$\eta_{II} = \frac{\text{Minimum available energy to do the work}}{\text{Actual available energy consumed}}$$

$$\text{or } \eta_{II} = \frac{A_{\min}}{A}$$

Where,  $A$  is the availability or exergy.

**Que 3.10.** Two kg of air at 500 kPa, 80 °C expands adiabatically in a closed system until its volume is doubled and its temperature becomes equal to that of the surroundings which is 100 kPa, 5 °C. For this process determine.

- The maximum work,
- The change in availability, and
- The irreversibility.

**AKTU 2016-17, Marks 10**

### Answer

**Given :**  $m = 2 \text{ kg}$ ,

Initial conditions,  $p_1 = 500 \text{ kPa}$ ,  $T_1 = 80^\circ\text{C} = 273 + 80 = 353 \text{ K}$

Final conditions,  $p_2 = 100 \text{ kPa}$ ,  $T_2 = 5^\circ\text{C} = 273 + 5 = 278 \text{ K}$

Volume get doubled by adiabatic expands.

**To Find :**

- Maximum work,
- Change in availability, and
- Irreversibility.

- From the property relation

$$TdS = dU + pdV$$

the entropy change of air between the initial and final states is

$$\int_1^2 dS = \int_1^2 \frac{mc_v dT}{T} + \int_1^2 \frac{mR dV}{V}$$

or

$$S_2 - S_1 = mc_v \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1}$$

- From Equation of Work Done,**

$$\begin{aligned} W_{\max} &= (U_1 - U_2) - T_0 (S_1 - S_2) \\ &= m \left[ c_v (T_1 - T_2) + T_0 \left( c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \right) \right] \\ &= 2 \left[ 0.718 (80 - 5) + 278 \left( 0.718 \ln \frac{278}{353} + 0.287 \ln \frac{2}{1} \right) \right] \\ &= 2 [53.85 + 278 (-0.172 + 0.199)] \\ &= 2 [53.85 + 7.51] = 122.72 \text{ kJ} \end{aligned}$$

- The Change in Availability,**

$$\begin{aligned} \phi_1 - \phi_2 &= (U_1 - U_2) - T_0 (S_1 - S_2) + p_0 (V_1 - V_2) \\ &= W_{\max} + p_0 (V_1 - V_2) \\ &= 122.72 + p_0 (V_1 - 2V_1) \\ &= 122.72 - 100 \times \frac{2 \times 0.287 \times 353}{500} = 82.2 \text{ kJ} \end{aligned}$$

- The Irreversibility,**

$$I = W_{\max \text{ useful}} - W_{\text{act}}$$

From the first law,

$$\begin{aligned} W_{\text{act}} &= Q - \Delta U = -\Delta U = U_1 - U_2 \\ I &= U_1 - U_2 - T_0(S_1 - S_2) - U_1 + U_2 \\ &= T_0(S_2 - S_1) \\ &= T_0(\Delta S)_{\text{system}} \end{aligned}$$

For adiabatic process,  $(\Delta S)_{\text{surr}} = 0$

$$\begin{aligned} I &= T_0 \left[ m c_v \ln \frac{T_2}{T_1} + m R \ln \frac{V_2}{V_1} \right] \\ &= 278 \times 2 \left[ 0.178 \ln \frac{278}{353} + 0.287 \ln 2 \right] \\ &= 278 \times 2 (-0.042 + 0.199) = 87 \text{ kJ} \end{aligned}$$

**Que 3.11.** Prove that in a closed system, when initial and final temperatures are equal to that of the environment and the system exchanges heat with the environment only, the work done is either equal to or greater than the change in the Helmholtz function.

AKTU 2012-13, Marks 05

### Answer

1. Let's consider a closed system which is initially and finally at surroundings temperature around it and has heat interactions with the atmosphere only,

2. From first law of thermodynamics,

$$\delta Q = dU + \delta W$$

3. From the second law of thermodynamics,

$$dS = \frac{\delta Q}{T} \Rightarrow \delta Q = T dS$$

4. For a non-flow reversible process,

$$\begin{aligned} W_{\text{max}} &= (U_1 - U_2) + Q \\ &= (U_1 - U_2) + T_0(S_2 - S_1) \\ &= (U_1 - T_0 S_1) - (U_2 - T_0 S_2) \end{aligned}$$

5. Since the process is taking place at constant temperature,  $T_0$  can be replaced by  $T_1$  or  $T_2$ .

$$\begin{aligned} \text{Then we have } W_{\text{max}} &= (U_1 - T_1 S_1) - (U_2 - T_2 S_2) \\ &= A_1 - A_2 \end{aligned}$$

6. The term  $(U - TS)$  is known as Helmholtz function and can be defined as the difference between the internal energy and the product of entropy and temperature.

7. If a closed system passes from one state to another state at same temperature while interacting heat only with the surrounding atmosphere at  $T_0 = T_1 = T_2$ , the maximum work obtained from the process is equal to the decrease in Helmholtz function of the system.

**Que 3.12.** Describe the Gibbs function. How does it differ from the availability function ?

Two tanks A and B contain 1 kg of air at 1 bar, 50 °C and 3 bar, 50 °C when atmosphere is at 1 bar 15 °C. Identify the tank in which stored energy is more. Also find the availability of air in each tank.

**AKTU 2011-12, Marks 06**

**Answer**

- The Gibbs function  $G$  is defined as  

$$G = H - TS = U + pV - TS$$
- For two equilibrium states at the same pressure  $p$  and temperature  $T$   

$$(G_1 - G_2)_{p,T} = (U_1 - U_2)_{p,T} + p(V_1 - V_2)_{p,T} - T(S_1 - S_2)_{p,T}$$

$$(W_u)_{\max} = (G_1 - G_2)_{p,T}$$

$$(W_u)_{p,T} \leq (G_1 - G_2)_{p,T}$$
- The decrease in the Gibbs function of a system sets as upper limit to the work that can be performed, exclusive of  $pdV$  work, in any process between two equilibrium states at the same temperature and pressure, provided the system exchanges heat only with the environment which is at the same temperature and pressure as the end states of the system.
- If the process is irreversible, the useful work is less than the maximum.

**B. Difference between Gibbs Function and Availability Function :**

S. No.	Availability Function (Exergy)	Gibbs Function
1.	Availability Function is a measurement of total available work until a system reaches equilibrium with its surroundings.	The Gibbs Function is the amount of available work for an isothermal and isobaric process.
2.	The amount of exergy a system has is not dependent on isothermal or isobaric process. It could be any type of process and it will still have the same amount of exergy regardless.	The same can not be said for the Gibbs Function.
3.	Exergy is more of a general term used to describe the useable amount of work that can be extracted from a thermodynamic system.	Gibbs Function is for a specific process (i.e., constant temperature and pressure).
4.	Exergy is dependent of the systems surroundings.	Gibbs Function is independent of the systems surroundings.

**Numerical :** Refer Q. 3.7, Page 3-8C, Unit-3.

**PART-2**

*Condition for Exact Differential Maxwell's Equations,  
Clapeyron's Equation.*

**CONCEPT OUTLINE : PART-2****Condition for Exact Differential :**

Total differential of a function  $f(x, y)$  is given by

$$df = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy$$

$$df = Mdx + Ndy$$

$$\frac{\partial f}{\partial x} = M(x, y) \text{ and } \frac{\partial f}{\partial y} = N(x, y)$$

For exact differential,  $\frac{\partial M}{\partial y} = \frac{\partial N}{\partial x}$

**Maxwell's Equations :**

$$\left( \frac{\partial T}{\partial v} \right)_s = - \left( \frac{\partial p}{\partial s} \right)_v$$

$$\left( \frac{\partial T}{\partial p} \right)_s = \left( \frac{\partial v}{\partial s} \right)_p$$

$$\left( \frac{\partial p}{\partial T} \right)_v = \left( \frac{\partial s}{\partial v} \right)_T$$

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

**Clapeyron's Equation :**

$$\left( \frac{dp}{dT} \right) = \left( \frac{h_{12}}{Tv_{12}} \right)$$

**Questions-Answers**

**Long Answer Type and Medium Answer Type Questions**

**Que 3.13.** What are the mathematical conditions for exact

differentials ? Show that  $\int \left[ \frac{dT}{T} - \frac{vdp}{T} \right]$  can be used as property of the system.

**Answer**

**Condition for exact differential :** If a relation exists among the variables  $x, y$  and  $z$ , then  $z$  may be expressed as a function of  $x$  and  $y$ , or

$$dz = \left( \frac{\partial z}{\partial x} \right)_y dx + \left( \frac{\partial z}{\partial y} \right)_x dy$$

$$\text{If } \left( \frac{\partial z}{\partial x} \right)_y = M, \text{ and } \left( \frac{\partial z}{\partial y} \right)_x = N$$

$$\text{then } dz = M dx + N dy$$

where  $z, M$  and  $N$  are functions of  $x$  and  $y$ . Differentiating  $M$  partially with respect to  $y$ , and  $N$  with respect to  $x$ .

$$\left( \frac{\partial M}{\partial y} \right)_x = \frac{\partial^2 z}{\partial x \partial y}$$

$$\left( \frac{\partial N}{\partial x} \right)_y = \frac{\partial^2 z}{\partial y \partial x}$$

$$\therefore \left( \frac{\partial M}{\partial y} \right)_x = \left( \frac{\partial N}{\partial x} \right)_y$$

This is the condition of exact (or perfect) differential.

For a thermodynamic property the essential condition is that it should be exact differential. The given condition  $\int \left[ \frac{dT}{T} - \frac{vdp}{T} \right]$  is an exact differential, hence can be used as thermodynamic property.

$$\text{i.e., } \int_1^2 \left[ \frac{dT}{T} - \frac{vdp}{T} \right] = [\ln T]_1^2 - \frac{v}{T} [p]_1^2$$

$$= (\ln T_2 - \ln T_1) - \frac{v}{T} (p_2 - p_1)$$

which is an exact differential.

**Que 3.14.** Derive the Maxwell relations and explain their importance in thermodynamics.



**Answer**

1. The equations that relate the partial derivatives of pressure 'p', entropy 's', temperature 'T' of a system to each other is known as Maxwell relation. The Maxwell relation can be developed by combining the first law and second law of thermodynamics.
2. Consider a simple compressible substance that undergoes for reversible process.

$$\delta Q - \delta w = dE \quad \dots(3.14.1)$$

3. Assume that 'E' = total energy of system,  
and  $p \cdot dv = dw$  = work done by the system in the reversible process.

4. From the first law of thermodynamics,

$$\delta Q_{\text{rev}} - p \cdot dv = dU$$

and

$$\delta Q_{\text{rev}} = Tds$$

$$Tds = dU + p \cdot dv \quad \dots(3.14.2)$$

$$dU = Tds - p \cdot dv$$

5. Properties  $h$ ,  $E$  and  $g$  may also given as,

$$dh = dU + p \cdot dv + v \cdot dp$$

$$= Tds + v \cdot dp \quad \dots(3.14.3)$$

6. Helmholtz and Gibbs functions are given as,

$$df = dU - Tds - s \cdot dT$$

$$= -p \cdot dv - s \cdot dT \quad \dots(3.14.4)$$

7. Gibbs function,  $dg = dh - Tds - s \cdot dT = v \cdot dp - s \cdot dT \quad \dots(3.14.5)$

8. All of these equations are result of the two laws of thermodynamics and exact differential equations.

$$\left. \begin{aligned} du &= \left[ \frac{\partial u}{\partial s} \right]_v \cdot ds + \left[ \frac{\partial u}{\partial v} \right]_s \cdot dv \\ dh &= \left[ \frac{\partial h}{\partial s} \right]_p \cdot ds + \left[ \frac{\partial h}{\partial p} \right]_s \cdot dp \\ df &= \left[ \frac{\partial f}{\partial v} \right]_T \cdot dv + \left[ \frac{\partial f}{\partial T} \right]_v \cdot dT \\ dg &= \left[ \frac{\partial g}{\partial p} \right]_T \cdot dp + \left[ \frac{\partial g}{\partial T} \right]_p \cdot dT \end{aligned} \right\} \quad \dots(3.14.6)$$

9. Comparing this eq. (3.14.6) with eq. (3.14.2), (3.14.3), (3.14.4) and (3.14.5).

$$\left[ \frac{\partial u}{\partial s} \right]_v = T = \left[ \frac{\partial h}{\partial s} \right]_p$$

$$\left[ \frac{\partial u}{\partial v} \right]_s = -p = \left[ \frac{\partial f}{\partial v} \right]_T$$

$$\left[ \frac{\partial h}{\partial p} \right]_s = v = \left[ \frac{\partial g}{\partial p} \right]_T$$

$$\left[ \frac{\partial f}{\partial T} \right]_v = -s = \left[ \frac{\partial g}{\partial T} \right]_p$$

10. On further solving the above equations, we get

$$\left( \frac{\partial T}{\partial v} \right)_s = - \left( \frac{\partial p}{\partial s} \right)_v$$

$$\left( \frac{\partial T}{\partial p} \right)_s = \left( \frac{\partial v}{\partial s} \right)_p$$

$$\left( \frac{\partial p}{\partial T} \right)_v = \left( \frac{\partial s}{\partial v} \right)_T$$

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

11. These equations are known as Maxwell equation. They are very useful in thermodynamics because they provide a means of determining the change in entropy which can not be measured directly.

**Que 3.15.** With the help of  $Tds$  equation prove that  $C_p$  is equal to  $C_v$  at absolute zero temperature.

**Answer**

1. The first  $Tds$  equation,

$$Tds = C_v dT + T \left( \frac{\partial p}{\partial T} \right)_v dv \quad \dots(3.15.1)$$

and second  $Tds$  equation,

$$Tds = C_p dT - T \left( \frac{\partial v}{\partial T} \right)_p dp \quad \dots(3.15.2)$$

2. At absolute zero temperature,  $T = 0$  K

3. Putting  $T = 0$  K in eq. (3.15.1) and (3.15.2),

$$Tds = C_v dT \quad \dots(3.15.3)$$

and  $Tds = C_p dT$  ... (3.15.4)

4. Equating eq. (3.15.3) and (3.15.4), we get

$$C_v = C_p$$

**Que 3.16.** Using Maxwell relation show that

$$c_p \cdot dT = T \cdot ds + \left( \frac{\partial v}{\partial T} \right)_p \times dp$$

**Answer**

1. Assume entropy ( $s$ ) as a function of  $T$  and  $v$

$$ds = \left( \frac{\partial s}{\partial T} \right)_v \cdot dT + \left( \frac{\partial s}{\partial v} \right)_T \cdot dv$$

$$Tds = T \cdot \left( \frac{\partial s}{\partial T} \right)_v \cdot dT + T \cdot \left( \frac{\partial s}{\partial v} \right)_T \cdot dv$$

$$T \left( \frac{\partial s}{\partial T} \right)_v = c_v \quad (\text{Heat capacity at constant volume})$$

2. From Maxwell equation,

$$\left( \frac{\partial s}{\partial v} \right)_T = \left( \frac{\partial p}{\partial T} \right)_v$$

$$Tds = c_v dT + T \left( \frac{\partial p}{\partial T} \right)_v \cdot dv$$

3. This is known as the first  $T \cdot ds$  equation.

$$ds = \left( \frac{\partial s}{\partial T} \right)_p \cdot dT + \left( \frac{\partial s}{\partial p} \right)_T \cdot dp$$

$$T \cdot ds = T \cdot \left( \frac{\partial s}{\partial T} \right)_p \cdot dT + \left( \frac{\partial s}{\partial p} \right)_T \cdot dp$$

4. Since  $T \left( \frac{\partial s}{\partial T} \right)_p = c_p$

also,  $\left( \frac{\partial s}{\partial p} \right)_T = - \left( \frac{\partial v}{\partial T} \right)_p$

Now,  $T \cdot ds = c_p \cdot dT - T \left( \frac{\partial v}{\partial T} \right)_p \cdot dp$

5. This is called as second  $T \cdot ds$  equation.

**Que 3.17.** Using Maxwell relation derive the following equation :

i. 
$$\left(\frac{\partial T}{\partial p}\right)_s = \frac{T.v\beta}{c_p}$$

ii. 
$$\left(\frac{\partial T}{\partial v}\right)_s = -\frac{T\beta}{c_v.k}$$

where,

$\beta$  = coefficient of cubical expansion, and  
 $k$  = isothermal compressibility.

**Answer**

i. **Proof :** From the Maxwell relation,

$$\left(\frac{\partial T}{\partial p}\right)_s = \left(\frac{\partial v}{\partial s}\right)_p = \left(\frac{\partial v}{\partial T}\right)_p \cdot \left(\frac{\partial T}{\partial s}\right)_p$$

As we have,  $c_p = T\left(\frac{\partial s}{\partial T}\right)_p$  and  $\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_p$

$$\left(\frac{\partial s}{\partial T}\right)_p = \frac{c_p}{T} \text{ and } \left(\frac{\partial v}{\partial T}\right)_p = \beta.v$$

So 
$$\left(\frac{\partial T}{\partial p}\right)_s = \frac{T.\beta.v}{c_p}$$

ii. **Proof :** From the Maxwell relation,

$$\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial p}{\partial s}\right)_v = -\left(\frac{\partial p}{\partial T}\right)_v \left(\frac{\partial T}{\partial s}\right)_v$$

As we have  $c_v = T\left(\frac{\partial s}{\partial T}\right)_v$  and  $k = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_T$

$$\frac{T}{c_v} = \left(\frac{\partial T}{\partial s}\right)_v \text{ and } \left(\frac{\partial v}{\partial p}\right)_T = -k.v$$

$$\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial p}{\partial T}\right)_v \cdot \frac{T}{c_v}$$

As we have  $\left(\frac{\partial p}{\partial v}\right)_T \left(\frac{\partial v}{\partial T}\right)_p \left(\frac{\partial T}{\partial p}\right)_v = -1$

$$\left(\frac{\partial p}{\partial T}\right)_v = -\left(\frac{\partial p}{\partial v}\right)_T \cdot \left(\frac{\partial v}{\partial T}\right)_p = -\frac{1}{(-k.v)} \cdot \beta.v = \frac{\beta}{k}$$

So, 
$$\left(\frac{\partial T}{\partial v}\right)_s = -\frac{T\beta}{c_v.k}$$

**Que 3.18.** Derive the Clausius-Clapeyron equation.

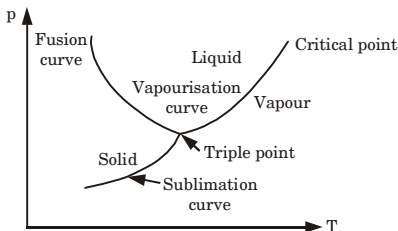
OR

**Explain Clausius-Clapeyron equation. Also represent on  $p$ - $T$  diagram.**

**Answer**

1. The Clausius-Clapeyron equation is one such equation which is used to determine the enthalpy change associated with a phase change.
2. Consider the Maxwell relation,

$$\left(\frac{\partial p}{\partial T}\right)_v = \left(\frac{\partial s}{\partial v}\right)_T$$



**Fig. 3.18.1.**  $p$ - $T$  diagram.

3. During the phase change the pressure is the saturation pressure, which depends on the temperature. Therefore the partial pressure derivative ( $dp/dT$ ) is expressed by

$$[s_g - s_f] = \left(\frac{dp}{dT}\right) \cdot [v_g - v_f]$$

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f}$$

Where,

$s_g$  = specific entropy of saturated vapour,

$s_f$  = specific entropy of saturated liquid,

$v_g$  = specific volume of saturated vapour, and

$v_f$  = specific volume of saturated liquid.

4. During this process the pressure also remains constant.

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f} = \frac{s_{fg}}{v_{fg}} = \frac{h_{fg}}{T \cdot v_{fg}}$$

Where,

$s_{fg}$  = increase in specific entropy,

$v_{fg}$  = increase in specific volume, and

$h_{fg}$  = latent heat added during evaporation.

$$\left(\frac{dp}{dT}\right) = \frac{h_{fg}}{Tv_{fg}}$$

5. Which is called the Clapeyron equation.
6. The Clapeyron equation is applicable to any phase change process that occurs at constant pressure and temperature. It can be expressed by following relation in general form,

$$\left(\frac{dp}{dT}\right) = \frac{h_{12}}{T.v_{12}}$$

Where 1 and 2 shows the two phases.

### VERY IMPORTANT QUESTIONS

*Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.*

**Q. 1. What is available and unavailable energy ?**

**Ans.** Refer Q. 3.1, Unit-3.

**Q. 2. Explain the availability of a closed system.**

**Ans.** Refer Q. 3.2, Unit-3.

**Q. 3. Explain the availability of open system.**

**Ans.** Refer Q. 3.3, Unit-3.

**Q. 4. What is mean by irreversibility and effectiveness of systems ?**

**Ans.** Refer Q. 3.5, Unit-3.

**Q. 5. What is the importance of availability, effectiveness and irreversibility ?**

**Ans.** Refer Q. 3.6, Unit-3.

**Q. 6. Define dead state and second law efficiency.**

**Ans.** Refer Q. 3.9, Unit-3.

**Q. 7. Prove that in a closed system, when initial and final temperatures are equal to that of the environment and the system exchanges heat with the environment only, the work done is either equal to or greater than the change in the Helmholtz function.**

**Ans.** Refer Q. 3.11, Unit-3.

**Q. 8. Describe the Gibbs function. How does it differ from the availability function ?**

Two tanks *A* and *B* contain 1 kg of air at 1 bar, 50 °C and 3 bar, 50 °C when atmosphere is at 1 bar 15 °C. Identify the tank in which stored energy is more. Also find the availability of air in each tank.

**Ans.** Refer Q. 3.12, Unit-3.

**Q. 9. Derive the Maxwell relations and explain their importance in thermodynamics.**

**Ans.** Refer Q. 3.14, Unit-3.

**Q. 10. Derive the Clausius-Clapeyron equation.**

**Ans.** Refer Q. 3.18, Unit-3.



# 4

## UNIT

# Properties of Steam and Rankine Cycle

## Part-1 ..... (4-2C to 4-25C)

- *Pure Substance*
- *Property of Pure Substance (Steam)*
- *Phase Transformation Process of Water*
- *Graphical representation of Pressure, Volume and Temperature*
- *Steam Table and Mollier Chart*
- *Dryness Factor and it's Measurement*
- *Simple Rankine Cycle*

A. *Concept Outline : Part-1* ..... 4-2C

B. *Long and Medium Answer Type Questions* ..... 4-2C

## Part-2 ..... (4-25C to 4-40C)

- *Psychometric Terms and their Definitions*
- *Psychometric Chart*
- *Psychometric Processes and their Representation*

A. *Concept Outline : Part-2* ..... 4-25C

B. *Long and Medium Answer Type Questions* ..... 4-26C



**PART-1**

*Pure Substance, Property of Pure Substance (Steam), Phase Transformation Process of Water, Graphical Representation of Pressure, Volume and Temperature, P-T and P-V Diagrams, T-S and H-S Diagrams, Steam Table and Mollier Chart, Dryness Factor and it's Measurement, and Simple Rankine Cycle.*

**CONCEPT OUTLINE : PART-1**

**Pure Substance :** A pure substance is defined as one that is homogeneous and invariable in chemical composition throughout its mass. The relative proportions of the chemical elements constituting the substance are also constant. Atmospheric air, steam water mixture and combustion product of a fuel are regarded as pure substances.

**Steam Table :** The properties of steam are estimated and presented in a tabulated form as steam table. It gives specific volume ( $V_f$ ,  $V_g$  and  $V_{fg}$ ), specific internal energy ( $u_f$ ,  $u_g$  and  $u_{fg}$ ), specific enthalpy ( $h_f$ ,  $h_g$  and  $h_{fg}$ ). This table is very useful to evaluate entropy drop, enthalpy drop, or change in internal energy during any process involving steam as the working fluid.

**Dryness Factor :** Dryness fraction determines the quality of steam. The dryness fraction of steam can be measured by using the following calorimeters :

- Tank or bucket calorimeter,
- Throttling calorimeter, and
- Separating and throttling calorimeter.

**Rankine Cycle :** It is the theoretical cycle on which the steam turbine works.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions****Que 4.1.****What is meant by pure substance ?****Answer**

- Pure substance is defined as single-component system which has a homogeneous and constant chemical composition irrespective of its phase.

2. A pure substance can be in solid phase (as ice), liquid phase (as water), gaseous phase (as vapour) or in mix phase (as ice + water + vapour).
3. Pure substances are the working substances for performing thermodynamic operations.
4. Therefore, a pure substance is one whose chemical composition is uniform and remains invariant during heat and work transfer with the surroundings e.g., water, ice, vapour, oxygen, nitrogen etc.
5. Its phase proportions may vary because of heat transfer with the surroundings.

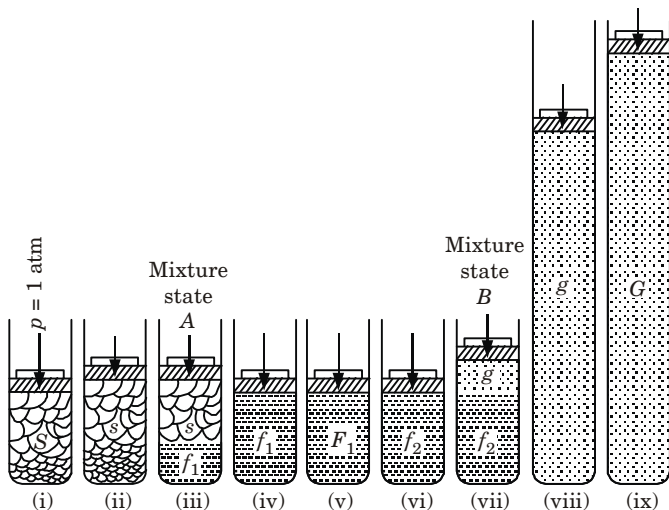
**Que 4.2.**

**Explain the phase equilibrium of a pure substance on  $T$ - $V$  diagram.**

**Answer**

**A. Phase Equilibrium of a Pure Substance on  $T$ - $V$  Diagram :**

1. Consider one kg of water ice contained in a cylinder and loaded piston arrangement as shown in Fig. 4.2.1(i), such that the pressure on the ice is one atmosphere.
2. Let the initial temperature of ice be  $-40^\circ\text{C}$  ( $-40^\circ\text{F}$ ). Also let heat be transferred to ice from outside the cylinder.
3. We will now trace the events, *i.e.*, changes of state of water that take place inside the cylinder as a result of this heating.



**Fig. 4.2.1. Water in different thermodynamic states.**

4. It is to be noted here that the pressure on water remains constant throughout as the weights on the piston, etc., and the cross-sectional area of the cylinder remain the same.
5. The changes that take place, in a stepwise manner, as depicted in Fig. 4.2.1, taken together with a temperature-specific volume plot of changes in Fig. 4.2.2, are follows :

**Step I : Process S-s :**

1. Ice initially at solid state  $S$  rises in temperature from  $-40^{\circ}\text{C}$  ( $-40^{\circ}\text{F}$ ) to  $0^{\circ}\text{C}$  ( $32^{\circ}\text{F}$ ).
2. At the end of this step, the ice is in state  $s$  as in Fig. 4.2.1(ii).

**Step 2 : Process s- $f_1$  :**

1. On further heating, ice in state  $s$  melts to water in state  $f_1$ , the temperature remain constant at  $0^{\circ}\text{C}$  ( $32^{\circ}\text{F}$ ).
2. Thus, there is a change of phase from solid to liquid. In the process, there is a nominal decrease in the specific volume, since liquid water at  $0^{\circ}\text{C}$  ( $32^{\circ}\text{F}$ ) is heavier than ice.
3. Until all the ice has melted to water as in Fig. 4.2.1(iv), in between such as at  $A$  in Fig. 4.2.2 there is a mixture of solid and liquid in equilibrium as shown in Fig. 4.2.1(iii).
4. It is seen from Fig. 4.2.2 that water-ice decreases in volume on melting. Normal substances increase in volume when changing from solid phase to liquid phase as shown in Fig. 4.2.1.

**Step 3 : Process  $f_1 - f_2$  :**

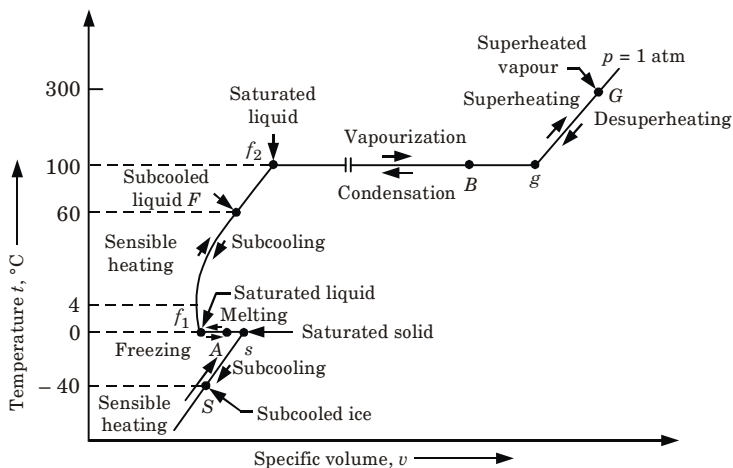
1. More heating causes the temperature of liquid water at  $f_1$  at  $0^{\circ}\text{C}$  ( $32^{\circ}\text{F}$ ) to rise.
2. The temperature continues to rise until point  $f_2$  at  $100^{\circ}\text{C}$  ( $212^{\circ}\text{F}$ ) is reached.
3. In the process, the specific volume of water first decreases as the temperature rises to about  $4^{\circ}\text{C}$ , and then increases.
4. A state of liquid water in between this process of heating, say  $F$  at  $60^{\circ}\text{C}$ , is shown in Fig. 4.2.1(v).
5. After reaching  $100^{\circ}\text{C}$  ( $212^{\circ}\text{F}$ ) temperature the state is shown in Fig. 4.2.1(vi).

**Step 4 : Process  $f_2 - g$  :**

1. If heating is continued, water in state  $f_2$  starts evaporating, the temperature remain constant at  $100^{\circ}\text{C}$  ( $212^{\circ}\text{F}$ ).
2. As a result, there is a large increase in specific volume of water as it changes from liquid phase to vapour phase.
3. Until all the liquid water has evaporated to vapour at  $g$  as in Fig. 4.2.1(viii), in between such as at  $B$  in Fig. 4.2.2, there is a mixture of liquid and vapour in equilibrium as shown in Fig. 4.2.1(vii).

**Step 5 : Process  $g-G$  :**

1. Further-heating of vapour at  $g$  causes its temperature to rise above  $100^\circ\text{C}$ , say to  $300^\circ\text{C}$  at  $G$ . The vapour at  $G$ , as shown in Fig. 4.2.1(ix), occupies a greater volume than the vapour at  $g$ .
2. We thus see that there are two kinds of changes of state taking place on addition of heat at constant pressure. These are :
  - a. Sensible heating, in which the temperature of the substance changes, but the phase remains the same.
  - b. Latent heating, in which the phase changes, with temperature remain constant.
3. In Fig. 4.2.2, we have melting of ice into water, process  $s-f_1$  at  $0^\circ\text{C}$ , and vaporization of liquid water into water vapour (or steam), process  $f_2-g$  at  $100^\circ\text{C}$ .



**Fig. 4.2.2.** Changes in state of water on heating and cooling at constant pressure on  $t$ - $v$  diagram.

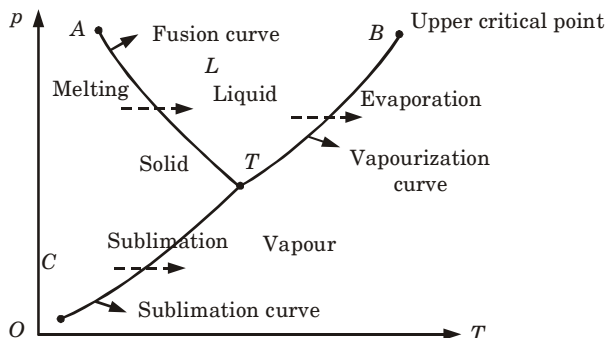
4. It is seen that if the process is carried in the opposite direction by cooling, starting from  $G$  initially, we will instead have process  $G-g$ , sensible cooling of water vapour first, followed by condensation of steam  $g$  into condensate water  $f_2$ , sensible cooling of water from  $f_2$  to  $f_1$ , via point  $F$ , fusion of water into ice from  $f_1$  to  $s$ , and finally sensible cooling of ice from  $s$  to  $S$ .

**Que 4.3.**

**Draw the  $p$ - $T$  diagram of pure substance and explain its various regions of the diagram in details.**

**Answer****A.  $p$ - $T$  Diagram of Pure Substance :**

1. A substance can exist in three different states *i.e.*, liquid, solid and vapour (gas). These states are known as 'phases' and are obtained when the substance receives or evolves heat.
2. On heating, solid phase first changes into liquid and then to vapour or gaseous phase. On cooling, phase transformation reverses from gas (vapour) to liquid and finally to solid state.
3. The change in phase takes place at a specific temperature known as "transition temperature".
4. For each substance, there is a set of pressure and temperature at which any two out of three phases may co-exist in equilibrium.
5. The Fig. 4.3.1 drawn below represents different phases of a substance as a function of pressure and temperature.

**Fig. 4.3.1.**

6. The Fig. 4.3.1 imparts following valuable information :

**a. Solid and Liquid Phases :**

1. Solid and liquid phases co-exist in equilibrium and are separated by the line  $TA$ .
2. The line  $TA$  is referred to as "fusion curve" and represents the variation of melting point with pressure and temperature.
3. The leftward slope of the line  $TA$  indicates that melting point decreases with pressure rise. These are the characteristics of "ice type substances".

**b. Liquid and Vapour Phases :**

1. Liquid and vapour phases co-exist in equilibrium and are separated by the line  $TB$ .
2. The line  $TB$  is known as "vaporization curve" vaporization curve has an upper end point (or upper critical point) above which no substance can exist in liquid state whatever amount of pressure is applied on it.

**c. Vapour and Solid Phases :**

1. Vapour and solid phases coexist in equilibrium and are separated by the line  $TC$ . The line  $TC$  is known as “sublimation curve”.
2. Sublimation is defined as the process during which a solid phase is directly changed into a vapour (gas) phase or vice-versa.

**d. Triple Point :**

1. Triple point is defined as a point at which pressure and temperature are such that all the three states (solid, liquid and vapour) of a substance co-exist in equilibrium.
2. Triple point is shown by the point  $T$  in the Fig. 4.3.1. At triple point, all the three curves namely sublimation, fusion and vaporization and phases of substance meet each other.

**Que 4.4.** Explain the process of steam formation at constant pressure.

**Answer****A. Formation of Steam :**

1. Steam is generally formed at constant pressure. Consider one kg of water at  $0^\circ\text{C}$  in a cylinder in which pressure ‘ $p$ ’ is maintained.
2. When heat energy is supplied, the temperature of water increases until it reaches the saturation temperature (or boiling temperature) corresponding to the pressure ‘ $p$ ’ maintained on the water.
3. Volume of water increases a little bit due to heat addition as shown in Fig. 4.4.1. The quantity of heat added to water during this process is given by

$$h_f = c_w T_s \quad \dots(4.4.1)$$

Where  $h_f$  = enthalpy of saturated water with  $0^\circ\text{C}$  as reference.

$c_w$  = specific heat of water.

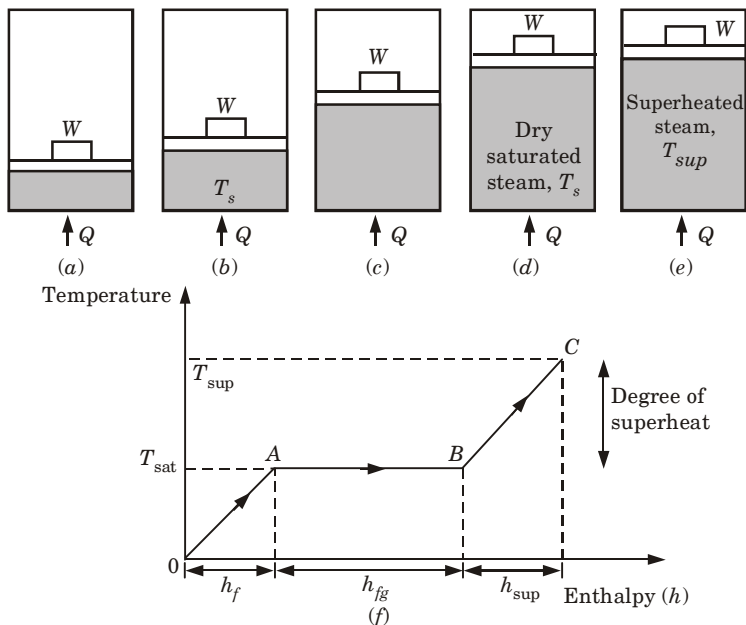
4. Further heat addition changes the phase from liquid to vapour state.
5. When part of water remains in liquid form but major part of it is converted into vapour form, the steam is known as wet steam. During this process, there is a large change of volume because water is getting converted into steam, as is shown in Fig. 4.4.1(c).
6. On further heat addition, remaining part of water gets evaporated into steam and it is continued till all the liquid is completely evaporated in steam as shown in Fig. 4.4.1(d).
7. The heat required to evaporate one kg of water from  $0^\circ\text{C}$  is the summation of  $h_f$  and  $h_{fg}$  and is given by  $h_g = h_f + h_{fg}$ .

Where

$h_f$  = Sensible heat of water.

$h_{fg}$  = Latent heat of steam.

$h_g$  = Total enthalpy or heat of steam at the saturated condition.



**Fig. 4.4.1.** Process of steam formation at constant pressure.

8. Further heat addition increases the temperature of steam above the saturated temperature ( $T_s$ ).
9. During this process of superheating, there is an increase in the volume as shown in Fig. 4.4.1(e).
10. Such a steam whose temperature is above its saturation temperature is called superheated steam and the amount of heat added above saturation condition is called enthalpy of superheat (or heat of superheat).

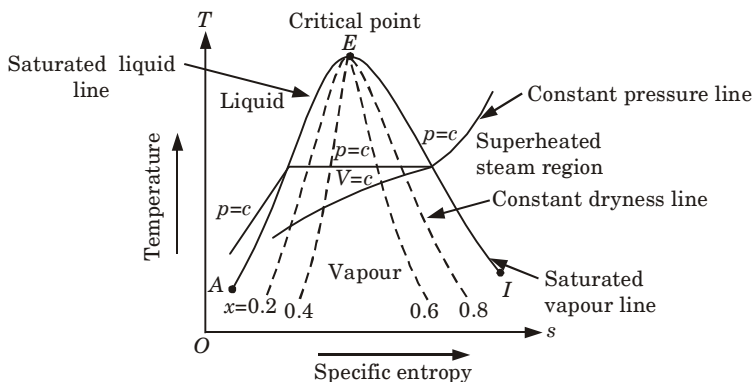
**Que 4.5.**

**Draw and explain temperature-entropy ( $T-s$ ) and enthalpy-entropy ( $h-s$ ) diagrams.**

**Answer**

#### **A. Temperature-Entropy ( $T-s$ ) Diagram :**

1. On  $T-s$  diagram, absolute temperature is plotted on Y-axis (ordinate) and specific entropy on the X-axis (abscissa).
2. Liquid boundary line originates at the axis of ordinates at 273.16 K; it is a must because liquid entropy at triple point is zero. The boundary curves and vapour line divide the entire diagram in three regions.
3. Region to the left of 'AE' is called liquid region. Region in between the line AE and EI is called wet steam region. Region to the right of line EI is known as the region of superheated steam.



**Fig. 4.5.1.  $T$ - $s$  diagram.**

- Both the boundary curves ( $AE$  and  $EI$ ) merge at point  $E$  which is the critical point of water with critical pressure of 221.2 bar and a critical temperature of 374.15 °C.
- The constant pressure lines are parallel to the constant temperature lines in the wet steam region. These two lines become curved in the superheated region. The constant dryness fraction lines are shown only in the wet steam region.
- The constant volume lines are steeper than the constant pressure lines in the superheated steam region.
- The slopes of constant pressure lines in the liquid region, wet steam region and superheated regions are governed by the equations

$$\left(\frac{\partial T}{\partial s}\right)_v = \frac{T}{c_v}$$

and 
$$\left(\frac{\partial T}{\partial s}\right)_p = \frac{T}{c_p}$$

- Area under the reversible process line and abscissa represents the amount of heat added to one kg of working medium and is given by

$$q = \int T ds$$

### **B. Enthalpy-Entropy ( $h$ - $s$ ) diagram or Mollier diagram :**

- Generation of steam is done at constant pressure and for constant pressure heating process,  $\delta q = \delta h$ .
- Calculations for heat supplied can be easily done if  $h$ - $s$  diagram is plotted in place of temperature-entropy diagram or ( $T$ - $s$ ) diagram. In the enthalpy-entropy diagram, enthalpy ' $h$ ' is plotted on the axis of ordinate and entropy is plotted along abscissa.
- In a Mollier diagram, the point where saturated liquid line and saturated vapour line merge is known as critical point. After this point, liquid directly gets transformed into superheated steam.



4. For a constant pressure process,

$$\delta q = T ds = dh$$

Therefore,  $\left(\frac{dh}{ds}\right)_p = T$

5. The slope of constant pressure lines will be equal to the absolute temperature on Mollier diagram.
6. In the wet steam region, the temperature of steam remains constant at a given pressure, hence the constant pressure lines are straight lines in the wet steam region. These lines become curved in the superheated region.

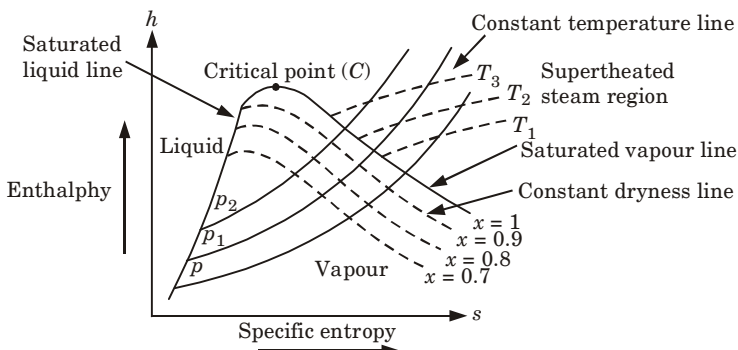


Fig. 4.5.2.

7. In the wet steam region, the constant temperature lines coincide with the constant pressure lines.
8. In the superheated region, isobaric and isothermal lines diverge. Isobaric lines turn upwards and have a positive slope and the isothermal lines tend to become horizontal straight lines. It is due to the fact that at higher temperature the superheated steam behaves as a perfect gas *i.e.*,

$$h = f(T)$$

9. The constant dryness fraction lines originate from the point C (in wet region only). These lines are approximately parallel to the saturation line ( $x = 1$ ). On a Mollier diagram, throttling process (also called isenthalpic or constant enthalpy process) is represented by a horizontal line.
10. The Mollier diagram makes it possible to easily and rapidly find out the steam parameters with accuracy sufficient for practical purposes and gives solution to the problems related to changes in the state of steam.

**Que 4.6.**

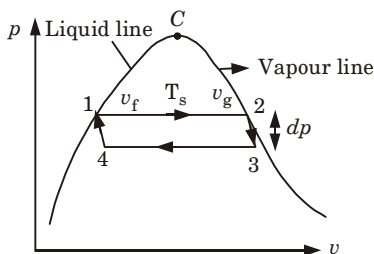
**Define specific volume of a fluid. How volume of dry, wet and superheated steam is determined ?**

**Answer**

- Specific volume of a fluid is the volume occupied by a unit mass of fluid. The value of specific volume decreases with increase in pressure, and values corresponding to different pressures can be read in the steam tables.

**a. Specific Volume of Dry Steam :**

- Its value can also be determined with the help of Clapeyron's equation. Let's consider an elementary Carnot cycle for dry saturated steam on  $p$ - $v$  diagram.
- Point '1' lies on liquid line, point '2' lies on vapour line, 1-2 and 3-4 represents isotherms.

**Fig. 4.6.1.**

- Efficiency of this elementary Carnot cycle

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{dT_s}{T_s} \quad \dots(4.6.1)$$

- Efficiency of a Carnot cycle can also be obtained from the relation,

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$\eta = \frac{(v_g - v_f)dp}{h_{fg}} \quad \dots(4.6.2)$$

Where,

$v_g \rightarrow$  Volume of dry steam

$v_f \rightarrow$  Volume of liquid

$h_{fg} \rightarrow$  Heat supply

$dp \rightarrow$  Pressure difference between isotherms

$\therefore$  From eq. (4.6.1) and eq. (4.6.2),

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{dT_s}{T_s} = \frac{(v_g - v_f)dp}{h_{fg}}$$

or

$$v_g - v_f = \frac{h_{fg}}{T_s} \cdot \frac{dT_s}{dp} \quad \dots(4.6.3)$$

5. This equation is known as Clapeyron's equation and it provides a very precise method to obtain specific volume at any required pressure or temperature.

**b. Specific Volume of Wet Steam :**

1. Volume of one kg of steam is equal to the sum of volume of dry part of steam and volume of water particles in suspension.
2. Let 'x' be the dryness fraction of wet steam, then 1 kg of wet steam consists of x kg of dry saturated steam and (1 - x) kg of water particles in suspension.

Volume of wet steam is

$$v_{\text{wet}} = (1 - x) v_f + x v_g$$

Where

$v_g$  = Specific volume of dry steam and

$v_f$  = Specific volume of wet steam

3. If  $p < 30$  bar and  $x > 0.8$  specific volume of water is practically insignificant;

Therefore

$$v_{\text{wet}} = x v_g$$

**c. Specific Volume of Superheated Steam :**

1. Since superheated steam behaves as a perfect gas therefore its specific volume can be found by applying Charle's law to steam at the beginning and at the completion of superheating process.

$$\therefore \frac{p v_g}{T_s} = \frac{p v_{\text{sup}}}{T_{\text{sup}}} \Rightarrow v_{\text{sup}} = \frac{v_g T_{\text{sup}}}{T_s} \text{ (Pressure remains constant)}$$

Where,

$T_s$  = Absolute temperature of dry steam,

$v_g$  = Specific volume of dry steam,

$T_{\text{sup}}$  = Absolute temperature of superheated steam.

$v_{\text{sup}}$  = Specific volume of superheated steam.

**Que 4.7.**

**What is the use of steam table ?**

**Answer**

1. Various properties of steam like saturation temperature (or boiling temperature) and pressure, enthalpies of water, evaporation, dry-saturated steam and superheated steam and their respective specific volumes and entropies can be found by experiments and by calculations with some thermodynamic relations. These properties of steam given in a tabular form are known as steam tables.
2. The steam tables give values of specific volume, enthalpy and entropy of saturated liquid and dry steam tabulated against pressure 'p' or corresponding saturation temperature ' $T_s$ '
3. Steam tables make it possible to rapidly find the basic characteristics of steam according to given certain parameters.

4. Parameters for intermediate values of pressure and temperature, which are not given in the steam tables, can be found by using interpolation method.
5. Important aspects on the application of steam tables :
  - a. Values of various properties have been given for one kg of water and one kg of steam (*i.e.*, per kg basis).
  - b. Datum taken for calculation of enthalpy and entropy is  $0^{\circ}\text{C}$ .
  - c. At lower and moderate pressures specific volume ' $v_f$ ' of water can be neglected compared to specific volume ' $v_g$ ' of steam but at higher values of pressure, specific volume of water cannot be neglected.
  - d. Steam tables give the properties for liquids and dry steam and not wet steam.

Specific volume,  $v = (1 - x) v_f + x v_g$

$$h = h_f + x h_{fg}$$

$$s = s_f + x s_{fg}$$

- e. The properties of superheated steam are tabulated separately.

**Que 4.8.**

**What is dryness fraction ? Explain the measurement of dryness fraction of steam by combined separating and throttling calorimeter.**

**AKTU 2013-14, Marks 10**

**Answer**

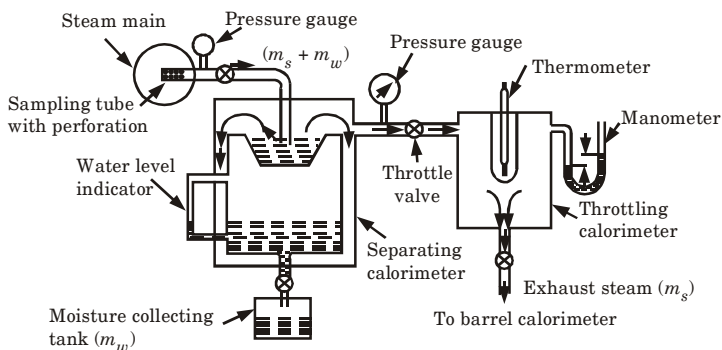
**A. Dryness Fraction (Quality) of Steam :**

1. The wet steam is a mixture of saturated water and steam and the relative amounts of each which are present in such a two phase mixture determine the quality of mixture.
2. Dryness fraction of steam is defined as the ratio of mass of dry saturated steam to the total mass of mixture (*i.e.*,  $m_s + m_w$ )
3. It is generally denoted by  $x$ .

$$x = \frac{\text{Mass of dry steam}}{\text{Mass of mixture}} = \frac{m_s}{m_s + m_w}$$

**B. Combined Separating and Throttling Calorimeter :**

1. Combined separating and throttling calorimeter has separating and throttling units arranged in series combination and is used for accurate measurement of dryness fraction of wet steam.
2. In this arrangement, a sampling pipe having transverse holes around the circumference is inserted into the main pipe which carries wet steam at  $p_1$  whose dryness fraction (quality) has to be determined.
3. The sample of steam thus obtained is passed through a separating unit through a control valve. This valve is kept fully open so that steam may not undergo any throttling at this stage.



**Fig. 4.8.1.** Combined separating and throttling calorimeter.

- When this steam is made to strike against the perforated cup, it undergoes a quick reversal of direction in its motion.
- The water particles in steam have greater inertia; therefore due to this sudden reversal of direction are thrown out of mixture.
- The amount of water thus separated is collected and measured. The remaining dry steam is now made to pass through a throttling unit where, while passing through a throttle valve, it gets throttled at constant enthalpy.
- Steam pressure is measured before and after throttling. Temperature of throttled steam is also measured.
- The throttled steam coming out of throttling calorimeter is then condensed and weighed.

**a. Calculations :**

- Let,  $m$  = Mass of wet steam taken as sample from steam main.  
 $m_1$  = Mass of water particles separated and collected in separating unit.  
 $m_2$  = Mass of steam condensed and weighed after throttling.
- Dryness fraction of wet steam considering separating unit

$$x_1 = \frac{m_2}{m_1 + m_2} \quad (m = m_1 + m_2) \quad \dots(4.8.1)$$

- Amount of water separated in separating unit,  
 $= (1 - x_1) m = (1 - x_1) (m_1 + m_2) \quad \dots(4.8.2)$

- Let  $x_2$  be the dryness fraction of steam entering the throttling unit,  
Amount of water carried by steam into the throttling unit  
 $= (1 - x_2) m_2 \quad \dots(4.8.3)$

- Now if  $x$  be the actual dryness fraction of steam in the steam main, then amount of water content initially in the steam

$$= (1-x)(m_1 + m_2) \quad \dots(4.8.4)$$

6. From law of conservation of mass,

$$(1-x)(m_1 + m_2) = (1-x_1)(m_1 + m_2) + (1-x_2)m_2$$

7. Divide both sides of equation by  $(m_1 + m_2)$

$$\text{We have, } (1-x) = (1-x_1) + (1-x_2) \frac{m_2}{m_1 + m_2}$$

$$\therefore 1-x = (1-x_1) + (1-x_2)x_1 \quad \left( \because x_1 = \frac{m_2}{m_1 + m_2} \right)$$

$$1-x = 1-x_1 + x_1 - x_1x_2$$

$$\therefore x = x_1x_2$$

8. Therefore the actual dryness 'x' of wet steam in the product of dryness fraction determined by separating calorimeter ( $x_1$ ) and throttling calorimeter ( $x_2$ ).

**Que 4.9.** Give a neat sketch of “separating and throttling calorimeter” for dryness measurement. In a throttling calorimeter the steam is admitted at a pressure of 10 bar. If it is discharged at atmospheric pressure and 110 °C after throttling, determine the dryness fraction of steam. Assume specific heat of steam as 2.2 kJ/kg-K.

**AKTU 2011-12, Marks 06**

### Answer

- A. Combined Separating and Throttling Calorimeter :** Refer Q. 4.8, Page 4-13C, Unit-4.  
**B. Numerical :**

**Given :** Admitted pressure ( $P_1$ ) = 10 bar

Pressure after throttling is atmospheric pressure,

Discharged temperature = 110 °C

**To Find :** Dryness fraction of steam.

1. Throttling is a constant enthalpy process,

$$h_1 = h_2$$

$$h_{f1} + x_1 h_{fg1} = h_{f2} + h_{fg2} + c_p (T_{\text{sup}} - T_{s2})$$

$$762.6 + x_1 \times 2013.6 = 417.5 + 2257.9 + 2.2(383 - 373)$$

$$[c_p = 2.2 \text{ kJ/kg-K}]$$

$$762.6 + x_1 \times 2013.6 = 2697.4$$

$$x_1 = \frac{1934.8}{2013.6}$$

$$x_1 = 0.96$$

This is the dryness fraction of steam after throttling.

**Que 4.10.** During a steady flow process, 4 kg of steam at 15 bar and 260 °C loses 3771 kJ of heat at constant pressure. Determine the final condition of steam.

**AKTU 2012-13, Marks 05**

**Answer**

**Given :** Mass of steam = 4 kg, Pressure = 15 bar,  
Temperature = 260 °C, Heat loss = 3771 kJ

**To Find :** Final condition of steam.

- From steam table at 15 bar the saturation temperature is 198.3 °C which shows that initial condition of steam is superheated hence the enthalpy of superheated steam is

$$h_{\text{sup}} = h_g + c_{ps}(T_{\text{sup}} - T_s)$$

- At 15 bar,  
so  $h_g = 2789.9 \text{ kJ/kg}$  and  $c_{ps} = 2.1 \text{ kJ/kg-K}$   
 $h_{\text{sup}} = 2789.9 + 2.1 \times (260 - 198.3) = 2919.47 \text{ kJ/kg}$

- The total enthalpy of steam =  $4 \times h_{\text{sup}}$   
 $= 4 \times 2919.47 \text{ kJ} = 11677.88 \text{ kJ}$

- Heat losses at constant pressure = 3771 kJ

- Remaining enthalpy of steam =  $\frac{(11677.88 - 3771)}{4}$

$$h_2 = 1976.72 \text{ kJ/kg}$$

- As pressure is constant so,  
 $h_2 = h_f + x_2 h_{fg}$

- From steam table at 15 bar,  
 $h_f = 844.7 \text{ kJ/kg}$ ,  $h_{fg} = 1945.2 \text{ kJ/kg}$ ,  $h_g = 2789.9 \text{ kJ/kg}$

$$\text{So, } 1976.72 = 844.7 + x_2 \times 1945.2$$

$$x_2 = 0.582 \approx 58.2 \%$$

The final condition of steam or dryness fraction = 58.2 %

**Que 4.11.** Throttling calorimeter has steam entering to it at 10 MPa and coming out of it at 0.05 MPa and 100°C. Determine dryness fraction of steam.

**AKTU 2016-17, Marks 05**

**Answer**

**Given :**  $P_1 = 10 \text{ MPa}$ ,  $P_2 = 0.05 \text{ MPa}$ ,  $T_2 = 100 \text{ °C}$

**To Find :** Dryness fraction of steam.

- From Steam Table :

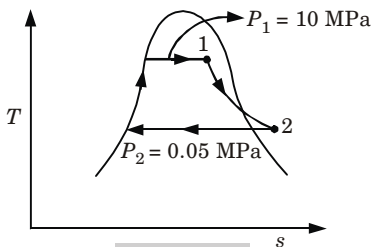


Fig. 4.11.1.

At  $P_1 = 10 \text{ MPa} = 100 \text{ bar}$   
 $h_{f1} = 1408 \text{ kJ/kg}$   
 $h_{fg1} = 1319.7 \text{ kJ/kg}$

At  $P_2 = 0.05 \text{ MPa} = 0.5 \text{ bar}$   
 $t_s = 81.35^\circ\text{C}$ ,  $C_p = 4.18 \text{ kJ/kgK}$   
 $h_{g2} = 2646 \text{ kJ/kg}$

$\therefore$  From 1 to 2 is throttling process. So,

$$h_1 = h_2$$

$$h_{f1} + x_1 h_{fg1} = h_{g2} + C_p (t_{\text{sup.}} - t_s)$$

$$1408 + x_1 \times 1319.7 = 2646 + 4.18 \times (100 - 81.35)$$

$$x_1 = 0.9971$$

**Que 4.12.** Describe simple Rankine cycle with  $p$ - $V$  diagram and any one method of dryness fraction measurement.

**AKTU 2014-15, Marks 10**

### Answer

#### A. Simple Rankine Cycle :

- Professor Rankine modified the Carnot cycle and presented a technically feasible cycle known as Rankine cycle. It is also a reversible cycle and it differs from Carnot cycle in following aspects :
  - The process of condensation is allowed to proceed to completion, i.e., exhaust steam from the steam turbine or steam engine is condensed back to liquid water. At the end of condensation process, the working substance is only liquid (water) and not a mixture of liquid and vapour.
  - Pressure of water can be easily raised to the boiler pressure by means of a small sized feed pump. Moreover, the steam can be superheated in the boiler so as to obtain the exhaust steam of high quality. It prevents pitting and erosion of turbine blades.



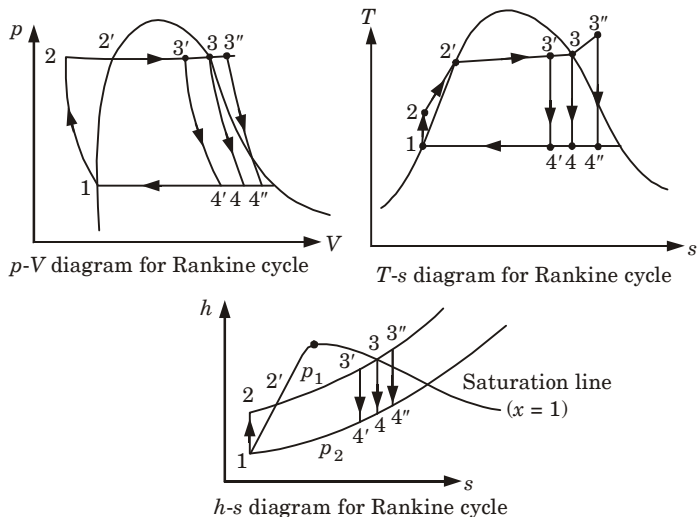


Fig. 4.12.1.

**Process (1-2) :**

1. Pumping of feed water to the boiler from back (or condenser pressure)  $p_b$  to boiler pressure  $p_1$ .
2. Compression process is a reversible adiabatic process.

**Process (2-3) :**

1. Feed water is converted into steam at constant pressure (boiler pressure  $p_1$ ).
2. Heat added during the process (2-3) is  $q_s$ .

**Process (3-4) :**

1. Process 3-4 refers to reversible adiabatic expansion of steam in the turbine from boiler pressure ' $p_1$ ' to condenser (or back) pressure ' $p_b$ '.
2. During the process 3-4, there is an enthalpy drop which is equal to the work done ' $W_T$ ' by turbine.

**Process (4-1) :**

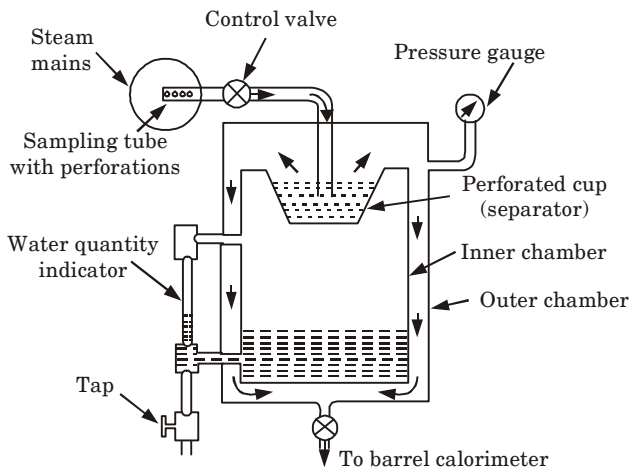
1. Exhaust steam from the steam turbine is condensed back to liquid form at constant pressure in the condenser.
2. The steam rejects its latent heat of vapourization to the cooling water. It is denoted by  $q_r$ .

**B. Measurement of Dryness Fraction :** Dryness fraction of steam is determined experimentally with the help of calorimeters. Calorimeters are of four types :

- a. Separating calorimeter.
- b. Throttling calorimeter.
- c. Combined separating and throttling calorimeter.
- d. Barrel calorimeter.

**a. Separating Calorimeter :**

1. In this calorimeter, the dryness fraction of steam is determined by separating the water particles associated with wet steam. Arrangement of this calorimeter is shown in Fig. 4.12.2.

**Fig. 4.12.2.** Separating calorimeter.

2. Wet steam at pressure ' $p$ ' is made to pass through the sampling tube from the steam main via control valve which is kept fully opened. The steam coming out of steam main tube strikes against the perforated cup which is called separator.
3. When the steam strikes against the separator, it undergoes a quick reversal of direction of motion. The water particles present in wet steam, due to greater inertia, get separated from the wet steam and get collected at the bottom of inner chamber.
4. The amount of water thus separated is measured with the help of a water quantity indicator. The mass of water is denoted by ' $m_w$ '.
5. Separated dry steam is finally condensed and its mass is measured which is denoted by ' $m_s$ '.
6. By definition, dryness fraction of steam,

$$x = \frac{\text{Mass of dry steam } (m_s)}{\text{Mass of mixture } (m_s \text{ and } m_w)}$$

$$\text{Mathematically, } x = \frac{m_s}{m_s + m_w}$$

This calorimeter gives considerably high value of  $x$ , since water particles cannot be completely separated from steam.

**Que 4.13.** Write down the analysis of Rankine cycle.

**Answer****A. Analysis of Rankine Cycle :**

1. Let's consider one kg of steam flow in the cycle. Apply steady flow energy equation (SFEE) to various processes discussed earlier :

**Process (2-3) : Boiler operation**

Heat supplied,  $q_s = (h_3 - h_2)$  (There is no work done)

at constant pressure ( $\Delta KE = 0, \Delta PE = 0$ )

**Process (3-4) : Turbine (adiabatic expansion)**

Turbine work,  $W_T = (h_3 - h_4)$  (There is no loss of heat)

**Process (4-1) : Condenser  $\Delta KE = 0, \Delta PE = 0$**

Heat rejected to cooling water,  $q_r = (h_4 - h_1)$  (Work done is zero)

**Process (1-2) : Feed pump**

Pump work,  $W_p = \int_{p_b}^{p_1} -V dp = -V(p_1 - p_b)$

2. Shaft work (Net work done),

$$W_{\text{net}} = \text{Turbine work} - \text{Pump work}$$

$$W_{\text{net}} = W_T - W_p$$

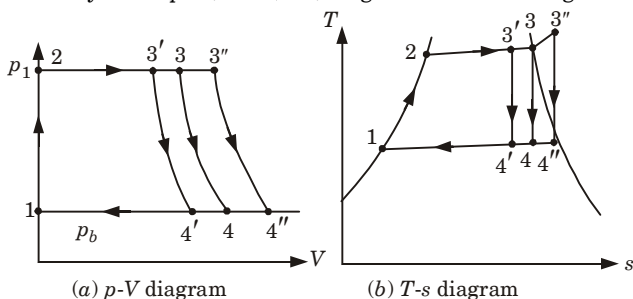
**B. Efficiency of Rankine cycle :**

$$\begin{aligned} 1. \quad \eta_{\text{Rankine}} &= \frac{\text{Net work done}}{\text{Heat supplied}} \\ &= \frac{W_T - W_p}{h_3 - h_2} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} \end{aligned}$$

2. Since compression process in the pump is carried out with liquid only for which specific volume is very small, therefore pump work ( $h_2 - h_1$ ) is quite small as compared to turbine work ( $W_T$ ) hence can be neglected. Rankine cycle efficiency now becomes without pump work,

$$\eta_{\text{Rankine}} = \frac{(h_3 - h_4)}{(h_3 - h_2)}$$

3. Rankine cycle on ( $p$ - $V$ ) and ( $T$ - $s$ ) diagram is shown in Fig. 4.13.1.



**Fig. 4.13.1.**

**Que 4.14.** Draw simple Rankine cycle on  $p$ - $V$ ,  $T$ - $s$  and  $h$ - $s$  diagram.

Steam enters at 80 bar and 450 °C in a steam turbine and expands isentropically up to condenser pressure of 0.1 bar. Find the state of steam at turbine exit and power developed by the turbine if the mass flow rate of steam is 5 kg/s.

**AKTU 2011-12, Marks 10**

**Answer**

**A.  $p$ - $V$ ,  $T$ - $s$  and  $h$ - $s$  diagram for simple Rankine Cycle :** Refer Q. 4.12, (Fig. 4.12.1), Page 4-17C, Unit-4.

**B. Numerical :**

**Given :** ( $P_1$ ) = 80 bar, ( $T_1$ ) = 450 °C, ( $P_2$ ) = 0.1 bar,

Flow rate of steam = 5 kg/s

**To Find :** State of steam at turbine exit and power developed.

1. Consider  $T$ - $s$  diagram

At  $p_1 = 80$  bar (450 °C),  $h_1 = 3270.2$  kJ/kg,  $s_1 = 6.511$  kJ/kg-K

At  $p_2 = 0.1$  bar,  $h_f = 191.8$  kJ/kg,  $h_{fg} = 2392.9$  kJ/kg,  $h_g = 2584.7$  kJ/kg,

$s_f = 0.649$  kJ/kg-K,  $s_{fg} = 7.502$  kJ/kg-K,  $s_g = 8.151$  kJ/kg-K

2. Now  $s_1 = s_2$

$$s_1 = s_f + x_2 s_{fg}$$

$$6.511 = 0.649 + x_2 \times 7.502$$

$$x_2 = 0.78$$

$$h_2 = h_f + x_2 h_{fg}$$

$$= 191.8 + 0.78 \times 2392.9 = 2058.26 \text{ kJ/kg}$$

3. Power developed by turbine :

$$W_T = \dot{m} (h_1 - h_2) = 5 \times (3270.2 - 2058.26) = 6059.69 \text{ kW}$$

( $\because$  Mass flow rate of steam,  $\dot{m} = 5$  kg/s)

**Que 4.15.** A steam turbine operating on Rankine cycle receives

steam at pressure 20 bar and degree of superheat is 89 °C. The exhaust pressure is 0.07 bar and the expansion of steam takes place isentropically. Calculate :

a. Heat supplied, assuming that feed pump supplies water to the boiler at 20 bar,

b. Heat rejected in condenser, and

c. Work done by turbine.

**AKTU 2012-13, Marks 10**

**Answer**

**Given :** Inlet Pressure = 20 bar, Degree of super heat = 89 °C,  
Exhaust pressure = 0.07 bar

**To Find :** Heat supplied, heat rejected, and work done by turbine.

**Data Assume :**  $c_{ps} = 2.1 \text{ kJ/kg-K}$

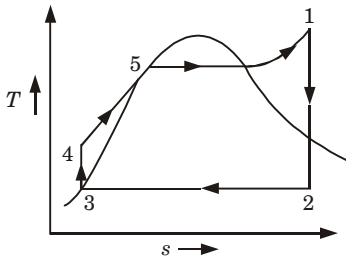
1. From steam table, at 20 bar, saturation temperature

$$T_s = 212.4 \text{ °C} = 485.4 \text{ K}$$

2. Temperature of superheated steam =  $T_s + \text{degree of superheat}$

$$T_{\text{sup}} = 212.4 + 89 = 301.4 \text{ °C} = 301.4 + 273$$

$$T_{\text{sup}} = 574.4 \text{ K}$$



**Fig. 4.15.1.**

3. Enthalpy,

$$h_{\text{sup}} = h_1 = h_g + c_{ps}(T_{\text{sup}} - T_s) \\ = 2797.2 + 2.1 \times 89 = 2984.1 \text{ kJ/kg}$$

4. From steam table at 20 bar,  $h_g = 2797.2 \text{ kJ/kg}$  and

$$s_g = 6.336 \text{ kJ/kg-K}$$

5. Entropy,

$$s_{\text{sup}} = s_1 = s_g + c_{ps} \ln \left( \frac{T_{\text{sup}}}{T_s} \right)$$

$$s_1 = 6.336 + 2.1 \ln \left( \frac{T_{\text{sup}}}{T_s} \right) = 6.6895 \text{ kJ/kg-K}$$

6. For isentropic expansion process

$$s_{\text{sup}} = s_2 \quad (s_{\text{sup}} = s_1)$$

$$6.6895 = s_{f2} + x_2 s_{fg2}$$

7. From steam table at pressure 0.07 bar

$$s_{f2} = 0.559 \text{ kJ/kg-K}, h_{f3} = 163.4 \text{ kJ/kg},$$

$$s_{fg2} = 7.717 \text{ kJ/kg-K}$$

Now,

$$6.6895 = 0.559 + x_2(7.712)$$

$$x_2 = 0.7949$$

8. Now workdone by pump,

$$W_{\text{pump}} = h_{f4} - h_{f3} = (v_F)_{p2} (p_1 - p_2)$$

$$h_{f4} - 163.4 = 0.001007(20 - 0.07) \times 100$$

$$h_{f4} = 165.4 \text{ kJ/kg}$$

a. Heat supplied,

$$Q_1 = h_1 - h_{f4} = 2984.1 - 165.4 = 2818.7 \text{ kJ/kg}$$

b. Heat rejected in condenser,

$$Q_2 = h_2 - h_{f3}$$

(At pressure 0.07 bar,  $h_{fg} = 2409.1 \text{ kJ/kg}$ )

$$h_2 = h_{f3} + x_2 h_{fg}$$

$$h_2 = 163.4 + 0.7949 \times 2409.1 = 2077.91 \text{ kJ/kg}$$

Heat rejected in condenser,

$$Q_2 = 2077.91 - 163.4 = 1914.51 \text{ kJ/kg}$$

c. Workdone by turbine,

$$W_T = h_1 - h_2 = 2984.1 - 2077.91 = 906.91 \text{ kJ/kg}$$

**Que 4.16.** Discuss the effect of pressure of steam at inlet to turbine, temperature at inlet to turbine and pressure at exit from turbine upon Rankine cycle performance.

**AKTU 2016-17, Marks 10**

### Answer

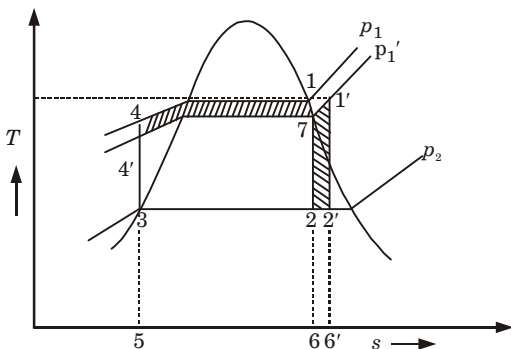
#### A. Pressure of Steam at Inlet to Turbine :

- For same back pressure and steam inlet temperature, the increase in steam inlet pressure from  $p_1$  to  $p_1'$  is accompanied by the reduction in net heat added as shown by area  $A_{1'2'271}$  and increase in net heat added by the amount shown by area  $A_{4'4174'}$ .

$$\text{Generally, } A_{1'2'271} = A_{4'4174'}$$

$$(\text{Heat rejected})_{\text{cycle } 1234} < (\text{Heat rejected})_{\text{cycle } 1'2'3'4'}$$

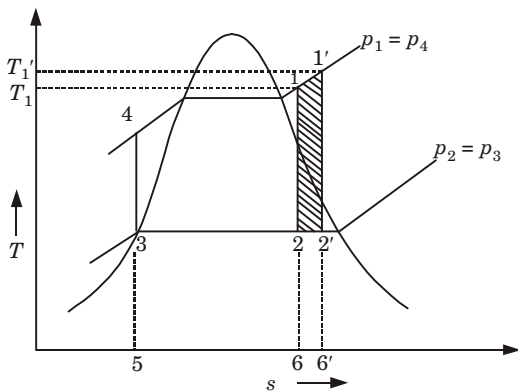
$$\eta_{\text{cycle}} = 1 - \frac{\text{Heat rejected}}{\text{Heat added}}$$



**Fig. 4.16.1.** Rankine cycle showing two different throttle pressures.

2. Increase in steam pressure at inlet to steam turbine is accompanied by increase in cycle thermal efficiency.

**B. Temperature of Steam at Inlet to Turbine :**



**Fig. 4.16.2.** Effect of increasing temperature at inlet to turbine.

1. It is also called superheating of steam at inlet to turbine.
2. From the given Fig. 4.16.2, it is clear that increase in inlet temperature from  $T_1$  to  $T_{1'}$  (Let  $T_1 < T_{1'}$ ) increases net work and heat addition.

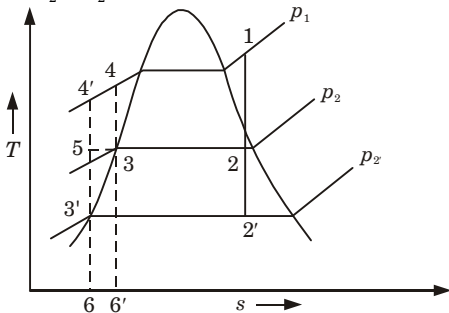
Net increased work = area  $A_{11'2'21}$

Net increased heat addition = area  $A_{11'6'61}$

3. So, it is clear that increase in steam temperature from  $T_1$  to  $T_{1'}$  increases mean temperature of heat addition, which increases the thermal efficiency.

**C. Pressure at the End of Expansion :**

1. The pressure at the end of expansion is called exhaust pressure or back pressure or condenser pressure.
2. With same maximum pressure and temperature, the reduction in back pressure from  $p_2$  to  $p_{2'}$  causes increment in net work and in heat addition.



**Fig. 4.16.3.** Effect of varying exhaust pressure.

3. From Fig. 4.16.3,  
 Increment in net work = Area 4'4322'3'54'  
 Increment in heat addition = Area 4'466'4'  
 So, the thermal efficiency of cycle increases by lowering back pressure as increase in heat addition is more than increase in heat rejection.

## PART-2

*Psychometric Terms and their Definitions, Psychometric Chart, Different Psychometric Processes and their Representation on Psychometric Chart.*

### CONCEPT OUTLINE : PART-2

#### Psychrometric Chart Terms :

1. DBT lines,
2. Specific humidity lines,
3. DPT lines,
4. WBT lines,
5. Enthalpy or total heat lines,
6. Specific volume lines,
7. Vapour pressure lines, and
8. Relative humidity lines.

#### Psychrometric Process :

##### 1. Sensible Heating :

Heat added ( $q$ ) =  $1.022 (t_{d2} - t_{d1})$  kJ/kg

##### 2. Sensible Cooling :

Heat rejected ( $q$ ) =  $1.022 (t_{d1} - t_{d2})$  kJ/kg

##### 3. Humidification :

$$LH = h_2 - h_1$$

**Dehumidification,**  $LH = h_1 - h_2$

##### 4. Cooling and Humidification :

$$\eta_H = \frac{t_{d1} - t_{d2}}{t_{d1} - t_{d3}} = \frac{W_2 - W_1}{W_3 - W_1}$$

##### 5. Cooling and Dehumidification :

$$SHF = \frac{SH}{SH + LH} = \frac{h_A - h_2}{h_1 - h_2}$$

##### 6. Heating and Humidification :

$$SHF = \frac{h_A - h_1}{h_2 - h_1}$$

##### 7. Heating and Dehumidification :

$$\eta_H = \frac{t_{d3} - t_{d1}}{t_{d2} - t_{d1}}$$



## Questions-Answers

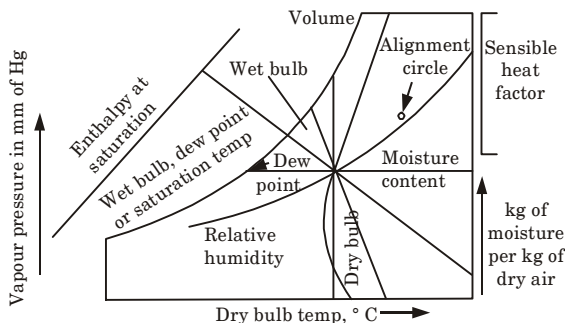
## Long Answer Type and Medium Answer Type Questions

**Que 4.17.** With the help of a neat sketch explain the psychrometric chart.

## Answer

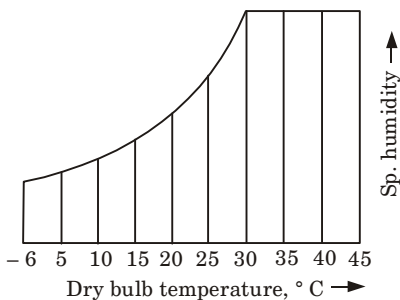
**A. Psychrometric Chart :**

1. It is a graphical representation of the various thermodynamic properties of moist air.
2. The psychrometric chart is very useful for finding out the properties of air and eliminates lot of calculations. The psychrometric chart is normally drawn for standard atmospheric pressure of 760 mm of Hg (or 1.01325 bar).
3. In a psychrometric chart, dry bulb temperature is taken as abscissa and specific humidity *i.e.*, moisture contents as ordinate.
4. Now the saturation curve is drawn by plotting the various saturation points at corresponding dry bulb temperatures.
5. The saturation curve represents 100 % relative humidity at various dry bulb temperatures and it also represents the wet bulb and dew point temperatures.



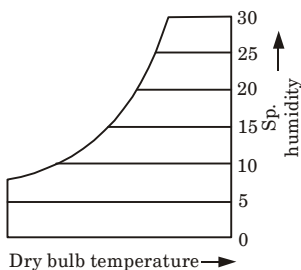
**Fig. 4.17.1.** Psychrometric chart.

6. The psychrometric chart has following important terms :
  - a. Dry Bulb Temperature Lines :** These lines are drawn parallel to the ordinate and the values of dry bulb temperatures are shown on the saturation curve.



**Fig. 4.17.2.** Dry bulb temperature lines.

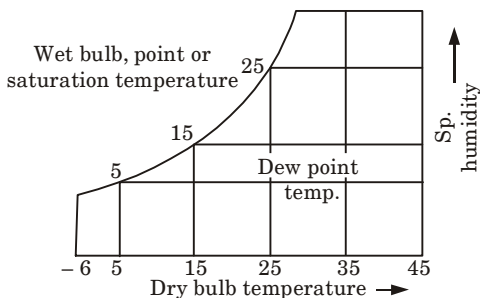
- b. Specific Humidity or Moisture Content Lines :** These lines are drawn parallel to the abscissa.



**Fig. 4.17.3.** Specific humidity lines.

- c. Dew Point Temperature Lines :**

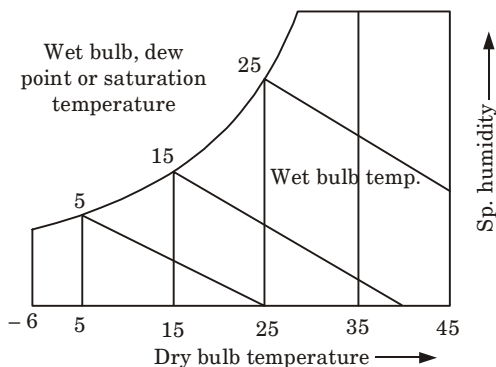
1. These are the temperature lines parallel to the abscissa. At any point on the saturation curve, the dry bulb and dew point temperatures are equal.
2. The values of dew point temperatures are generally given along the saturation curve.



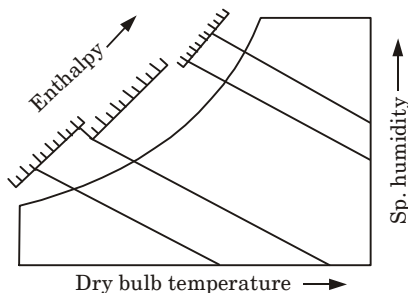
**Fig. 4.17.4.** Dew point temperature lines.

**d. Wet Bulb Temperature Lines :**

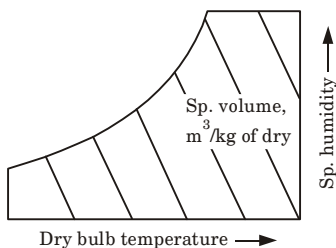
1. These are shown on the diagonal coordinate coinciding with the heat coordinates. At any point on the saturation curve, the dry bulb and wet bulb temperatures are equal.
2. The values of wet bulb temperatures are generally along the saturation curve and the diagonals run downwards to the right at an angle of  $30^\circ$  to the horizontal.

**Fig. 4.17.5. Wet bulb temperature lines.****e. Enthalpy or Total Heat Lines :**

1. The enthalpy lines are inclined straight lines and these lines are parallel to the wet bulb temperature lines and are drawn up to the saturation curve.
2. The values of total enthalpy are given on a scale above the saturation curve and these lines coincide with the wet bulb temperature lines.

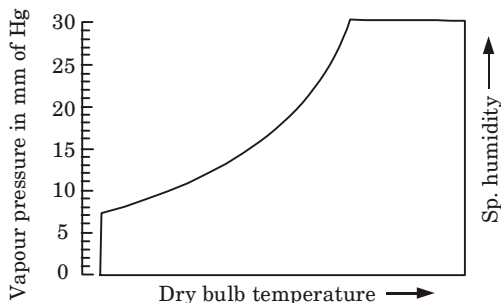
**Fig. 4.17.6. Enthalpy lines.****f. Specific Volume Lines :**

1. These lines are obliquely inclined straight lines and these lines are drawn up to the saturation curve.
2. The values of volume lines are generally given at the base of the chart.



**Fig. 4.17.7.** Specific volume lines.

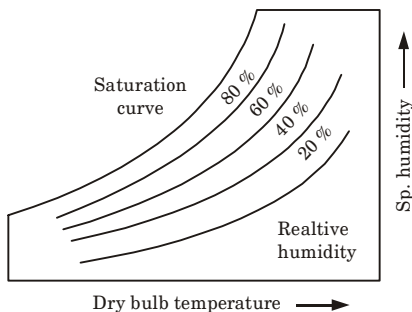
- g. Vapour Pressure Lines :** The vapour pressure lines are not drawn in the main chart but a scale showing vapour pressure in mm of Hg is given on the extreme left side of the chart.



**Fig. 4.17.8.** Vapour pressure lines.

**h. Relative Humidity Lines :**

1. The relative humidity lines are shown by curved lines and follow the saturation curve.
2. The values of relative humidity lines are generally given along the lines themselves and the saturation curve represents 100 % relative humidity.



**Fig. 4.17.9.** Relative humidity lines.

**Que 4.18.** Plotting psychrometric charts, explain common psychrometric processes on this chart.

**Answer**

**A. Psychrometric Chart :** Refer Q. 4.17, Page 4-26C, Unit-4.

**B. Importance of Psychrometric Chart in Air Conditioning :**

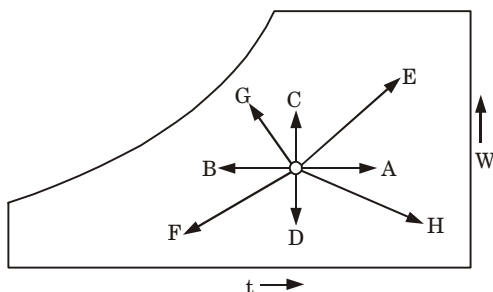
1. All data essential for the complete thermodynamic and psychrometric analysis of air conditioning processes can be summarised in a psychrometric chart.
2. It gives various thermodynamic properties of moist air.
3. It is very useful for finding out the properties of air and eliminates lot of calculations.

**C. Psychrometric Processes :**

1. The processes which affect the psychrometric properties of air are called psychrometric processes.

The important psychrometric processes are given below :

- a. Sensible heating (Process OA),
- b. Sensible cooling (Process OB),
- c. Humidification and dehumidification (Process OC and OD),
- d. Cooling and humidification (Process OG),
- e. Cooling and dehumidification (Process OF),
- f. Heating and humidification (Process OE),
- g. Heating and dehumidification (Process OH), and
- h. Mixing of two air streams.

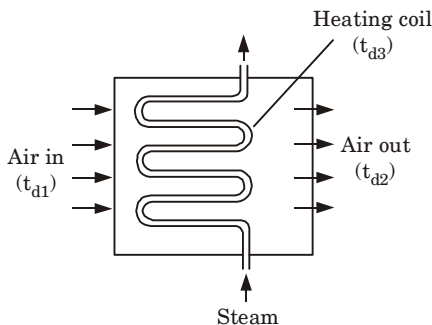


**Fig. 4.18.1.** Basic psychrometric process.

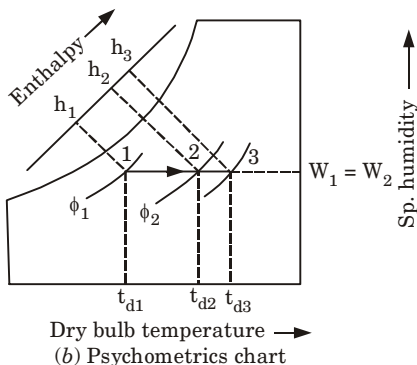
**a. Sensible Heating :**

1. The heating of air, without any change in its specific humidity is known as sensible heating. Thus the heating can be achieved by passing the air over heating coil like electric resistance heating coils or steam coils.

- The heat absorbed by the air during sensible heat is obtained from the psychrometric chart by the enthalpy difference ( $h_2 - h_1$ ) and the specific humidity during the sensible heating remains constant i.e.,  $W_1 = W_2$
- Let air at temperature  $t_{d1}$  passes over a heating coil of temperature  $t_{d3}$  and the temperature of air leaving the heating coil  $t_{d2}$  will be less than  $t_{d3}$ . The amount of heat added during sensible heating may be obtain by the relation :



(a) Psychrometrics process

**Fig. 4.18.2. Sensible heating.**

- Heat added,

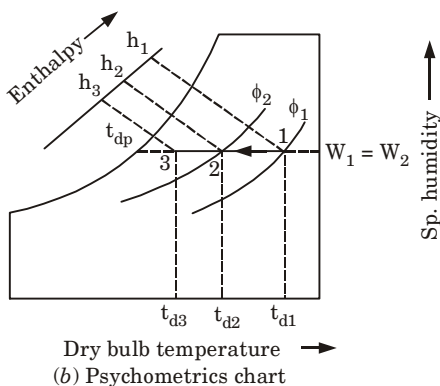
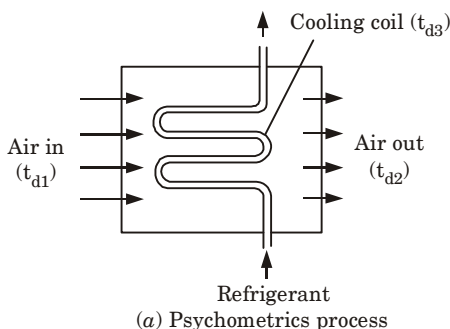
$$\begin{aligned}
 q &= h_2 - h_1 \\
 &= c_{pa} (t_{d2} - t_{d1}) + W c_{ps} (t_{d2} - t_{d1}) \\
 &= (c_{pa} + W c_{ps}) (t_{d2} - t_{d1}) \\
 &= c_{pm} (t_{d2} - t_{d1})
 \end{aligned}$$

Then term  $(c_{pa} + W c_{ps})$  is called humid specific heat ( $c_{pm}$ ) and its value is taken as  $1.022 \text{ kJ/kg-K}$ .

$$\therefore \text{Heat added } (q) = 1.022 (t_{d2} - t_{d1}) \text{ kJ/kg}$$

**b. Sensible Cooling :**

1. The cooling of air, without any change in its specific humidity is known as sensible cooling.
2. Thus the sensible cooling can be achieved by passing the air over cooling coil like evaporating coil of the refrigeration cycle or secondary brine coil.

**Fig. 4.18.3. Sensible cooling.**

3. The heat rejected by air during sensible cooling is obtained from the psychometric chart by the enthalpy difference ( $h_1 - h_2$ ).
4. Let air at temperature  $t_{d1}$  passes over a cooling coil of temperature  $t_{d3}$  and the temperature of air leaving the cooling coil ( $t_{d2}$ ) will be more than  $t_{d3}$ . The specific humidity during the sensible cooling remains constant i.e.,  $W_1 = W_2$ .
5. The dry bulb temperature reduces from  $t_{d1}$  to  $t_{d2}$  and relative humidity increases from  $\phi_1$  to  $\phi_2$ .
6. The amount of heat rejected during sensible cooling is obtained from the relation :

i. Heat rejected,

$$q = h_1 - h_2 = c_{pa} (t_{d1} - t_{d2}) + W c_{ps} (t_{d1} - t_{d2})$$

$$= (c_{pa} + W c_{ps}) (t_{d1} - t_{d2}) = c_{pm} (t_{d1} - t_{d2})$$

$$\therefore \text{Heat rejected } q = 1.022 (t_{d1} - t_{d2}) \text{ kJ/kg}$$

ii. For air conditioning purposes, the sensible heat per minute is given by,

$$SH = m_a c_{pm} \Delta t \quad (\because m_a = V\rho)$$

$$= V\rho c_{pm} \Delta t \text{ kJ/min} \quad \dots(4.18.1)$$

where

$V$  = rate of dry air flowing in  $\text{m}^3/\text{min}$ ,

$\rho$  = density of moist air at  $20^\circ\text{C}$  and 50 % relative humidity

=  $1.2 \text{ kg/m}^3$  of dry air,

$c_{pm}$  = humid specific heat

=  $1.022 \text{ kJ/kg-K}$ , and

$\Delta t = t_{d1} - t_{d2}$  = difference of dry bulb temperatures between the entering and leaving conditions of air in  $^\circ\text{C}$ .

iii. Putting the value of  $\rho$  and  $c_{pm}$  in eq. (4.18.1), we get

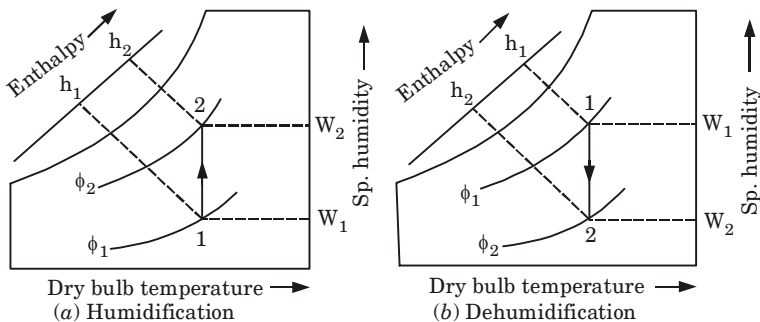
$$SH = V \times 1.2 \times 1.022 \times \Delta t$$

$$= 1.2264 V \times \Delta t \text{ kJ/min}$$

$$= \frac{1.2264 V \times \Delta t}{60} = 0.02044 V \times \Delta t \text{ kJ/s}$$

### c. Humidification and Dehumidification :

1. The gain of moisture to the air, without change in its dry bulb temperature, is known as humidification and removal of moisture from the air, without change in its dry bulb temperature is known as dehumidification.
2. The humidification and dehumidification processes are shown in Fig. 4.18.4(a) and (b) on the psychrometric chart :



**Fig. 4.18.4.** Humidification and dehumidification.

3. In humidification, the relative humidity increases from  $\phi_1$  to  $\phi_2$  but decreases from  $\phi_1$  to  $\phi_2$  in dehumidification and specific humidity also increases from  $W_1$  to  $W_2$  but decreases in dehumidification as shown in Fig. 4.18.5(a) and (b).



4. The change in enthalpy in humidification is shown by the intercept  $(h_2 - h_1)$  on the psychrometric chart by which dry bulb temperature of air during the humidification remains constant, therefore its sensible heat also remains constant.
5. So, the change in enthalpy per kg of dry air due to the increased moisture content equal to  $(W_2 - W_1)$  kg per kg of dry air is considered to cause a latent heat transfer ( $LH$ ).

i. **Mathematically :**

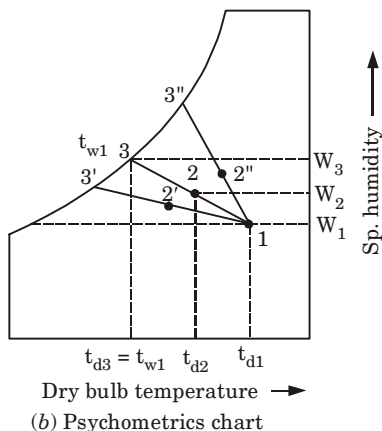
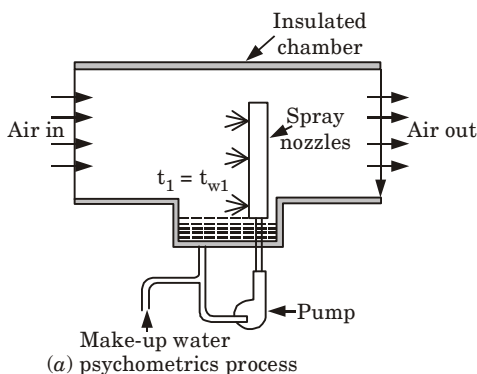
$$LH = (h_2 - h_1) = h_{fg} (W_2 - W_1)$$

where  $h_{fg}$  is the latent heat of vaporization at dry bulb temperature ( $t_{d1}$ ).

- ii. Similarly for dehumidification, the above equation can be written as :

$$LH = (h_1 - h_2) = h_{fg} (W_1 - W_2)$$

d. **Cooling and Humidification :**



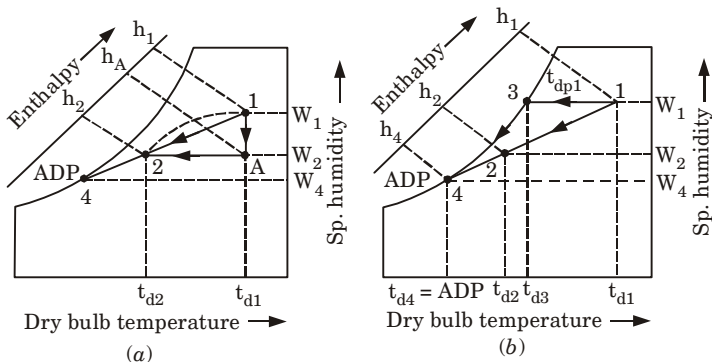
**Fig. 4.18.5. Cooling with adiabatic humidification.**

1. When the air is passed through an insulated chamber having sprays of water maintained at a temperature ( $t_1$ ) higher than the dew point temperature of entering air ( $t_{dp1}$ ), but lower than its dry bulb temperature of entering air or equal to the wet bulb temperature of the entering air ( $t_{w1}$ ), then air is said to be cooled and humidified as shown in Fig. 4.18.6(a) and (b).
2. Since no heat is supplied or rejected from the spray water as the same water is recirculated again and again, therefore, a condition of adiabatic saturation will be reached in this case.
3. The temperature of spray water will reach the thermodynamic wet bulb temperatures of the air entering the spray water.
4. In an ideal case (*i.e.*, when the humidifying efficiency of the spray chamber is 100 %), the final condition of the air will be at point 3 but in actual practice, perfect humidification is never achieved.
5. Therefore, the final condition of air at outlet is represented by point 2 on the line 1 - 3.
6. The effectiveness or the humidifying efficiency of the spray chamber is given by,

$$\begin{aligned}
 \eta_H &= \frac{\text{actual drop in DBT}}{\text{ideal drop in DBT}} \\
 &= \frac{\text{actual drop in specific humidity}}{\text{ideal drop in specific humidity}} \\
 &= \frac{t_{d1} - t_{d2}}{t_{d1} - t_{d3}} = \frac{W_2 - W_1}{W_3 - W_1}
 \end{aligned}$$

**e. Cooling and Dehumidification :**

1. In this process, the dry bulb temperature as well as the specific humidity of air decreases and the final relative humidity of the air is generally higher than that of the entering air.



**Fig. 4.18.6. Cooling and dehumidification.**

2. The dehumidification of air is only possible when the effective surface temperature of the cooling coil is less than the dew point temperatures of the air entering the coil (*i.e.*  $t_{dp1}$ ).
3. The effective surface temperature of the coil is known as apparatus dew point (ADP).

4. The process of cooling and dehumidification is shown below :

- i. Let
 
$$t_{d1} = \text{dry bulb temperature of air entering the coil,}$$

$$t_{dp1} = \text{dew point temperature of the entering air}$$

$$= t_{d3}, \text{ and}$$

$$t_{d4} = \text{effective surface temperature or ADP of the coil.}$$
- ii. Under ideal conditions, the dry bulb temperature of the air leaving the cooling coil (*i.e.*  $t_{d4}$ ) should be equal to the surface temperature of the cooling coil (*i.e.*, ADP), which is never possible due to inefficiency of the cooling coil. Thus, the resulting condition of air coming out of the coil is shown by a point 2 on the line 1 – 4.
- iii. The total heat removed from the air during the cooling and dehumidification process is,

$$q = h_1 - h_2 = (h_1 - h_A) + (h_A - h_2)$$

$$= LH + SH$$

where  $LH = h_1 - h_A =$  latent heat removed due to condensation of vapour of the reduced moisture content ( $W_1 - W_2$ ), and

$$SH = h_A - h_2 = \text{sensible heat removed.}$$

- iv. We know that sensible heat factor,

$$SHF = \frac{\text{sensible heat}}{\text{total heat}} = \frac{SH}{LH + SH} = \frac{h_A - h_2}{h_1 - h_2}$$

#### **f. Heating and Humidification :**

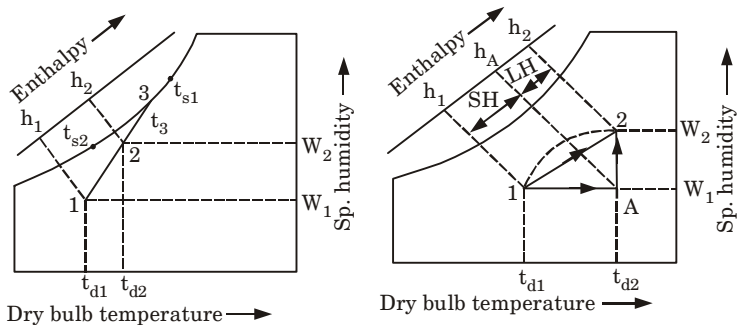
1. This process is reverse process of cooling and dehumidification.
2. When air is passed through a humidifier having spray water temperature higher than the dry bulb temperature of the entering air, the unsaturated air will reach the condition of saturation and thus the air becomes hot.
3. The heat of vaporization of water is absorbed from the spray water itself and hence it gets cooled.
4. In this way, the air becomes heated and humidified.
5. In this process, the dry bulb temperature as well as specific humidity of air increases and the final relative humidity of the air can be lower or higher than that of the entering air.
6. The total heat added to the air during heating and humidification is,

$$q = h_2 - h_1 = (h_2 - h_A) + (h_A - h_1)$$

$$= q_L + q_S$$

where  $q_L = (h_2 - h_A) =$  latent heat of vaporization of the increased moisture content ( $W_2 - W_1$ ), and

$$q_S = (h_A - h_1) = \text{sensible heat added}$$



**Fig. 4.18.7.** Heating and humidification.

7. We know that sensible heat factor,

$$\text{SHF} = \frac{\text{sensible heat}}{\text{total heat}} = \frac{q_s}{q} = \frac{q_s}{q_s + q_L} = \frac{h_A - h_1}{h_2 - h_1}$$

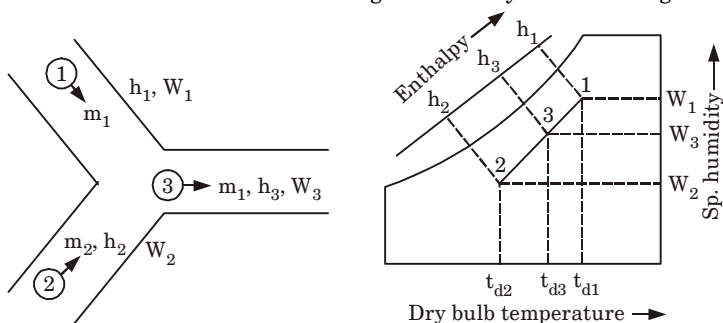
**g. Heating and Dehumidification :**

1. In this process, the air is passed over chemicals which have an affinity for moisture. As the air comes in contact with these chemicals, the moisture gets condensed out of the air and gives up its latent heat.
2. Due to the condensation, the specific humidity decreases and the heat of condensation supplies sensible heat for heating the air and thus increasing its dry bulb temperature.
3. The effectiveness or efficiency of the dehumidifier is given as,

$$\eta_H = \frac{\text{actual increase in DBT}}{\text{ideal increase in DBT}} = \frac{t_{d3} - t_{d1}}{t_{d2} - t_{d1}}$$

**h. Mixing of Two Air Streams :**

1. When two quantities of air having different enthalpies and different specific humidity's are mixed, the final condition of the air mixture depends upon the masses involved and on the enthalpy and specific humidity of each of the constituent masses which enter the mixture.
2. The two air streams 1 and 2 mixing adiabatically is shown in Fig. 4.18.8.



**Fig. 4.18.8.** Adiabatic mixing of two air streams.

3. Let  $m_1$  = mass of air entering at 1,  
 $h_1$  = enthalpy of air entering at 1,  
 $W_1$  = specific humidity of air entering at 1,  
 $m_2, h_2$  and  $W_2$  = corresponding values of air entering at 2, and  
 $m_3, h_3$  and  $W_3$  = corresponding values of the mixture leaving at 3.

4. Assuming no loss of enthalpy and specific humidity during the air mixing process, we have

For the mass balance,

$$m_1 + m_2 = m_3 \quad \dots(4.18.1)$$

For the energy balance,

$$m_1 h_1 + m_2 h_2 = m_3 h_3 \quad \dots(4.18.2)$$

And for the mass balance of water vapour,

$$m_1 W_1 + m_2 W_2 = m_3 W_3 \quad \dots(4.18.3)$$

5. Substituting the value of  $m_3$  from eq. (4.18.1) in eq. (4.18.2)

$$m_1 h_1 + m_2 h_2 = (m_1 + m_2) h_3 = m_1 h_3 + m_2 h_3$$

$$\text{or} \quad m_1 h_1 - m_1 h_3 = m_2 h_3 - m_2 h_2$$

$$m_1 (h_1 - h_3) = m_2 (h_3 - h_2)$$

$$\therefore \quad \frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} \quad \dots(4.18.4)$$

6. Similarly, substituting the value of  $m_3$  from eq. (4.18.1) in eq. (4.18.3)

$$\frac{m_1}{m_2} = \frac{W_3 - W_2}{W_1 - W_3} \quad \dots(4.18.5)$$

7. Now from eq. (4.18.4) and eq. (4.18.5), we get

$$\frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} = \frac{W_3 - W_2}{W_1 - W_3}$$

**Que 4.19.** A mixture of dry air and water vapour is at a temperature

of 22 °C under a total pressure of 730 mm Hg. The dew point temperature is 15 °C. Find :

- Partial pressure of water vapour;
- Relative humidity;
- Specific humidity;
- Enthalpy of air per kg of dry air;
- Specific volume of air per kg of dry air.

**Answer**

**Given :**  $t_{db} = 22 \text{ }^\circ\text{C}$ ;  $t_{dp} = 15 \text{ }^\circ\text{C}$ ;

$$p_t = 1.01325 \times \frac{730}{760} = 0.9732 \text{ bar}$$

- i. From steam tables partial pressure of water vapour at 15 °C dew point temperature,

$$p_v = 0.017 \text{ bar}$$

- ii. Saturation pressure of water vapour at 22 °C DBT,

$$p_{vs} = 0.0264 \text{ bar}$$

∴ Relative humidity,

$$\phi = \frac{p_v}{p_{vs}} = \frac{0.017}{0.0264}$$

iii. Specific humidity,

$$\begin{aligned} W &= \frac{0.622 p_v}{p_t - p_v} \\ &= \frac{0.622 \times 0.017}{0.9732 - 0.017} = 0.011 \text{ kg/kg of dry air} \end{aligned}$$

iv. Enthalpy of air,  $h = 1.005 t_{db} + W(2500 + 1.88 t_{db})$   
 $= 1.005 \times 22 + 0.011(2500 + 1.88 \times 22)$   
 $= 22.11 + 27.95 = 50.06 \text{ kJ/kg of dry air}$

v. Specific volume of air is equal to the volume of 1 kg of dry air or 0.011 kg of water vapour. Based on dry air part

$$\begin{aligned} v = v_a &= \frac{R_a \times T_a}{p_a} = \frac{R_a \times T_a}{(p_t - p_v)} \\ &= \frac{287 \times (22 + 273)}{(0.9732 - 0.017) \times 10^5} \\ &= 0.885 \text{ m}^3/\text{kg of dry air} \end{aligned}$$

**Que 4.20.** In laboratory test, a psychrometer recorded dry bulb

temperature as 33 °C and wet bulb temperature 28 °C. Calculate :

- Vapour pressure;
- Relative humidity;
- Specific humidity;
- Degree of saturation;
- Dew point temperature;
- Enthalpy of mixture.

Barometric pressure = 1.0132 bar.

**Answer**

**Given :**  $t_{db} = 35 \text{ °C}; t_{wb} = 28 \text{ °C}; p_t = 1.0132 \text{ bar}$

From steam tables, corresponding to 28 °C,

$$(p_{vs})_{wb} = 0.0378 \text{ bar}$$

i. Vapour pressure is given by the relation :

$$\begin{aligned} p_v &= (p_{vs})_{wb} - \frac{[p_t - (p_{vs})_{wb}](t_{db} - t_{wb})}{1527.4 - 1.3t_{wb}} \\ &= 0.0378 - \frac{[1.0132 - 0.0378](35 - 28)}{1527.4 - 1.3 \times 28} \\ &= 0.0378 - \frac{6.8278}{1491} = 0.0332 \text{ bar} \end{aligned}$$

ii. Relative humidity,  $\phi = \frac{p_v}{p_{vs}}$

From steam tables corresponding to 35 °C,  $p_{vs} = 0.0563$  bar

$$\therefore \phi = \frac{0.0332}{0.0563} = 0.5897 \text{ or } 58.97 \%$$

iii. Specific humidity,  $W = \frac{0.622 p_v}{p_t - p_v} = \frac{0.622 \times 0.0332}{1.0132 - 0.0332}$   
 $= 0.21 \text{ kg/kg of dry air}$

iv. Degree of saturation,

$$\mu = \frac{p_v(p_t - p_{vs})}{p_{vs}(p_t - p_v)} = \frac{0.0332(1.0132 - 0.0563)}{0.0563(1.0132 - 0.0332)} = 0.5 \%$$

v. Dew point temperature,  $t_{db}$ , corresponding to

$$p_v \text{ (i.e., } 0.0332 \text{ bar)} \approx 26^\circ\text{C}$$

(From steam tables)

vi. Enthalpy of mixture,

$$\begin{aligned} h &= 1.005 t_{db} + W(2500 + 1.88 t_{db}) \\ &= 1.005 \times 35 + 0.021(2500 + 1.88 \times 35) \\ &= 35.175 + 53.882 = 89.06 \text{ kJ/kg of dry air} \end{aligned}$$

### VERY IMPORTANT QUESTIONS

*Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.*

**Q. 1.** Draw the  $p$ - $T$  diagram of pure substance and explain its various regions of the diagram in details.

**Ans.** Refer Q. 4.3, Unit-4.

**Q. 2.** What is dryness fraction ? Explain the measurement of dryness fraction of steam by combined separating and throttling calorimeter.

**Ans.** Refer Q. 4.8, Unit-4.

**Q. 3.** Describe simple Rankine cycle with  $p$ - $V$  diagram and any one method of dryness fraction measurement.

**Ans.** Refer Q. 4.12, Unit-4.

**Q. 4.** Write down the analysis of Rankine cycle.

**Ans.** Refer Q. 4.13, Unit-4.

**Q. 5.** Draw simple Rankine cycle on  $p$ - $V$ ,  $T$ - $s$  and  $h$ - $s$  diagram. Steam enters at 80 bar and 450 °C in a steam turbine and expands isentropically up to condenser pressure of 0.1 bar. Find the state of steam at turbine exit and power developed by the turbine if the mass flow rate of steam is 5 kg/s.

**Ans.** Refer Q. 4.14, Unit-4.

**Q. 6.** Discuss the effect of pressure of steam at inlet to turbine, temperature at inlet to turbine and pressure at exit from turbine upon Rankine cycle performance.

**Ans.** Refer Q. 4.16, Unit-4.

**Q. 7.** With the help of a neat sketch explain the psychrometric chart.

**Ans.** Refer Q. 4.17, Unit-4.

**Q. 8.** Plotting psychrometric charts, explain common psychrometric processes on this chart.

**Ans.** Refer Q. 4.18, Unit-4.

**Q. 9.** A mixture of dry air and water vapour is at a temperature of 22 °C under a total pressure of 730 mm Hg. The dew point temperature is 15 °C. Find :

- i. Partial pressure of water vapour;
- ii. Relative humidity;
- iii. Specific humidity;
- iv. Enthalpy of air per kg of dry air;
- v. Specific volume of air per kg of dry air.

**Ans.** Refer Q. 4.19, Unit-4.

**Q. 10.** In laboratory test, a psychrometer recorded dry bulb temperature as 33 °C and wet bulb temperature 28 °C. Calculate :

- i. Vapour pressure;
  - ii. Relative humidity;
  - iii. Specific humidity;
  - iv. Degree of saturation;
  - v. Dew point temperature;
  - vi. Enthalpy of mixture.
- Barametric pressure = 1.0132 bar.

**Ans.** Refer Q. 4.20, Unit-4.





# 5

## UNIT

# Refrigeration Cycles

### Part-1 ..... (5-2C to 5-12C)

- *Refrigeration Capacity*
- *Unit of Refrigeration*
- *Reversed Carnot Cycle for Gas and Vapour*
- *Air Refrigeration Cycles*
- *Reversed Brayton Cycle and Bell Coleman Cycle*

A. Concept Outline : Part-1 ..... 5-2C

B. Long and Medium Answer Type Questions ..... 5-2C

### Part-2 ..... (5-12C to 5-23C)

- *Vapour Compression Refrigeration Cycle*
- *Simple Saturated Cycle and Actual Vapour Compression Refrigeration Cycle*
- *Analysis of Cycles*
- *Effect of Superheating*
- *Subcooling and Change in Evaporator and Condenser Pressure on Performance of Vapour Compression Refrigeration Cycle*

A. Concept Outline : Part-2 ..... 5-12C

B. Long and Medium Answer Type Questions ..... 5-13C

### Part-3 ..... (5-24C to 5-30C)

- *Refrigerant*
- *Classification and Desirable Properties of Refrigerant*
- *Vapour Absorption Refrigeration System*

A. Concept Outline : Part-3 ..... 5-24C

B. Long and Medium Answer Type Questions ..... 5-24C

**PART-1**

*Refrigeration Capacity, Unit of Refrigeration, Reversed Carnot Cycle for Gas and Vapour, Air Refrigeration Cycles, Reversed Brayton Cycle and Bell Coleman Cycle.*

**CONCEPT OUTLINE : PART-1**

**Refrigeration :** It means a continued extraction of heat from a body whose temperature is already below the temperature of surroundings.

**Unit of Refrigeration :** The unit of refrigeration is TR.

$$1\text{TR} = 232.6 \text{ kJ / min}$$

In actual,  $1\text{TR} = 210 \text{ kJ / min}$  or  $3.5 \text{ kW}$

**Coefficient of Performance of a Refrigerator :**

$$\text{COP} = \frac{\text{Heat extracted}}{\text{Amount of work done}} = \frac{Q}{W}$$

**Refrigeration Effect :** The amount of heat extracted from the system is termed as refrigeration effect.

**Air Refrigeration Cycle :**

1. Open air refrigeration cycle.
2. Closed air refrigeration cycle.
3. Reversed Carnot cycle.
4. Reversed Brayton cycle.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions**

**Que 5.1.** Define the terms, 'refrigeration effect' and unit of refrigeration ?

**Answer**

**A. Refrigeration Effect :**

1. It is defined as the amount of cooling produced by a system.
2. This cooling is obtained at an expense of some energy. Hence, it is customary to define a term known as coefficient of performance.
3. The ratio of heat extracted in the refrigerator to the work done on the refrigerant is known as coefficient of performance or theoretical coefficient of performance of a refrigerator (COP).

Mathematically,

$$\text{COP (theoretical)} = \frac{Q}{W}$$

Where,

$Q$  = Amount of heat extracted in the refrigerator or capacity of a refrigerator, and

$W$  = Amount of work done.

### B. Unit of Refrigeration :

1. The practical unit of refrigeration is expressed in terms of 'tonne of refrigeration' or TR.
2. A tonne of refrigeration is defined as the amount of refrigeration effect produced by the uniform melting of one tonne of ice at  $0^\circ\text{C}$  in 24 hours. Since the latent heat of ice is  $335 \text{ kJ / kg}$ , therefore one tonne of refrigeration is given by,

$$1 \text{ TR} = 1000 \times 335 \text{ kJ in 24 hours}$$

$$= \frac{1000 \times 335}{24 \times 60} = 232.6 \text{ kJ / min}$$

**Note :** In actual practice, one tonne of refrigeration is taken as equivalent to  $210 \text{ kJ / min}$  or  $3.5 \text{ kW}$  (i.e.,  $3.5 \text{ kJ / s}$ )

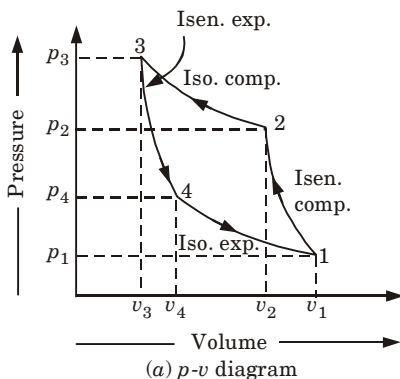
**Que 5.2.**

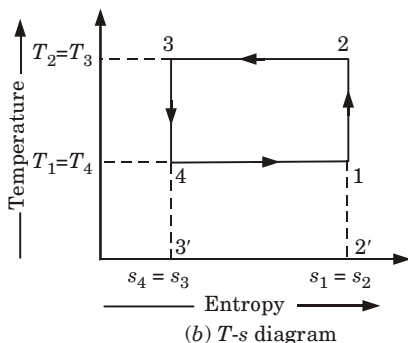
**Describe a reversed Carnot cycle with the help of a neat**

**labelled sketch.**

**Answer**

1. A refrigerating system working on the reversed Carnot cycle, will have the maximum possible coefficient of performance but the production of such a machine has not been possible practically because the adiabatic portion of the stroke would need a high speed while during isothermal portion of the stroke, there is a need of a very low speed. This variation of speed during the stroke is not practicable.
2. The working of reversed Carnot cycle are shown on  $p$ - $v$  and  $T$ - $s$  diagram below :





**Fig. 5.2.1.** Reversed Carnot cycle.

3. The four processes of the reversed Carnot cycle are as follows :

**a. Isentropic Compression Process (1-2) :**

1. During this process, the pressure of air increases from  $p_1$  to  $p_2$ , specific volume decreases from  $v_1$  to  $v_2$  and temperature increases from  $T_1$  to  $T_2$ . During isentropic compression, no heat is absorbed or rejected by the air.

**b. Isothermal Compression Process (2-3) :**

1. During this process, the pressure of air increases from  $p_2$  to  $p_3$  and specific volume decreases from  $v_2$  to  $v_3$ .
2. Heat rejected by the air during isothermal compression per kg of air is given by,

$$\begin{aligned} q_{2-3} &= \text{Area } 2-3-3'-2' \\ &= T_3 (s_2 - s_3) \\ &= T_2 (s_2 - s_3) \end{aligned}$$

**c. Isentropic Expansion Process (3-4) :**

1. During this process, the pressure of air decreases from  $p_3$  to  $p_4$ , specific volume increases from  $v_3$  to  $v_4$  and the temperature decreases from  $T_3$  to  $T_4$ .

**d. Isothermal Expansion Process (4-1) :**

1. During this process, the pressure of air decreases from  $p_4$  to  $p_1$ , and specific volume increases from  $v_4$  to  $v_1$ .
2. Heat absorbed by the air (or heat extracted from the cold body) during isothermal expansion per kg of air is given by,

$$\begin{aligned} q_{4-1} &= \text{Area } 4-1-2'-3' \\ &= T_4 (s_1 - s_4) = T_4 (s_2 - s_3) = T_1 (s_2 - s_3) \end{aligned}$$

3. Since, in a refrigerating machine, heat rejected is more than heat absorbed.

4. Therefore, workdone during the cycle per kg of air

$$= \text{Heat rejected} - \text{Heat absorbed}$$

$$= q_{2-3} - q_{4-1}$$

$$= T_2 (s_2 - s_3) - T_1 (s_2 - s_3)$$

$$= (T_2 - T_1) (s_2 - s_3)$$

5. Therefore, coefficient of performance of the refrigeration system working on reversed Carnot cycle is given by,

$$\begin{aligned} (\text{COP})_R &= \frac{\text{Heat absorbed}}{\text{Workdone}} = \frac{q_{4-1}}{q_{2-3} - q_{4-1}} \\ &= \frac{T_1 (s_2 - s_3)}{(T_2 - T_1) (s_2 - s_3)} = \frac{T_1}{T_2 - T_1} \end{aligned}$$

**Que 5.3.** Describe a Bell-Coleman or reversed Joule air refrigeration cycle with the help of a neat labelled sketch.

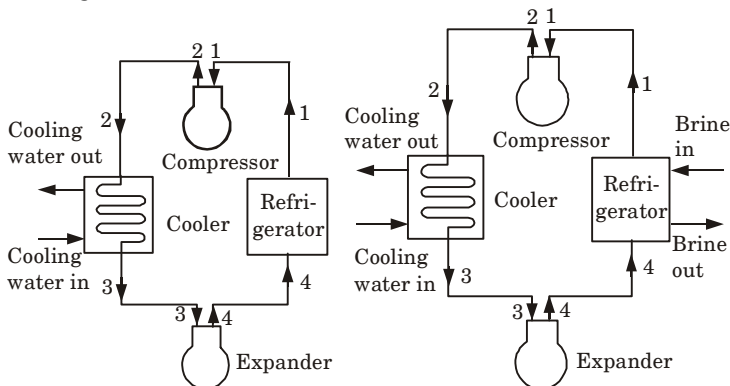
**OR**

Discuss the Bell-Coleman cycle for gas refrigeration with the help of schematic,  $T$ - $s$  and  $p$ - $v$  diagrams.

**Answer**

**A. Bell-Coleman or Reversed Brayton or Joule Cycle :**

1. This cycle consists of a compressor, a cooler, an expander and a refrigerator as shown below :



(a) Open cycle Bell-Coleman refrigerator.

(b) Closed cycle or dense air Bell-Coleman refrigerator.

**Fig. 5.3.1.**

2. The Bell-Coleman cycle is a modification of reversed Carnot cycle.
3. The four processes of this cycle are shown on  $p$ - $v$  and  $T$ - $s$  diagram below :

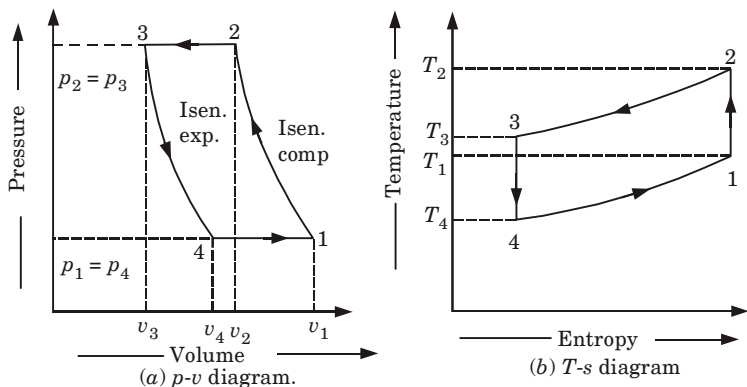


Fig. 5.3.2. Bell-Coleman cycle.

4. The four process of the cycle are as follows :

**a. Isentropic Compression Process (1-2) :**

1. During the compression stroke, the cold air from the refrigerator is drawn into the compressor cylinder where it is compressed isentropically in the compressor.
2. In this process, both the pressure and temperature increases and the specific volume of air at delivery from compressor reduces from  $v_1$  to  $v_2$ .

**b. Constant Pressure Cooling Process (2-3) :**

1. During this process, the warm air from the compressor is passed into the cooler where it is cooled at constant pressure  $p_3 (= p_2)$ , reducing the temperature from  $T_2$  to  $T_3$  (temperature of cooling water). The specific volume also reduces from  $v_2$  to  $v_3$ .
2. Heat rejected by the air during constant pressure per kg of air is given by,

$$Q_{2-3} = c_p (T_2 - T_3)$$

**c. Isentropic Expansion Process (3-4) :**

1. During this process, the air from the cooler is now drawn into the expander cylinder where it is expanded isentropically from pressure  $p_3$  to the refrigerator pressure  $p_4$  which is equal to the atmospheric pressure and the temperature of air during expansion falls from  $T_3$  to  $T_4$ . The specific volume of air at entry to the refrigerator increases from  $v_3$  to  $v_4$ .

**d. Constant Pressure Expansion Process (4-1) :**

1. During this process, the cold air from expander is passed to the refrigerator where it is expanded at constant pressure  $p_4 (= p_1)$  and the temperature of air increases from  $T_4$  to  $T_1$ . Due to heat from the refrigerator, the specific volume of the air changes from  $v_4$  to  $v_1$ .

2. Heat absorbed by the air (or heat extracted from the refrigerator) during constant pressure expansion per kg of air is given by,

$$q_{4-1} = c_p (T_1 - T_4)$$

5. We know that the work done during the cycle per kg of air,  
 = Heat rejected – Heat absorbed  
 =  $c_p (T_2 - T_3) - c_p (T_1 - T_4)$

6. Therefore, coefficient of performance (COP) =  $\frac{\text{Heat absorbed}}{\text{Workdone}}$

$$= \frac{c_p (T_1 - T_4)}{c_p (T_2 - T_3) - c_p (T_1 - T_4)} = \frac{T_4 \left( \frac{T_1}{T_4} - 1 \right)}{T_3 \left( \frac{T_2}{T_3} - 1 \right) - T_4 \left( \frac{T_1}{T_4} - 1 \right)} \quad \dots(5.3.1)$$

7. For isentropic compression process (1-2),

$$\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \quad \dots(5.3.2)$$

Similarly, for isentropic expansion process (3-4),

$$\frac{T_3}{T_4} = \left( \frac{p_3}{p_4} \right)^{\frac{\gamma-1}{\gamma}} \quad \dots(5.3.3)$$

8. Since,  $p_2 = p_3$  and  $p_1 = p_4$ , therefore from eq. (5.3.2) and eq. (5.3.3), we get

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad \text{or} \quad \frac{T_2}{T_3} = \frac{T_1}{T_4}$$

9. Now substituting these values in eq. (5.3.1), we get

$$\begin{aligned} \text{COP} &= \frac{T_4}{T_3 - T_4} = \frac{1}{\frac{T_3}{T_4} - 1} \\ &= \frac{1}{\left( \frac{p_3}{p_4} \right)^{\frac{\gamma-1}{\gamma}} - 1} = \frac{1}{\left( \frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1} = \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}} - 1} \end{aligned}$$

Where  $r_p$  = Compression or expansion ratio =  $\frac{p_2}{p_1} = \frac{p_3}{p_4}$

**Que 5.4.** Explain open and closed air refrigeration cycle.

**Answer**

#### A. Open Air Refrigeration Cycle :

1. In an open air refrigeration cycle, the air is directly led to the space to be cooled and allowed to circulate through the cooler and then returned to the compressor to start another cycle.

2. Since the air is supplied to the refrigerator at atmospheric pressure, therefore, volume of air handled by the compressor and expander is large.
3. Thus the size of compressor and expander should be large.

#### **B. Closed Air Refrigeration Cycle :**

1. In a closed air refrigeration cycle, the air is passed through the pipes and component parts of the system at all times.
2. The air is used for absorbing heat from the fluid (say brine) and this cooled brine is circulated into the space to be cooled.
3. The closed air refrigeration cycle has the following advantages :
  - a. It can work at a suction pressure higher than that of atmospheric pressure, therefore this reduces the volume handled by the compressor and expander.
  - b. The operating pressure ratio can be reduced, which results in high COP.

**Que 5.5.** Give the difference between open and closed air refrigeration cycles.

**Answer**

S.No.	Open air refrigeration cycle	Closed air refrigeration cycle
1.	The air comes in contact directly with the space to be cooled.	The air does not come in contact with the space to be cooled.
2.	The size of compressor and expander is large.	The size of compressor can be kept within reasonable limit by using dense air.
3.	It requires drier.	It does not require any drier.
4.	COP is lower.	COP is higher.
5.	The expansion of the refrigerant can be varied only upto atmospheric pressure prevailing in the cold chamber.	There is no such restriction.

**Que 5.6.** A scientist claims to have developed a refrigerator which maintains a freezer temperature of  $-15^{\circ}\text{C}$  in a room whose



temperature is 35 °C and have a COP of 6.5. Justify, whether his claim is true or false.

### Answer

**Given :**  $T_2 = 273 + (-15) = 258 \text{ K}$ ,  $T_1 = 273 + 35 = 308 \text{ K}$ , COP = 6.5

**To Find :** Scientist claim is true or false.

1. The COP of the refrigerating unit will be maximum when it is working on reversed Carnot cycle.
2. Therefore, maximum possible COP

$$= \frac{T_2}{T_1 - T_2} = \frac{258}{308 - 258} = \frac{258}{50} = 5.16$$

Since, the COP claimed by the scientist is more than the maximum possible COP, hence claim of the scientist is false.

### Que 5.7.

A cold storage plant is required to store 20 tonnes of fish. The temperature of fish when supplied was 27 °C, storage temperature of fish required = - 9 °C, specific heat of fish above freezing point = 2.95 kJ/kg-°C, specific heat of fish below freezing point = 1.25 kJ/kg-°C, freezing point of ice = - 3 °C, latent heat of fish = 230 kJ/kg. If the cooling is achieved within 10 hours, find the capacity of refrigeration plant.

### Answer

**Give :**  $T_1 = 27 \text{ °C}$ ,  $T_2 = - 9 \text{ °C}$

Specific heat of fish above freezing point = 2.95 kJ/kg-°C

Specific heat of fish below freezing point = 1.25 kJ/kg-°C

Latent heat of fish = 230 kJ/kg

**To Find :** The capacity of refrigeration plant.

1. Heat removed in 10 hours from each kg of fish,
 
$$\begin{aligned}
 &= 1 \times 2.95 \times [27 - (-3)] \\
 &\quad + 230 + 1 \times 1.25 [-3 - (-9)] \\
 &= 88.5 + 230 + 7.5 \\
 &= 326 \text{ kJ/kg}
 \end{aligned}$$
2. Heat removed by the plant / hour,
 
$$= \frac{326 \times 20 \times 1000}{10} = 652000 \text{ kJ/h}$$
3. Capacity of refrigerating plant,
 
$$= \frac{650800}{210 \times 60} = 51.75 \text{ tonnes}$$

**Que 5.8.**

A refrigeration system working on reversed Brayton cycle operates between 1 bar and 5 bar. The temperatures at the inlet to the compressor and expander are  $30^\circ\text{C}$  and  $40^\circ\text{C}$ , respectively. Isentropic efficiency for the compression is 0.8 and same for expansion is 0.9. If the capacity of the system is 5 tonnes of refrigeration, determine :

- Mass flow rate of air, and
- Power input to the compressor.

Take :  $\gamma = 1.4$  and  $c_p = 1.004 \text{ kJ/kg}\cdot\text{K}$ .

**Answer**

**Given :**  $p_1 = p_4 = 1 \text{ bar}$ ;  $p_2 = p_3 = 5 \text{ bar}$ ;

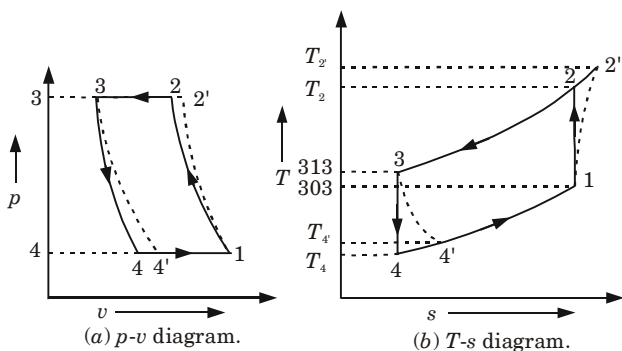
$T_1 = 30^\circ\text{C} = 30 + 273 = 303 \text{ K}$ ;  $T_3 = 40^\circ\text{C} = 40 + 273 = 313 \text{ K}$

$\eta_c = 0.8$ ;  $\eta_T = 0.9$ ;  $c_p = 1.004 \text{ kJ/kg}\cdot\text{K}$ ;  $Q = 5 \text{ TR}$ ;  $\gamma = 1.4$

**To Find :** i. Mass flow rate of air.

ii. Power input to the compressor.

- The  $p$ - $v$  and  $T$ - $s$  diagrams for the cycle are shown in Fig. 5.8.1(a) and (b)



**Fig. 5.8.1.**

- Let,  $T_2$  = Temperature of air at the end of the isentropic compression in the compressor,  
 $T_{2'}$  = Actual temperature of air at the end of compression in the compressor,  
 $T_4$  = Temperature of air at the end of isentropic expansion in the turbine, and  
 $T_{4'}$  = Actual temperature of air leaving the turbine.
- We know that for isentropic compression process, 1-2,

$$\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} = \left( \frac{5}{1} \right)^{\frac{1.4-1}{1.4}} = 1.584$$

$$T_2 = T_1 \times 1.584 = 303 \times 1.584$$

$$\therefore T_2 = 479.95 \approx 480 \text{ K}$$

4. Similarly, for isentropic expansion process, 3-4,

$$\frac{T_3}{T_4} = \left( \frac{p_3}{p_4} \right)^{\frac{\gamma-1}{\gamma}} = (5)^{\frac{1.4-1}{1.4}} = 1.584$$

$$T_4 = \frac{T_3}{1.584} = \frac{313}{1.584} = 197.6 \text{ K}$$

5. We know that isentropic efficiency of the compressor,

$$\eta_c = \frac{\text{Isentropic increase in temperature}}{\text{Actual increase in temperature}}$$

$$= \frac{T_2 - T_1}{T_{2'} - T_1}$$

$$0.8 = \frac{480 - 303}{T_{2'} - 303}$$

$$T_{2'} - 303 = \frac{480 - 303}{0.8} = \frac{117}{0.8} = 221.3$$

$$T_{2'} = 524.3 \text{ K}$$

6. Isentropic efficiency of the turbine,

$$\eta_T = \frac{\text{Actual decrease in temperature}}{\text{Isentropic decrease in temperature}}$$

$$0.9 = \frac{T_3 - T_{4'}}{T_3 - T_4}$$

$$0.9 = \frac{313 - T_{4'}}{313 - 197.6}$$

$$313 - T_{4'} = 103.86$$

$$\therefore T_{4'} = 209.14 \text{ K}$$

7. Heat extracted from the refrigerator or refrigeration effect,  
 $= c_p (T_1 - T_{4'}) = 1.005 (303 - 209.14)$   
 $= 94.33 \text{ kJ/kg}$

8. Mass of air flowing per minute,

$$m_a = \frac{\text{Heat extracted per min}}{\text{Heat extracted per kg}}$$

$$= \frac{210 \times 5}{94.33} = 11.13 \text{ kg/min}$$

$$(\because 1 \text{ TR} = 210 \text{ kJ/min})$$

9. We know that

Compressor work,

$$\begin{aligned} W_C &= m_a c_p (T_2 - T_1) \\ &= 11.13 \times 1.005 (524.3 - 303) \\ &= 2475.38 \text{ kJ/min} \end{aligned}$$

Turbine work,

$$\begin{aligned} W_T &= m_a c_p (T_3 - T_4) \\ &= 11.13 \times 1.005 (313 - 209.14) \\ &= 1161.74 \text{ kJ/min} \end{aligned}$$

Net work done,

$$\begin{aligned} W_{\text{net}} &= W_C - W_T \\ &= 2475.38 - 1161.74 \\ &= 1313.64 \text{ kJ/min} \end{aligned}$$

10. Work done per second is known as power,

$$\begin{aligned} W_{\text{net}} &= 1313.64 \text{ kJ/min} \\ \text{Power} &= \frac{W_{\text{net}}}{60} = \frac{1313.64}{60} \\ &= 21.894 \text{ kW} \end{aligned}$$

## PART-2

*Vapour Compression Refrigeration Cycle, Simple Saturated Cycle and Actual Vapour Compression Refrigeration Cycle, Analysis of Cycles, Effect of Superheating, Subcooling and Change in Evaporator and Condenser Pressure on Performance of Vapour Compression Refrigeration Cycle.*

## CONCEPT OUTLINE : PART-2

**Vapour Compression Refrigeration System :** In this low pressure vapour refrigerant from the evaporator is changed into high pressure vapour refrigerant in the compressor, therefore it is named as vapour compression refrigeration system.

**Actual Vapour Compression Cycle :**

The main deviations between the theoretical cycle and actual cycle are as follows :

1. The vapour refrigerant leaving the evaporator is in superheated state.
2. The compression of refrigerant is neither isentropic nor polytropic.
3. The liquid refrigerant before entering the expansion valve is sub-cooled in the condenser.
4. The pressure drops in evaporator and condenser.

### Questions-Answers

#### Long Answer Type and Medium Answer Type Questions

**Que 5.9.** Describe vapour compression refrigeration system and what are its advantages over air refrigeration system ?

#### Answer

##### **A. Vapour Compression Refrigeration System :**

1. It is an improved type of air refrigeration system in which a suitable working substance termed as refrigerant is used.
2. The refrigerant does not leave the system. Condensed and evaporated alternately and is circulated throughout the system.
3. During evaporation, the refrigerant absorbs its latent heat from the brine (salt water) which is used for circulating it around the cold chamber.
4. While condensing, it gives out its latent heat to the circulating water of the cooler.
5. Therefore, vapour compression refrigeration system is a latent heat pump, as it pumps its latent heat from the brine and delivers it to the cooler.

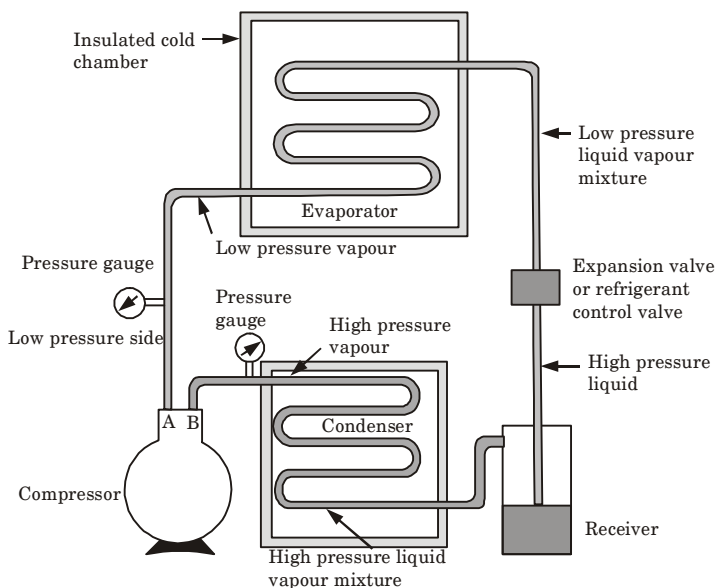
##### **B. Advantages of Vapour Compression Refrigeration System over Air Refrigeration System :**

1. It has smaller size for the given capacity of refrigeration.
2. It has less running cost.
3. It can be employed over a large range of temperatures.
4. The coefficient of performance is quite high.

**Que 5.10.** Describe the mechanism of a simple vapour compression refrigeration system.

**Answer**

This mechanism consists of following essential parts as shown in Fig. 5.10.1.



**Fig. 5.10.1.** Simple vapour compression refrigeration system.

**a. Compressor :**

1. The low pressure and temperature vapour refrigerant from evaporator is drawn into the compressor through the inlet or suction valve A, where it is compressed to a high pressure and temperature.
2. This high pressure and temperature vapour refrigerant is discharged into the condenser through the delivery or discharge valve B.

**b. Condenser :**

1. The condenser or cooler consists of coils of pipe in which the high pressure and temperature vapour refrigerant is cooled and condensed.
2. The refrigerant, while passing through the condenser, gives up its latent heat to the surrounding condensing medium which is normally air or water.

**c. Receiver :**

1. The condensed liquid refrigerant from the condenser is stored in a vessel known as receiver from where it is supplied to the evaporator through the expansion valve or refrigerant control valve.

**d. Expansion Valve :**

1. It is also called throttle or refrigerant control valve.
2. The function of the expansion valve is to allow the liquid refrigerant under high pressure and temperature to pass at a controlled rate after reducing its pressure and temperature.

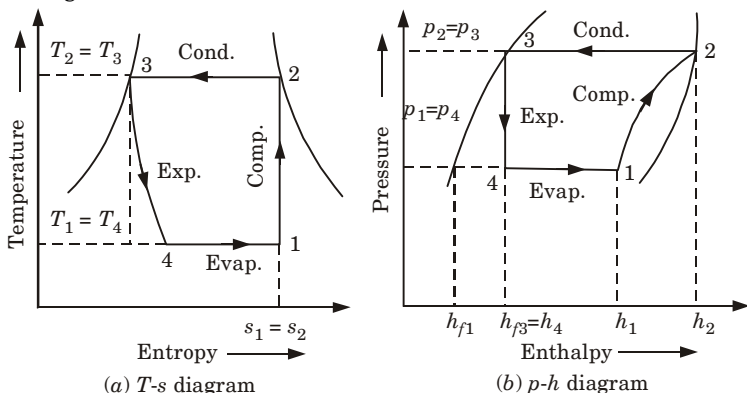
**e. Evaporator :**

1. An evaporator consists of coils of pipe in which the liquid-vapour refrigerant at low pressure and temperature is evaporated and changed into vapour refrigerant at low pressure and temperature.
2. During evaporation, the liquid vapour refrigerant absorbs its latent heat of vapourization from the medium (air, water or brine) which is to be cooled.

**Que 5.11.** Draw a single stage simple vapour compression refrigeration cycle on  $(T-s)$  and  $(p-h)$  diagrams and show how can you make a thermodynamic analysis of the cycle and calculate its COP.

**Answer**

1. The four process of the cycle is shown on  $T-s$  and  $p-h$  diagrams in Fig. 5.11.1(a) and (b).



**Fig. 5.11.1.** Theoretical vapour compression cycle with dry saturated vapour after compression.

**a. Compression Process :**

1. The vapour refrigerant at low pressure  $p_1$  and temperature  $T_1$  is compressed isentropically to dry saturated vapour as shown by the vertical line 1-2 on  $T-s$  diagram and by the curve 1-2 on  $p-h$  diagram.
2. Work done during isentropic compression per kg is given by,

$$W = h_2 - h_1$$

Where

$h_1$  = Enthalpy of vapour refrigerant at temperature  $T_1$  (i.e., at suction of the compressor), and  
 $h_2$  = Enthalpy of the vapour refrigerant at temperature  $T_2$  (i.e., at discharge of the compressor).

**b. Condensing Process :**

1. The high temperature and pressure vapour refrigerant from the compressor is passed through the condenser where it is completely condensed at constant pressure  $p_2$  and temperature  $T_2$  as shown by the horizontal line 2-3 on  $T$ -s and  $p$ -h diagrams.
2. The vapour refrigerant is changed into liquid refrigerant.

**c. Expansion Process :**

1. The liquid refrigerant at pressure  $p_3 = p_2$  and temperature  $T_3 = T_2$  is expanded by throttling process through the expansion valve to a low pressure  $p_4 = p_1$  and temperature  $T_4 = T_1$ , as shown by the curve 3-4 on  $T$ -s diagram and by the vertical line 3-4 on  $p$ -h diagram.
2. During the throttling process, no heat is absorbed or rejected by the liquid refrigerant.

**d. Evaporation Process :**

1. The liquid vapour mixture of the refrigerant at pressure  $p_4 = p_1$  and temperature  $T_4 = T_1$  is evaporated and changed into vapour refrigerant at constant pressure and temperature, as shown by the horizontal line 4-1 on  $T$ -s and  $p$ -h diagrams.
2. During evaporation, the liquid vapour refrigerant absorbs its latent heat of vapourization from the medium (i.e., air, water or brine) which is to be cooled and the process of vaporization continues up to point 1 which is the starting point and thus the cycle is completed.
3. The heat absorbed or extracted by the liquid vapour refrigerant during evaporation per kg of refrigerant is given by

$$R_E = h_1 - h_4 = h_1 - h_{f3} \quad (\because h_{f3} = h_4)$$

Where

$h_{f3}$  = Sensible heat at temperature  $T_3$  (i.e., enthalpy of liquid refrigerant leaving the condenser)

4. It may be noticed from the cycle that the liquid vapour refrigerant has extracted heat during evaporation and the work will be done by the compressor for isentropic compression of the high pressure and temperature vapour refrigerant.
5. Therefore, coefficient of performance is given by,

$$\begin{aligned} \text{COP} &= \frac{\text{Refrigeration effect}}{\text{Work done}} \\ &= \frac{h_1 - h_4}{h_2 - h_1} = \frac{h_1 - h_{f3}}{h_2 - h_1} \end{aligned}$$



**Que 5.12.** What are the factors which affects the performance of a simple vapour compression system ?

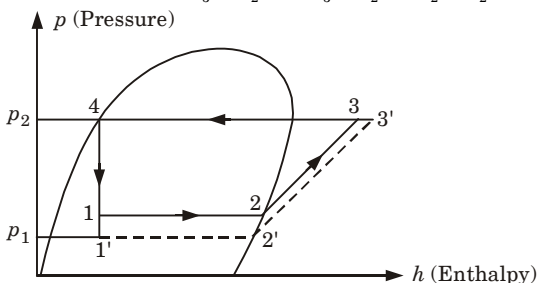
**Answer**

1. The factors which affect the performance of a vapour compression system are as follows :

**a. Effect of Suction Pressure :**

1. The effect of decrease in suction pressure in  $p-h$  diagram is shown in Fig. 5.12.1.

$$\text{COP} = \frac{h_2 - h_{1'}}{h_3 - h_{2'}} = \frac{(h_2 - h_1) - (h_2 - h_{2'})}{(h_3 - h_2) - (h_{2'} - h_2) + (h_3 - h_3)}$$



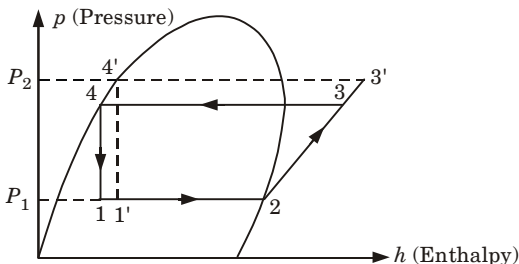
**Fig. 5.12.1.** Effect of decrease in suction pressure.

3. The above equation shows that when suction pressure decreases, the refrigerating effect decreases and work required increases.

**b. Effect of Delivery Pressure :**

1. The effect of increase in delivery pressure in  $p-h$  diagram is shown in Fig. 5.12.2.
2. COP of the cycle when delivery pressure increases is given by,

$$\text{COP} = \frac{h_2 - h_{1'}}{h_3 - h_{2'}} = \frac{(h_2 - h_1) - (h_{1'} - h_1)}{(h_3 - h_2) + (h_3 - h_3)}$$

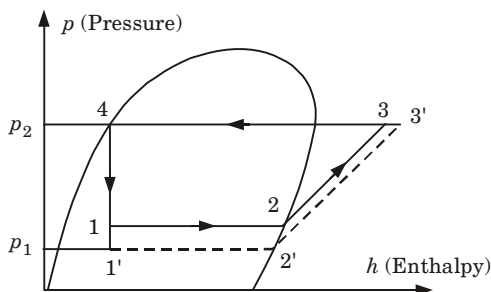


**Fig. 5.12.2.** Effect of increase in delivery pressure.

3. The effect of increasing the delivery pressure is just similar to the effect of decreasing the suction pressure. The basic difference is that the effect of decreasing the suction pressure is more predominant than the effect of increasing the discharge pressure.

**c. Effect of Superheating :**

1. The effect of superheating in  $p$ - $h$  diagram is shown in Fig. 5.12.3.

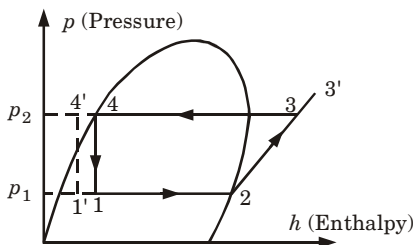


**Fig. 5.12.3.** Effect of decrease in suction pressure.

2. The effect of superheating increases the refrigerating effect which increases the amount of work spent to attain the upper pressure limit.
3. Since, the increase in work is more as compared to increase in refrigerating effect, therefore overall effect of the superheating is to give a low value of COP.

**d. Effect of Sub-Cooling of Liquid :**

1. Sub-cooling is the process of cooling the liquid refrigerant below the condensing temperature for a given pressure. The effect of sub-cooling in  $p$ - $h$  diagram is shown in Fig. 5.12.4.
2. The sub-cooling results in increase of COP provided that no further energy has to be spent to obtain the extra cold coolant required.



**Fig. 5.12.4.** Effect of increase in delivery pressure.

**Que 5.13.** A vapour compression refrigeration system of 5 tonne capacity operates at  $40^\circ\text{C}$  condenser and  $-16^\circ\text{C}$  evaporator

temperatures. The vapour is superheated by 5 °C at the entry to the compressor. Determine COP and power requirement. Use the following properties of the refrigerant (do not use other property tables as refrigerant is not known to you) :

At  $t_{\text{sat}} = 40\text{ °C}$  ( $p_{\text{sat}} = 1.0166\text{ MPa}$ );  
 $h_f = 256.41\text{ kJ/kg}$ ,  
 $h_g = 419.43\text{ kJ/kg}$ ,  
 $s_g = 1.711\text{ kJ/kg K}$ , and

For superheated vapour,  $c_p = 1.145\text{ kJ/kg K}$

At  $t_{\text{sat}} = -16\text{ °C}$  ( $p_{\text{sat}} = 0.15728\text{ MPa}$ );  
 $h_g = 389.02\text{ kJ/kg}$ ,  
 $s_g = 1.7379\text{ kJ/kg K}$ , and

For superheated vapour,  $c_p = 0.831\text{ kJ/kg K}$

### Answer

**Given :** Capacity = 5 tonne, Condenser temperature = 40 °C

Evaporator temperature = - 16 °C

**To Find :** COP and power required.

1. Since,  $s_1 = s_1' + c_{pv} \ln \left( \frac{T_1}{T_1'} \right)$   
 $= 1.7379 + 0.831 \ln \left( \frac{273 + 5}{273 - 16} \right)$   
 $= 1.8032\text{ kJ/kg K}$  ... (5.13.1)

$s_2 = s_2' + c_{pv} \ln \left( \frac{T_2}{T_2'} \right)$   
 $= 1.711 + 0.831 \ln \left( \frac{T_2}{273 + 40} \right)$  ... (5.13.2)

$$s_1 = s_2$$

$$1.8032 = 1.711 + 0.831 \ln \left( \frac{T_2}{313} \right)$$

$$T_2 = 349.74\text{ K}$$

2. And,  $h_1 = h_1' + C_{pl} (T_1 - T_1')$   
 $= 389.02 + 1.415 (278 - 257)$   
 $= 418.74\text{ kJ/kg}$

$$h_2 = h_2' + C_{pl} (T_2 - T_2')$$

$$= 419.43 + 1.145 (349.74 - 313)$$

$$= 461.50 \text{ kJ/kg}$$

3. Therefore, 
$$\text{COP} = \frac{h_1 - h_{f_3}}{h_2 - h_1} = \frac{418.74 - 256.41}{461.50 - 418.74} = 3.8$$

4. Work done during compression,

$$= \dot{m} v (h_2 - h_1)$$

$$= \frac{Q}{R_E} (h_2 - h_1)$$

$$= \frac{5 \times 210}{418.74 - 256.41} (461.50 - 418.74)$$

$$= 276.58 \text{ kJ/min}$$

Hence, power required =  $\frac{276.58}{60} = 4.61 \text{ kJ/s}$  or 4.61 kW

**Que 5.14.** A vapour compression machine is used to maintain  $-23^\circ\text{C}$  in a refrigerated space. The ambient temperature is  $37^\circ\text{C}$ . The compressor takes in dry saturated vapour of R12. A minimum  $10^\circ\text{C}$  temperature difference is required at the evaporator as well as at condenser. There is no sub cooling of liquid. If the refrigerant flow rate is 1 kg/min, find

- Tonne of refrigeration,
- Power required, and
- Ratio of COP of this cycle to COP of Carnot cycle.

**Answer**

**Given :**  $m_R = 1 \text{ kg/min}$ ,  $T_1 = -23^\circ\text{C}$ ,  $h_1 = 200.4 \text{ kJ/kg}$ ,  $h_{g1} = 176.5 \text{ kJ/kg}$   
 $T_4 = 10^\circ\text{C}$ ,  $h_4 = 218.6 \text{ kJ/kg}$ ,  $h_{g4} = 191.7 \text{ kJ/kg}$

**To Find :** a. Tonne of refrigeration,  
 b. Power required,  
 c. Ratio of COP of this cycle to COP of Carnot cycle.

**a. Tonne of refrigeration :**

- Refrigeration effect produced per kg of refrigerant,  

$$= h_1 - h_{g4} = 200.4 - 191.7 = 8.7 \text{ kJ/kg}$$
- The total heat extracted is given by,  

$$= m_R \times R_E$$

$$= 1 \times 8.7 = 8.7 \text{ kJ/min}$$

3. So, the capacity of refrigerant is

$$Q = \frac{8.7}{210}$$

$$= 0.041 \text{ TR} \quad (\because 1 \text{ TR} = 210 \text{ kJ/min})$$

**b. Power required :**

1. Work done during compression of refrigerant

$$= m_R (h_4 - h_1)$$

$$= 1 \times (218.6 - 200.4) = 18.2 \text{ kJ/min}$$

$$\therefore \text{Power required} = \frac{18.2}{60} = 0.303 \text{ kW}$$

**c. Ratio of COP of this cycle to COP of Carnot cycle :**

1. COP of this cycle,

$$= \frac{h_1 - h_{f4}}{h_2 - h_1} = \frac{8.7}{18.2} = 0.47$$

2. COP of Carnot cycle,

$$= \frac{R_E}{W} = \frac{8.7}{8.7} = 1$$

$$3. \quad \text{Ratio} = \frac{0.47}{1} = 0.47$$

**Que 5.15.** The temperature limits of an ammonia refrigerating system are  $25^\circ\text{C}$  and  $-10^\circ\text{C}$ . If the gas is dry at the end of compression, calculate the coefficient of performance of cycle assuming no under cooling of the liquid ammonia.

Temperature ( $^\circ\text{C}$ )	Liquid heat (kJ/kg) ( $h_f$ )	Latent heat (kJ/kg) ( $h_{fg}$ )	Liquid entropy (kJ/kg-K) ( $h_{sf}$ )
25	298.9	1166.94	1.1242
-10	135.37	1297.68	0.5443

**Answer**

**Given :**  $T_2 = T_3 = 25^\circ\text{C} = 25 + 273 = 298 \text{ K}$  ;

$T_1 = T_4 = -10^\circ\text{C} = -10 + 273 = 263 \text{ K}$  ;

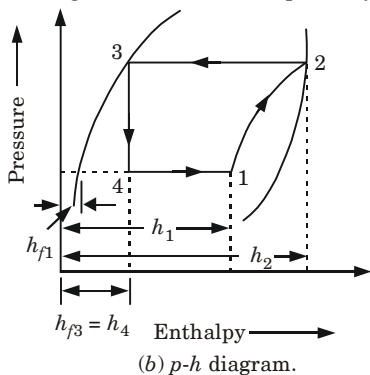
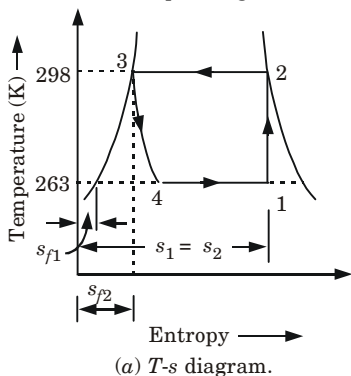
$h_{f3} = h_4 = 298.9 \text{ kJ/kg}$  ;  $h_{fg2} = 1166.94 \text{ kJ/kg}$  ;  $s_{f2} = 1.1242 \text{ kJ/kg-K}$  ;

$h_{f1} = 135.37 \text{ kJ/kg}$  ;

$h_{fg1} = 1297.68 \text{ kJ/kg}$  ;  $s_{f1} = 0.5443 \text{ kJ/kg-K}$

**To Find :** Coefficient of performance (COP).

1. The  $T$ - $s$  and  $p$ - $h$  diagrams are shown in Fig. 5.15.1(a) and (b) respectively.



**Fig. 5.15.1.**

2. Let,  $x_1$  = dryness fraction at point 1.  
 3. We know that entropy at point 1,

$$\begin{aligned} s_1 &= s_{f1} + \frac{x_1 h_{fg1}}{T_1} \\ &= 0.5443 + \frac{x_1 \times 1297.68}{263} \\ &= 0.5443 + 4.934 x_1 \end{aligned} \quad \dots(5.15.1)$$

4. Similarly, entropy at point 2,

$$\begin{aligned} s_2 &= s_{f2} + \frac{h_{fg2}}{T_2} \\ &= 1.1242 + \frac{1166.94}{298} = 5.04 \end{aligned} \quad \dots(5.15.2)$$

5. Since the entropy at point 1 is equal to entropy at point 2, therefore equating eq. (5.15.1) and (5.15.2), we get

$$0.5443 + 4.934 x_1 = 5.04 \text{ or } x_1 = 0.91$$

6. We know that enthalpy at point 1,

$$\begin{aligned} h_1 &= h_{f1} + x_1 h_{fg1} = 135.37 + 0.91 \times 1297.68 \\ &= 1316.26 \text{ kJ/kg} \end{aligned}$$

and enthalpy at point 2,

$$\begin{aligned} h_2 &= h_{f2} + h_{fg2} = 298.9 + 1166.94 \\ &= 1465.84 \text{ kJ/kg} \end{aligned}$$

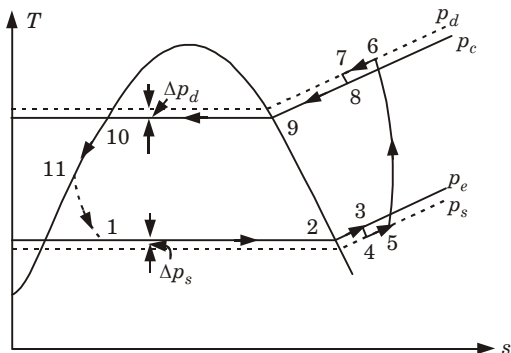
7. Therefore, coefficient of performance of the cycle,

$$\text{COP} = \frac{h_1 - h_{f3}}{h_2 - h_1} = \frac{1316.26 - 298.9}{1465.84 - 1316.26} = 6.8$$

**Que 5.16.** Explain the working of an actual vapour compression cycle with the help of  $T$ - $s$  diagrams.

**Answer**

1. The actual vapour compression cycle on  $T$ - $s$  is shown in Fig. 5.16.1.



**Fig. 5.16.1.** Actual vapour compression cycle ( $T$ - $s$  diagram).

2. The various processes are given below :
- Process 1-2-3 :** This process represents passage of refrigerant through the evaporator, with 1-2 indicating gain of latent heat of vaporization and 2-3, the gain of superheat before entrance to compressor.
  - Process 3-4-5-6-7-8 :**
    - The process represents the passage of the vapour refrigerant from entrance to the discharge of the compressor.
    - In above Fig. 5.16.1, path 3-4 represents the throttling action that occurs during passage through the suction valves and path 7-8 represents the throttling during passage through exhaust valves.
    - Both of these actions are accompanied by an entropy increase and a slight drop in temperature.
    - Compression of the refrigerant occurs along path 5-6, which is actually neither isentropic nor polytropic and the heat transfer indicated by path 4-5 and 6-7 occurs essentially at constant pressure.
  - Process 8-9-10-11 :** This process represents the passage of refrigerant through the condenser with 8-9 indicating removal of superheat, 9-10 for the removal of latent heat and 10-11 for removal of heat of liquid or sub-cooling.
  - Process 11-1 :** This process represents passage of the refrigerant (*i.e.*, an irreversible adiabatic path) through the expansion valve, both theoretically and practically.

**PART-3**

*Refrigerant, Their Classification and Desirable Properties, and Vapour Absorption Refrigeration System.*

**CONCEPT OUTLINE : PART-3**

**Refrigerant :** It is a heat carrying medium which during their cycle in the system absorbs heat from a low temperature system and discards the heat so absorbed to a higher temperature system.

**Types of Refrigerant :**

1. Primary refrigerants.
2. Secondary refrigerants.

**Principle of Vapour Absorption System :** The system uses heat energy, instead of mechanical energy as in vapour compression system, in order to change the conditions of the refrigerant required for the operation of the refrigeration cycle.

**Components of Simple Vapour Absorption System :**

1. Generator,
2. Condenser,
3. Absorber,
4. Receiver, and
5. Evaporator.

**Practical Vapour Absorption System :**

1. Analyser,
2. Rectifier, and
3. Heat exchangers.

**Questions-Answers****Long Answer Type and Medium Answer Type Questions**

**Que 5.17.** What is the basic function of refrigerants in a refrigeration cycle and how they are classified ? Write some desirable properties of refrigerants. What is the basic difference between primary and secondary refrigerants ?

**Answer**

**A. Refrigerant :**

1. A refrigerant is defined as any substance that absorbs heat through expansion or vapourization and loses it through condensation in a refrigeration system.



**B. Function :**

1. The basic function of refrigerant is take heat from the evaporator and loose the heat in the condenser with reasonable heat transfer rate and establishes the effective heat exchange in the system.

**C. Desirable Properties of an Ideal Refrigerant :**

1. Low boiling point.
2. Low specific heat of liquid.
3. Low specific volume of vapour.
4. Low cost.
5. High critical temperature.
6. High latent heat of vapourization.
7. Non-corrosive to metal.
8. Non-flammable and non-explosive.
9. Non-toxic.
10. Easy to liquefy at moderate pressure and temperature.

**D. Classification of Refrigerants :** The refrigerants are basically classified as follow :

**a. Primary Refrigerants :**

1. Those refrigerants which directly take part in the refrigeration system and cool the substance by the absorption of latent heat.

**Example :** Ammonia, Caron dioxide, Sulphur dioxide, Methyl chloride, Freon group etc.

2. The primary refrigerants are further classified into the following four groups :

- i. Halo-carbon refrigerants,
- ii. Azeotrope refrigerants,
- iii. Inorganic refrigerants, and
- iv. Hydro-carbon refrigerant.

**i. Halo-Carbon Refrigerants :**

1. The halocarbon compounds are obtained after replacing one or more of hydrogen atoms of hydrocarbon methane or ethane by one or more of the three halogens : chlorine, fluorine and bromine.
2. Some of the commonly used halo-carbon compounds are given in the following table :

Refrigerant number	Chemical name	Chemical formula
R-11	Trichloromonofluoromethane	$\text{CCl}_3\text{F}$
R-12	Dichlorodifluoromethane	$\text{CCl}_2\text{F}_2$
R-13	Monochlorotrifluoromethane	$\text{CClF}_3$
R-14	Carbontetrafluoride	$\text{CF}_4$
R-21	Dichloromonofluoromethane	$\text{CHCl}_2\text{F}$
R-22	Monochlorodifluoromethane	$\text{CHClF}_2$
R-30	Methylene chloride	$\text{CH}_2\text{Cl}_2$
R-40	Methyl chloride	$\text{CH}_3\text{Cl}$
R-100	Ethyl chloride	$\text{C}_2\text{H}_5\text{Cl}$
R-113	Trichlorotrifluoroethane	$\text{CCl}_2\text{FCClF}_2$
R-114	Dichlorotetrafluoroethane	$\text{CClF}_2\text{CClF}_2$
R-115	Monochloropentafluoroethane	$\text{CClF}_2\text{CF}_3$

### ii. Azeotrope Refrigerant :

- The term 'azeotrope' refers to a stable mixture of refrigerants whose vapour and liquid phases retain identical compositions over a wide range of temperatures.
- Some of the azeotropes are given in the following table :

Refrigerant number	Azeotropic mixing refrigerants	Chemical formula
R-500	73.8 % R-12 and 26.2 % R-152	$\text{CCl}_2\text{F}_2/\text{CH}_3\text{CHF}_2$
R-502	48.8 % R-22 and 51.2 % R-115	$\text{CHClF}_2/\text{CClF}_2\text{CF}_3$
R-503	40.1 % R-23 and 59.9 % R-13	$\text{CHF}_3/\text{CClF}_3$
R-504	48.2 % R-32 and 51.8 % R-115	$\text{CH}_2\text{F}_2/\text{CClF}_2\text{CF}_3$

### iii. Inorganic Refrigerant :

- The inorganic refrigerants were most commonly used before the introduction of hydro-carbon group for all purposes.
- These refrigerants are still in use due to their inherent thermodynamic and physical properties.
- The important inorganic refrigerants are given in the following table :

Refrigerant number	Chemical name	Chemical formula
R-717	Ammonia	$\text{NH}_3$
R-729	Air	—
R-744	Carbon dioxide	$\text{CO}_2$
R-764	Sulphur dioxide	$\text{SO}_2$
R-118	Water	$\text{H}_2\text{O}$

**iv. Hydro-Carbon Refrigerants :**

1. Most of the refrigerants of this group are organic compounds and these are successfully used in industrial and commercial installations.
2. Some of the important refrigerants of this group are given in the table below :

Refrigerant number	Chemical name	Chemical formula
R-170	Ethane	$C_2H_6$
R-290	Propane	$C_3H_8$
R-600	Butane	$C_4H_{10}$
R-600a	Isobutane	$CH(CH_3)_3$
R-1120	Trichloroethylene	$C_2HCl_3$
R-1130	Dichloroethylene	$C_2H_2Cl_2$
R-1150	Ethylene	$C_2H_4$
R-1270	Propylene	$C_3H_6$

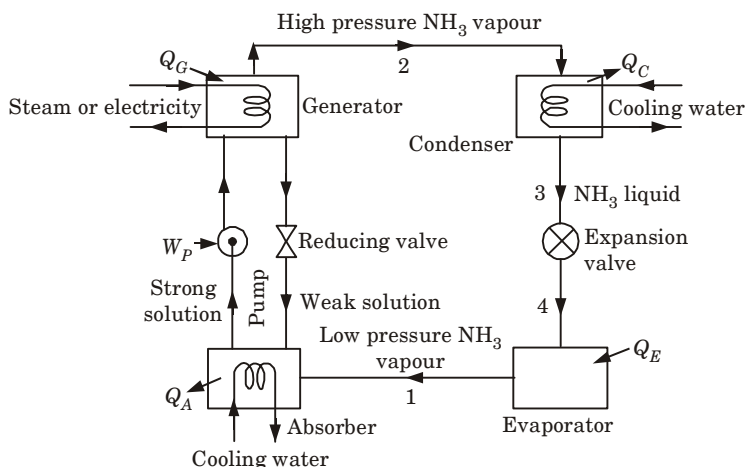
**b. Secondary Refrigerants :**

1. Those refrigerants which are first cooled with the help of the primary refrigerants and are then employed for cooling purposes are known as secondary refrigerant.
2. These refrigerants cool substances by absorption of their sensible heat.
3. The commonly used secondary refrigerants are as follows :
  - i. Water,
  - ii. Sodium chloride brine,
  - iii. Calcium chloride brine,
  - iv. Ethylene glycol, and
  - v. Propylene glycol etc.

**Que 5.18.** Draw a neat and labelled schematic diagram of a simple vapour absorption refrigeration system.

**Answer**

1. It consists of an absorber, a pump, a generator and a pressure reducing valve to replace the compressor of vapour compression system.
2. The other components of the system are condenser, receiver, expansion valve and evaporator.



**Fig. 5.18.1.** Simple vapour absorption system.

#### A. Working :

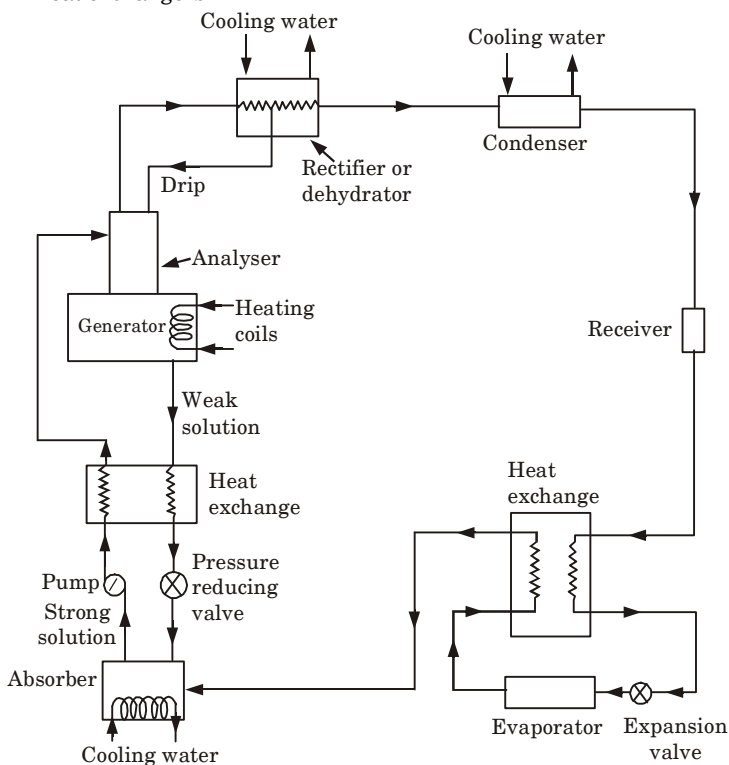
1. In this system, the low pressure ammonia vapour leaving the evaporator enters in the absorber where it is absorbed by the cold water in the absorber.
2. The absorption of ammonia vapour in water lowers the pressure in the absorber which in turn draws more ammonia vapour from the evaporator and thus raises the temperature of solution.
3. Cooling arrangement is employed in the absorber to remove the heat of solution evolved there.
4. This is necessary in order to increase the absorption capacity of water because at higher temperature water absorbs less ammonia vapour.
5. Thus the strong solution (rich in ammonia) is formed in the absorber which is pumped to the generator where heat ( $Q_G$ ) is supplied from an external source (*i.e.*, steam, electricity, etc.)
6. Since, the boiling point of ammonia is less than that of water, the ammonia vapour is driven off from the aqua-ammonia solution at high pressure, and the weak solution returns to the absorber through a pressure reducing valve.
7. The high pressure ammonia vapour from the generator is condensed in the condenser to high pressure liquid ammonia.
8. This liquid ammonia is throttled by the expansion valve and then evaporates, absorbing the heat of evaporation from the surroundings or brine to be chilled. This completes the simple vapour absorption cycle.

**Que 5.19.** With the help of schematic diagram, explain the working of a practical aqua-ammonia vapour absorption refrigerating system. Highlight the advantage of using analyser, rectifier and heat exchanger.

### Answer

#### A. Practical Vapour Absorption System :

1. The simple absorption system is not very economical.
2. In order to improve the performance and working of the plant, following accessories are fitted :
  - a. Analyser,
  - b. Rectifier, and
  - c. Heat exchangers.



**Fig. 5.19.1.** Practical vapour absorption system.

#### a. Analyser :

1. When ammonia is vapourized out of the solution in the generator some water is also vapourized and will flow into the condenser along with the ammonia vapours in the simple system.

2. To stop these unwanted water particles flowing to the condenser, an analyser is used.
3. An analyser (may be built as an integral part of the generator or made as a separate piece of equipment) is a direct heat exchanger consisting of a series of trays mounted above the generator.
4. The strong solution from the absorber flows downward over the trays to cool the outgoing vapours.
5. Since the saturation temperature of water is higher than that of ammonia at a given pressure, it is the water vapour which condenses first.
6. As the vapour passes upward through the analyzer, it is cooled and enriched by ammonia, and the liquid is heated.
7. Thus the vapour going to the condenser is lower in temperature and richer in ammonia and the heat input to the generator is decreased.

**b. Rectifier :**

1. A rectifier is a water-cooled heat exchanger which condenses water vapour (and some ammonia) and sends back to the generator by a drip return pipe.
2. Its function is to cool further the ammonia vapours leaving the analyzer so that the remaining water vapours are condensed. Thus, only dry or anhydrous ammonia vapours flow to the condenser.

**c. Heat Exchanger :**

1. The heat exchanger provided between the pump and the generator is used to cool the weak hot solution returning from the generator to the absorber.
2. The heat removed from the weak solution raises the temperature of the strong solution leaving the pump and going to analyzer and generator.
3. This operation reduces the heat supplied to the generator and the amount of cooling required for the absorber. Thus, the economy of the plant increases.
4. The heat exchanger provided between the condenser and the evaporator also called liquid sub-cooler.
5. In this heat exchanger, the liquid refrigerant leaving the condenser is sub-cooled by the low temperature ammonia vapour from the evaporator.
6. This sub-cooled liquid is now passed to the expansion valve and then to the evaporator.
7. In this system, the net refrigerating effect is the heat absorbed by the refrigerant in the evaporator.
8. The total energy supplied to the system is the sum of work done by the pump and the heat supplied in the generator.
9. Therefore, the coefficient of performance of the system is given by,

$$\text{COP} = \frac{\text{Heat absorbed in evaporator}}{\text{Work done by pump} + \text{heat supplied in generator}}$$

**VERY IMPORTANT QUESTIONS**

*Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.*

**Q. 1. Describe a reversed Carnot cycle with the help of a neat labelled sketch.**

**Ans.** Refer Q. 5.2, Unit-5.

**Q. 2. Describe a Bell-Coleman or reversed joule air refrigeration cycle with the help of a neat labelled sketch.**

**Ans.** Refer Q. 5.3, Unit-5.

**Q. 3. Give the difference between open and closed air refrigeration cycles.**

**Ans.** Refer Q. 5.5, Unit-5.

**Q. 4. Describe vapour compression refrigeration system and what are its advantages over air refrigeration system ?**

**Ans.** Refer Q. 5.9, Unit-5.

**Q. 5. Describe the mechanism of a simple vapour compression refrigeration system.**

**Ans.** Refer Q. 5.10, Unit-5.

**Q. 6. Draw a single stage simple vapour compression refrigeration cycle on ( $T-s$ ) and ( $P-h$ ) diagrams and show how can you make a thermodynamic analysis of the cycle and calculate its COP.**

**Ans.** Refer Q. 5.11, Unit-5.

**Q. 7. What are the factors which affects the performance of a simple vapour compression system ?**

**Ans.** Refer Q. 5.12, Unit-5.

**Q. 8. Explain the working of an actual vapour compression cycle with the help of  $T-s$  diagrams.**

**Ans.** Refer Q. 5.16, Unit-5.

**Q. 9. What is the basic function of refrigerants in a refrigeration cycle and how they are classified ? Write some desirable properties of refrigerants. What is the basic difference between primary and secondary refrigerants ?**

**Ans.** Refer Q. 5.17, Unit-5.

**Q. 10. With the help of schematic diagram, explain the working of a practical aqua-ammonia vapour absorption refrigerating system. Highlight the advantage of using analyser, rectifier and heat exchanger.**

**Ans.** Refer Q. 5.19, Unit-5.



**1****UNIT**

## Introduction (2 Marks Questions)

### Memory Based Questions

**1.1. What do you mean by open system ?**

**Ans.** Open system is the system in which matter and energy both flows into or out of the system.

**1.2. What do you mean by isolated system ?**

**Ans.** Isolated system is the system which exchanges neither energy nor matter with any other system or with environment.

**1.3. What do you mean by macroscopic approach ?**

**Ans.** Macroscopic approach is the thermodynamic approach in which a certain quantity of matter is considered without taking into account the events occurring at molecular level.

**1.4. Define microscopic approach.**

**Ans.** Microscopic approach is the thermodynamic approach in which the system is made up of a very large number of discrete particles known as molecules. These molecules have different velocities and energies.

**1.5. What do you mean by intensive and extensive properties ?**

**Ans. Intensive Properties :** These properties do not depend on the mass of the system.

Example : Temperature and pressure.

**Extensive Properties :** These properties depend on the mass of the system.

Example : Volume.

**1.6. Briefly explain quasi-static process.**



**Ans.** This process is a succession of equilibrium states and infinite slowness is its characteristic feature. This process is also called a reversible process.

**1.7. How does a homogeneous system differ from a heterogeneous system ?**

**AKTU 2016-17, Marks 02**

**Ans.**

**Homogeneous system :** A system consisting of a single phase is called "homogeneous system". *e.g.*, milk + water, aqua ammonia.

**Heterogeneous system :** A system consisting of more than one phase is called "heterogeneous system". *e.g.*, wet steam, water + mercury.

**1.8. What do you mean by non-flow process and flow process ?**

**Ans. Non-Flow Process :** It is the process in which a fixed mass within the defined boundary is undergoing a change of state.

**Flow Process :** It is the process in which mass is entering and leaving through the boundary of an open system.

**1.9. State steady and unsteady flows.**

**AKTU 2015-16, Marks 02**

**Ans. Steady Flow :** It is the process in which mass is crossing the boundary from surroundings at entry, and an equal mass is crossing the boundary at the exit so that the total mass of the system remains constant.

**Unsteady Flow :** It is the process in which mass at entry and mass at exit is not equal *i.e.*, total mass of the system does not remain constant.

**1.10. What do you mean by point function ?**

**Ans.** When two properties locate a point on the graph (co-ordinate axes) then those properties are called as point function. Example : Pressure, temperature, volume etc.

**1.11. State zeroth law of thermodynamics.**

**Ans.** Zeroth law of thermodynamics states that if two systems are each equal in temperature to a third separately, then they will be equal in temperature to each other.

**1.12. List any five physical properties of matter which can be used for measurement of temperature.**

**AKTU 2016-17, Marks 02**

**Ans.**

1. Length	2. Radiation
3. Thermal EMF	4. Volume

## 5. Pressure

**1.13. State reversible and irreversible processes.**

**Ans.** **Reversible Process :** It is defined as the process which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states.

**Irreversible Process :** It is the process in which heat is transferred through a finite temperature.

**1.14. State first law of thermodynamics.**

**Ans.** First law of thermodynamics states that heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant.

**1.15. Write the limitations of first law of thermodynamics.**

**Ans.**

1. The first law fixes the exchange rate between heat and work and puts no restrictions on the direction of change.
2. Process can only take place in a particular direction but these processes cannot be reversed, though the reversal of a process does not violate first law of thermodynamics.
3. The first law of thermodynamics provides a necessary but not a sufficient condition for a process to take place.
4. There exists some directional law which would tell whether a particular process occurs or not. This forms the basis of second law of thermodynamics.

**1.16. What do you mean by work ?**

**Ans.** Work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight.

**1.17. Explain free expansion process ?**

**AKTU 2015-16, Marks 02**

**Ans.** Let us consider a gas separated from the vacuum by a partition. Let the partition be removed. The gas rushes to fill the entire volume. The expansion of a gas against vacuum is called free expansion.

**1.18. Define heat.**

**Ans.** Heat is defined as the form of energy that is transferred across a boundary by virtue of a temperature difference.

**1.19. Write Boyle's law and Charle's law.**

**Ans.** **Boyle's law :** According to this law, volume of a given mass of a perfect gas varies inversely with absolute pressure when temperature is kept constant.

Product of absolute pressure and volume of a given quantity of gas is constant when the temperature is kept constant.

$$\text{i.e., } V \propto \frac{1}{p} \text{ or } pV = \text{constant}$$

**Charle's Law :** According to this law, the volume of a given mass of a perfect gas varies directly with its absolute temperature when pressure is kept constant *i.e.*,

$$\frac{V}{T} = \text{Constant.} \quad (\text{At constant pressure})$$

**1.20. What do you mean by throttling process ?**

**Ans.** Expansion of working fluid from a region of high pressure across a restriction or very small opening under a steady flow without any heat transfer is referred to as throttling process.

**1.21. Define perpetual motion machine of the first kind.**

**Ans.** Since there can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind. A PMM 1 is thus impossible.

**1.22. What do you mean by control surface ?**

**Ans.** Control surface is defined as the boundary of a control volume which is a fixed region in space upon which attention is concentrated in the analysis of a problem.



# 2

## UNIT

# Second Law of Thermodynamics (2 Marks Questions)

### Memory Based Questions

#### 2.1. Define thermal energy reservoir.

**Ans.** Thermal energy reservoir is defined as a large body of infinite heat capacity, which is capable of absorbing or rejecting an unlimited quantity of heat without suffering appreciable changes in its thermodynamic coordinates.

#### 2.2. Define mechanical energy reservoir.

**Ans.** Mechanical energy reservoir is defined as a large body enclosed by an adiabatic impermeable wall capable of storing work as potential energy or kinetic energy.

#### 2.3. State the various statements of second law of thermodynamics ?

AKTU 2015-16, Marks 02

**Ans. Kelvin-Planck Statement :** It states that it is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

**Clausius Statement :** It is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a cooler to hotter body.

#### 2.4. Define PMM 2.

**Ans.** If heat rejection is zero, the heat engine will produce net work in a complete cycle by exchanging heat with only one reservoir, thus violating the Kelvin-Planck statement. Such a heat engine is called a PMM2. A PMM2 is impossible.

#### 2.5. What is exergy ?

AKTU 2015-16, Marks 02

**Ans.** The maximum work output obtained from a certain heat input in a cycle heat engine is called the available energy (A.E) or exergy.

**2.6. Define heat pump.**

**Ans.** Heat pump is a device which, operating in a cycle, maintains a body, at a temperature higher than the temperature of the surroundings.

**2.7. Compare heat pump and refrigerator.**

AKTU 2016-17, Marks 02

**Ans. Compare heat pump and refrigerator :**

1. A refrigerator is a thermodynamic device which operating on a cycle removes heat from a low temperature body and reject it to a high temperature body at the expense of external work supplied. A heat pump delivers heat energy to a body at higher temperature  $T_1$  at the expense of work energy supplied. A heat pump is generally used to keep the rooms warm in winter.

$$2. \text{COP}_{\text{ref}} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} = \frac{\text{Heat extracted at low temperature}}{\text{Work Input}}$$

$$\text{COP}_{\text{HP}} = \frac{Q_1}{W} = \frac{Q_1}{Q_1 - Q_2} = \frac{\text{Heat supplied to high temperature}}{\text{Work Input}}$$

$$(\text{COP})_{\text{HP}} = 1 + (\text{COP})_{\text{ref}}$$

**2.8. Define coefficient of performance.**

**Ans.** Coefficient of performance is defined as the ratio of desired effect to the work done.

**2.9. What are the causes of irreversibility of a process ?**

**Ans.** Following are the main causes of irreversibility of a process :

- a. Lack of equilibrium during the process.
- b. Involvement of dissipative effects.

**2.10. What is the condition for reversibility ?**

**Ans.** A process will be reversible when it is performed in such a way that the system is at all times infinitesimally near a state of thermodynamic equilibrium and in the absence of dissipative effect of any form.

**2.11. What do you mean by Carnot cycle ?**

**Ans.** Carnot cycle is an ideal hypothetical cycle in which all the processes constituting the cycle are reversible.

**2.12. State Carnot theorem.** AKTU 2015-16, 2016-17; Marks 02

**Ans.** Carnot theorem states that of all heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

**2.13. What is the corollary of Carnot's theorem ?**

**Ans.** The corollary of Carnot's theorem is that the efficiency of a reversible engine is independent of the nature or amount of the working substance undergoing the cycle.

**2.14. What is the difference between internal and external irreversibility ?**

**Ans.** The internal irreversibility is caused by the internal dissipative effects like friction, turbulence etc., within the system.

The external irreversibility refers to the irreversibility occurring at the system boundary like heat interaction with the surroundings due to a finite temperature gradient.

**2.15. Define entropy.**

**Ans.** Entropy is a function of a quantity of heat which shows the possibility of conversion of that heat into work.

**2.16. What do you mean by Clausius theorem ?**

**Ans.** Clausius theorem states that the cyclic integral of  $\frac{dQ}{T}$  for a reversible cycle is equal to zero.

$$\text{i.e.,} \quad \oint_R \frac{dQ}{T} = 0$$

**2.17. What is the inequality of Clausius ?**

**Ans.** **Inequality of Clausius :** According to this,

$$\oint \frac{dQ}{T} \leq 0$$

$$\text{i.e., if} \quad \oint \frac{dQ}{T} = 0, \text{ the cycle is reversible.}$$

$$\oint \frac{dQ}{T} < 0, \text{ the cycle is irreversible and possible.}$$

$$\oint \frac{dQ}{T} > 0 ; \text{ the cycle is impossible.}$$

**2.18. What do you mean by entropy principle ?**

**Ans.** According to this principle, the entropy of an isolated system can never decrease. It always increases and remains constant only when the process is reversible.

Mathematically,

$$dS_{iso} \geq 0$$

**2.19. How will you increase the entropy of a closed system ?**

**Ans.** The entropy of any closed system can increase in two ways :

- By heat interaction and
- By internal irreversibilities or dissipative effects.

**2.20. Define entropy generation.**

**Ans.** The entropy increase due to internal irreversibility is called entropy production or entropy generation. It is denoted by  $S_{\text{gen}}$ .

**2.21. State third law of thermodynamics.**

AKTU 2016-17, Marks 02

**Ans.** Third law of thermodynamics states that the entropy of a perfect crystal is zero at the absolute zero of temperature and it represents the maximum degree of order.

**Application Based Questions****2.22. Prove that  $\text{COP}_P = 1 + \text{COP}_R$ .**

AKTU 2015-16, Marks 02

**Ans.** Since,

$$\text{COP} = \frac{\text{desired effect}}{\text{work done}}$$

$$\text{then, } \text{COP}_P = \frac{Q_1}{Q_1 - Q_2} \quad \dots(i)$$

$$\text{and } \text{COP}_R = \frac{Q_2}{Q_1 - Q_2} \quad \dots(ii)$$

where,  $Q_1$  = heat transfer to engine, and  
 $Q_2$  = heat transfer from cold reservoir.

Subtracting equation (ii) from equation (i),

$$\begin{aligned} \text{COP}_P - \text{COP}_R &= \frac{Q_1}{Q_1 - Q_2} - \frac{Q_2}{Q_1 - Q_2} \\ &= \frac{Q_1 - Q_2}{Q_1 - Q_2} = 1 \end{aligned}$$

$$\Rightarrow \text{COP}_P = 1 + \text{COP}_R$$

**2.23. A system composed of 2 kg air 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. Take air as ideal gas having ( $C_v = 0.718 \text{ kJ/kgK}$  and  $R = 0.287 \text{ kJ/kgK}$ ).**

AKTU 2015-16, Marks 02

**Ans. Given :**

$$M = 2 \text{ kg}$$

$$P_1 = 1 \text{ MPa}$$

$$T_1 = 100 + 273 = 373 \text{ K}$$

$$T_2 = 30 + 273 = 303 \text{ K}$$

$$C_V = 0.718 \text{ kJ/kg K}$$

$$R = 0.287 \text{ kJ/kg K}$$

Since, there is no heat transfer. It is an adiabatic process.

$$\begin{aligned}\text{Then, net work} &= \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} \\ &= \frac{mRT_1 - mRT_2}{\gamma - 1} = \frac{mR(T_1 - T_2)}{\gamma - 1}\end{aligned}$$

$$\therefore C_V = \frac{R}{\gamma - 1}$$

Then

$$\text{net work} = mC_V(T_1 - T_2)$$

On putting the given values,

$$\begin{aligned}\text{Net work} &= 2 \times 0.718 (373 - 303) \\ &= 100.52 \text{ kJ}\end{aligned}$$





# 3

## UNIT

# Availability and Irreversibility (2 Marks Questions)

### Memory Based Questions

**3.1. What do you mean by available energy and unavailable energy ?**

**AKTU 2015-16, Marks 02**

**Ans.** The maximum work output obtained from a certain heat input in a cycle heat engine is called the available energy (A.E) or exergy. The minimum energy that has to be rejected to the sink by the second law is called the unavailable energy (U.E.) or anergy.

**3.2. What is the difference between first and second law of thermodynamics ?**

**Ans.** The first law states that energy is always conserved quantity wise, while the second law emphasizes that energy always degrades quality wise.

**3.3. Define dead state.**

**Ans.** Dead state is defined as the state of a system in which the system must have zero velocity and minimum potential energy.

**3.4. Define availability.**

**Ans.** The availability of a system is defined as the maximum useful work that is obtainable in a process in which the system comes to equilibrium with its surroundings.

**3.5. Is the availability function same for a non-flow and a flow process ? Justify.**

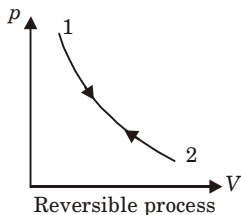
**Ans.** Availability function is same for a non-flow and a flow process because for both process, the irreversibility is equal to  $T_0 \Delta S_{\text{gen}}$ . It is equal to decrease in  $AE$  or increase in  $UE$ .

**3.6. Explain reversible process with an example.**

**AKTU 2013-14, Marks 02**

**Ans.**

1. A process is called reversible if after the conclusion of reversed process the initial states of system and surroundings are restored without any extraordinary changes either in the system or surroundings.
2. A reversible process is a quasi-static process, a process carried out infinitely slowly with infinitesimal gradient with the system passing through a series of equilibrium states.

**Fig. 3.6.1.****3.7. State the Gouy-Stodola theorem.**

**Ans.** Gouy-Stodola theorem states that the rate of loss of available energy or exergy in a process is proportional to the rate of entropy generation, *i.e.*,

$$\dot{I} = T_0 \dot{S}_{\text{gen}}$$

**3.8. Define second law efficiency.**
**AKTU 2013-14, 2015-16; Marks 02**

**Ans.** Second law efficiency is defined as the ratio of the minimum available energy (or exergy) which must be consumed to do a task divided by the actual amount of available energy (or exergy) consumed in performing the task.

$$\eta_{II} = \frac{\text{minimum exergy intake to perform the given task}}{\text{actual exergy intake to perform the same task}}$$

**3.9. Define first law efficiency.**

**Ans.** First law efficiency is defined as the ratio of the output energy of a device to the input energy of the device.

**3.10. What do you mean by Helmholtz function ?**

**Ans.** The term  $(u - Ts)$  is known as Helmholtz function, this gives maximum possible output when the heat  $Q$  is transferred at constant temperature.

**3.11. What are the Maxwell relations ?**

**Ans. Maxwell Relations :**

$$\begin{aligned} \text{i. } \left(\frac{\partial T}{\partial v}\right)_s &= -\left(\frac{\partial p}{\partial s}\right)_v, & \text{ii. } \left(\frac{\partial T}{\partial p}\right)_s &= \left(\frac{\partial v}{\partial s}\right)_p, \\ \text{iii. } \left(\frac{\partial p}{\partial T}\right)_v &= \left(\frac{\partial s}{\partial v}\right)_T, \text{ and} & \text{iv. } \left(\frac{\partial v}{\partial T}\right)_p &= -\left(\frac{\partial s}{\partial p}\right)_T. \end{aligned}$$

**3.12. What is the importance of Maxwell equations ?**

**Ans.** Maxwell equations are very useful in thermodynamics because they provide a means of determining the change in entropy which cannot be measured directly.

**3.13. What do you mean by Clausius-Clapeyron equation ?**

**Ans. Clausius-Clapeyron Equation :** This equation is a relationship between the saturation pressure, temperature, the enthalpy of evaporation, and the specific volume of the two phase involved. It gives the slope of a curve separating the two phases in the  $p$ - $T$  diagram.

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f} = \frac{s_{fg}}{v_{fg}} = \frac{h_{fg}}{T.v_{fg}}$$

This equation is known as Clausius-Clapeyron equation.

**3.14. What is Joule-Thomson coefficient ?**

**Ans. Joule-Thomson Coefficient :** The temperature and pressure behaviour of fluids during a throttling process is described by the Joule-Thomson coefficient ( $\mu$ ).

$$\mu = \left(\frac{\partial T}{\partial p}\right)_h$$

**3.15. What is coefficient of volume expansion ?**

**Ans. Coefficient of Volume Expansion :** It is defined as,

$$\beta = \frac{1}{v} \left(\frac{\partial v}{\partial T}\right)_p$$

This is also known as volume expansivity. It is a measure of the change in volume with temperature at constant pressure.

**3.16. What is isothermal compressibility ?**

**Ans. Isothermal Compressibility :** Isothermal compressibility ' $\alpha$ ' is defined as,

$$\alpha = -\frac{1}{v} \left(\frac{\partial v}{\partial p}\right)_T$$

It is positive quantity for all substances in all phase.

**3.17. What do you mean by adiabatic compressibility ?**

**Ans. Adiabatic Compressibility :** It is represented by following relation,

$$k = -\frac{1}{v} \left( \frac{\partial v}{\partial p} \right)_s$$

### Application Based Questions

**3.18. 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/kgK, find the entropy change of universe.**

**AKTU 2015-16, Marks 02**

**Ans. Given :**

$$m = 2 \text{ kg}$$

$$T_1 = 25 + 273 = 298 \text{ K}$$

$$T_2 = 30 + 273 = 303 \text{ K}$$

$$c = 4.187 \text{ kJ/kgK}$$

$\therefore$  Entropy charge =  $\Delta S$

$$\Delta S = mc \ln \frac{T_2}{T_1}$$

$$= 2 \times 4.187 \ln \frac{303}{298}$$

$$\Delta S = 0.1393 \text{ kJ/K}$$



4

UNIT

## Properties of Steam and Rankine Cycle (2 Marks Questions)

### Memory Based Questions

#### 4.1. Define degree of superheat.

**Ans.** The difference between the temperature of the superheated vapour and the saturation temperature at that pressure is called the superheat or the degree of superheat.

#### 4.2. Define triple point.

**Ans.** Triple point is defined as a point at which pressure and temperature are such that all the three states (solid, liquid and vapour) of a substance co-exist in equilibrium.

#### 4.3. State critical point.

**Ans.** Critical point is the point where distinction between the entropy of water and the entropy of dry steam disappears.

#### 4.4. Define dryness fraction of steam ?

**AKTU 2016-17, Marks 02**

**Ans.** Dryness fraction of steam is defined as the ratio of mass of dry steam present in a known quantity of wet steam to the total mass of steam.

Mathematically,

$$x = \frac{m_s}{m_s + m_w}$$

where,

$x$  = dryness fraction,

$m_s$  = mass of dry steam, and

$m_w$  = mass of water particle.

#### 4.5. What do you mean by external work and internal latent heat ?

**Ans.** **External Work :** When water is evaporated at a specified pressure and temperature, there is a significant increase in the volume during conversion of liquid into vapour state. The work is thus done by steam in increasing its volume. This work is known as external work of evaporation.

**Internal Latent Heat :** A certain amount of latent heat supplied to water during the process of evaporation is utilized in expanding the volume and thus producing external work.

The difference of latent heat of steam and external work of evaporation is known as internal latent heat.

#### 4.6. What is a saturation state ?

**Ans.** Saturation state is a state from which a change of phase may occur without a change of pressure or temperature.

#### 4.7. What do you mean by vapour dome ?

**Ans.** The saturated liquid line with respect to vapourization and the saturated vapour line incline towards each other and form which is known as the saturation or vapour dome.

#### 4.8. How does triple point exist on the $P$ - $V$ diagram ?

**Ans.** The triple point is a line on the  $P$ - $V$  diagram, where all the three phases, solid, liquid and gas, exist in equilibrium.

#### 4.9. What advantages are obtained if superheated steam is used in steam prime movers ?

AKTU 2016-17, Marks 02

**Ans.** It increases the work output of prime movers which directly increases the efficiency.

#### 4.10. What are the different types of calorimeters ?

**Ans.** Following are the types of calorimeters :

1. Separating calorimeter,
2. Throttling calorimeter,
3. Combined separating and throttling calorimeter, and
4. Barrel calorimeter.

#### 4.11. Define psychrometry.

**Ans.** Psychrometry is defined as the branch of engineering science which deals with the study of moist air *i.e.*, dry air mixed with water vapour or humidity.

#### 4.12. What do you mean by specific humidity ?

**Ans.** Specific humidity is defined as the amount of water vapour in kg present along with 1 kg of dry air in a mixture of dry air and water vapour. It is also called humidity ratio or humidity. And it is denoted by  $\omega$ .

It is expressed in terms of kg per kg of dry air.

**4.13. What is absolute humidity ?**

**Ans.** Absolute humidity is defined as the amount of water vapour present in kg in  $1 \text{ m}^3$  volume of mixture of dry air and water vapour.

**4.14. What do you mean by relative humidity ?**

**Ans.** Relative humidity is defined as the ratio between actual amount of water vapour *i.e.*, present in a given volume of mixture and the maximum amount of water vapour that could be present in the same volume at the same temperature when the mixture is saturated.

It is denoted by  $RH$  or  $\phi$ .

**4.15. What is dry bulb temperature ?**

**Ans.** Dry bulb temperature (DBT) is the temperature, recorded by an ordinary thermometer whose reading is not affected by moisture present in the air or by thermal radiation.

**4.16. Define wet bulb temperature.**

**Ans.** Wet bulb temperature is the temperature recorded by a thermometer whose bulb is covered with a wet cloth and exposed to current of moving air (atmospheric air).

**4.17. What is wet bulb depression ?**

**Ans.** Wet bulb depression is the difference between dry bulb temperature and wet bulb temperature.

$$WBD = DBT - WBT$$

**4.18. What do you mean by dew point temperature (DPT) ?**

**Ans.** Dew point temperature (DPT) is the temperature at which the water vapour present in the moist air just begins to condense when the mixture of moist air is cooled at constant pressure.

**4.19. What is dew point depression ?**

**Ans.** Dew point depression is the difference between the dry bulb temperature and dew point temperature of air.

$$DPD = DBT - DPT$$

**4.20. Define degree of saturation.**

**Ans.** Degree of saturation is defined as the ratio of actual humidity ratio and saturated humidity ratio, both being at the same temperature and total barometric pressure.

It is denoted by  $\mu$ .

$$\mu = \frac{\omega}{\omega_s}$$

where,  $\omega$  = actual humidity ratio, and  
 $\omega_s$  = saturated humidity ratio.

#### 4.21. Define bypass factor.

**Ans.** Bypass factor is defined as the ratio of actual change in temperature to the maximum change in temperature. It is denoted by  $x$ .  
 For heating,

$$x = \frac{t_2 - t_3}{t_2 - t_1}$$

where,  $t_2$  = temperature of heating coil,  
 $t_3$  = actual temperature of moist air after heating, and  
 $t_1$  = temperature of moist air before heating.

#### 4.22. Define humidification and dehumidification.

**Ans. Humidification :** The addition of moisture to the air, without change in its dry bulb temperature, is known as humidification.

**Dehumidification :** The removal of moisture from the air, without change in its dry bulb temperature, is known as dehumidification.

#### 4.23. What do you mean by sensible heat factor ?

**Ans.** Since, the heat added during a psychrometric process may be split up into sensible heat and latent heat. The ratio of the sensible heat to the total heat is known as sensible heat factor ( $SHF$ ) or sensible heat ratio ( $SHR$ ).

$$SHF = \frac{SH}{SH + LH}$$

where,  $SH$  = sensible heat, and  
 $LH$  = latent heat.

#### 4.24. What do you understand by adiabatic mixing of two air streams ?

**Ans.** When two quantities of air having different enthalpies and different specific humidity are mixed, the final condition of the air mixture depends upon the masses involved, and on the enthalpy and specific humidity of each of the constituent masses which enter the mixture. This type of mixing of two air streams is known as adiabatic mixing.







## Refrigeration Cycles (2 Marks Questions)

### Memory Based Questions

**5.1. What do you mean by refrigeration ?**

**Ans. Refrigeration :** It is the science of the producing and maintaining temperatures below that of the surrounding atmosphere *i.e.*, removing of heat from a substance under controlled conditions.

**5.2. Write two application of refrigeration.**

**Ans. Application of Refrigeration :**

1. Making of ice, and
2. Used in transportation of food at a required temperature.

**5.3. What is unit of refrigeration ?**

**Ans.** The practical unit of refrigeration is tonne of refrigeration. It is written as TR.

**5.4. Define a tonne of refrigeration.**

**Ans. Tonne of Refrigeration :** It is defined as the amount of refrigeration effect produced by the uniform melting of one tonne (1000 kg) of ice and at  $0^{\circ}\text{C}$  in 24 hours.

Practically,

$$1 \text{ TR} = 210 \text{ kJ / min}$$

**5.5. Define refrigeration effect.**

**Ans. Refrigeration Effect :** The amount of heat extracted from the system is termed as refrigeration effect.

**5.6. Define coefficient of performance of a refrigerator.**

**Ans. Coefficient of Performance of a Refrigerator :** It is defined as the ratio of heat extracted in the refrigerator to the work done on the refrigerant.

Mathematically,

$$\text{COP} = \frac{Q}{W}$$

where,  $Q$  = amount of heat extracted in the refrigerator,  
and  
 $W$  = amount of work done.

### 5.7. Define refrigerator.

**Ans. Refrigerator :** It is a reversed heat engine which cools or maintains the temperature of a body lower than the atmospheric temperature.

$$(\text{COP})_R = \frac{Q_1}{W_R}$$

where,  $(\text{COP})_R$  = coefficient of performance of refrigerator,  
 $Q_1$  = amount of heat taken from the cold body, and  
 $W_R$  = the amount of work required to be done on the system.

### 5.8. Name the systems by which mechanical refrigeration can be accomplished.

**Ans.** Mechanical refrigeration can be accomplished with :

1. Compressor,
2. Evaporator,
3. Expander, and
4. Condenser.

### 5.9. What are the components of Carnot refrigeration cycle ?

**Ans. Carnot Refrigeration Cycle :** It consists of four basic components :

1. Compressor,
2. A heat rejection device,
3. An expander coupled to the compressor, and
4. A cold chamber.

### 5.10. Write two merit and demerit of air refrigeration system.

**Ans. Merits :**

1. The air is easily available and there is no cost of the refrigerant.
2. The air is non-toxic and non-inflammable.

**Demerits :**

1. Low COP.
2. The rate of air circulation is relatively large.

### 5.11. Write the components of a Bell-Coleman cycle.

**Ans.** A Bell-Coleman cycle consists of the following components :

1. Compressor,
2. Cooler,

3. Expander, and
4. Refrigerator.

**5.12. Write two advantage and two disadvantage of VCR system over air refrigeration system ?**

**Ans. Advantages :**

1. It has smaller size for the given capacity of refrigeration.
2. The coefficient of performance is quite high.

**Disadvantages :**

1. The initial cost is high.
2. The prevention of leakage of the refrigerant is the major problem in vapour compression system.

**5.13. What are the types of vapour compression cycles ?**

**Ans.** Following are the types of vapour compression cycles :

1. Cycle with dry saturated vapour after compression.
2. Cycle with wet vapour after compression.
3. Cycle with superheated vapour after compression.
4. Cycle with superheated vapour before compression.
5. Cycle with undercooling or subcooling of refrigerant.

**2.14. How will you improve simple saturation cycle ?**

**Ans.** The simple saturation cycle may be improved by the following methods :

1. By introducing the flash chamber between the expansion valve and the evaporator.
2. By using the accumulator or pre-cooler.
3. By subcooling the liquid refrigerant by the vapour refrigerant.
4. By subcooling the liquid refrigerant leaving the condenser by liquid refrigerant from the expansion valve.

**5.15. What do you mean by refrigeration efficiency ( $\eta_R$ ) ?**

**Ans.** Refrigeration efficiency ( $\eta_R$ ) : is defined as the ratio of COP of vapour compression cycle to the COP of Carnot cycle.

It is also called performance index ( $P.I.$ ).

**5.16. What will be the effect of superheating the vapour before suction to compression in a VCR system ?**

**Ans. Effects of Superheating :**

1. Increases the work of compression.
2. Increases the heat rejection in the condenser.
3. May increase or decrease COP.

**5.17. What will be the effect of suction pressure on decreasing its value in a VCR system ?**

**Ans.** The COP of the refrigerating system will be decreased for the same amount of refrigerant flow. So, the refrigerating capacity of the system will decrease and the refrigeration cost will increase.

**5.18. Define refrigerant ?**

**Ans.** Refrigerant is a heat carrying medium which during its cycle in the refrigeration system absorbs heat from a low temperature system and discards the heat so absorbed to a higher temperature system.

**5.19 Define primary and secondary refrigerant.**

**Ans. Primary Refrigerant :** The refrigerants which directly take part in the refrigeration system are called primary refrigerants.

For example : R-12,  $\text{NH}_3$  and  $\text{SO}_2$  etc.

**Secondary Refrigerant :** The refrigerants which are first cooled by primary refrigerants and then used for cooling purpose are known as secondary refrigerant.

For example :  $\text{H}_2\text{O}$ , brine solution of  $\text{NaCl}$  and  $\text{CaCl}_2$  etc.

**5.20. Write two examples of halo-carbon refrigerants ?**

**Ans.** The two examples of halo-carbon refrigerants are as follows :

1. R-11, trichloro-monofluoro-methane ( $\text{CCl}_3\text{F}$ ), and
2. R-12, dichloro-difluoro-methane ( $\text{CCl}_2\text{F}_2$ ).

**5.21. Define azeotrope refrigerants with examples.**

**Ans. Azeotrope Refrigerants :** These are referred to a stable mixture of refrigerants whose vapour and liquid phase retain identical compositions over a wide range of temperatures.

Examples :

1. R-500, and
2. R-502.

**5.22. Give two examples of inorganic refrigerants.**

**Ans.** Following are the two examples of inorganic refrigerants :

1. R-717 (ammonia), and
2. R-729 (air).

**5.23. Write down desirable properties of refrigerants.**

**Ans.**

1. Low boiling point
2. Low specific heat of liquid
3. Low specific volume of vapour
4. Low cost
5. Nontoxic and non corrosive to metal.

**5.24. What is the function of absorber in VAR system ?**

**Ans.** Absorber is used to absorption of the refrigerant vapour by its weak or poor solution in a suitable absorbent or adsorbent, forming a strong or rich solution of the refrigerant in the absorbent / adsorbent.



**B.Tech.****(SEM. III) ODD SEMESTER THEORY****EXAMINATION, 2015-16****THERMODYNAMICS****Time : 3 Hours****Total Marks : 100****Section – A**

1. Attempt **all** parts. All parts carry **equal** marks. Write answer of each part in short. (2 × 10 = 20)
- a. Briefly explain quasi static process.
- b. State steady and unsteady flows.
- c. Explain free expansion process ?
- d. State Carnot theorem.
- e. State the various statements of second law of thermodynamics ?
- f. A system composed of 2 kg air 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. Take air as ideal gas having ( $C_V = 0.718 \text{ kJ/kgK}$  and  $R = 0.287 \text{ kJ/kgK}$ ).
- g. 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.
- h. What is exergy ?
- i. Define second law efficiency.
- j. Prove that  $\text{COP}_P = 1 + \text{COP}_R$ .

**Section – B**Attempt any **five** questions from this section. (10 × 5 = 50)

2. Derive available energy and irreversibility for open system and closed system ?

3. Define thermodynamic equilibrium and also show that energy is a property of a system.
4. State first law of thermodynamics with its limitations.
5. 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 exits from the nozzle.
  - b. If the inlet area is  $0.1 \text{ m}^2$  and the specific volume at inlet is  $0.187 \text{ m}^3/\text{kg}$ , find the mass flow rate.
  - c. If the specific volume at the nozzle exit is  $0.498 \text{ m}^3/\text{kg}$ , find the exit area of the nozzle.
6. 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 ejects 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 ejects heat ? What is the rate of heat ejection from the heat pump if the rate of heat supply to the engine is 50 kW ?
7. 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  $C = 8.4 \text{ kJ/K}$ , 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 ?
8. An air preheater is used to heat up the air used for combustion by cooling the outgoing products of combustion from a furnace. The rate of flow of the products is 10 kg/s, and the products are cooled from 300 °C to 200 °C, and for the products at this temperature  $c_p = 1.09 \text{ kJ/kgK}$ . The rate of air flow is 9 kg/s, the initial air temperature is 40 °C, and for the air  $c_p = 1.005 \text{ kJ/kgK}$ .
  - a. What is the initial and final availability of the product ?
  - b. What is the irreversibility for this process ?
  - c. If the heat transfer from the products were to take place reversibly through heat engines, what would be the final temperature of the air ?

9. Discuss exergy destruction. A reversible engine, as shown in Fig. 1, during a cycle of operations 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.

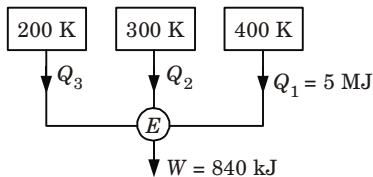


Fig. 1.

### Section – C

Attempt any **two** questions. All questions carry equal marks.

(15 × 2 = 30)

10. Explain the working of a two stroke SI engine giving neat sketches and differentiate between two stroke and four stroke spark ignition engine.
11. Explain simple Rankine cycle with neat schematic diagram and also show different processes involved in it on  $T$ - $s$  diagram,  $h$ - $s$  diagram and  $p$ - $V$  diagram.
12. What is perpetual motion machine of second type? 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  $0.20 \text{ m}^3$  and  $1.20 \text{ m}^3$ . 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  $\text{m}^3/\text{kg}$ . Calculate the net heat transfer and the maximum internal energy of the gas attained during expansion.



**SOLUTION OF PAPER (2015-16)****Section – A**

1. Attempt **all** parts. All parts carry **equal** marks. Write answer of each part in short. (2 × 10 = 20)

**a. Briefly explain quasi static process.**

**Ans.** This process is a succession of equilibrium states and infinite slowness is its characteristic feature. This process is also called a reversible process.

**b. State steady and unsteady flows.**

**Ans. Steady Flow :** It is the process in which mass is crossing the boundary from surroundings at entry, and an equal mass is crossing the boundary at the exit so that the total mass of the system remains constant.

**Unsteady Flow :** It is the process in which mass at entry and mass at exit is not equal *i.e.*, total mass of the system does not remain constant.

**c. Explain free expansion process ?**

**Ans.** Let us consider a gas separated from the vacuum by a partition. Let the partition be removed. The gas rushes to fill the entire volume. The expansion of a gas against vacuum is called free expansion.

**d. State Carnot theorem.**

**Ans.** Carnot theorem states that of all heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

**e. State the various statements of second law of thermodynamics ?**

**Ans. Kelvin-Planck Statement :** It states that it is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

**Clausius Statement :** It is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a cooler to hotter body.

- f. A system composed of 2 kg air 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. Take air as ideal gas having ( $C_v = 0.718 \text{ kJ/kgK}$  and  $R = 0.287 \text{ kJ/kgK}$ ).**



**Ans.**

**Given :**  $M = 2 \text{ kg}$ ,  $P_1 = 1 \text{ MPa}$ ,  $T_1 = 100 + 273 = 373 \text{ K}$ ,  
 $T_2 = 30 + 273 = 303 \text{ K}$ ,  $C_v = 0.718 \text{ kJ/kg K}$ ,  $R = 0.287 \text{ kJ/kg K}$   
**To Find :** Net work for the process

1. Since, there is no heat transfer. It is an adiabatic process.

$$\begin{aligned}
 2. \text{ Then, net work} &= \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} \\
 &= \frac{mRT_1 - mRT_2}{\gamma - 1} = \frac{mR(T_1 - T_2)}{\gamma - 1} \left( \because C_v = \frac{R}{\gamma - 1} \right) \\
 &= mC_v (T_1 - T_2)
 \end{aligned}$$

3. On putting the given values,  
 Net work  $= 2 \times 0.718 (373 - 303)$   
 $= 100.52 \text{ kJ}$

**g. 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.**

**Given :**  $m = 2 \text{ kg}$ ,  $T_1 = 25 + 273 = 298 \text{ K}$ ,  $T_2 = 30 + 273 = 303 \text{ K}$ ,  
 $c = 4.187 \text{ kJ/kgK}$ ,

**To Find :** Entropy change of the universe

1. Entropy change  $= \Delta S$

$$\begin{aligned}
 &= mc \ln \frac{T_2}{T_1} \\
 &= 2 \times 4.187 \ln \frac{303}{298} \\
 \Delta S &= 0.1393 \text{ kJ/K}
 \end{aligned}$$

**h. What is exergy ?**

**Ans.** The maximum work output obtained from a certain heat input in a cycle heat engine is called the available energy (AE) or exergy.

**i. Define second law efficiency.**

**Ans.** Second law efficiency is defined as the ratio of the minimum available energy (or exergy) which must be consumed to do a task divided by the actual amount of available energy (or exergy) consumed in performing the task.

$$\eta_{II} = \frac{\text{minimum exergy intake to perform the given task}}{\text{actual exergy intake to perform the same task}}$$

j. Prove that  $\text{COP}_P = 1 + \text{COP}_R$ .

**Ans.**

1. We know,  $\text{COP} = \frac{\text{desired effect}}{\text{work done}}$

2. For pump,  $\text{COP}_P = \frac{Q_1}{Q_1 - Q_2} \quad \dots(1)$

3. For refrigerator,  $\text{COP}_R = \frac{Q_2}{Q_1 - Q_2} \quad \dots(2)$

Where,  $Q_1$  = heat transfer to engine, and  
 $Q_2$  = heat transfer from cold reservoir.

4. Subtracting eq. (2) from eq. (1),

$$\begin{aligned} \text{COP}_P - \text{COP}_R &= \frac{Q_1}{Q_1 - Q_2} - \frac{Q_2}{Q_1 - Q_2} \\ &= \frac{Q_1 - Q_2}{Q_1 - Q_2} = 1 \end{aligned}$$

$$\Rightarrow \text{COP}_P = 1 + \text{COP}_R$$

### Section - B

Attempt any **five** questions from this section. **(10 × 5 = 50)**

2. **Derive available energy and irreversibility for open system and closed system ?**

**Ans.**

**A. Available Energy for Open System :**

1. Let's consider a steady flow system and let the working substance has following parameters :

$u$  — Specific internal energy

$v$  — Specific volume

$h$  — Specific enthalpy

$p$  — Pressure

$C$  — Velocity

$Z$  — Elevation

2. When the working substance flows through a system, its properties will change.

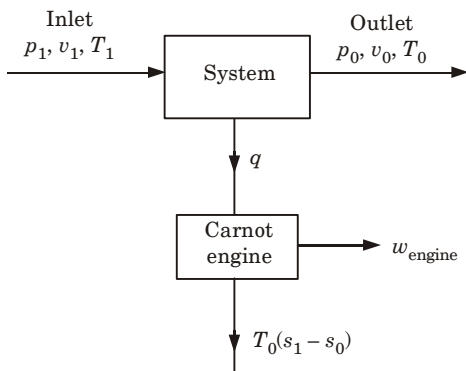
3. At the inlet of a system let fluid properties and characteristics be written as  $u_1, v_1, h_1, p_1, C_1$  and  $Z_1$ .

4. At the outlet the corresponding values will be  $u_0, v_0, h_0, p_0, C_0$  and  $Z_0$ .

5. Let  $Q$  be the heat rejected by the system and  $W$  be the work done by the system.

6. The SFEE can be written as

$$u_1 + p_1 v_1 + \frac{C_1^2}{2} + gZ_1 - q = u_0 + p_0 v_0 + \frac{C_0^2}{2} + gZ_0 + w$$



**Fig. 1.** Availability of a steady flow system.

7. Let changes in kinetic and potential energies be negligible  
i.e.,  $\Delta KE = 0$  and  $\Delta PE = 0$

8. The SFEE is reduced to

$$u_1 + p_1 v_1 - q = u_0 + p_0 v_0 + w$$

But enthalpy  $h = u + pv$

$$\therefore h_1 - q = h_0 + w$$

$$\text{or } w = (h_1 - h_0) - q$$

( $w$  is the shaft work)

9. The output of this engine,

$$\begin{aligned} w_{\text{engine}} &= q - q \frac{T_0}{T_1} \\ &= q \left( 1 - \frac{T_0}{T_1} \right) = q - T_0 (s_1 - s_0) \end{aligned}$$

10. Therefore, maximum available net work

$$\begin{aligned} w_{\text{net}} &= w + w_{\text{engine}} = (h_1 - h_0) - q + q - T_0 (s_1 - s_0) \\ &= (H_1 - T_0 S_1) - (H_0 - T_0 S_0) \\ &= B_1 - B_0 \end{aligned}$$

Where,  $B = h - T_0 s$  is called steady flow availability function.

It is also a composite property of system and surroundings.

### B. Available Energy for Closed System :

- Let's consider a piston cylinder arrangement substance at  $p_1$ ,  $T_1$  and  $V_1$  is expanded reversibly to close state at  $p_0$ ,  $V_0$  and  $T_0$ .
- The working substance expands and  $W_{\text{expansion}}$  is obtained.
- From the law of conservation of energy,

$$\begin{aligned} Q &= dU + W \\ -Q &= W_{\text{expansion}} + (U_0 - U_1) \end{aligned}$$

(Heat interaction is negative because it leaves the system.)

$$\text{Therefore, } W_{\text{expansion}} = (U_1 - U_0) - Q$$

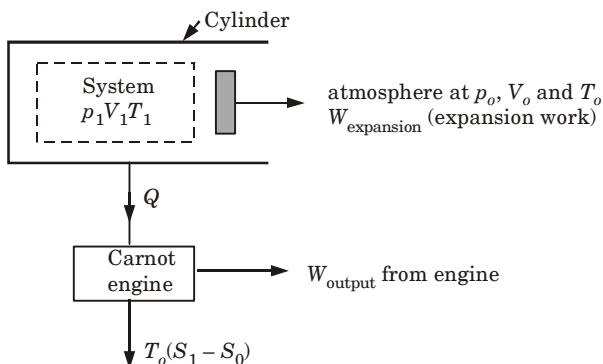


Fig. 2.

4. This heat rejected from the piston-cylinder arrangement can be used to run a reversible heat engine. Work output of the reversible engine is equal to

$$W_{\text{engine}} = Q - Q \frac{T_0}{T} = Q \left[ 1 - \frac{T_0}{T} \right]$$

$$\therefore W_{\text{engine}} = Q - T_0 (S_1 - S_0)$$

5. Maximum work obtained from the cylinder piston assembly is the sum of  $W_{\text{expansion}}$  and  $W_{\text{engine}}$ .

$$\begin{aligned} W_{\text{max}} &= W_{\text{expansion}} + W_{\text{engine}} \\ &= [(U_1 - U_0) - Q] + [Q - T_0 (S_1 - S_0)] \\ &= (U_1 - U_0) - T_0 (S_1 - S_0) \end{aligned}$$

6. Surrounding work,  $W_{\text{surrounding}} = p_0 (V_0 - V_1)$

This is the work which the piston, while moving outwards, has to spend in pushing the atmosphere against its own pressure.

7. Therefore maximum available useful network,

$$\begin{aligned} W_{\text{net}} &= W_{\text{max}} - W_{\text{surrounding}} \\ &= (U_1 - U_0) - T_0 (S_1 - S_0) - p_0 (V_0 - V_1) \\ &= (U_1 + p_0 V_1 - T_0 S_1) - (U_0 + p_0 V_0 - T_0 S_0) \\ &= A_1 - A_0 \end{aligned}$$

Where  $A = U + p_0 V - T_0 S$  is called non-flow availability function.

### C. Irreversibility for Open and Closed System :

- Maximum useful work (or net work), from a system corresponds to a reversible process in which the system has heat interaction with the environments. Since the processes in real practice are irreversible, the actual work done by the system for the given change of state is always less than reversible work.
- Therefore, irreversibility of a process is defined as the difference of reversible work and the actual work.
- In mathematical form,

$$\text{Irreversibility, } I = W_{\text{rev}} - W_{\text{useful}}$$

$$I = (U_1 - T_o S_1) - (U_2 - T_o S_2) - [-Q - (U_2 - U_1)] \\ = Q + T_o (S_2 - S_1)$$

4. Change in entropy of surroundings due to heat addition at constant atmospheric temperature,  $T_o$  is

$$(dS)_{\text{surrounding}} = \frac{Q}{T_o}$$

or

$$Q = T_o (dS)_{\text{surrounding}}$$

Therefore, irreversibility,  $I = T_o (dS)_{\text{system}} + T_o (dS)_{\text{surrounding}}$

$$I = T_o (dS)_{\text{universe}}$$

5. From the above expression irreversibility equals the product of entropy production and surroundings temperature.
6. The expression  $T_o (dS)_{\text{universe}}$  also represents an increase in the unavailable part of energy (or Anergy) and therefore it can be stated that irreversibility causes an increase in Anergy.

3. **Define thermodynamic equilibrium and also show that energy is a property of a system.**

**Ans.**

**A. Thermodynamic Equilibrium :**

1. A system is said to exist in a state of thermodynamic equilibrium when no spontaneous change in any macroscopic property is registered, if the system is isolated from its surroundings.

“If the system exists in equilibrium state, there can be no spontaneous change in any macroscopic property of the system”.

2. A system will be in thermodynamic equilibrium, if following three types of equilibrium are satisfied.

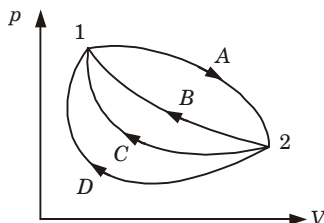
- Mechanical Equilibrium :** System is in mechanical equilibrium if there is no unbalanced force (pressure forces) within the system and also between system and its surroundings.
- Chemical Equilibrium :** If there is no chemical reaction, or transfer of matter from one part of system to another, (such as diffusion or solution), system is in chemical equilibrium.
- Thermal Equilibrium :** Condition or state in which the temperature of system is uniform.

**B. Energy is a Property of System :**

1. Let's consider a closed system which changes its state from 1 to 2 by path A and comes back to its original state '1' by any of the following paths :
- Along the path 2-B-1.
  - Along the path 2-C-1.
  - Along the path 2-D-1.
2. For the cyclic process 1-A-2-B-1,

$$\text{Apply first law, } \oint \delta Q = \oint \delta W \text{ or } \oint (\delta Q - \delta W) = 0$$

$$\therefore \int_{1, \text{Via A}}^2 (\delta Q - \delta W) + \int_{2, \text{Via B}}^1 (\delta Q - \delta W) = 0 \quad \dots(1)$$



**Fig. 3.** Standard energy in a point function.

3. Similarly for the cyclic process 1-A-2-C-1,

$$\int_{1, \text{Via } A}^2 (\delta Q - \delta W) + \int_{2, \text{Via } C}^1 (\delta Q - \delta W) = 0 \quad \dots(2)$$

and for the cyclic process 1-A-2-D-1

$$\int_{1, \text{Via } A}^2 (\delta Q - \delta W) + \int_{2, \text{Via } D}^1 (\delta Q - \delta W) = 0 \quad \dots(3)$$

4. Comparing eq. (1), eq. (2) and eq. (3), we have

$$\int_{2, \text{Via } B}^1 (\delta Q - \delta W) = \int_{2, \text{Via } C}^1 (\delta Q - \delta W) = \int_{2, \text{Via } D}^1 (\delta Q - \delta W)$$

5. Since B, C and D indicate arbitrary paths between states 1 and 2, it

can be concluded that the expression  $\int_2^1 (\delta Q - \delta W)$  remains the same irrespective of the path along which the system is proceeding solely depends on the initial and final states of the system. Therefore energy is a point function and hence a property of the system.

6. The integral  $\int_2^1 (\delta Q - \delta W)$  is called energy of the system and is denoted by  $dU$ .

Therefore for a process,  $dU = \delta Q - \delta W$

or  $\delta Q = dU + \delta W$

#### 4. State first law of thermodynamics with its limitations.

**Ans.**

1. First law of thermodynamics is related with principle of conservation of energy according to which the total energy of an isolated system is conserved.
2. It can be concluded that all forms of energies are equivalent and convertible. If one form of energy disappears, it must appear in an equivalent amount of some other form of energy.
3. Thus first law stipulates that when a thermodynamic process is carried out, energy is neither gained nor lost.
4. Energy is only transformed from one form into another and the energy balance is maintained.
5. First law fails to state the conditions under which energy conversion takes place.

6. The limitations of 1<sup>st</sup> law of thermodynamics can be explained with the help of following illustrations :
- Temperature of liquid contained in a vessel increases when it is churned by paddle work. But paddle work can not be restored on cooling the liquid to its initial state.
  - When a block slides down a rough place, it gets warmer. However, the reverse process when the block slides up the plane and becomes cooler is not true even if the first law of thermodynamics still holds good.
  - Electrical current flowing through a resistor produces heat according to equation,

$$H = i^2 R t.$$

Current once dissipated as heat cannot be converted back into electricity.

- Fuel (solid or liquid) burns with air and gets converted into products of combustion. Fuel once burnt cannot be restored back to its original form.
  - Work is easily converted into heat. However there is a maximum limit up to which the conversion of heat is possible in a heat engine. Work is superior to heat, and a complete transformation of low grade energy (heat) into high grade energy (work) is not possible.
5. 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.
- Find the velocity at exits from the nozzle.
  - If the inlet area is 0.1 m<sup>2</sup> and the specific volume at inlet is 0.187 m<sup>3</sup>/kg, find the mass flow rate.
  - If the specific volume at the nozzle exit is 0.498 m<sup>3</sup>/kg, find the exit area of the nozzle.

**Ans.**

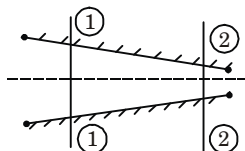
**Given :** At the inlet, Enthalpy,  $h_1 = 3000$  kJ/kg, Velocity,  $C_1 = 60$  m/s, At the discharge end, Enthalpy  $h_2 = 2762$  kJ/kg

**To Find :** i. Velocity at exit.

ii. Mass flow rate.

iii. Exit area.

- At the discharge end,



**Fig. 4.**

Enthalpy,  $h_2 = 2762 \text{ kJ/kg}$

It is given that nozzle is horizontal and there is negligible heat loss from it.

2. Applying SFEE, between section (1) and section (2),

$$h_1 + \frac{1}{2000} C_1^2 + \frac{gZ_1}{1000} + \dot{Q} = h_2 + \frac{1}{2000} C_2^2 + \frac{gZ_2}{1000} + \dot{w} \quad \dots(1)$$

3. Since,  $Z_1 = Z_2$

And assuming, there is no heat transfer and work transfer.

Then from eq. (1),

$$h_1 + \frac{1}{2000} C_1^2 = h_2 + \frac{1}{2000} C_2^2$$

4. On putting given values,

$$3000 + \frac{1}{2000} \times (60)^2 = 2762 + \frac{1}{2000} C_2^2$$

$$C_2^2 = 479600$$

$$C_2 = 692.53 \text{ m/s}$$

Hence, the velocity at exit from the nozzle,

$$C_2 = 692.53 \text{ m/s}$$

5. Inlet area,  $a_1 = 0.1 \text{ m}^2$

Specific volume,  $v_1 = 0.187 \text{ m}^3/\text{kg}$

6. Now from continuity equation, at inlet

$$\begin{aligned} \dot{m} v_1 &= a_1 C_1 \\ \dot{m} \times 0.187 &= 0.1 \times 60 \\ \dot{m} &= 32.08 \text{ kg/s} \end{aligned}$$

Hence, the mass flow rate,  $\dot{m} = 32.08 \text{ kg/s}$ .

7. Specific volume at exit =  $v_2$

$$v_2 = 0.498 \text{ m}^3/\text{kg}$$

8. Then, from continuity equation at exit,

$$\begin{aligned} a_2 C_2 &= \dot{m} v_2 \\ a_2 \times 692.53 &= 32.08 \times 0.498 \\ a_2 &= 0.02307 \text{ m}^2 \end{aligned}$$

Hence, the exit area of the nozzle,

$$a_2 = 0.02307 \text{ m}^2$$

6. 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 ejects 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 ejects heat ? What is the rate of heat ejection from the heat pump if the rate of heat supply to the engine is 50 kW ?



**Ans.**

**Given :**  $T_1 = 1000 \text{ K}$ ,  $T_2 = 300 \text{ K}$ ,  $T_3 = 300 \text{ K}$ ,  $\eta_{HE} = 0.4$  ( $\eta_{HE})_{\max}$   
 $\text{COP}_{HP} = 0.5 \times (\text{COP}_{HP})_{\max}$ ,  $Q_1 = 50 \text{ kW}$ ,  $Q_3 = 2 Q_2$

**To Find :** Temperature of reservoir, Rate of heat rejected.

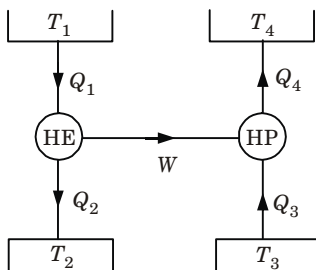
$$1. \text{ Since, } (\eta_{HE})_{\max} = 1 - \frac{T_2}{T_1}$$

$$= 1 - \frac{300}{1000} = 0.7$$

$$\text{So, } \eta_{HE} = 0.4 \times 0.7 = 0.28$$

$$2. \text{ But } \eta_{HE} = \frac{W}{Q_1}$$

$$\text{then, } W = 0.28 \times 50 = 14 \text{ kW}$$



**Fig. 5.**

$$3. \text{ Since, } (\text{COP}_{HP})_{\max} = \frac{T_4}{T_4 - T_3} = \frac{T_4}{T_4 - 300}$$

$$\text{So, } \text{COP}_{HP} = 0.5 \times \frac{T_4}{T_4 - 300} \quad \dots(1)$$

4. For heat engine,

$$Q_2 = Q_1 - W = 50 - 14$$

$$Q_2 = 36 \text{ kW}$$

$$\text{Since, } Q_3 = 2Q_2 = 2 \times 36 = 72 \text{ kW}$$

5. Now, for heat pump,

$$Q_4 = W + Q_3$$

$$= 14 + 72 = 86 \text{ kW}$$

$\dots(2)$

6. Since, we know that,

$$\text{COP}_{HP} = \frac{Q_4}{W}$$

7. Now from eq. (1),

$$\frac{86}{14} = \frac{0.5 T_4}{T_4 - 300}$$

$$T_4 - 300 = 0.08139 T_4$$

$$T_4 = 326.58 \text{ K}$$

$\dots(3)$

8. Hence from eq. (2) and eq. (3), the temperature of the reservoir to which the heat pump rejects heat = 326.58 K, and the rate of heat rejection from the heat pump = 86 kW
7. 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  $C = 8.4 \text{ kJ/K}$ , 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 ?

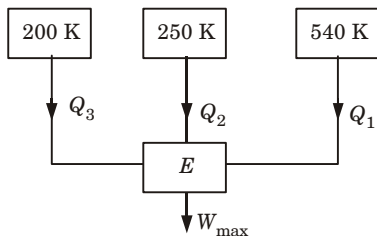
**Ans.****Given :**  $T_1 = 540 \text{ K}$ ,  $T_2 = 250 \text{ K}$ ,  $T_3 = 200 \text{ K}$ ,  $C = 8.41 \text{ kJ/K}$ **To Find :** Maximum amount of work.

1. Assuming final temperature of three bodies =  $T_F$ .
2. According to entropy principle for maximum work output,

$$(\Delta S)_{\text{universe}} = 0$$

$$(\Delta S)_1 + (\Delta S)_2 + (\Delta S)_3 = 0$$

$$C \ln \left( \frac{T_F}{540} \right) + C \ln \left( \frac{T_F}{250} \right) + C \ln \left( \frac{T_F}{200} \right) = 0$$

**Fig. 6.**

$$\Rightarrow \ln \left( \frac{T_F^3}{540 \times 250 \times 200} \right) = 0$$

$$\Rightarrow \frac{T_F^3}{540 \times 250 \times 200} = e^0 = 1$$

$$T_F = 300 \text{ K}$$

3. According to first law of thermodynamics,

$$\delta q = du + \delta w$$

4. For maximum work,  $dq = 0$  ;

$$(dw)_{\max} = -du = u_1 - u_2$$

$\therefore$  It is given that  $u = CT$

$$\text{So, } (w_1)_{\max} = 8.4 (540 - 300) = 2016 \text{ kJ}$$

(where,  $C = 8.4 \text{ kJ/K}$ )

$$(w_2)_{\max} = 8.4 (250 - 300) = -420 \text{ kJ}$$

$$(w_3)_{\max} = 8.4 (200 - 300) = -840 \text{ kJ}$$

$$5. \quad (w_{\text{net}})_{\text{max}} = (w_1)_{\text{max}} + (w_2)_{\text{max}} + (w_3)_{\text{max}} \\ = 2016 - 420 - 840 = 756 \text{ kJ.}$$

8. An air preheater is used to heat up the air used for combustion by cooling the outgoing products of combustion from a furnace. The rate of flow of the products is 10 kg/s, and the products are cooled from 300 °C to 200 °C, and for the products at this temperature  $c_p = 1.09 \text{ kJ/kgK}$ . The rate of air flow is 9 kg/s, the initial air temperature is 40 °C, and for the air  $c_p = 1.005 \text{ kJ/kgK}$ .

- What is the initial and final availability of the product ?
- What is the irreversibility for this process ?
- If the heat transfer from the products were to take place reversibly through heat engines, what would be the final temperature of the air ?

**Ans.**

**Given :**  $\dot{m}_g = 10 \text{ kg/s}$ ,  $T_{g1} = 300 + 273 = 573 \text{ K}$ ,

$T_{g2} = 200 + 273 = 473 \text{ K}$ ,  $c_{pg} = 1.09 \text{ kJ/kgK}$ ,  $\dot{m}_a = 9 \text{ kg/s}$ ,

$T_{a1} = 40 + 273 = 313 \text{ K}$ ,  $c_{pa} = 1.005 \text{ kJ/kgK}$

**To Find :** Initial and final availability of product Irreversibility of the process and final temperature of air.

**Data Assume :** Let,  $T_o = 300 \text{ K}$  (atmospheric temperature)

- Initial availability of the product,

$$\psi_1 = (h_1 - h_0) - T_0 (S_1 - S_0)$$

$$\psi_1 = c_{pg} (T_{g1} - T_0) - T_0 c_{pg} \ln \left( \frac{T_{g1}}{T_0} \right)$$

$$= 1.09 (573 - 300) - 300 \times 1.09 \ln \left( \frac{573}{300} \right)$$

$$\psi_1 = 297.57 - 211.6$$

$$\psi_1 = 85.97 \text{ kJ/kg}$$

- Final availability of the product,

$$\psi_2 = (h_2 - h_0) - T_0 (S_2 - S_0)$$

$$= 1.09 (473 - 300) - 300 \times 1.09 \ln \left( \frac{473}{300} \right)$$

$$= 188.57 - 148.89$$

$$\psi_2 = 39.68 \text{ kJ/kg}$$

- Decrease in availability of the products  $= \psi_1 - \psi_2$

$$= 85.97 - 39.68 = 46.29 \text{ kJ/kg}$$

- By making an energy balance for the air preheater,

$$\dot{m}_g c_{pg} (T_{g1} - T_{g2}) = \dot{m}_a c_{pa} (T_{a2} - T_{a1})$$

$$10 \times 1.09 (573 - 473) = 9 \times 1.005 [T_{a2} - 313]$$

$$T_{a2} = \frac{1090}{9.045} + 313$$

$$T_{a2} = 433.508 \text{ K}$$

5. Now, increase in availability of the air
- $$= \psi_2 - \psi_1 = (h_2 - h_1) - T_0 (S_2 - S_1)$$
- $$= c_{pa} (T_{a2} - T_{a1}) - T_0 c_{pa} \ln \left( \frac{T_{a2}}{T_{a1}} \right)$$
- $$= 1.005 (433.508 - 313) - 300 \times 1.005 \ln \left( \frac{433.508}{313} \right)$$
- $$= 121.1105 - 98.2006 = 22.9099 \text{ kJ/kg}$$
6. Hence the irreversibility of the process
- $$= 10 \times 46.29 - 9 \times 22.9099$$
- $$= 462.9 - 206.1891 = 256.7109 \text{ kW.}$$

7.  $\Delta \dot{S}_{\text{univ}} = 0$

$$\Delta \dot{S}_{\text{sys}} + \Delta \dot{S}_{\text{surr}} = 0$$

$$\Delta \dot{S}_{\text{product}} + \Delta \dot{S}_{\text{air}} = 0$$

$$\Delta \dot{S}_{\text{product}} = -\Delta \dot{S}_{\text{air}}$$

$$\dot{m}_g c_{pg} \ln \frac{T_{g2}}{T_{g1}} = -\dot{m}_a c_{pa} \ln \frac{T_{a2}}{T_{a1}}$$

$$10 \times 1.09 \ln \left( \frac{473}{573} \right) = -9 \times 1.005 \ln \left( \frac{T_{a2}}{313} \right)$$

$$\Rightarrow T_{a2} = 394.38 \text{ K}$$

Hence the final temperature of air = 394.38 K.

9. **Discuss exergy destruction. A reversible engine, as shown in Fig. 7, during a cycle of operations 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.**

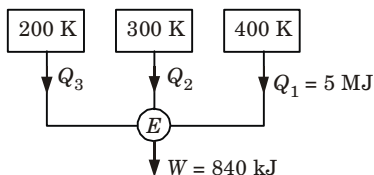


Fig. 7.

**Ans.**

#### A. Exergy Destruction :

1. In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir.

- When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment.
- Exergy is the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero.
- Determining exergy was also the first goal of thermodynamics.
- Exergy is never destroyed during a process, it changes from one form to another. In contrast, exergy accounts for the irreversibility of a process due to increase in entropy.
- Exergy is always destroyed when a process involves a temperature change. This destruction is proportional to the entropy increase of the system together with its surroundings. The destroyed exergy has been called anergy.

### B. Numerical :

- Assuming the positive direction of  $Q_1$ ,  $Q_2$  and  $Q_3$  as shown in Fig. 8.

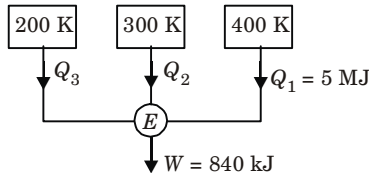


Fig. 8.

- Then, according to first law of thermodynamics,

$$Q_1 + Q_2 + Q_3 = W$$

$$Q_2 + Q_3 = 0.840 - 5$$

$$Q_2 + Q_3 = -4.16 \text{ MJ}$$

...(1)

- Now, according to Clausius inequality principle,

$$\frac{Q_1}{400} + \frac{Q_2}{300} + \frac{Q_3}{200} = 0$$

$$\frac{Q_2}{3} + \frac{Q_3}{2} = \frac{-5}{4} \quad \text{or} \quad 2Q_2 + 3Q_3 = -7.5$$

...(2)

- On solving eq. (1) and eq. (2),

$$Q_2 = -4.98 \text{ MJ}, Q_3 = +0.82 \text{ MJ}$$

### Section - C

Attempt any **two** questions. All questions carry equal marks.

(15 × 2 = 30)

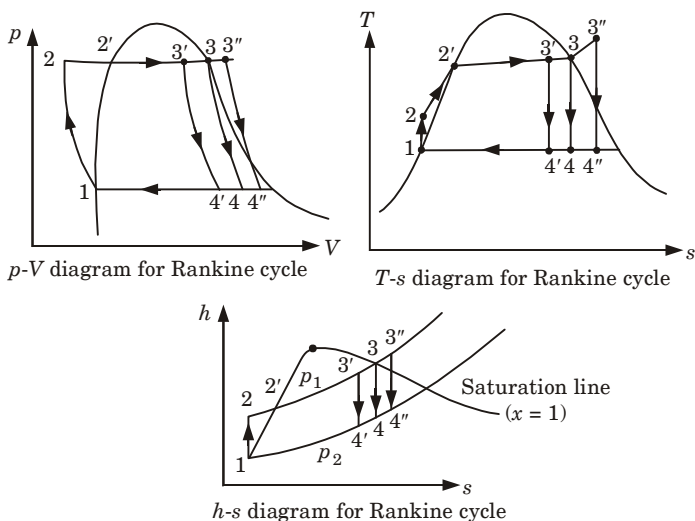
- Explain the working of a two stroke SI engine giving neat sketches and differentiate between two stroke and four stroke spark ignition engine.

**Ans.** This question is out of syllabus starting from session 2017-18.

- Explain simple Rankine cycle with neat schematic diagram and also show different processes involved in it on  $T$ - $s$  diagram,  $h$ - $s$  diagram and  $p$ - $V$  diagram.

**Ans.**

1. Professor Rankine modified the Carnot cycle and presented a technically feasible cycle known as Rankine cycle. It is also a reversible cycle and it differs from Carnot cycle in following aspects :
    - i. The process of condensation is allowed to proceed to completion, *i.e.*, exhaust steam from the steam turbine or steam engine is condensed back to liquid water. At the end of condensation process, the working substance is only liquid (water) and not a mixture of liquid and vapour.
    - ii. Pressure of water can be easily raised to the boiler pressure by means of a small sized feed pump.
- Moreover, the steam can be superheated in the boiler so as to obtain the exhaust steam of high quality. It prevents pitting and erosion of turbine blades.

**Fig. 9.**

2. Different processes of simple Rankine cycle are as follows :

- i. **Process (1-2) :**

1. Pumping of feed water to the boiler from back (or condenser pressure)  $p_b$  to boiler pressure  $p_1$ .
2. Compression process is a reversible adiabatic process.

- ii. **Process (2-3) :**

1. Feed water is converted into steam at constant pressure (boiler pressure  $p_1$ ).
2. Heat added during the process (2-3) is  $q_s$ .

- iii. **Process (3-4) :**

1. Process 3-4 refers to reversible adiabatic expansion of steam in the turbine from boiler pressure ' $p_1$ ' to condenser (or back) pressure ' $p_b$ '.

- During the process 3-4, there is an enthalpy drop which is equal to the work done ' $W_T$ ' by turbine.

**iv. Process (4-1) :**

- Exhaust steam from the steam turbine is condensed back to liquid form at constant pressure in the condenser.
- The steam rejects its latent heat of vapourization to the cooling water. It is denoted by  $q_r$ .

- What is perpetual motion machine of second type ? 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  $0.20 \text{ m}^3$  and  $1.20 \text{ m}^3$ . The specific internal energy of the gas is given by the relation.**

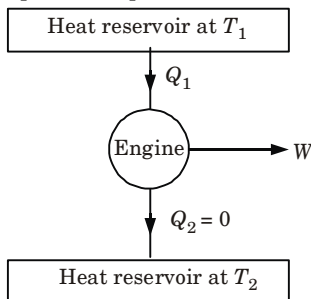
$$u = 1.5 pv - 85 \text{ kJ/kg.}$$

Where  $p$  is in kPa and  $v$  is in  $\text{m}^3/\text{kg}$ . Calculate the net heat transfer and the maximum internal energy of the gas attained during expansion.

**Ans.**

**A. Perpetual Motion Machine of Second Kind (PMM-2) :**

- A device or machine which violates the second law of thermodynamics is known as perpetual motion machine of second kind (PMM-2).
- A PMM-2 will exchange heat from a single thermal (or heat) reservoir and produce equal amount of work energy.



**Fig. 10.**

- If heat rejection  $Q_2$  to the heat reservoir at  $T_2$  is zero, then

$$Q_1 = W$$

$$\text{i.e.,} \quad \eta_E = \frac{W}{Q_1} = \frac{W}{W} = 100 \%$$

i.e., engine is 100 % efficient.

- This is a violation of Kelvin-Planck statement of second law of thermodynamics. So it is impossible to construct a perpetual motion machine of second kind.

**B. Numerical :**

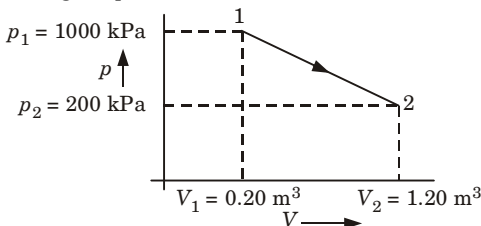
**Given :**  $m = 1.5 \text{ kg}$ ,  $p_1 = 1000 \text{ kPa}$ ,  $p_2 = 200 \text{ kPa}$ ,  $V_1 = 0.20 \text{ m}^3$ ,  $V_2 = 1.20 \text{ m}^3$ ,  $p = a + bV$ , Assume,  $\gamma = 1.20$ .

**To Find :** Net heat transfer and maximum internal energy.

1. Specific internal energy,

$$u = 1.5pv - 85 \text{ kJ/kg} \quad \dots(1)$$

2. On plotting the  $p$ - $V$  curve,



**Fig. 11.**

3. Net work done, from Fig. 10.

$$\begin{aligned} W_{1-2} &= \text{Area of } (1-V_1-V_2-2) \\ &= \frac{1}{2} \times (1.20 - 0.20) \times (1000 - 200) + 200 \times (1.20 - 0.20) \\ &= 400 + 200 = 600 \text{ kJ} \quad \dots(2) \end{aligned}$$

4. Now from eq. (1),

Change in internal energy =  $\Delta u$

$$\begin{aligned} \Delta u &= u_2 - u_1 \\ &= 1.5(p_2v_2 - p_1v_1) \quad \left( \because v = \frac{V}{m} \right) \\ &= 1.5 \left( 200 \times \frac{1.20}{1.5} - 1000 \times \frac{0.2}{1.5} \right) \end{aligned}$$

$$\Delta u = 40 \text{ kJ/kg}$$

$$\Delta U = 40 \times 1.5 \text{ kJ}$$

$$\Delta U = 60 \text{ kJ}$$

5. Net heat transfer,

$$\delta Q = dU + \delta W$$

$$= 60 + 600$$

$$\delta Q = 660 \text{ kJ}$$

6. For maximum internal energy,

$$\frac{du}{dv} = 0$$

$$\text{then } \frac{d}{dv} (1.5pv - 85) = 0$$

$$\frac{d}{dv} [1.5(a + bV)v - 85] = 0 \quad (\because p = a + bV)$$



$$\frac{d}{dv} [1.5(a + bmv)v - 85] = 0$$

$$a + 2bmv = 0$$

$$\left[ \because v = \frac{V}{m} \right]$$

$$\Rightarrow v = \frac{-a}{2bm} \quad \dots(3)$$

$\therefore$  It is given that

$$p = a + bV$$

7. Now putting the given values,

$$1000 = a + b \times 0.20 \quad \dots(4)$$

$$200 = a + b \times 1.20 \quad \dots(5)$$

8. After solving eq. (4) and eq. (5),

$$a = 1160$$

$$b = -800$$

9. Putting these values in eq. (3),

$$v = \frac{-1160}{2 \times (-800) \times 1.5}$$

$$v = 0.4833 \text{ m}^3/\text{kg}$$

10. Since,

$$u = 1.5(a + bV)v - 85$$

$$= 1.5[(a + bmv)v] - 85$$

11. Now putting the values of  $a$ ,  $b$  and  $v$  for maximum internal energy,

$$u_{\max} = 1.5[1160 + (-800) \times 1.5 \times 0.4833] \times 0.4833 - 85$$

$$u_{\max} = 335.499 \text{ kJ/kg}$$

$$U_{\max} = 1.5 \times 335.499 \text{ kJ}$$

$$U_{\max} = 503.25 \text{ kJ}$$



**B.Tech.**  
**(SEM. III) ODD SEMESTER THEORY**  
**EXAMINATION, 2016-17**  
**THERMODYNAMICS**

**Time : 3 Hours****Total Marks : 100**

**Section-A**

1. Answer **all** parts. All parts carry equal marks. Write answer of each part in short. (2 × 10 = 20)
- a. **List any five physical properties of matter which can be used for measurement of temperature.**
- b. **How does a homogeneous system differ from a heterogeneous system ?**
- c. **Write Boyle's law and Charle's law.**
- d. **State Carnot theorem.**
- e. **Compare heat pump and refrigerator.**
- f. **State third law of thermodynamics.**
- g. **Is the availability function same for a non-flow and a flow process ? Justify.**
- h. **What advantages are obtained if superheated steam is used in steam prime movers ?**
- i. **Define dryness fraction of steam.**
- j. **Define brake power in an IC Engine.**

**Section-B**

Attempt any **five** questions from this section. (10 × 5 = 50)

2. **In a gas turbine unit, the gases flow through the turbine is 15 kg/s and the power developed by the turbine is 12000 kW. The enthalpies of gases at the inlet and outlet are 1260 kJ/kg and 400 kJ/kg respectively, and the velocity of**

gases at the inlet and outlet are 50 m/s and 110 m/s respectively. Calculate :

- i. The rate at which heat is rejected to the turbine, and
  - ii. The area of the inlet pipe given that the specific volume of the gases at the inlet is  $0.45 \text{ m}^3/\text{kg}$ .
3. 3 kg of air at 1.5 bar pressure and  $77^\circ\text{C}$  temperature at state 1 is compressed polytropically to state 2 at pressure 7.5 bar, index of compression being 1.2. It is then cooled at constant temperature to its original state 1. Find the net work done and heat transferred.
  4. Explain the entropy principle and apply it to a closed system.
  5. Two kg of air at 500 kPa,  $80^\circ\text{C}$  expands adiabatically in a closed system until its volume is doubled and its temperature becomes equal to that of the surroundings which is 100 kPa,  $5^\circ\text{C}$ . For this process determine.
    - a. The maximum work,
    - b. The change in availability, and
    - c. The irreversibility.
  6. Show that violation of Kelvin Planck statement of second law of thermodynamics implies a violation of Clausius statement.
  7. Draw the  $p$ - $T$  diagram of pure substance and explain its various regions of the diagram in details ?
  8. Discuss the effect of pressure of steam at inlet to turbine temperature at inlet to turbine and pressure at exit from turbine upon Rankine cycle performance.
  9. Explain the following :
    - a. Brake specific fuel consumption,
    - b. Brake mean effective pressure,
    - c. Mechanical efficiency,
    - d. Brake thermal efficiency, and
    - e. Indicated thermal efficiency.

### Section-C

**Note :** Attempt any **two** questions from this section.

(15 × 2 = 30)

10. a Compare SI engines with CI engines.

- b. Define a thermodynamic system. Differentiate between open system, closed system and an isolated system.

- 11.a. Derive the steady flow energy equation applied to compressor.**
- b. Throttling calorimeter has steam entering to it at 10 MPa and coming out of it at 0.05 MPa and 100°C. Determine dryness fraction of steam.**
- 12. Three reversible engines of Carnot type are operating in series as shown between the limiting temperatures of 1100 K and 300 K. Determine the intermediate temperatures if the work output from engines is in proportion of 3 : 2 : 1.**



## SOLUTION OF PAPER (2016-17)

### Section-A

1. Answer **all** parts. All parts carry equal marks. Write answer of each part in short. (2 × 10 = 20)

- a. List any five physical properties of matter which can be used for measurement of temperature.

**Ans.**

1. Length	2. Radiation
3. Thermal EMF	4. Volume
5. Pressure	

- b. How does a homogeneous system differ from a heterogeneous system ?

**Ans.** **Homogeneous system :** A system consisting of a single phase is called "homogeneous system". *e.g.*, milk + water, aqua ammonia.  
**Heterogeneous system :** A system consisting of more than one phase is called "heterogeneous system". *e.g.*, wet steam, water + mercury.

- c. Write Boyle's law and Charle's law.

**Ans.** **Boyle's law :** According to this law, volume of a given mass of a perfect gas varies inversely with absolute pressure when temperature is kept constant.

Product of absolute pressure and volume of a given quantity of gas is constant when the temperature is kept constant.

$$\text{i.e., } V \propto \frac{1}{p} \text{ or } pV = \text{constant}$$

**Charle's Law :** According to this law, the volume of a given mass of a perfect gas varies directly with its absolute temperature when pressure is kept constant *i.e.*,

$$\frac{V}{T} = \text{Constant. (At constant pressure)}$$

- d. State Carnot theorem.

**Ans.** Carnot theorem states that of all heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

- e. Compare heat pump and refrigerator.

**Ans.**

S. No.	Refrigerator	Heat Pump
1.	It is a reversed heat engine which cools or maintains the temperature of a body lower than the atmospheric temperature.	A heat pump is a device, which operating in a cycle, maintains a body, at a temperature higher than the temperature of the surroundings.
2.	$(\text{COP})_R = \frac{Q_1}{W_R}$	$(\text{COP})_P = \frac{Q_2}{W_P}$

**f. State third law of thermodynamics.**

**Ans.** Third law of thermodynamics states that the entropy of a perfect crystal is zero at the absolute zero of temperature and it represents the maximum degree of order.

**g. Is the availability function same for a non-flow and a flow process ? Justify.**

**Ans.** Availability function is same for a non-flow and a flow process because for both process, the irreversibility is equal to  $T_0 \Delta S_{\text{gen}}$ . It is equal to decrease in  $AE$  or increase in  $UE$ .

**h. What advantages are obtained if superheated steam is used in steam prime movers ?**

**Ans.** It increases the work output of prime movers which directly increases the efficiency.

**i. Define dryness fraction of steam.**

**Ans.** Dryness fraction of steam is defined as the ratio of mass of dry steam present in a known quantity of wet steam to the total mass of steam.

Mathematically,

$$x = \frac{m_s}{m_s + m_w}$$

Where,

$x$  = Dryness fraction,

$m_s$  = Mass of dry steam, and

$m_w$  = Mass of water particle.

**j. Define brake power in an IC Engine.**

**Ans.** Brake power is the useful power available at the engine crankshaft. In other words, the power developed by an engine at the output shaft is known as brake power.

## Section-B

Attempt any **five** questions from this section. **(10 × 5 = 50)**

2. In a gas turbine unit, the gases flow through the turbine is 15 kg/s and the power developed by the turbine is 12000 kW. The enthalpies of gases at the inlet and outlet are 1260 kJ/kg and 400 kJ/kg respectively, and the velocity of gases at the inlet and outlet are 50 m/s and 110 m/s respectively. Calculate :
- The rate at which heat is rejected to the turbine, and
  - The area of the inlet pipe given that the specific volume of the gases at the inlet is 0.45 m<sup>3</sup>/kg.

**Ans.**

**Given :**  $\dot{m} = 15$  kg/sec, Power developed  $W_s = 12000$  kW,  
Enthalpy at inlet,  $h_1 = 1260$  kJ/kg, Enthalpy at outlet,  $h_2 = 400$  kJ/kg,  
Velocity at inlet  $C_1 = 50$  m/s, Velocity at outlet  $v_2 = 110$  m/s

**To Find :** i. Rate of heat rejected.

ii. Area of the inlet pipe.

$$1. \quad Q - W_s = \Delta KE + \Delta PE + \Delta H$$

$$= \frac{1}{2} \times 15 \times ((110)^2 - 50^2) + 0 + (400 - 1260) \times 15 \times 1000$$

$$= \frac{1}{2} \times 15 \times 9600 + (-860) \times 15 \times 1000$$

$$= \frac{1}{2} \times 144000 - 860 \times 15 \times 1000$$

$$Q - 12000 \times 10^3 = 72000 - 860 \times 15 \times 10^3$$

$$Q - 12000 \times 10^3 = 72 \times 10^3 - 860 \times 10^3 \times 15$$

$$Q = -828 \times 10^3 \text{ J/s}$$

$$Q = -828 \text{ kJ/s}$$

Hence, the rate at which heat is rejected to the turbine = 828 kJ/s

$$2. \quad \dot{m} = \frac{A_1 C_1}{v_1} = \frac{A_2 C_2}{v_2}$$

Specific volume of the gases at inlet  $v_1 = 0.45$  m<sup>3</sup>/kg

$$15 = \frac{A_1 \times 50}{0.45}$$

$$A_1 = \frac{6.75}{50} = 0.135 \text{ m}^2 = 0.135 \text{ m}^2$$

3. 3 kg of air at 1.5 bar pressure and 77 °C temperature at state 1 is compressed polytropically to state 2 at pressure 7.5 bar, index of compression being 1.2. It is then cooled at constant temperature to its original state 1. Find the net work done and heat transferred.

**Ans.****Given :**  $m = 3 \text{ kg}$ ,  $p_1 = 1.5 \text{ bar}$ ,  $T_1 = 77^\circ\text{C}$ ,  $p_2 = 7.5 \text{ bar}$ ,  $n = 1.2$ **To Find :** Net work done and heat transferred.

1. For polytropic compression :

$$pV^{1.2} = C$$

Since,  $p_1 V_1^{1.2} = p_2 V_2^{1.2}$

$$\left(\frac{V_1}{V_2}\right)^{1.2} = \left(\frac{p_2}{p_1}\right) \quad \dots(1)$$

$$p_1 V_1 = mRT_1$$

$$1.5 V_1 = 3 \times 0.287 \times 350$$

$$V_1 = 200.9 \text{ m}^3$$

2. From eq. (1)

$$V_2^{1.2} = \frac{p_1}{p_2} V_1^{1.2}$$

$$= \frac{1.5 \times (200.9)^{1.2}}{7.5} = \frac{1.5 \times 580.197}{7.5}$$

$$V_2^{1.2} = 116.039, V_2 = 52.54 \text{ m}^3$$

3. Work done during process 1 - 2;

$$W_{1-2} = \frac{p_1 V_1 - p_2 V_2}{n - 1} = \frac{1.5 \times 200.9 - 7.5 \times 52.54}{1.2 - 1}$$

$$W_{1-2} = -\frac{92.713}{0.2} = -463.565$$

4. Work done during process 2 - 1;

$$W_{2-1} = p_1 V_1 \ln \frac{p_2}{p_1}$$

$$= 1.5 \times 200.9 \times \ln \left(\frac{7.5}{1.5}\right) = 485.00 \text{ J}$$

5. Hence, net work done =
- $W_{1-2} + W_{2-1}$

$$\delta W = -463.565 + 485.00 = 21.435 \text{ J}$$

6. From first law of thermodynamics;

$$\delta Q = du + \delta W$$

7. Process is cyclic, therefore

$$du = 0$$

Hence, heat transfer during process;

$$\delta Q = \delta W = 21.435 \text{ J}.$$

4. Explain the entropy principle and apply it to a closed system.

**Ans.****A. Entropy Principle :**

1. According to this principle, "Entropy of an isolated system either increases, or in the limit, remains constant."



2. An isolated system does not undergo any energy interaction (*i.e.*, work or heat energy) with its surroundings, and the total energy of all the possible states remains constant. Therefore for an isolated system,

$$\delta Q = 0$$

$$\therefore (dS)_{\text{Isolated}} \geq 0$$

If the process is reversible,  $(dS)_{\text{Isolated}} = 0$  and if the process is irreversible,  $(dS)_{\text{Isolated}} > 0$ .

3. From above we see that the entropy of an isolated system can never decrease. It always increases with every irreversible process and remains constant during a reversible process. This is called "Principle of entropy increase".

### B. Entropy Principle for a Closed System :

1. Let's consider a piston cylinder arrangement substance at  $p_1$ ,  $T_1$  and  $V_1$  is expanded reversibly to close state at  $p_o$ ,  $V_o$  and  $T_o$ . The working substance expands and  $W_{\text{expansion}}$  is obtained.

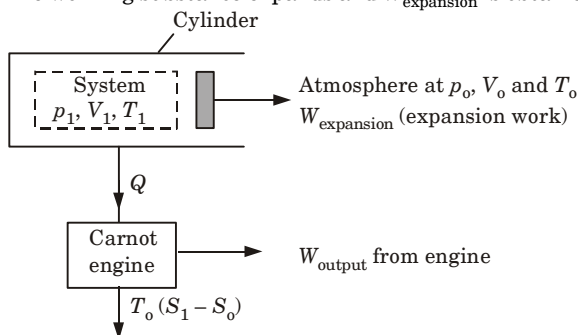


Fig. 1.

2. From the law of conservation of energy,

$$Q = dU + W$$

$$-Q = W_{\text{expansion}} + (U_o - U_1)$$

(Heat interaction is negative because it leaves the system.)

$$\text{Therefore } W_{\text{expansion}} = (U_1 - U_o) - Q$$

3. This heat rejected from the piston-cylinder arrangement can be used to run a reversible heat engine. Work output of the reversible engine is equal to

$$W_{\text{engine}} = Q - Q \frac{T_o}{T} = Q \left[ 1 - \frac{T_o}{T} \right]$$

$$\therefore W_{\text{engine}} = Q - T_o (S_1 - S_o)$$

4. Maximum work obtained from the cylinder piston assembly is the sum of  $W_{\text{expansion}}$  and  $W_{\text{engine}}$ .

$$\begin{aligned} W_{\text{max}} &= W_{\text{expansion}} + W_{\text{engine}} \\ &= [(U_1 - U_o) - Q + Q - T_o (S_1 - S_o)] \\ &= (U_1 - U_o) - T_o (S_1 - S_o) \end{aligned}$$

And surrounding work,  $W_{\text{surrounding}} = p_o (V_o - V_1)$

(This is the work which the piston, while moving outwards, has to spend in pushing the atmosphere against its own pressure.)

5. Therefore maximum available useful net work,

$$\begin{aligned} W_{\text{net}} &= W_{\text{max}} - W_{\text{surrounding}} \\ &= (U_1 - U_o) - T_o (S_1 - S_o) - p_o (V_o - V_1) \\ &= (U_1 + p_o V_1 - T_o S_1) - (U_o + p_o V_o - T_o S_o) = A_1 - A_o \end{aligned}$$

Where  $A = U + p_o V - T_o S$  is called non-flow availability function. This is a composite property of the system and surrounding because it consists of extensive properties (internal energy  $U$ , volume  $V$  and entropy  $S$ ) and intensive property of the environment (pressure  $p_o$  and temperature  $T_o$ ).

Thus availability is a function of properties of the surrounding and also of end states of the closed system.

6. Entropy change for a closed system can be calculated from the relation,

$$\begin{aligned} \delta Q &= dU + \delta W \\ TdS &= m c_v dT + pdV \\ dS &= \frac{m c_v dT}{T} + \frac{pdV}{T} \end{aligned}$$

$$\left[ dS = \frac{\delta Q}{T}, dU = mc_v dT \text{ and } \delta W = pdV \right]$$

7. Integrating between initial and final states, we have

$$\begin{aligned} \int_1^2 dS &= \int_1^2 \frac{m c_v dT}{T} + \int_1^2 \frac{mRdV}{V} \quad \left[ \because pV = mRT, \therefore \frac{p}{T} = \frac{mR}{V} \right] \\ S_2 - S_1 &= m c_v \ln \frac{T_2}{T_1} + m R \ln \frac{V_2}{V_1} \end{aligned}$$

5. Two kg of air at 500 kPa, 80 °C expands adiabatically in a closed system until its volume is doubled and its temperature becomes equal to that of the surroundings which is 100 kPa, 5 °C. For this process determine.
- The maximum work,
  - The change in availability, and
  - The irreversibility.

**Ans.**

**Given :**  $m = 2$  kg,

Initial conditions,  $p_1 = 500$  kPa,  $T_1 = 80$  °C = 273 + 80 = 353 K

Final conditions,  $p_2 = 100$  kPa,  $T_2 = 5$  °C = 273 + 5 = 278 K

Volume get doubled by adiabatic expands.

**To Find :** a. Maximum work,

b. Change in availability, and

c. Irreversibility.

1. From the property relation

$$TdS = dU + pdV$$

the entropy change of air between the initial and final states is

$$\int_1^2 dS = \int_1^2 \frac{mc_v dT}{T} + \int_1^2 \frac{mR dV}{V}$$

or 
$$S_2 - S_1 = mc_v \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1}$$

2. From equation of work done,

$$\begin{aligned} W_{\max} &= (U_1 - U_2) - T_0 (S_1 - S_2) \\ &= m \left[ c_v (T_1 - T_2) + T_0 \left( c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \right) \right] \end{aligned}$$

$$\begin{aligned} &= 2 \left[ 0.718 (80 - 5) + 278 \left( 0.718 \ln \frac{278}{353} + 0.287 \ln \frac{2}{1} \right) \right] \\ &= 2 [53.85 + 278 (-0.172 + 0.199)] \\ &= 2 [53.85 + 7.51] = 122.72 \text{ kJ} \end{aligned}$$

3. The change in availability,

$$\begin{aligned} \phi_1 - \phi_2 &= (U_1 - U_2) - T_0 (S_1 - S_2) + p_0 (V_1 - V_2) \\ &= W_{\max} + p_0 (V_1 - V_2) \\ &= 122.72 + p_0 (V_1 - 2V_1) \\ &= 122.72 - 100 \times \frac{2 \times 0.287 \times 353}{500} = 82.2 \text{ kJ} \end{aligned}$$

4. The irreversibility,

$$I = W_{\max \text{ useful}} - W_{\text{act}}$$

From the first law,

$$\begin{aligned} W_{\text{act}} &= Q - \Delta U = -\Delta U = U_1 - U_2 \\ I &= U_1 - U_2 - T_0 (S_1 - S_2) - U_1 + U_2 \\ &= T_0 (S_2 - S_1) \\ &= T_0 (\Delta S)_{\text{system}} \end{aligned}$$

5. For adiabatic process,  $(\Delta S)_{\text{surr}} = 0$

$$\begin{aligned} I &= T_0 \left[ mc_v \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1} \right] \\ &= 278 \times 2 \left[ 0.178 \ln \frac{278}{353} + 0.287 \ln 2 \right] \\ &= 278 \times 2 (-0.042 + 0.199) = 87 \text{ kJ} \end{aligned}$$

6. Show that violation of Kelvin Planck statement of second law of thermodynamics implies a violation of Clausius statement.

**Ans.**

- A. Violating Kelvin Planck Statement Leads to Violation of Clausius Statement :**

- Let's consider a heat engine which violates Kelvin Planck statement by absorbing heat from source at  $T_1$  and converts it completely into work.  

$$\therefore W = Q_1$$
- Now let's introduce a refrigerator which gets work input from the engine.
- The refrigerator extracts  $Q_2$  from the low temperature heat reservoir and rejects heat  $Q_1 + Q_2$  to the high temperature heat reservoir.

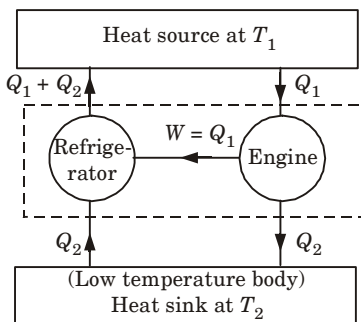


Fig. 2.

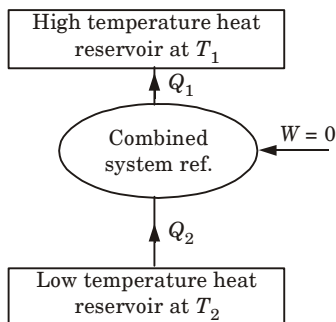


Fig. 3. Combined system (refrigerator) violates Clausius statement.

- Combining the engine the refrigerator into one system working between same temperature limits, we observe that the sole effect of combined system is to transfer  $Q_2$  from low temperature heat reservoir  $T_2$  to high temperature heat reservoir without any work input thus violating the Clausius statement Fig. 2.

### B. Violation of Clausius Statement Leads to Violation of Kelvin Planck Statement :

- Let's consider a refrigerator which violates Clausius statement as shown in the Fig. 4.
- Refrigerator absorbs heat  $Q_2$  from low temperature heat reservoir and rejects the same to the high temperature reservoir without the aid of any external work *i.e.*,  $W = 0$ .
- Let's introduce a heat engine which receives heat  $Q_1$  ( $Q_1 > Q_2$ ) from the high temperature reservoir and rejects heat  $Q_2$  and produces work,

$$W = Q_1 - Q_2.$$

- Now combining the refrigerator and heat engine into one system. We observe that the combined system operates as a heat engine, which receives heat from a single high temperature reservoir as  $Q_1 - Q_2$  and converts the same into equal amount of work energy without any heat rejection.

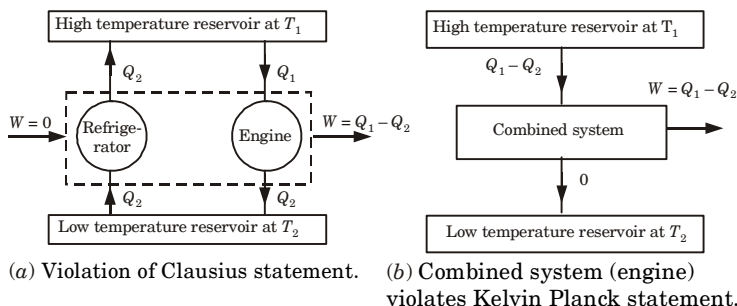


Fig. 4.

- This violates the Kelvin Planck statement of second law of thermodynamics.
- Draw the  $p$ - $T$  diagram of pure substance and explain its various regions of the diagram in details ?

**Ans.****A.  $p$ - $T$  Diagram of Pure Substance :**

- A substance can exist in three different states *i.e.*, liquid, solid and vapour (gas). These states are known as 'phases' and are obtained when the substance receives or evolves heat.
- On heating, solid phase first changes into liquid and then to vapour or gaseous phase. On cooling, phase transformation reverses from gas (vapour) to liquid and finally to solid state.
- The change in phase takes place at a specific temperature known as "transition temperature".
- For each substance, there is a set of pressure and temperature at which any two out of three phases may co-exist in equilibrium.
- The Fig. 5 drawn below represents different phases of a substance as a function of pressure and temperature.

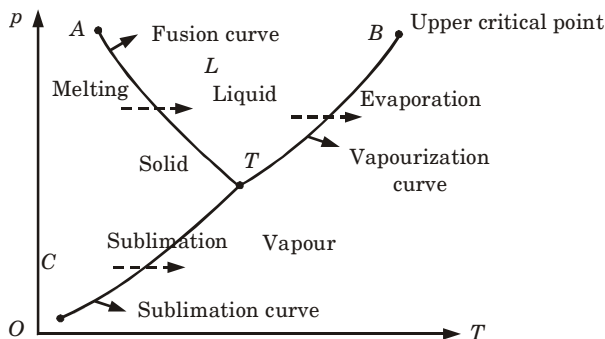


Fig. 5.

6. The Fig. 5 imparts following valuable information :

**i. Solid and Liquid Phases :**

1. Solid and liquid phases co-exist in equilibrium and are separated by the line  $TA$ .
2. The line  $TA$  is referred to as “fusion curve” and represents the variation of melting point with pressure and temperature.
3. The leftward slope of the line  $TA$  indicates that melting point decreases with pressure rise. These are the characteristics of “ice type substances”.

**ii. Liquid and Vapour Phases :**

1. Liquid and vapour phases co-exist in equilibrium and are separated by the line  $TB$ .
2. The line  $TB$  is known as “vaporization curve” vaporization curve has an upper end point (or upper critical point) above which no substance can exist in liquid state whatever amount of pressure is applied on it.

**iii. Vapour and Solid Phases :**

1. Vapour and solid phases coexist in equilibrium and are separated by the line  $TC$ . The line  $TC$  is known as “sublimation curve”.
2. Sublimation is defined as the process during which a solid phase is directly changed into a vapour (gas) phase or vice-versa.

**iv. Triple Point :**

1. Triple point is defined as a point at which pressure and temperature are such that all the three states (solid, liquid and vapour) of a substance co-exist in equilibrium.
2. Triple point is shown by the point  $T$  in the Fig. 5. At triple point, all the three curves namely sublimation, fusion and vaporization and phases of substance meet each other.

**8. Discuss the effect of pressure of steam at inlet to turbine temperature at inlet to turbine and pressure at exit from turbine upon Rankine cycle performance.**

**Ans.**

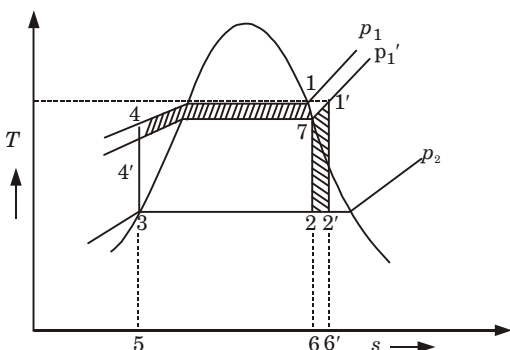
**A. Pressure of Steam at Inlet to Turbine :**

1. For same back pressure and steam inlet temperature, the increase in steam inlet pressure from  $p_1$  to  $p_1'$  is accompanied by the reduction in net heat added as shown by area  $A_{1'2'271}$  and increase in net heat added by the amount shown by area  $A_{4'4174'}$ .

Generally,  $A_{1'2'271} = A_{4'4174'}$   
 (Heat rejected)<sub>cycle 1234</sub> < (Heat rejected)<sub>cycle 1'2'34'</sub>

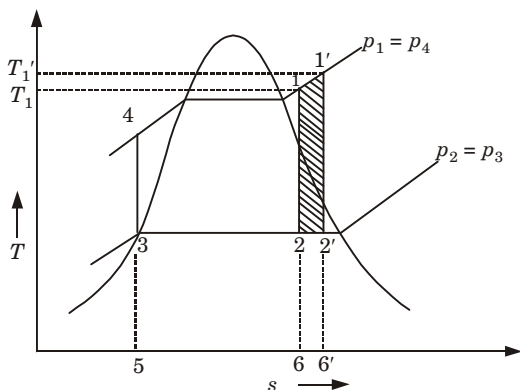
$$\eta_{\text{cycle}} = 1 - \frac{\text{Heat rejected}}{\text{Heat added}}$$

2. Increase in steam pressure at inlet to steam turbine is accompanied by increase in cycle thermal efficiency.



**Fig. 6.** Rankine cycle showing two different throttle pressures.

### B. Temperature of Steam at Inlet to Turbine :

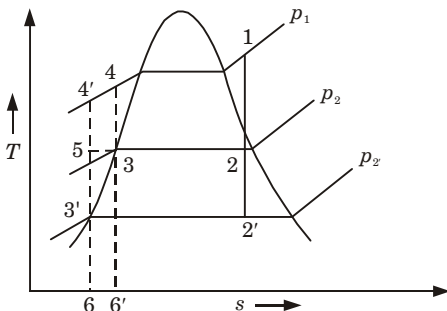


**Fig. 7.** Effect of increasing temperature at inlet to turbine.

1. It is also called superheating of steam at inlet to turbine.
2. From the given Fig. 7, it is clear that increase in inlet temperature from  $T_1$  to  $T_1'$  (Let  $T_1 < T_1'$ ) increases net work and heat addition.  
Net increased work = area  $A_{11'2'21}$   
Net increased heat addition = area  $A_{11'6'61}$
3. So, it is clear that increase in steam temperature from  $T_1$  to  $T_1'$ , increases mean temperature of heat addition, which increases the thermal efficiency.

### C. Pressure at the End of Expansion :

1. The pressure at the end of expansion is called exhaust pressure or back pressure or condenser pressure.
2. With same maximum pressure and temperature, the reduction in back pressure from  $p_2$  to  $p_2'$ , causes increment in net work and in heat addition.



**Fig. 8.** Effect of varying exhaust pressure.

3. From Fig. 8,

Increment in net work = Area  $4'4322'3'54'$

Increment in heat addition = Area  $4'466'4'$

So, the thermal efficiency of cycle increases by lowering back pressure as increase in heat addition is more than increase in heat rejection.

**9. Explain the following :**

- Brake specific fuel consumption,
- Brake mean effective pressure,
- Mechanical efficiency,
- Brake thermal efficiency, and
- Indicated thermal efficiency.

**Ans.** This question is out of syllabus from starting session 2017-18.

### Section-C

**Note :** Attempt any **two** questions from this section. (15 × 2 = 30)

**10. a Compare SI engines with CI engines.**

**Ans.** This question is out of syllabus starting from session 2017-18.

**b. Define a thermodynamic system. Differentiate between open system, closed system and an isolated system.**

**Ans.**

**A. Thermodynamic System :**

- A thermodynamic system is a macroscopic region of the universe under study, with a quantity of matter of fixed identity.
- It is defined by boundaries, which control the transfers between the system and the surroundings (everything which is outside the boundary).
- The types of transfers that can occur in a thermodynamic process are mass and energy (work and heat).



## B. Difference between Open System, Closed System and an Isolated System :

S. No.	Open System	Closed System	Isolated System
1.	All such thermodynamic systems where both the mass interaction and energy interaction occur between the concerned system and its surroundings are called open systems.	All such thermodynamic systems where only energy interaction occurs between the concerned system and its surroundings are called closed systems. Thus, no mass interaction occurs between a closed system and its surroundings.	All such thermodynamic systems where neither mass interaction nor energy interaction occurs between the concerned system and its surroundings are called isolated systems.
2.	<b>Examples :</b> Boiler, Nuclear reactor, Combustion chamber, Turbine, Condenser, Pump, Heat exchanger, etc.	<b>Examples :</b> Refrigerant or working fluid of refrigerator unit can be considered as closed system.	<b>Examples :</b> The matter inside a flask having inbuilt radiation shields can be considered as isolated system.

### 11.a. Derive the steady flow energy equation applied to compressor.

**Ans.**

- Let's consider the flow of a fluid through a control volume as shown in Fig. 9. In the time interval " $dt$ ", there occurs a flow (or flux) of mass and energy into the control volume.
- Section 1-1 is the inlet side and section 2-2 is the outlet side.
- At the inlet side (section 1-1) to control volume following are the fluid parameters :  
 Average velocity =  $C_1$   
 Pressure =  $p_1$   
 Specific volume =  $v_1$   
 Internal energy =  $u_1$
- At the outlet (section 2-2), following are fluid parameters :  
 Velocity =  $C_2$   
 Pressure =  $p_2$   
 Specific volume =  $v_2$   
 Internal energy =  $u_2$

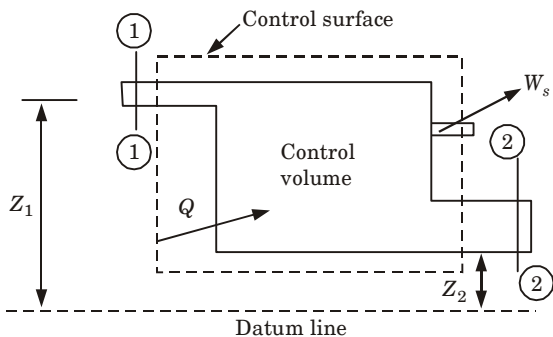


Fig. 9.

5. During the flow of fluid through the control volume, heat ' $Q$ ' and mechanical work ' $W_s$ ' are also supposed to cross the control surface. While writing the energy balance equation on the sides of the control volume, following energies are taken into consideration :
- Internal energy stored in the fluid.
  - Potential energy and kinetic energy.
  - Flow energy (or flow work) required to push the fluid in or out of control volume.
  - Heat and shaft (mechanical) work which may cross the control volume.
  - Since the energy is conserved therefore energy balance for the control volume mentioned above can be written in the following form

$$m_1 \left[ u_1 + p_1 v_1 + \frac{C_1^2}{2} + gZ_1 \right] + Q = m_2 \left[ u_2 + p_2 v_2 + \frac{C_2^2}{2} + gZ_2 \right] + W_s \dots (1)$$

7. The eq. (1) is a general energy equation and can be applied to all fluids compressible or incompressible, ideal or real fluids, liquids and gases.
- b. Throttling calorimeter has steam entering to it at 10 MPa and coming out of it at 0.05 MPa and 100°C. Determine dryness fraction of steam.**

**Ans.**

**Given :**  $P_1 = 10 \text{ MPa}$ ,  $P_2 = 0.05 \text{ MPa}$ ,  $T_2 = 100^\circ \text{C}$

**To Find :** Dryness fraction of steam.

1. From Steam Table :

At  $P_1 = 10 \text{ MPa} = 100 \text{ bar}$

$h_{f1} = 1408 \text{ kJ/kg}$

$h_{fg1} = 1319.7 \text{ kJ/kg}$

At  $P_2 = 0.05 \text{ MPa} = 0.5 \text{ bar}$

$$t_s = 81.35^\circ\text{C}, C_p = 4.18 \text{ kJ/kgK}$$

$$h_{g2} = 2646 \text{ kJ/kg}$$

$\therefore$  From 1 to 2 is throttling process. So,

$$h_1 = h_2$$

$$h_{f1} + x_1 h_{fg1} = h_{g2} + C_p (t_{\text{sup.}} - t_s)$$

$$1408 + x_1 \times 1319.7 = 2646 + 4.18 \times (100 - 81.35)$$

$$x_1 = 0.9971$$

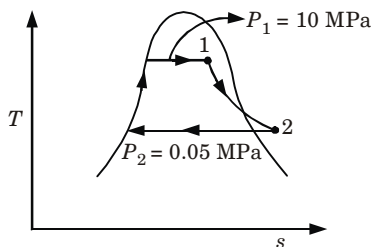


Fig. 10.

12. Three reversible engines of Carnot type are operating in series as shown between the limiting temperatures of 1100 K and 300 K. Determine the intermediate temperatures if the work output from engines is in proportion of 3 : 2 : 1.

**Ans.**

**Given :**  $W_1 : W_2 : W_3 = 3 : 2 : 1$

**To Find :** The intermediate temperature.

1. Efficiency of heat engine 1 :

$$\eta_1 = \frac{W_1}{Q_1} = \frac{T_1 - T_2}{T_1}$$

Since,

$$W_1 = Q_1 - Q_2$$

$$Q_1 = W_1 + Q_2$$

So, 
$$\frac{W_1}{W_1 + Q_2} = \frac{T_1 - T_2}{T_1} \quad \text{or} \quad \frac{W_1 + Q_2}{W_1} = \frac{T_1}{T_1 - T_2}$$

$$1 + \frac{Q_2}{W_1} = \frac{T_1}{T_1 - T_2} \quad \text{or} \quad \frac{Q_2}{W_1} = \frac{T_1}{T_1 - T_2} - 1$$

$$\frac{Q_2}{W_1} = \frac{T_1 - (T_1 - T_2)}{T_1 - T_2} = \frac{T_2}{T_1 - T_2}$$

Hence, 
$$W_1 = Q_2 \left( \frac{T_1 - T_2}{T_2} \right) \quad \dots(1)$$

2. For heat engine 2 :

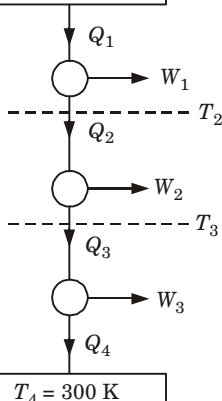
$$\eta_2 = \frac{W_2}{Q_2} = \frac{T_2 - T_3}{T_2}$$

$$W_2 = Q_2 \left( \frac{T_2 - T_3}{T_2} \right) \quad \dots(2)$$

Since,

$$W_2 = Q_2 - Q_3 = W_2 + Q_3$$

$$T_1 = 1100 \text{ K}$$



**Fig. 11.**

So, 
$$\frac{W_2}{W_2 + Q_3} = \frac{T_2 - T_3}{T_2} \quad \text{or} \quad \frac{T_2}{T_2 - T_3} = \frac{W_2 + Q_3}{W_2}$$

$$1 + \frac{Q_3}{W_2} = \frac{T_2}{T_2 - T_3} \quad \text{or} \quad \frac{Q_3}{W_2} = \frac{T_2}{T_2 - T_3} - 1$$

$$\frac{Q_3}{W_2} = \frac{T_2 - (T_2 - T_3)}{T_2 - T_3} = \frac{T_3}{T_2 - T_3}$$

$$W_2 = Q_3 \left( \frac{T_2 - T_3}{T_3} \right) \quad \dots(3)$$

3. For heat engine 3 :

$$\eta_3 = \frac{W_3}{Q_3} = \frac{T_3 - T_4}{T_3}$$

$$W_3 = Q_3 \left( \frac{T_3 - T_4}{T_3} \right) \quad \dots(4)$$

Now 
$$\frac{W_1}{W_2} = \frac{3}{2}$$

4. Put the value of  $W_1$  and  $W_2$  from eq. (1) and eq. (2).

$$\frac{Q_2 \left( \frac{T_1 - T_2}{T_2} \right)}{Q_2 \left( \frac{T_2 - T_3}{T_2} \right)} = \frac{3}{2}$$

$$2(T_1 - T_2) = 3(T_2 - T_3)$$

$$5T_2 - 3T_3 = 2T_1$$

$$T_1 = 1100 \text{ K}$$

$$5T_2 - 3T_3 = 2200 \text{ K}$$

...(5)

5. Ratio of  $W_2$  and  $W_3$

$$\frac{W_2}{W_3} = \frac{2}{1}$$

6. Put the value of  $W_2$  and  $W_3$  from eq. (3) and eq. (4),

$$\frac{Q_3 \left( \frac{T_2 - T_3}{T_3} \right)}{Q_3 \left( \frac{T_3 - T_4}{T_3} \right)} = \frac{2}{1}$$

$$2(T_3 - T_4) = T_2 - T_3$$

$$T_2 = 3T_3 - 2T_4$$

$$T_4 = 300 \text{ K}$$

$$T_2 = 3T_3 - 600$$

...(6)

7. Put the value of  $T_2$  into eq. (5),

$$5(3T_3 - 600) - 3T_3 = 2200$$

$$12T_3 = 5200$$

$$T_3 = \frac{5200}{12} = 433.33 \text{ K}$$

8. Put the value of  $T_3$  in eq. (6),

$$T_2 = 3 \times 433.33 - 600 \approx 700 \text{ K}$$



**B.Tech.****(SEM. III) ODD SEMESTER THEORY  
EXAMINATION, 2017-18  
THERMODYNAMICS****Time : 3 Hours****Max. Marks : 70**

- Note :**
1. Attempt **all** sections. If require any missing data; then choose suitably.
  2. Use of steam tables and Mollier chart is permitted.

**Section-A**

1. Attempt **all** questions in brief. (2 × 7 = 14)
- a. What is quasi static process ? Discuss it.
- b. Define the Carnot theorem.
- c. What is the concept of entropy ?
- d. What is the second law efficiency ? Define it.
- e. Define Joule-Thomson coefficient.
- f. Discuss the triple point and critical point.
- g. What is the refrigeration effect ?

**Section-B**

2. Attempt any **three** of the following : (7 × 3 = 21)
- a. Derive steady flow energy equation (SFEE). Also write the steady flow energy equation for heat exchanger, nozzle, turbine, pump and boiler with suitable assumptions.
- b. The following equation gives the internal energy of a certain substance  
 $u = 3.4 pV + 85$ ; where  $u$  is kJ/kg,  $p$  is in kPa and  $V$  is in  $\text{m}^3/\text{kg}$ .  
A system composed of 2.5 kg of this substance expands from an initial pressure of 500 kPa and a volume of  $0.25 \text{ m}^3$  to a final pressure 100 kPa in a process in which pressure and volume are related by  $pV^{1.25} = \text{constant}$ .

- i. If the expansion is quasi-static, find  $Q$ ,  $dU$  and  $W$  for the process
  - ii. In another process, the same system expands according to the same pressure-volume relationship as in part (i), and from the same initial state to the same final state as in part (i), but the heat transfer in this case is 32 kJ. Find the work transfer for this process.
  - iii. Explain the difference in work transfer in parts (i) and (ii).
- c. Two reversible heat engines 'A' and 'B' are arranged in series, engine 'A' rejecting heat directly to engine '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 :
- i. The intermediate temperature between engine 'A' and engine 'B'.
  - ii. The efficiency of each engine.
  - iii. The heat rejected to the cold sink.
- d. An iron cube at a temperature of 400 °C is dropped into an insulated bath containing 10 kg water at 25 °C. The water finally reaches a temperature of 50 °C at steady state. Given that the specific heat of water is equal to 4186 J/kg K. Find the entropy changes for the iron cube and the water. Is the process reversible ? If so why ?
- e. Discuss the coefficient of volume expansion, adiabatic and isothermal compressibility. Also find the loss in available energy due to given heat transfer. If 3 kg of gas ( $C_v = 0.81$  kJ/kg K) initially at 2.5 bar and 400 K receives 600 kJ of heat from an infinite source at 1200 K and the surrounding temperature is 290 K.

### Section-C

3. Attempt any **one** part of the following : (7 × 1 = 7)
- a. 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.
    - i. Find the velocity at exit from the nozzle.
    - ii. If the inlet area is 0.1 m<sup>2</sup> and the specific volume at inlet is 0.187 m<sup>3</sup>/kg, find the mass flow rate.
    - iii. If the specific volume at the nozzle exit is 0.498 m<sup>3</sup>/kg, find the exit area of the nozzle.

- b. A mass of 8 kg gas expands within a flexible container so that the  $p$ - $V$  relationship is of the form  $pV = \text{constant}$ . The initial pressure is 1000 kPa and the initial volume is  $1 \text{ m}^3$ . 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.
4. Attempt any **one** part of the following : (7 × 1 = 7)
- a. 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).
- b. What are limitations of the first law of thermodynamics ? Discuss the statements of the second law of thermodynamics. Also prove that the violation of the Kelvin Planck statement leads to the violation of the Clausius statement.
5. Attempt any **one** part of the following : (7 × 1 = 7)
- a. What is the maximum useful work which can be obtained when 100 kJ are abstracted from a heat reservoir at 675 K in an environment at 288 K ? What is the loss of useful work if a temperature drop of 50 °C is introduced between the heat source and the heat engine, on the one hand, and the heat engine and the heat sink ?
- b. Discuss the Clapeyron equation and also explain the Joule-Kelvin effect with help of inversion curve and inversion temperature.
6. Attempt any **one** part of the following : (7 × 1 = 7)
- a. Explain the Rankine cycle with the help of neat sketch,  $p$ - $V$  and  $T$ - $s$  diagram. If 5 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 change in volume, enthalpy, internal energy and entropy.
- b. 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 ?



7. Attempt any **one** part of the following : (7 × 1 = 7)
- a. **Explain the vapour compression refrigeration cycle and its COP with the help of  $T-s$ ,  $p-h$  and flow diagram. Can this cycle be reversible ? If not, why ?**
- b. **A refrigerator working on Bell Coleman cycle operates between pressure limits of 1.05 bar and 8.5 bar. Air is drawn from the cold chamber at 10 °C. Air coming out compressor is cooled at 30 °C before entering the expansion cylinder. Expansion and compression follow the  $pV^{1.35} = \text{constant}$ . Determine COP of the system.**



## SOLUTION OF PAPER (2017-18)

- Note :**
1. Attempt **all** sections. If require any missing data; then choose suitably.
  2. Use of steam tables and Mollier chart is permitted.

### Section-A

1. Attempt **all** questions in brief. (2 × 7 = 14)

**a. What is quasi static process ? Discuss it.**

**Ans.** This process is a succession of equilibrium states and infinite slowness is its characteristic feature. This process is also called a reversible process.

**b. Define the Carnot theorem.**

**Ans.** Carnot theorem states that of all heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

**c. What is the concept of entropy ?**

**Ans.** Entropy is a function of a quantity of heat which shows the possibility of conversion of that heat into work.

**d. What is the second law efficiency ? Define it.**

**Ans.** Second law efficiency is defined as the ratio of the minimum available energy (or exergy) which must be consumed to do a task divided by the actual amount of available energy (or exergy) consumed in performing the task.

$$\eta_{II} = \frac{\text{minimum exergy intake to perform the given task}}{\text{actual exergy intake to perform the same task}}$$

**e. Define Joule-Thomson coefficient.**

**Ans.** The temperature and pressure behaviour of fluids during a throttling process is described by the Joule-Thomson coefficient ( $\mu$ ).

$$\mu = \left( \frac{\partial T}{\partial p} \right)_h$$

**f. Discuss the triple point and critical point.**

**Ans. Triple Point :** Triple point is defined as a point at which pressure and temperature are such that all the three states (solid, liquid and vapour) of a substance co-exist in equilibrium.

**Critical Point :** Critical point is the point where distinction between the entropy of water and the entropy of dry steam disappears.

**g. What is the refrigeration effect ?**

**Ans.** The amount of heat extracted from the system is termed as refrigeration effect.

### Section-B

**2. Attempt any three of the following : (7 × 3 = 21)**

**a. Derive steady flow energy equation (SFEE). Also write the steady flow energy equation for heat exchanger, nozzle, turbine, pump and boiler with suitable assumptions.**

**Ans.**

**A. Assumptions Made in the Analysis of SFEE :**

1. There is no accumulation or decrease of mass in the control volume at any time *i.e.*, there is no other source or sink of mass in the control volume.
2. Rate of mass flow in and out of the control volume is equal and constant with respect to time.
3. State, velocity and elevation of fluid mass entering and leaving the surface do not change with time.
4. Rate of heat and work transfers across the control volume is constant.

**B. General Energy Equation For Steady Flow Processes :**

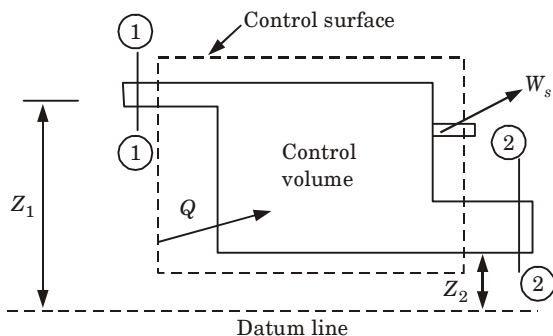
1. Let's consider the flow of a fluid through a control volume as shown in Fig. 1. In the time interval "*dt*", there occurs a flow (or flux) of mass and energy into the control volume.
2. Section 1-1 is the inlet side and section 2-2 is the outlet side.
3. At the inlet side (section 1-1) to control volume following are the fluid parameters :

Average velocity =  $C_1$

Pressure =  $p_1$

Specific volume =  $v_1$

Internal energy =  $u_1$



**Fig. 1.**

4. At the outlet (section 2-2), following are fluid parameters :

$$\text{Velocity} = C_2$$

$$\text{Pressure} = p_2$$

$$\text{Specific volume} = v_2$$

$$\text{Internal energy} = u_2$$

5. During the flow of fluid through the control volume, heat 'Q' and mechanical work 'W<sub>s</sub>' are also supposed to cross the control surface. While writing the energy balance equation on the sides of the control volume, following energies are taken into consideration :
- Internal energy stored in the fluid.
  - Potential energy and kinetic energy.
  - Flow energy (or flow work) required to push the fluid in or out of control volume.
  - Heat and shaft (mechanical) work which may cross the control volume.
6. Since the energy is conserved therefore energy balance for the control volume mentioned above can be written in the following form

$$m_1 \left[ u_1 + p_1 v_1 + \frac{C_1^2}{2} + gZ_1 \right] + Q = m_2 \left[ u_2 + p_2 v_2 + \frac{C_2^2}{2} + gZ_2 \right] + W_s \dots (1)$$

7. The eq. (1) is a general energy equation and can be applied to all fluids compressible or incompressible, ideal or real fluids, liquids and gases.

### C. SFEE for Nozzle :

- The flow through a nozzle is characterized by following features :
  - Shaft work is zero *i.e.*,  $W_s = 0$
  - If the flow is reversible adiabatic manner, then  $Q = 0$ .
  - If the nozzle is horizontal, change in elevation, *i.e.*,  $dZ$  will be zero  
 $\therefore Z_1 = Z_2$ .
- Under these features, SFEE for a nozzle / diffuser is reduced to

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$

$$\text{or} \quad h_1 - h_2 = \frac{C_2^2}{2} - \frac{C_1^2}{2}$$

3. For a nozzle

Enthalpy drop = Increase in kinetic energy

### D. SFEE for Heat Exchanger :

- A heat exchanger is characterized by the following features :
  - Shaft work is zero,  $W_s = 0$
  - Change in KE = 0
  - Change in PE = 0
  - It is a perfectly insulated system *i.e.*, no external heat interaction.
- From energy balance equation, we can write,  
 Energy given by fluid A = Energy gained by fluid B

**E. SFEE for Turbine :**

1. A steam or gas turbine has following features :
  - i.  $\Delta KE$  or  $d$  (kinetic energy) = 0
  - ii.  $\Delta PE$  or  $d$  (potential energy) = 0
- iii.  $Q = 0$  since walls are insulated.
2. Therefore, SFEE for a turbine is reduced to

$$mh_1 = mh_2 + W_s$$

$$\text{or } W_s = m(h_1 - h_2)$$

Obviously the work is done by the turbine at the expense of enthalpy.

**F. SFEE for Boiler :**

1. A boiler has following features :
    - i. Shaft work is zero,  $W_s = 0$ .
    - ii. Change in kinetic energy is negligible,  $\frac{C_2^2 - C_1^2}{2} = 0$ .
    - iii. Change in elevation between inlet and outlet point is negligible,  $Z_1 = Z_2$ .
  2. Therefore SFEE is reduced to
- $$mh_1 + Q = mh_2 \Rightarrow Q = m(h_2 - h_1)$$

**G. SFEE for Pump :**

1. For a pump,  $Q = 0$ ,  $dU = 0$   
(Since there is no change in the temperature of water)
2. Work is negative since it is done on the system.
3. SFEE for a pump is reduced to

$$m \left[ p_1 v_1 + \frac{C_1^2}{2} + gZ_1 \right] = m \left[ p_2 v_2 + \frac{C_2^2}{2} + gZ_2 \right] - W$$

**b. The following equation gives the internal energy of a certain substance**

$u = 3.4 pV + 85$ ; where  $u$  is kJ/kg,  $p$  is in kPa and  $V$  is in  $\text{m}^3/\text{kg}$ . A system composed of 2.5 kg of this substance expands from an initial pressure of 500 kPa and a volume of  $0.25 \text{ m}^3$  to a final pressure 100 kPa in a process in which pressure and volume are related by  $pV^{1.25} = \text{constant}$ .

- i. If the expansion is quasi-static, find  $Q$ ,  $dU$  and  $W$  for the process
- ii. In another process, the same system expands according to the same pressure-volume relationship as in part (i), and from the same initial state to the same final state as in part (i), but the heat transfer in this case is 32 kJ. Find the work transfer for this process.
- iii. Explain the difference in work transfer in parts (i) and (ii).

**Ans.**

**Given :** Internal energy equation,  $u = 3.4 pV + 85$ ,  
 Initial volume,  $V_1 = 0.25 \text{ m}^3$ , Initial pressure,  $p_1 = 500 \text{ kPa}$   
 Final pressure,  $p_2 = 100 \text{ kPa}$ , Process :  $pV^{1.25} = \text{Constant}$ .

**To Find :** i. Heat transfer, internal energy and work.  
 ii. Work transfer when heat transfer is 32 kJ.  
 iii. Difference in work transfer in part (i) and (ii).

1. As we know that,

$$p_1 V_1^{1.25} = p_2 V_2^{1.25}$$

$$V_2 = V_1 \left( \frac{p_1}{p_2} \right)^{\frac{1}{1.25}}$$

$$V_2 = 0.25 \left( \frac{500}{100} \right)^{\frac{1}{1.25}}$$

$$= 0.906 \text{ m}^3$$

2. According to question,

$$u = 3.4 pV + 85$$

$$\Delta u = u_2 - u_1$$

$$= 3.4 [p_2 V_2 - p_1 V_1]$$

$$\Delta U = 3.4 [p_2 V_2 - p_1 V_1]$$

$$\Delta U = 3.4 (100 \times 10^3 \times 0.906 - 500 \times 10^3 \times 0.25)$$

$$= 3.4 \times 10^5 (0.906 - 5 \times 0.25)$$

$$= -3.4 \times 10^5 \times 0.344$$

$$\Delta U = -116.9 \text{ kJ}$$

3. For quasi-static process

$$W_{qs} = \int p dV = \frac{p_1 V_1 - p_2 V_2}{n - 1}$$

$$= \frac{500 \times 10^3 \times 0.25 - 100 \times 10^3 \times 0.906}{1.25 - 1}$$

$$= 137.6 \text{ kJ}$$

$$\therefore Q = \Delta U + W$$

$$= -116.9 + 137.6$$

$$= 20.7 \text{ kJ}$$

4. Here,  $Q = 32 \text{ kJ}$

Since the end states are the same,  $\Delta U$  would remain the same.

$$\therefore W_1 = Q - \Delta U$$

$$= 32 - (-116.9)$$

$$= 148.9 \text{ kJ}$$

Since, the  $W_1$  is not equal to  $W_{qs}$ , hence the process is not quasi-static.

- c. Two reversible heat engines 'A' and 'B' are arranged in series, engine 'A' rejecting heat directly to engine '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 :
- The intermediate temperature between engine 'A' and engine 'B'.
  - The efficiency of each engine.
  - The heat rejected to the cold sink.

**Ans.****Given :**  $W_A = 2W_B$ ,  $Q_1 = 200$  kJ,  $T_1 = 421$  °C,  $T_3 = 4.4$  °C

**To Find :**

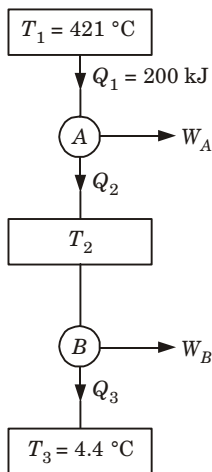
- The intermediate temperature ( $T_2$ ) between engine 'A' and engine 'B'.
- The efficiency of each engine.
- The heat rejected ( $Q_3$ ) to the cold sink.

1. The efficiency of the engine A is given by,

$$\eta_A = \frac{W_A}{Q_1}$$

$$\frac{T_1 - T_2}{T_1} = \frac{W_A}{Q_2 + W_A}$$

$$W_A = (Q_2 + W_A) \left( \frac{T_1 - T_2}{T_1} \right)$$

**Fig. 2.**

$$W_A \left[ 1 - \left( \frac{T_1 - T_2}{T_1} \right) \right] = Q_2 \left( \frac{T_1 - T_2}{T_1} \right)$$

$$W_A \left( \frac{T_2}{T_1} \right) = Q_2 \left( \frac{T_1 - T_2}{T_1} \right)$$

$$W_A = Q_2 \left( \frac{T_1 - T_2}{T_2} \right) \quad \dots(1)$$

2. The efficiency of engine B is given by,

$$\eta_B = \frac{W_B}{Q_2}$$

$$\frac{T_2 - T_3}{T_2} = \frac{W_B}{Q_2}$$

$$W_B = Q_2 \left( \frac{T_2 - T_3}{T_2} \right) \quad \dots(2)$$

3. It is given that

$$W_A = 2W_B$$

$$Q_2 \left( \frac{T_1 - T_2}{T_2} \right) = 2Q_2 \left( \frac{T_2 - T_3}{T_2} \right) \quad (\text{From eq. (1) and eq. (2)})$$

$$T_1 - T_2 = 2T_2 - 2T_3$$

$$3T_2 = T_1 + 2T_3$$

$$3T_2 = 421 + 2 \times 4.4$$

$$T_2 = 143.26^\circ\text{C} = 416.26\text{ K}$$

4. As we know that,

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

$$Q_2 = \frac{200 \times 416.26}{694}$$

$$Q_2 = 119.96\text{ kJ}$$

5. Also,

$$\frac{Q_2}{Q_3} = \frac{T_2}{T_3}$$

$$Q_3 = \frac{119.96 \times 277.4}{416.26}$$

$$Q_3 = 79.94\text{ kJ}$$

6. Efficiency of engine A,

$$\eta_A = \frac{T_1 - T_2}{T_1}$$

$$= \frac{694 - 416.26}{694}$$



$$\eta_A = 40 \%$$

7. Efficiency of engine B,

$$\eta_B = \frac{T_2 - T_3}{T_2} = \frac{416.26 - 277.4}{416.26}$$

$$\eta_B = 33.36 \%$$

- d. An iron cube at a temperature of 400 °C is dropped into an insulated bath containing 10 kg water at 25 °C. The water finally reaches a temperature of 50 °C at steady state. Given that the specific heat of water is equal to 4186 J/kg K. Find the entropy changes for the iron cube and the water. Is the process reversible ? If so why ?

**Ans.**

**Given :** Temperature of iron cube = 400 °C = 673 K,  
 Temperature of water = 25 °C = 298 K, Mass of water = 10 kg  
 Temperature of water and cube after equilibrium = 50 °C = 323 K,  
 Specific heat of water,  $C_{pw} = 4186 \text{ J/kg K}$

**To Find :** i. Entropy changes for the iron cube and the water.  
 ii. Is the process reversible ?

1. Heat lost by iron cube = Heat gained by water

$$m_i C_{pi} (673 - 323) = m_w C_{pw} (323 - 298)$$

$$= 10 \times 4186 \times (323 - 298)$$

$$\therefore m_i C_{pi} = \frac{10 \times 4186 \times (323 - 298)}{(673 - 323)} = 2990$$

Where,  $m_i$  = Mass of iron, kg, and  
 $C_{pi}$  = Specific heat of iron, J/kg K.

2. Entropy of iron at 673 K,

$$= m_i C_{pi} \ln \left( \frac{673}{273} \right) = 2990 \times \ln \left( \frac{673}{273} \right)$$

$$= 2697.8 \text{ J/K} \quad [\text{Taking } 0^\circ\text{C as datum}]$$

3. Entropy of water at 298 K,

$$= m_w C_{pw} \ln \left( \frac{298}{273} \right)$$

$$= 10 \times 4186 \times \ln \left( \frac{298}{273} \right) = 3667.8 \text{ J/K}$$

4. Entropy of iron at 323 K,

$$= 2990 \times \ln \left( \frac{323}{273} \right) = 502.8 \text{ J/K}$$

5. Entropy of water at 323 K,

$$= 10 \times 4186 \times \ln \left( \frac{323}{273} \right) = 7040.04 \text{ J/K}$$

6. Changes in entropy of iron =  $502.8 - 2697.8 = -2195 \text{ J/K}$
7. Change in entropy of water =  $7040.04 - 3667.8 = 3372.24 \text{ J/K}$
8. Net change in entropy =  $3372.24 - 2195 = 1177.24 \text{ J/K}$   
Since  $\Delta S > 0$ , hence the process is irreversible.

- e. **Discuss the coefficient of volume expansion, adiabatic and isothermal compressibility. Also find the loss in available energy due to given heat transfer. If 3 kg of gas ( $C_v = 0.81 \text{ kJ/kg K}$ ) initially at 2.5 bar and 400 K receives 600 kJ of heat from an infinite source at 1200 K and the surrounding temperature is 290 K.**

**Ans.**

- A. Coefficient of Volume Expansion :** The increase of volume in the unit area of any substance on increasing the temperature by  $1^\circ\text{C}$  is called coefficient of volume expansion. It is denoted by  $r$ .

$$r = \frac{\text{Increase in volume}}{\text{Initial volume} \times \text{Increase in temperature}}$$

$$= \frac{\Delta V}{V \times \Delta T}$$

- B. Adiabatic Compressibility :** It is defined as the change in specific volume with change in pressure at constant entropy. It is given as,

$$k_s = - \frac{1}{V} \left( \frac{dV}{dp} \right)_s$$

- C. Isothermal Compressibility :** It is defined as the change in volume with change in pressure at constant temperature. It is given as,

$$k_T = - \frac{1}{V} \left( \frac{dV}{dP} \right)_T$$

- D. Numerical :**

**Given :** Mass of gas,  $m_g = 3 \text{ kg}$ , Initial pressure of gas = 2.5 bar,  
Initial temperature of gas,  $T_1' = 400 \text{ K}$ ,  
Quantity of heat received by gas,  $Q = 600 \text{ kJ}$ ,  
Specific heat of gas,  $C_v = 0.81 \text{ kJ/kg K}$ ,  
Surrounding temperature = 290 K,  
Temperature of infinite source,  $T_1 = 1200 \text{ K}$   
**To Find :** Loss in available energy.

1. Heat received by the gas is given by

$$Q = m_g C_v (T_2' - T_1')$$

$$600 = 3 \times 0.81 (T_2' - 400)$$

$$\therefore T_2' = \frac{600}{3 \times 0.81} + 400 = 646.9 \text{ K say } 647 \text{ K}$$

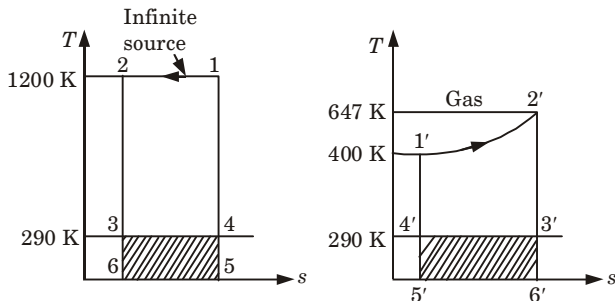


Fig. 3.

2. Available energy with the source = Area 1-2-3-4-1

$$= (1200 - 290) \times \frac{600}{1200} = 455 \text{ kJ}$$

3. Change in entropy of the gas

$$= m_g C_v \log_e \left( \frac{T_2'}{T_1'} \right) = 3 \times 0.81 \times \log_e \left( \frac{647}{400} \right)$$

$$= 1.168 \text{ kJ/K}$$

4. Unavailability of the gas = Area 3'-4'-5'-6'-3'

$$= 290 \times 1.168 = 338.72 \text{ kJ}$$

5. Available energy with the gas = 600 - 338.72 = 261.28 kJ

6. Loss in available energy due to heat transfer

$$= 455 - 261.28 = 193.72 \text{ kJ}$$

### Section-C

3. Attempt any **one** part of the following : (7 × 1 = 7)

**a** 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.

- i. Find the velocity at exit from the nozzle.
- ii. If the inlet area is 0.1 m<sup>2</sup> and the specific volume at inlet is 0.187 m<sup>3</sup>/kg, find the mass flow rate.
- iii. If the specific volume at the nozzle exit is 0.498 m<sup>3</sup>/kg, find the exit area of the nozzle.

**Ans.**

**Given :** At the inlet, Enthalpy,  $h_1 = 3000 \text{ kJ/kg}$ , Velocity,  $C_1 = 60 \text{ m/s}$  At the discharge end, Enthalpy  $h_2 = 2762 \text{ kJ/kg}$

**To Find :** i. Velocity at exit.  
ii. Mass flow rate.  
iii. Exit area.

1. At the discharge end,

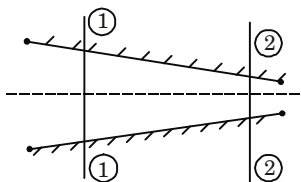


Fig. 4.

Enthalpy,  $h_2 = 2762 \text{ kJ/kg}$

It is given that nozzle is horizontal and there is negligible heat loss from it.

2. Applying SFEE, between section (1) and section (2),

$$h_1 + \frac{1}{2000} C_1^2 + \frac{gZ_1}{1000} + \dot{Q} = h_2 + \frac{1}{2000} C_2^2 + \frac{gZ_2}{1000} + \dot{w} \quad \dots(1)$$

3. Since,  $Z_1 = Z_2$

And assuming, there is no heat transfer and work transfer.  
Then from eq. (1),

$$h_1 + \frac{1}{2000} C_1^2 = h_2 + \frac{1}{2000} C_2^2$$

4. On putting given values,

$$3000 + \frac{1}{2000} \times (60)^2 = 2762 + \frac{1}{2000} C_2^2$$

$$C_2^2 = 479600$$

$$C_2 = 692.53 \text{ m/s}$$

Hence, the velocity at exit from the nozzle,

$$C_2 = 692.53 \text{ m/s}$$

5. Inlet area,  $a_1 = 0.1 \text{ m}^2$

Specific volume,  $v_1 = 0.187 \text{ m}^3/\text{kg}$

6. Now from continuity equation, at inlet

$$\dot{m} v_1 = a_1 C_1$$

$$\dot{m} \times 0.187 = 0.1 \times 60$$

$$\dot{m} = 32.08 \text{ kg/s}$$

Hence, the mass flow rate,  $\dot{m} = 32.08 \text{ kg/s}$ .

7. Specific volume at exit =  $v_2$

$$v_2 = 0.498 \text{ m}^3/\text{kg}$$

8. Then, from continuity equation at exit,

$$a_2 C_2 = \dot{m} v_2$$

$$a_2 \times 692.53 = 32.08 \times 0.498$$

$$a_2 = 0.02307 \text{ m}^2$$

Hence, the exit area of the nozzle,

$$a_2 = 0.02307 \text{ m}^2$$

- b. A mass of 8 kg gas expands within a flexible container so that the  $p$ - $V$  relationship is of the form  $pV = \text{constant}$ . The initial pressure is 1000 kPa and the initial volume is  $1 \text{ m}^3$ . 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.**

**Given :**  $m = 8 \text{ kg}$ ,  $p_1 = 1000 \text{ kPa}$ ,  $V_1 = 1 \text{ m}^3$ ,  $p_2 = 5 \text{ kPa}$

$\Delta U = -40 \text{ kJ/kg}$

**To Find :** Heat transfer in magnitude and direction.

1. Since  $pV = C$ , it means the process is isothermal process.

$$\begin{aligned}\text{So, Work, } W &= p_1 V_1 \ln \left( \frac{p_1}{p_2} \right) \\ &= 1000 \times 1 \times \ln \left( \frac{1000}{5} \right) \\ &= 5298.3 \text{ kJ/kg}\end{aligned}$$

2. Heat transfer  $= \Delta U + W$   
 $= (-40) + 5298.3$   
 $= 5258 \text{ kJ/kg}$

3. The value of heat transfer is positive. It means that heat is added from system to surrounding.

4. Attempt any **one** part of the following : (7 × 1 = 7)

- a. **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.**

**Given :**  $m_1 = 2 \text{ kg}$ ,  $T_1 = 80 \text{ °C} = 353 \text{ K}$ ,  $m_2 = 3 \text{ kg}$ ,

$T_2 = 30 \text{ °C} = 303 \text{ K}$ ,  $C_p = 4.187 \text{ kJ/kg K}$

**To Find :** Entropy change.

1. During mixing of fluids,

$$m_1 C_1 (T_1 - T_f) = m_2 C_2 (T_f - T_2)$$

Where,  $T_f$  = Final temperature

$$2 \times (80 - T_f) = 3 \times (T_f - 30)$$

$$(\because C_1 = C_2)$$

$$160 - 2T_f = 3T_f - 90$$

$$5T_f = 250$$

$$T_f = 50 \text{ °C} = 323 \text{ K}$$

2. Entropy change for 2 kg water  $= m_1 C_1 \ln \frac{T_f}{T_1}$

$$= 2 \times 4.187 \times \ln \left( \frac{323}{353} \right)$$

$$= -0.7437$$

3. Entropy change for 3 kg water  $= m_2 C_1 \ln \frac{T_f}{T_2}$

$$= 3 \times 4.187 \times \ln \left( \frac{323}{303} \right)$$

$$= 0.08029$$

4. Net entropy change = Entropy change for 2 kg water + Entropy change for 3 kg water

$$= -0.7437 + 0.08029$$

$$= 0.059 \text{ kJ/K}$$

- b. What are limitations of the first law of thermodynamics ? Discuss the statements of the second law of thermodynamics. Also prove that the violation of the Kelvin Planck statement leads to the violation of the Clausius statement.**

**Ans.**

**A. Limitations of First Law of Thermodynamics :**

1. The limitations of 1<sup>st</sup> law of thermodynamics can be explained with the help of following illustrations :
  - i. Temperature of liquid contained in a vessel increases when it is churned by paddle work. But paddle work can not be restored on cooling the liquid to its initial state.
  - ii. When a block slides down a rough place, it gets warmer. However, the reverse process when the block slides up the plane and becomes cooler is not true even if the first law of thermodynamics still holds good.
  - iii. Electrical current flowing through a resistor produces heat according to equation,

$$H = i^2 R t.$$

Current once dissipated as heat cannot be converted back into electricity.

- iv. Fuel (solid or liquid) burns with air and gets converted into products of combustion. Fuel once burnt cannot be restored back to its original form.
- v. Work is easily converted into heat. However there is a maximum limit up to which the conversion of heat is possible in a heat engine. Work is superior to heat, and a complete transformation of low grade energy (heat) into high grade energy (work) is not possible.

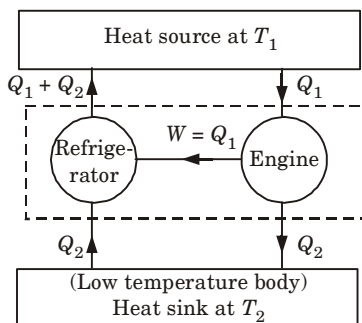
**B. Second Law of Thermodynamics :** We have two statements of second law of thermodynamics which are as follows :

- i. **Kelvin-Planck Statement :** According to this statement, “It is impossible to construct a heat engine that operates in a cycle and produces no effect other than work output and exchange of heat with a single heat reservoir.”
  - ii. **Clausius Statement :** According to this statement “It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a region of low temperature to another system at high temperature.”
- C. Violation of the Kelvin-Planck Statement Leads to Violation of the Clausius Statement :**

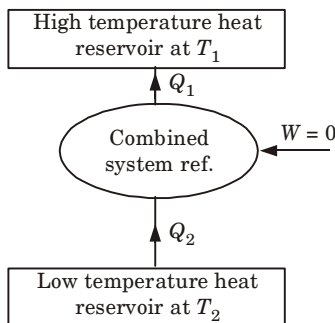
1. Let's consider a heat engine which violates Kelvin Planck statement by absorbing heat from source at  $T_1$  and converts it completely into work.

$$\therefore W = Q_1$$

2. Now let's introduce a refrigerator which gets work input from the engine.
3. The refrigerator extracts  $Q_2$  from the low temperature heat reservoir and rejects heat  $Q_1 + Q_2$  to the high temperature heat reservoir.
4. Combining the engine the refrigerator into one system working between same temperature limits, we observe that the sole effect of combined system is to transfer  $Q_2$  from low temperature heat reservoir  $T_2$  to high temperature heat reservoir without any work input thus violating the Clausius statement Fig. 5.



**Fig. 5.**



**Fig. 6.** Combined system (refrigerator) violates Clausius statement.

5. Attempt any **one** part of the following : (7 × 1 = 7)
- a. What is the maximum useful work which can be obtained when 100 kJ are abstracted from a heat reservoir at 675 K in an environment at 288 K ? What is the loss of useful work if a temperature drop of 50 °C is introduced between the heat source and the heat engine, on the one hand, and the heat engine and the heat sink ?

**Ans.**

**Given :**  $Q_1 = -100$  kJ,  $T = 675$  K,  $T_o = 288$  K

**To Find :**

1. Maximum useful work.
2. Loss of useful work on temperature drop of 50 °C.

1. Entropy change for this process,

$$\Delta s = \frac{Q}{T} - \frac{100}{675}$$

$$= 0.14815 \text{ kJ/k}$$

$$W_{\max} = (T - T_o) \Delta s$$

$$= (675 - 288) \times 0.14815$$

$$= 57.333 \text{ kJ}$$

2. Now maximum work obtainable,

$$W'_{\max} = 100 \left( 1 - \frac{338}{625} \right)$$

$$= 45.92 \text{ kJ}$$

3. Loss of available work =  $W_{\max} - W'_{\max} = 57.333 - 45.92 = 11.413$  kJ



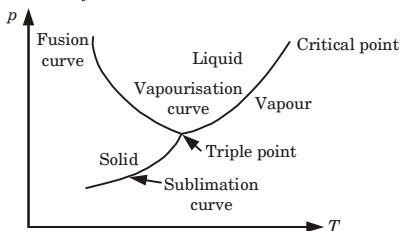
- b. Discuss the Clapeyron equation and also explain the Joule-Kelvin effect with help of inversion curve and inversion temperature.

**Ans.**

**A. Clapeyron Equation :**

1. The Clausius-Clapeyron equation is one such equation which is used to determine the enthalpy change associated with a phase change.
2. Consider the Maxwell relation,

$$\left(\frac{\partial p}{\partial T}\right)_v = \left(\frac{\partial s}{\partial v}\right)_T$$



**Fig. 7.**  $p$ - $T$  diagram.

3. During the phase change the pressure is the saturation pressure, which depends on the temperature. Therefore the partial pressure derivative ( $dp/dT$ ) is expressed by

$$[s_g - s_f] = \left(\frac{dp}{dT}\right) \cdot [v_g - v_f]$$

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f}$$

Where,

$s_g$  = specific entropy of saturated vapour,  
 $s_f$  = specific entropy of saturated liquid,  
 $v_g$  = specific volume of saturated vapour, and  
 $v_f$  = specific volume of saturated liquid.

4. During this process the pressure also remains constant.

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f} = \frac{s_{fg}}{v_{fg}} = \frac{h_{fg}}{T \cdot v_{fg}}$$

Where,

$s_{fg}$  = increase in specific entropy,  
 $v_{fg}$  = increase in specific volume, and  
 $h_{fg}$  = latent heat added during evaporation.

$$\left(\frac{dp}{dT}\right) = \frac{h_{fg}}{T v_{fg}}$$

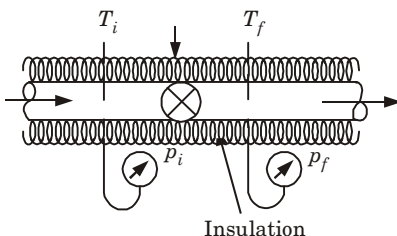
5. Which is called the Clapeyron equation.
6. The Clapeyron equation is applicable to any phase change process that occurs at constant pressure and temperature. It can be expressed by following relation in general form,

$$\left(\frac{dp}{dT}\right) = \frac{h_{12}}{T.v_{12}}$$

Where 1 and 2 shows the two phases.

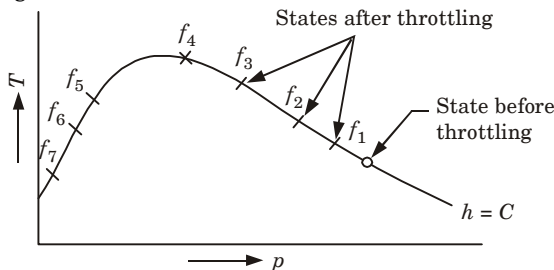
### B. Joule-Kelvin Effect :

1. A gas is made to undergo continuous throttling process by a valve as shown in Fig. 8.



**Fig. 8.** Joule-Thomson expansion.

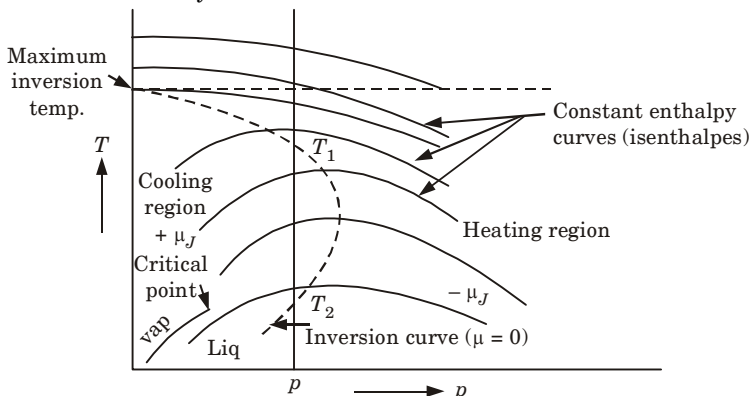
2. The pressures and temperatures of the gas in the insulated pipe upstream and downstream of the valve are measured with suitable manometers and thermometers.
3. Let  $p_i$  and  $T_i$  be the arbitrarily chosen pressure and temperature before throttling and let them be kept constant.
4. By operating the valve manually, the gas is throttled successively to different pressures and temperatures  $p_{f1}, T_{f1}; p_{f2}, T_{f2}; p_{f3}, T_{f3}$  and so on. These are then plotted on the  $T$ - $p$  coordinates as shown in Fig. 9.



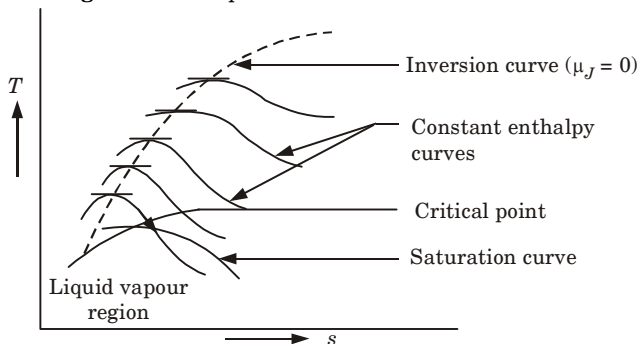
**Fig. 9.** Isenthalpic states of a gas.

5. All the points represent equilibrium states of some constant mass of gas, say, 1 kg, at which the gas has the same enthalpy.
6. The curve passing through all these points is an isenthalpic curve. It is not the graph of a throttling process, but the graph through points of equal enthalpy.
7. The initial temperature and pressure of the gas (before throttling) are then set to new values, and by throttling to different states, a family of isenthalpes is obtained for the gas, as shown in Fig. 10.
8. The curve passing through the maxima of these isenthalpes is called the inversion curve.

9. The numerical value of the slope of an isenthalpe on a  $T$ - $p$  diagram at any point is called the Joule-Kelvin coefficient and is denoted by  $\mu_J$ .
10. Thus the locus of all points at which  $\mu_J$  is zero is the inversion curve. The region inside the inversion curve where  $\mu_J$  is positive is called the cooling region and the region outside where  $\mu_J$  is negative is called the heating region.
- So, 
$$\mu_J = \left( \frac{\partial T}{\partial p} \right)_h$$
11. For achieving the effect of cooling by Joule-Kelvin expansion, the initial temperature of the gas must be below the point where the inversion curve intersects the temperature axis, i.e., below the maximum inversion temperature.
12. For nearly all substances, the maximum inversion temperature is above the normal ambient temperature and hence cooling can be obtained by the Joule-Kelvin effect.



**Fig. 10.** Isenthalpic curves and the inversion curve.



**Fig. 11.** Inversion and saturation curves on  $T$ - $s$  plot.

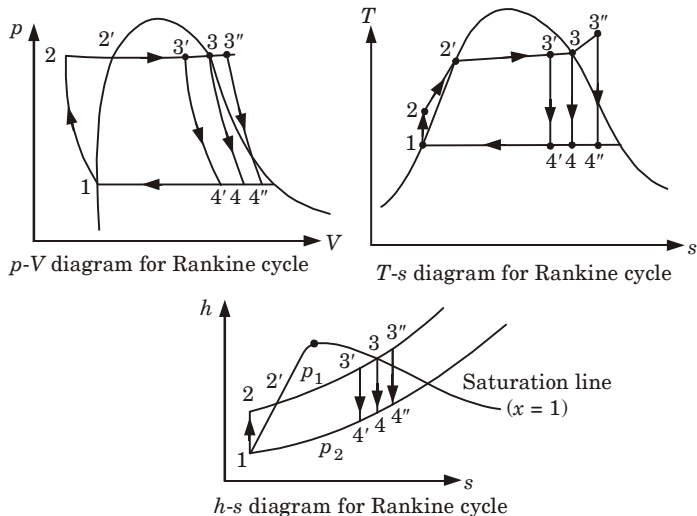
6. Attempt any **one** part of the following : (7 × 1 = 7)
- a. **Explain the Rankine cycle with the help of neat sketch,  $p$ - $V$  and  $T$ - $s$  diagram. If 5 kg of water at 45 °C is heated at a constant pressure of 10 bar until it becomes superheated vapour at 300 °C. Find the change in volume, enthalpy, internal energy and entropy.**

**Ans.**

**A. Rankine Cycle :**

1. Professor Rankine modified the Carnot cycle and presented a technically feasible cycle known as Rankine cycle. It is also a reversible cycle and it differs from Carnot cycle in following aspects :
  - i. The process of condensation is allowed to proceed to completion, *i.e.*, exhaust steam from the steam turbine or steam engine is condensed back to liquid water. At the end of condensation process, the working substance is only liquid (water) and not a mixture of liquid and vapour.
  - ii. Pressure of water can be easily raised to the boiler pressure by means of a small sized feed pump.

Moreover, the steam can be superheated in the boiler so as to obtain the exhaust steam of high quality. It prevents pitting and erosion of turbine blades.



**Fig. 12.**

2. Various process of Rankine cycle are as follows :
  - i. **Process (1-2) :**
    1. Pumping of feed water to the boiler from back (or condenser pressure)  $p_b$  to boiler pressure  $p_1$ .
    2. Compression process is a reversible adiabatic process.

**ii. Process (2-3) :**

1. Feed water is converted into steam at constant pressure (boiler pressure  $p_1$ ).
2. Heat added during the process (2-3) is  $q_s$ .

**iii. Process (3-4) :**

1. Process 3-4 refers to reversible adiabatic expansion of steam in the turbine from boiler pressure ' $p_1$ ' to condenser (or back) pressure ' $p_b$ '.
2. During the process 3-4, there is an enthalpy drop which is equal to the work done ' $W_T$ ' by turbine.

**iv. Process (4-1) :**

1. Exhaust steam from the steam turbine is condensed back to liquid form at constant pressure in the condenser.
2. The steam rejects its latent heat of vapourization to the cooling water. It is denoted by  $q_r$ .

**B. Numerical :**

**Given :**  $m = 5 \text{ kg}$ ,  $p = 10 \text{ bar}$ ,  $T_1 = 45^\circ\text{C} = 318 \text{ K}$ ,

$T_2 = 300^\circ\text{C} = 573 \text{ K}$

**To Find :**

- i. Change in volume,
- ii. Change in enthalpy,
- iii. Change in internal energy, and
- iv. Change in entropy.

1. We know that,

$$W = p(V_2 - V_1) = mR(T_2 - T_1)$$

$$10 \times \Delta V = 5 \times 0.462 \times (573 - 318)$$

$$[\because R = 0.462 \text{ kJ/kgK}]$$

$$\Delta V = 59 \text{ m}^3$$

2. Change in enthalpy,

$$\Delta h = mC_p(T_2 - T_1)$$

$$= 5 \times 4.187 \times (573 - 318) \quad [\because C_p = 4.187 \text{ kJ/kgK}]$$

$$= 5338.425 \text{ kJ/kg}$$

3. Change in internal energy,

$$\Delta U = mC_v(T_2 - T_1)$$

$$= 5 \times (4.187 - 0.462) (573 - 318)$$

$$[\because C_p - C_v = R]$$

$$= 4749.375 \text{ kJ}$$

4. Change in entropy,

$$\begin{aligned}\Delta s &= mC_p \ln \left( \frac{T_2}{T_1} \right) \\ &= 5 \times 4.187 \times \ln \left( \frac{573}{318} \right) \\ &= 12.33 \text{ kJ/K}\end{aligned}$$

- b. 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.**

**Given :**  $p_1 = 1.2 \text{ MPa}$ ,  $T_1 = 188 \text{ °C}$ ,  $h_1 = 2785 \text{ kJ/kg}$ ,  $C_1 = 33.3 \text{ m/s}$   
 $z_1 = 3 \text{ m}$ ,  $p_2 = 20 \text{ kPa}$ ,  $h_2 = 2512 \text{ kJ/kg}$ ,  $C_2 = 100 \text{ m/s}$

$z_2 = 0 \text{ m}$ ,  $Q = -0.29 \text{ kJ/s}$ ,  $\dot{m} = 0.42 \text{ kg/s}$

**To Find :** Power output of turbine ( $W$ ).

1. SFEE for turbine,

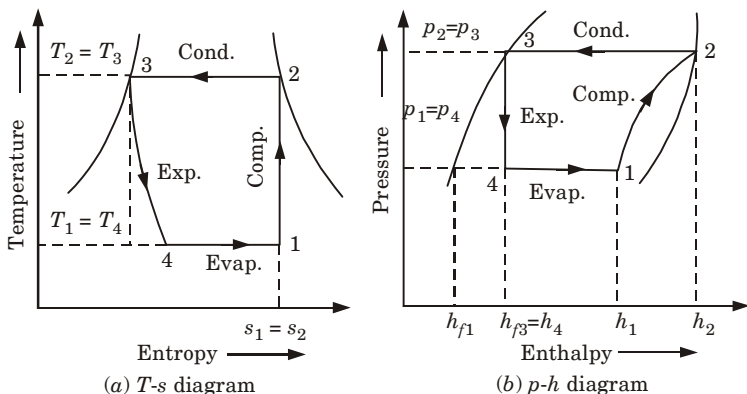
$$\dot{m} \left( h_1 + \frac{C_1^2}{2} + z_1 g \right) + Q = \dot{m} \left( h_2 + \frac{C_2^2}{2} + z_2 g \right) + W$$

$$\begin{aligned}W &= \dot{m} \left[ (h_1 - h_2) + \frac{C_1^2 - C_2^2}{2} + (z_1 - z_2)g \right] + Q \\ &= 0.42 \left[ (2785 - 2512) + \frac{(33.3)^2 - (100)^2}{2 \times 1000} + \frac{(3 - 0) 9.81}{1000} \right] + (-0.29) \\ &= 0.42 [273 - 4.445 + 0.0294] - 0.29 \\ W &= -112.51 \text{ kJ/s}\end{aligned}$$

7. Attempt any **one** part of the following : (7 × 1 = 7)  
**a. Explain the vapour compression refrigeration cycle and its COP with the help of  $T$ - $s$ ,  $p$ - $h$  and flow diagram. Can this cycle be reversible ? If not, why ?**

**Ans.**

1. The four process of the cycle is shown on  $T$ - $s$  and  $p$ - $h$  diagrams in Fig. 13(a) and (b).



**Fig. 13.** Theoretical vapour compression cycle with dry saturated vapour after compression.

### i. Compression Process :

1. The vapour refrigerant at low pressure  $p_1$  and temperature  $T_1$  is compressed isentropically to dry saturated vapour as shown by the vertical line 1-2 on  $T$ - $s$  diagram and by the curve 1-2 on  $p$ - $h$  diagram.
2. Work done during isentropic compression per kg is given by,

$$W = h_2 - h_1$$

Where  $h_1$  = Enthalpy of vapour refrigerant at temperature  $T_1$  (i.e., at suction of the compressor), and  $h_2$  = Enthalpy of the vapour refrigerant at temperature  $T_2$  (i.e., at discharge of the compressor).

### ii. Condensing Process :

1. The high temperature and pressure vapour refrigerant from the compressor is passed through the condenser where it is completely condensed at constant pressure  $p_2$  and temperature  $T_2$  as shown by the horizontal line 2-3 on  $T$ - $s$  and  $p$ - $h$  diagrams.
2. The vapour refrigerant is changed into liquid refrigerant.

### iii. Expansion Process :

1. The liquid refrigerant at pressure  $p_3 = p_2$  and temperature  $T_3 = T_2$  is expanded by throttling process through the expansion valve to a low pressure  $p_4 = p_1$  and temperature  $T_4 = T_1$ , as shown by the curve 3-4 on  $T$ - $s$  diagram and by the vertical line 3-4 on  $p$ - $h$  diagram.
2. During the throttling process, no heat is absorbed or rejected by the liquid refrigerant.

### iv. Evaporation Process :

1. The liquid vapour mixture of the refrigerant at pressure  $p_4 = p_1$  and temperature  $T_4 = T_1$  is evaporated and changed into vapour refrigerant at constant pressure and temperature, as shown by the horizontal line 4-1 on  $T$ - $s$  and  $p$ - $h$  diagrams.
2. During evaporation, the liquid vapour refrigerant absorbs its latent heat of vapourization from the medium (i.e., air, water or brine)

which is to be cooled and the process of vaporization continues up to point 1 which is the starting point and thus the cycle is completed.

3. The heat absorbed or extracted by the liquid vapour refrigerant during evaporation per kg of refrigerant is given by

$$R_E = h_1 - h_4 = h_1 - h_{f3} \quad (\because h_{f3} = h_4)$$

Where  $h_{f3}$  = Sensible heat at temperature  $T_3$  (i.e., enthalpy of liquid refrigerant leaving the condenser)

4. It may be noticed from the cycle that the liquid vapour refrigerant has extracted heat during evaporation and the work will be done by the compressor for isentropic compression of the high pressure and temperature vapour refrigerant.
5. Therefore, coefficient of performance is given by,

$$\begin{aligned} \text{COP} &= \frac{\text{Refrigeration effect}}{\text{Work done}} \\ &= \frac{h_1 - h_4}{h_2 - h_1} = \frac{h_1 - h_{f3}}{h_2 - h_1} \end{aligned}$$

6. The compression refrigeration cycle is not reversible cycle, since it involves throttling which is an irreversible process.

- b. A refrigerator working on Bell Coleman cycle operates between pressure limits of 1.05 bar and 8.5 bar. Air is drawn from the cold chamber at 10 °C. Air coming out compressor is cooled at 30 °C before entering the expansion cylinder. Expansion and compression follow the  $pV^{1.35} = \text{constant}$ . Determine COP of the system.**

**Ans.**

**Given :**  $p_1 = p_4 = 1.05 \text{ bar}$ ,  $p_2 = p_3 = 8.5 \text{ bar}$ ,

$T_1 = 10 \text{ °C} = 10 + 273 = 283 \text{ K}$ ,  $T_3 = 30 \text{ °C} = 30 + 273 = 303 \text{ K}$ ,

$n = 1.3$

**To Find :** COP of the system.

1. The  $p$ - $V$  and  $T$ - $s$  diagrams for a refrigerator working on the Bell-Coleman cycle is shown in Fig. 14(a) and (b) respectively.
2. Let  $T_2$  and  $T_4$  = Temperature of air at the end of compression and expansion respectively.



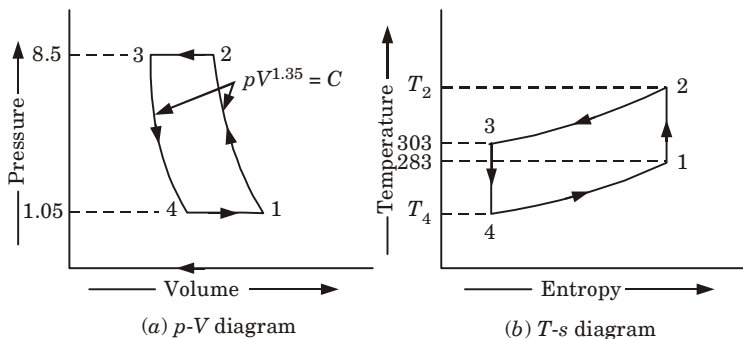


Fig. 14.

3. Since the compression and expansion follows the law  $pV^{1.35} = C$ , therefore,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} = \left(\frac{8.5}{1.05}\right)^{\frac{1.35-1}{1.35}} = (8.1)^{0.259} = 1.72$$

$$\therefore T_2 = T_1 \times 1.72 = 283 \times 1.72 = 486.76 \text{ K}$$

4. Similarly, 
$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{n-1}{n}} = \left(\frac{8.5}{1.05}\right)^{\frac{1.35-1}{1.35}}$$

$$\therefore T_4 = T_3/1.72 = 303/1.72 = 176.16 \text{ K}$$

5. We know that theoretical coefficient of performance,

$$\begin{aligned} \text{COP} &= \frac{T_1 - T_4}{\frac{n}{n-1} \times \frac{(\gamma-1)}{\gamma} [(T_2 - T_3) - (T_1 - T_4)]} \\ &= \frac{(283 - 176.16)}{\frac{1.35}{1.35-1} \times \frac{(1.4-1)}{1.4} [(486.76 - 303) - (283 - 176.16)]} \\ &\quad \dots (\text{Taking } \gamma = 1.4) \\ &= \frac{106.84}{84.75} = 1.26 \end{aligned}$$



**B.Tech.****(SEM. III) ODD SEMESTER THEORY****EXAMINATION, 2018-19****THERMODYNAMICS****Time : 3 Hours****Max. Marks : 70**

**Note :** 1. Attempt **all** sections. If require any missing data; then choose suitably.

**Section-A**

1. Attempt **all** questions in brief. (2 × 7 = 14)
- a. Differentiate between intensive and extensive properties.
- b. What do you mean by Joule-Thompson coefficient and inversion curve ?
- c. State Kelvin-Planck and Clausius statement of second law of thermodynamics.
- d. What is refrigeration and what are the required properties of a refrigerant ?
- e. What do you mean by available and unavailable energy ?
- f. What is the difference between the critical point and the triple points ?
- g. Explain what you understand by thermodynamic equilibrium.

**Section-B**

2. Attempt any **three** of the following : (7 × 3 = 21)
- a. A heat pump is used to meet the heating requirement of a house and maintain it at 20 °C. On a day when the outdoor air temperature drops to - 2 °C, the house is estimated to lose heat at a rate of 80000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine (a) the power consumed by the heat pump and (b) the rate at which heat is absorbed from.

- b. When a man return to his well sealed house on a summer day, he finds that the house is at  $32^{\circ}\text{C}$ . He turns on the air conditioner, which cools the entire house to  $20^{\circ}\text{C}$  in 15 min. If the COP of the air conditioning system is 2.5, determine the power drawn by the air conditioner. Assume the entire mass within the house is equivalent to 800 kg of air for which  $c_v = 0.72 \text{ kJ/kg }^{\circ}\text{C}$  and  $c_p = 1.0 \text{ kJ/kg }^{\circ}\text{C}$ .
- c. Define in pure substance by suitable phase change diagram the term (i) Triple point (ii) Critical point (iii) Saturation states (iv) Sub cooled state (v) Superheated vapour state.
- d. An insulated rigid tank is divided into two equal part by a partition. Initially, one part contains 4 kg of an ideal gas at 800 kPa and  $50^{\circ}\text{C}$ , and the other part is evacuated. The partition is now removed, and the gas expands into the entire tank. Determine the final temperature and pressure in the tank.
- e. Write down the first and second  $Tds$  equations and derive the expression for the difference in heat capacities,  $C_p$  and  $C_v$ .

### Section-C

3. Attempt any **one** part of the following : (7 × 1 = 7)
- a. A piston cylinder device initially contains  $0.4 \text{ m}^3$  of air at 100 kPa and  $80^{\circ}\text{C}$ . The air is now compressed to  $0.1 \text{ m}^3$  in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.
- b. Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.
4. Attempt any **one** part of the following : (7 × 1 = 7)
- a. The two Carnot engines work in series between the sources and sink temperatures of 550 K and 350 K. If both engines develop equal power, determine the intermediate temperature.
- b. Show that the Kelvin-Planck and the Clausius statement of the second law of thermodynamics are equivalent.

5. Attempt any **one** part of the following : (7 × 1 = 7)
- a. In a certain process, a vapour while condensing at 420 °C, transfers heat to water evaporating at 250 °C. The resulting steam is used in power cycle, which rejects heat at 35 °C. What is the fraction of the available energy in the heat transferred from the process vapour at 420 °C that is lost due to the irreversible heat transfer at 250 °C ?
- b. State the Clapeyron equation and discuss its importance during phase change of pure substance. Derive the equation for Clausius-Clapeyron equation for evaporation of liquids.
6. Attempt any **one** part of the following : (7 × 1 = 7)
- a. Steam at 20 bar and 360 °C is expanded in a steam turbine to 0.08 bar. It then enters a condenser, where it is condensed to saturated liquid water. The pump feeds back the water into the boiler. (a) Assuming ideal processes, find per kg of steam the net work and the cycle efficiency. (b) If the turbine and the pump have each 80 % efficiency, find the percentage reduction in the net work and cycle efficiency.
- b. Explain the following processes and show them on psychrometric chart :
- Sensible heating and cooling.
  - Heating and humidification.
  - Cooling and dehumidification.
7. Attempt any **one** part of the following : (7 × 1 = 7)
- a. Explain the vapour compression cycle with the help of  $T-s$  and  $p-h$  diagram.
- b. A refrigerator operates on ideal vapour compression cycle between 0.14 MPa and 0.8 MPa. If the mass flow rate of the refrigerant is 0.06 Kg/s, determine : (a) the rate of heat removal from the refrigerated space, (b) the power input to the compressor, (c) the heat rejection rate in the condenser and (d) the COP.



**SOLUTION OF PAPER (2018-19)**

**Note :** 1. Attempt **all** sections. If require any missing data; then choose suitably.

**Section-A**

1. Attempt **all** questions in brief. (2 × 7 = 14)  
 a. **Differentiate between intensive and extensive properties.**

**Ans.**

S.No.	Intensive Properties	Extensive Properties
1.	These properties do not depend on the mass of the system.	These properties depend on the mass of the system.
2.	Example : Temperature and pressure.	Example : Volume.

- b. **What do you mean by Joule-Thompson coefficient and inversion curve ?**

**Ans.** **Joule-Thomson Coefficient :** The temperature and pressure behaviour of fluids during a throttling process is described by the Joule-Thomson coefficient ( $\mu$ ).

$$\mu = \left( \frac{\partial T}{\partial p} \right)_h$$

**Inversion Curve :**

The curve passing through the maxima of isenthalpes is called the inversion curve.

- c. **State Kelvin-Planck and Clausius statement of second law of thermodynamics.**

**Ans.** **Kelvin-Planck Statement :** It states that it is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

**Clausius Statement :** It is impossible to construct a device which, operating in a cycle, will produce no affect other than the transfer of heat from a cooler to hotter body.

- d. **What is refrigeration and what are the required properties of a refrigerant ?**

**Ans.** **Refrigeration :** It is the science of the producing and maintaining temperatures below that of the surrounding atmosphere *i.e.*, removing of heat from a substance under controlled conditions.

**Properties of Refrigerant :**

1. Low boiling point
2. Low specific heat of liquid
3. Low specific volume of vapour
4. Low cost
5. Nontoxic and non corrosive to metal.

**e. What do you mean by available and unavailable energy ?**

**Ans.** The maximum work output obtained from a certain heat input in a cycle heat engine is called the available energy (A.E) or exergy. The minimum energy that has to be rejected to the sink by the second law is called the unavailable energy (U.E.) or anergy.

**f. What is the difference between the critical point and the triple points ?**

**Ans.**

Critical Point	Triple Point
It is the point where distinction between the entropy of water and the entropy of dry steam disappears.	It is the point at which all the three states (solid, liquid and vapour) of a substance co-exist in equilibrium.

**g. Explain what you understand by thermodynamic equilibrium.**

**Ans.** A system is said to exist in a state of thermodynamic equilibrium when no spontaneous change in any macroscopic property is registered, if the system is isolated from its surroundings. "If the system exists in equilibrium state, there can be no spontaneous change in any macroscopic property of the system".

**Section-B**

2. Attempt any **three** of the following : (7 × 3 = 21)

- a. A heat pump is used to meet the heating requirement of a house and maintain it at 20 °C. On a day when the outdoor air temperature drops to - 2 °C, the house is estimated to lose heat at a rate of 80000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine (a) the power consumed by the heat pump and (b) the rate at which heat is absorbed from.**

**Ans.**

**Given :**  $T_1 = -2\text{ °C} = -2 + 273 = 271\text{ K}$ ,  $Q_2 = 80000\text{ kJ/h}$   
 $T_2 = 20\text{ °C} = 20 + 273 = 293\text{ K}$ , COP = 2.5

**To Find :** i. Power consumed by the heat pump.  
 ii. Rate at which heat is absorbed.

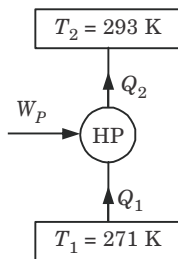


Fig. 1.

1. COP of heat pump,

$$\text{COP} = \frac{Q_2}{W_P}$$

$$\begin{aligned} W_P &= \frac{Q_2}{\text{COP}} = \frac{80000}{2.5} \\ &= 32000 \text{ kJ/h} \\ &= 8.88 \text{ kJ/second} = 8.88 \text{ kW} \end{aligned}$$

2. By energy balance,

$$\begin{aligned} W_P + Q_1 &= Q_2 \\ W_P &= Q_2 - Q_1 \end{aligned}$$

$$\begin{aligned} \text{COP} &= \frac{Q_2}{Q_2 - Q_1} \\ 2.5 &= \frac{80000}{80000 - Q_1} \end{aligned}$$

$$(80000 - Q_1) = \frac{80000}{2.5}$$

$$\begin{aligned} Q_1 &= 48000 \text{ kJ/h} = \frac{48000}{3600} \\ &= 13.33 \text{ kJ/second} \end{aligned}$$

- b. When a man return to his well sealed house on a summer day, he finds that the house is at  $32^\circ\text{C}$ . He turns on the air conditioner, which cools the entire house to  $20^\circ\text{C}$  in 15 min. If the COP of the air conditioning system is 2.5, determine the power drawn by the air conditioner. Assume the entire mass within the house is equivalent to 800 kg of air for which  $c_v = 0.72 \text{ kJ/kg } ^\circ\text{C}$  and  $c_p = 1.0 \text{ kJ/kg } ^\circ\text{C}$ .

**Ans.**

**Given :**  $T_1 = 35^\circ\text{C} = 308 \text{ K}$ ,  $T_2 = 20^\circ\text{C} = 293 \text{ K}$ ,  
 $t = 15 \text{ min} = 900 \text{ sec}$ ,  $\text{COP} = 2.5$ ,  $c_v = 0.72 \text{ kJ/kg } ^\circ\text{C}$ ,  
 $c_p = 1.0 \text{ kJ/kg } ^\circ\text{C}$ ,  $m = 800 \text{ kg}$

**To Find :** Power drawn by air conditioner.

1. Heat removed,

$$\begin{aligned} Q_2 &= \frac{mc_v(T_1 - T_2)}{t} \\ &= \frac{800 \times 0.72(32 - 20)}{900} \\ &= 7.68 \text{ kW} \end{aligned}$$

2. We know that,

$$\text{COP} = \frac{\text{Heat removed}}{\text{Work input}}$$

$$\text{Work input} = \frac{7.68}{2.5} = 3.07 \text{ kW}$$

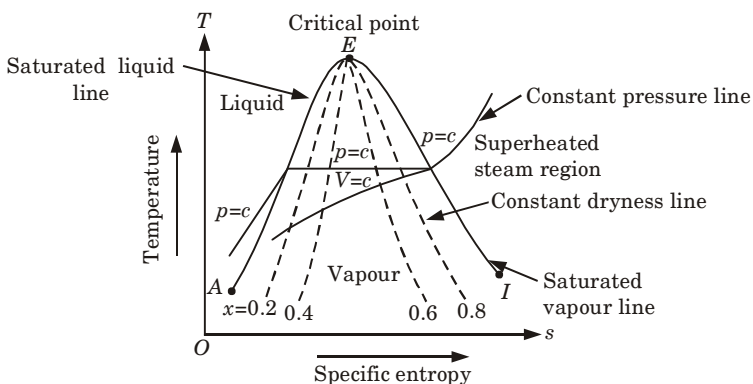
$$\begin{aligned} \text{Power drawn by air conditioner} &= \text{Work input} \\ &= 3.07 \text{ kW} \end{aligned}$$

- c. Define in pure substance by suitable phase change diagram the term (i) Triple point (ii) Critical point (iii) Saturation states (iv) Sub cooled state (v) Superheated vapour state.

**Ans. Phase Diagram :**

**A. Temperature-Entropy ( $T$ - $s$ ) Diagram for Pure Substance :**

- On  $T$ - $s$  diagram, absolute temperature is plotted on Y-axis (ordinate) and specific entropy on the X-axis (abscissa).
- Liquid boundary line originates at the axis of ordinates at 273.16 K; it is a must because liquid entropy at triple point is zero. The boundary curves and vapour line divide the entire diagram in three regions.
- Region to the left of 'AE' is called liquid region. Region in between the line AE and EI is called wet steam region. Region to the right of line EI is known as the region of superheated steam.



**Fig. 2.**  $T$ - $s$  diagram.

- Both the boundary curves (AE and EI) merge at point E which is the critical point of water with critical pressure of 221.2 bar and a critical temperature of 374.15 °C.



- The constant pressure lines are parallel to the constant temperature lines in the wet steam region. These two lines become curved in the superheated region. The constant dryness fraction lines are shown only in the wet steam region.
- The constant volume lines are steeper than the constant pressure lines in the superheated steam region.
- The slopes of constant pressure lines in the liquid region, wet steam region and superheated regions are governed by the equations

$$\left(\frac{\partial T}{\partial s}\right)_v = \frac{T}{c_v}$$

and  $\left(\frac{\partial T}{\partial s}\right)_p = \frac{T}{c_p}$

- Area under the reversible process line and abscissa represents the amount of heat added to one kg of working medium and is given by

$$q = \int T ds$$

### B. Enthalpy-Entropy ( $h$ - $s$ ) Diagram for Pure Substance :

- Generation of steam is done at constant pressure and for constant pressure heating process,  $\delta q = \delta h$ .
- Calculations for heat supplied can be easily done if  $h$ - $s$  diagram is plotted in place of temperature-entropy diagram or ( $T$ - $s$ ) diagram. In the enthalpy-entropy diagram, enthalpy ' $h$ ' is plotted on the axis of ordinate and entropy is plotted along abscissa.
- In a Mollier diagram, the point where saturated liquid line and saturated vapour line merge is known as critical point. After this point, liquid directly gets transformed into superheated steam.
- For a constant pressure process,

$$\delta q = T ds = dh$$

Therefore,  $\left(\frac{dh}{ds}\right)_p = T$

- The slope of constant pressure lines will be equal to the absolute temperature on Mollier diagram.
- In the wet steam region, the temperature of steam remains constant at a given pressure, hence the constant pressure lines are straight lines in the wet steam region. These lines become curved in the superheated region.
- In the wet steam region, the constant temperature lines coincide with the constant pressure lines.
- In the superheated region, isobaric and isothermal lines diverge. Isobaric lines turn upwards and have a positive slope and the isothermal lines tend to become horizontal straight lines. It is due to the fact that at higher temperature the superheated steam behaves as a perfect gas *i.e.*,

$$h = f(T)$$

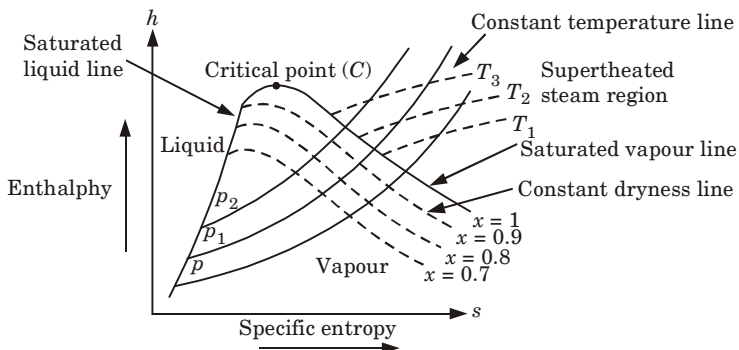


Fig. 3.

9. The constant dryness fraction lines originate from the point C (in wet region only). These lines are approximately parallel to the saturation line ( $x = 1$ ). On a Mollier diagram, throttling process (also called isenthalpic or constant enthalpy process) is represented by a horizontal line.
10. The Mollier diagram makes it possible to easily and rapidly find out the steam parameters with accuracy sufficient for practical purposes and gives solution to the problems related to changes in the state of steam.

### C. Triple Point :

1. Triple point is defined as a point at which pressure and temperature are such that all the three states (solid, liquid and vapour) of a substance co-exist in equilibrium.
2. At triple point, all the three curves namely sublimation, fusion and vaporization and phases of substance meet each other.

**d. An insulated rigid tank is divided into two equal part by a partition. Initially, one part contains 4 kg of an ideal gas at 800 kPa and 50 °C, and the other part is evacuated. The partition is now removed, and the gas expands into the entire tank. Determine the final temperature and pressure in the tank.**

**Ans.**

**Given :**  $p_1 = 8 \text{ bar}$ ,  $T_1 = 50 + 273 = 323 \text{ K}$ ,  $V_1 = V/2$ ,  $V_2 = V$

**To Find :** Final pressure and temperature of air in the vessel.

1. We know that

$$p_1 V_1 = p_2 V_2$$

$$p_2 = \frac{p_1 V_1}{V_2} = \frac{8 \times V / 2}{V} = 4 \text{ bar}$$

$$\begin{aligned}
 2. \quad \frac{V_1}{T_1} &= \frac{V_2}{T_2} \\
 \frac{V/2}{323} &= \frac{V}{T_2} \\
 T_2 &= 323 \times 2 = 646 \text{ K} \\
 T_2 &= 373^\circ\text{C}
 \end{aligned}$$

- e. Write down the first and second  $Tds$  equations and derive the expression for the difference in heat capacities,  $C_p$  and  $C_v$ .

**Ans.**

**A.  $Tds$  Equations :**

1. First  $Tds$  equation,

$$Tds = C_v dT + T \left( \frac{\partial p}{\partial T} \right)_v dv$$

2. Second  $Tds$  equation,

$$Tds = C_p dT - T \left( \frac{\partial v}{\partial T} \right)_p dp$$

**B. Expression for Difference in Heat Capacities :**

1. Consider a perfect gas being heated at constant pressure from  $T_1$  to  $T_2$ .

2. According to non flow equation,

$$Q = (U_2 - U_1) + W$$

3. Also for a perfect gas,

$$\begin{aligned}
 U_2 - U_1 &= mc_v(T_2 - T_1) \\
 Q &= mc_v(T_2 - T_1) + W \quad \dots(1)
 \end{aligned}$$

4. In a constant pressure process, the work done by the fluid,

$$\begin{aligned}
 W &= p(V_2 - V_1) \\
 W &= mR(T_2 - T_1) \quad \dots(2)
 \end{aligned}$$

$$\left[ \begin{aligned}
 \because p_1 V_1 &= mRT_1 \\
 p_2 V_2 &= mRT_2 \\
 p_1 &= p_2 = p \text{ in this case}
 \end{aligned} \right]$$

5. On substituting value of  $W$  from eq. (2) in eq. (1), we get

$$Q = mc_v(T_2 - T_1) + mR(T_2 - T_1) = m(c_v + R)(T_2 - T_1) \quad \dots(3)$$

6. But for a constant pressure process,

$$Q = mc_p(T_2 - T_1) \quad \dots(4)$$

7. By equating the eq. (3) and eq. (4), we have

$$m(c_v + R)(T_2 - T_1) = mc_p(T_2 - T_1)$$

$$\therefore c_v + R = c_p$$

$$\text{or } c_p - c_v = R$$

### Section-C

3. Attempt any **one** part of the following : (7 × 1 = 7)

- a. A piston cylinder device initially contains 0.4 m<sup>3</sup> of air at 100 kPa and 80 °C. The air is now compressed to 0.1 m<sup>3</sup> in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.

**Ans.**

**Given :**  $V_1 = 0.4 \text{ m}^3$ ,  $p_1 = 100 \text{ kPa} = 1 \text{ bar}$ ,  $T_1 = 80 \text{ }^\circ\text{C}$ ,  $V_2 = 0.1 \text{ m}^3$

**To Find :** Work done.

1. Work done during isothermal process is given as,

$$W = p_1 V_1 \ln \frac{V_2}{V_1}$$

$$W = 1 \times 0.4 \ln \left( \frac{0.1}{0.4} \right)$$

$$W = -0.55 \text{ J}$$

Here negative sign indicates that the work is done on the system.

- b. Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.

**Ans.**

**Given :**  $V_1 = 100 \text{ kPa} = 1 \text{ bar}$ ,  $T_1 = 280 \text{ K}$ ,  $P_2 = 600 \text{ kPa} = 6 \text{ bar}$ ,  $T_2 = 400 \text{ K}$ ,  $m = 0.02 \text{ kg/s}$ ,  $Q = 16 \text{ kJ/kg}$

**To Find :** Power input to compressor.

1. SFEE for compressor is,

$$m \left( h_1 + \frac{c_1^2}{2} \right) - Q = m \left( h_2 + \frac{c_2^2}{2} \right) - W_s$$

2. As change in kinetic and potential energies is negligible, therefore the above equation reduces to

$$mh_1 - Q = mh_2 - W_s$$

$$W = m(h_2 - h_1) + Q$$

$$W = mc_p(T_2 - T_1) + Q$$

$$W_s = 0.02 \times 1.005(400 - 280) + 16$$

$$(c_p \text{ for air} = 1.005 \text{ kJ/kg-K})$$

$$W_s = 18.412 \text{ kJ/s}$$

$$W_s = 18.412 \text{ kW}$$

4. Attempt any **one** part of the following : (7 × 1 = 7)  
 a. The two Carnot engines work in series between the sources and sink temperatures of 550 K and 350 K. If both engines develop equal power, determine the intermediate temperature.

**Ans.****Given :**  $T_1 = 550 \text{ K}$ ,  $T_2 = 350 \text{ K}$ **To Find :** Intermediate temperature.

1. The efficiencies of the engines  $HE_1$  and  $HE_2$  are given by

$$\eta_1 = \frac{W}{Q_1} = \frac{T_1 - T_2}{T_1} = \frac{W}{Q_2 + W} \quad \dots(1)$$

$$\eta_2 = \frac{W}{Q_2} = \frac{T_2 - T_3}{T_2} = \frac{W}{Q_3 + W} \quad \dots(2)$$

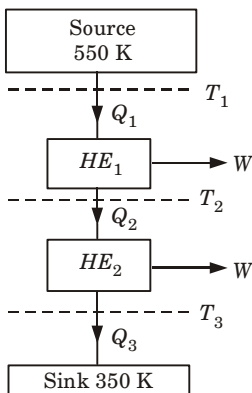
2. From eq. (1), we get

$$W = (Q_2 + W) \left( \frac{T_1 - T_2}{T_1} \right)$$

$$\therefore W \left[ 1 - \left( \frac{T_1 - T_2}{T_1} \right) \right] = Q_2 \left( \frac{T_1 - T_2}{T_1} \right)$$

$$\therefore W \left( \frac{T_2}{T_1} \right) = Q_2 \left( \frac{T_1 - T_2}{T_1} \right)$$

$$\therefore W = Q_2 \left( \frac{T_1 - T_2}{T_2} \right) \quad \dots(3)$$

**Fig. 4.**

3. Similarly from eq. (2), we get

$$W = Q_2 \left( \frac{T_2 - T_3}{T_2} \right) \quad \dots(4)$$

4. Now from eq. (3) and eq. (4), we get

$$T_1 - T_2 = T_2 - T_3$$

$$2T_2 = T_1 + T_3 = 550 + 350$$

$$\therefore T_2 = 450 \text{ K}$$

Hence intermediate temperature = 450 K

- b. Show that the Kelvin-Planck and the Clausius statement of the second law of thermodynamics are equivalent.**

**Ans. Equivalence of Kelvin-Planck and Clausius Statements :**

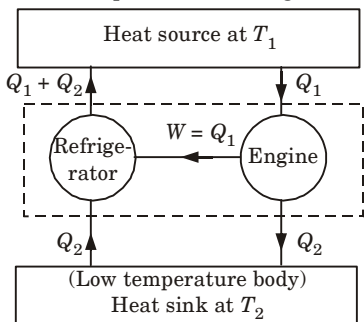
- Both Kelvin Planck and Clausius statements appear to be different but both are interlinked and are complementary to each other.
- Equivalence of these two statements can be proved by showing that violating one statement leads to the violation of other statement and vice-versa.

**i. Violating Kelvin Planck Statement Leads to Violation of Clausius Statement :**

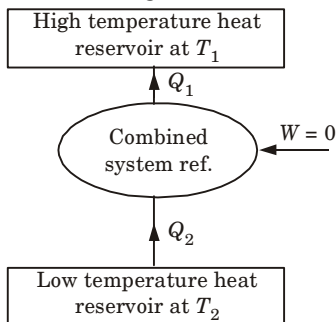
- Let's consider a heat engine which violates Kelvin Planck statement by absorbing heat from source at  $T_1$  and converts it completely into work.

$$\therefore W = Q_1$$

- Now let's introduce a refrigerator which gets work input from the engine.
- The refrigerator extracts  $Q_2$  from the low temperature heat reservoir and rejects heat  $Q_1 + Q_2$  to the high temperature heat reservoir.
- Combining the engine the refrigerator into one system working between same temperature limits, we observe that the sole effect of combined system is to transfer  $Q_2$  from low temperature heat reservoir  $T_2$  to high temperature heat reservoir without any work input thus violating the Clausius statement Fig. 5



(a)



(b) Combined system (refrigerator) violates clausius statement.

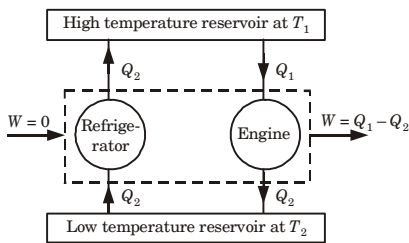
**Fig. 5.**

## ii. Violation of Clausius Statement Leads to Violation of Kelvin Planck Statement :

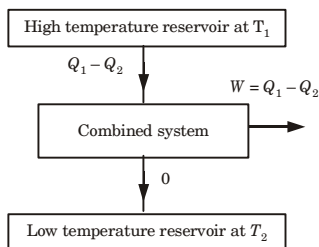
1. Let's consider a refrigerator which violates Clausius statement as shown in the Fig. 6(a).
2. Refrigerator absorbs heat  $Q_2$  from low temperature heat reservoir and rejects the same to the high temperature reservoir without the aid of any external work i.e.,  $W = 0$ .
3. Let's introduce a heat engine which receives heat  $Q_1$  ( $Q_1 > Q_2$ ) from the high temperature reservoir and rejects heat  $Q_2$  and produces work,

$$W = Q_1 - Q_2.$$

4. Now combining the refrigerator and heat engine into one system. We observe that the combined system operates as a heat engine, which receives heat from a single high temperature reservoir as  $Q_1 - Q_2$  and converts the same into equal amount of work energy without any heat rejection.



(a) Violation of Clausius statement.



(b) Combined system (engine) violates Kelvin Planck statement.

**Fig. 6.**

5. This violates the Kelvin Planck statement of second law of thermodynamics.

5. Attempt any **one** part of the following : (7 × 1 = 7)

- a. In a certain process, a vapour while condensing at  $420^\circ\text{C}$ , transfers heat to water evaporating at  $250^\circ\text{C}$ . The resulting steam is used in power cycle, which rejects heat at  $35^\circ\text{C}$ . What is the fraction of the available energy in the heat transferred from the process vapour at  $420^\circ\text{C}$  that is lost due to the irreversible heat transfer at  $250^\circ\text{C}$ ?

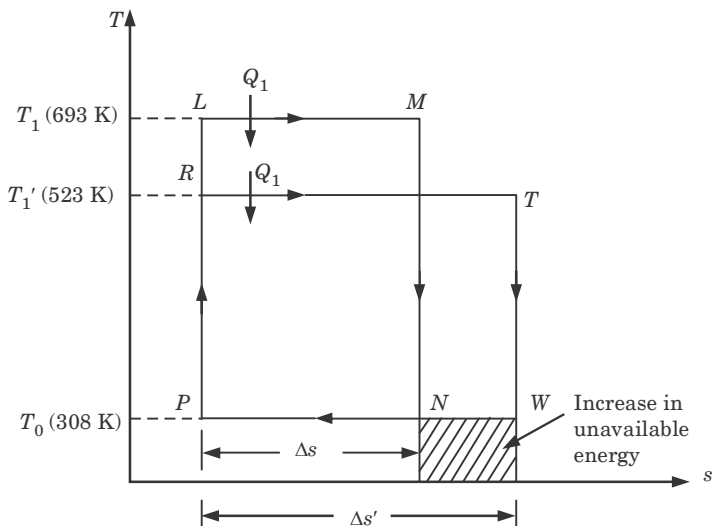
**Ans.**

**Given :**  $T_1 = 420 + 273 = 693\text{ K}$ ,  $T_1' = 250 + 273 = 523\text{ K}$ ,  
 $T_0 = 35 + 273 = 308\text{ K}$

**To Find :** Fraction of available energy.

1. *LMNP* (Fig. 7) would have been the power cycle, if there was no temperature difference between the vapour condensing and the vapour evaporating, and the area under *NP* would have been the

unavailable energy.  $RTWP$  is the power cycle when the vapour condenses at  $420^\circ\text{C}$  and the water evaporates at  $250^\circ\text{C}$ . The unavailable energy becomes the area under  $PW$ . Therefore, the increase in unavailable energy due to irreversible heat transfer is represented by the area under  $NW$ .



**Fig. 7.**

2. Now,

$$Q_1 = T_1 \Delta s = T_1' \Delta s'$$

$$\frac{\Delta s'}{\Delta s} = \frac{T_1}{T_1'}$$

$W$  = Work done in cycle  $LMNP$

$$= (T_1 - T_0) \Delta s \quad \text{per unit mass}$$

$W'$  = Work done in cycle  $RTWP$

$$= (T_1 - T_0) \Delta s' \quad \text{per unit mass}$$

3. The fraction of energy that becomes unavailable due to irreversible heat transfer,

$$\begin{aligned} \frac{W - W'}{W} &= \frac{(T_1 - T_0) \Delta s - (T_1 - T_0) \Delta s'}{(T_1 - T_0) \Delta s} = \frac{T_0 (\Delta s' - \Delta s)}{(T_1 - T_0) \Delta s} \\ &= \frac{T_0 \left( \frac{\Delta s'}{\Delta s} - 1 \right)}{(T_1 - T_0)} = \frac{T_0 \left( \frac{T_1}{T_1'} - 1 \right)}{(T_1 - T_0)} \\ &= \frac{T_0 (T_1 - T_1')}{T_1' (T_1 - T_0)} = \frac{308(693 - 523)}{523(693 - 308)} = 0.26 \end{aligned}$$



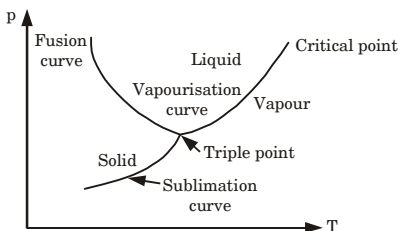
Hence the fraction of energy that becomes unavailable = 0.26 or 26 %.

- b. State the Clapeyron equation and discuss its importance during phase change of pure substance. Derive the equation for Clausius-Clapeyron equation for evaporation of liquids.**

**Ans.**

1. The Clausius-Clapeyron equation is one such equation which is used to determine the enthalpy change associated with a phase change.
2. Consider the Maxwell relation,

$$\left(\frac{\partial p}{\partial T}\right)_v = \left(\frac{\partial s}{\partial v}\right)_T$$



**Fig. 8.**  $p$ - $T$  diagram.

3. During the phase change the pressure is the saturation pressure, which depends on the temperature. Therefore the partial pressure derivative ( $dp/dT$ ) is expressed by

$$[s_g - s_f] = \left(\frac{dp}{dT}\right) \cdot [v_g - v_f]$$

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f}$$

Where,

$s_g$  = Specific entropy of saturated vapour,

$s_f$  = Specific entropy of saturated liquid,

$v_g$  = Specific volume of saturated vapour, and

$v_f$  = Specific volume of saturated liquid.

4. During this process the pressure also remains constant.

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f} = \frac{s_{fg}}{v_{fg}} = \frac{h_{fg}}{T \cdot v_{fg}}$$

Where,

$s_{fg}$  = Increase in specific entropy,

$v_{fg}$  = Increase in specific volume, and

$h_{fg}$  = Latent heat added during evaporation.

$$\left(\frac{dp}{dT}\right) = \frac{h_{fg}}{Tv_{fg}}$$

5. Which is called the Clapeyron equation.
6. The Clapeyron equation is applicable to any phase change process that occurs at constant pressure and temperature. It can be expressed by following relation in general form,

$$\left(\frac{dp}{dT}\right) = \frac{h_{12}}{T.v_{12}}$$

Where 1 and 2 shows the two phases.

6. Attempt any **one** part of the following : (7 × 1 = 7)
- a. **Steam at 20 bar and 360 °C is expanded in a steam turbine to 0.08 bar. It then enters a condenser, where it is condensed to saturated liquid water. The pump feeds back the water into the boiler. (a) Assuming ideal processes, find per kg of steam the net work and the cycle efficiency. (b) If the turbine and the pump have each 80 % efficiency, find the percentage reduction in the net work and cycle efficiency.**

**Ans.**

**Given :**  $p_1 = 20$  bar,  $T_1 = 360$  °C,  $p_2 = 0.08$  bar

**To Find :** i. Net work and cycle efficiency.

ii. Percentage reduction in net work and cycle efficiency.

1. From steam tables,  
At 20 bar and 360 °C

$$h_1 = 3158 \text{ kJ/kg}$$

$$s_1 = 6.9917 \text{ kJ/kg K}$$

At 0.08 bar,

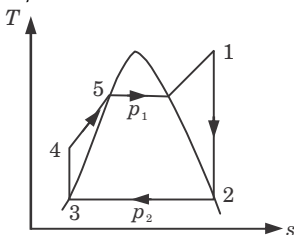
$$h_3 = h_f = 173.88 \text{ kJ/kg}$$

$$s_3 = s_f = 0.5926 \text{ kJ/kg K}$$

$$h_{fg} = 2403 \text{ kJ/kg}$$

$$s_{fg} = 7.6361 \text{ kJ/kg K}$$

$$v_f = 0.00108 \text{ m}^3/\text{kg}$$



**Fig. 9.**

2. Since process 1-2 is isentropic,

$$s_1 = s_2$$

$$s_1 = s_f + x_2 s_{fg2}$$

$$6.9917 = 0.5926 + x_2 \times 7.6361$$

$$x_2 = 0.838$$

Also, 
$$h_2 = h_f + x_2 h_{fg} = 173.88 + 0.838 \times 2403$$
  

$$= 2187.59 \text{ kJ/kg}$$

3. Net work, 
$$W_{\text{net}} = W_T - W_{\text{pump}}$$

$$W_{\text{pump}} = h_{f4} - h_{f3} = v_f (p_1 - p_2)$$

$$= 0.00108 \times (20 - 0.08) \times 10^2 \text{ kN/m}^2$$

$$= 2.15 \text{ kJ/kg}$$

$$h_{f4} = 173.88 + 2.15 = 176.03 \text{ kJ/kg}$$

$$W_T = h_1 - h_2 = 3158 - 2187.59 = 970.41 \text{ kJ/kg}$$

$$W_{\text{net}} = 970.41 - 2.15$$

$$= 968.26 \text{ kJ/kg}$$

4. Cycle efficiency,

$$\eta_{\text{cycle}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_{\text{pump}}}{h_1 - h_{f4}} = \frac{970.41 - 2.15}{3158 - 176.03}$$

$$= 0.324 = 32.4 \%$$

5. If turbine and pump have 80 % efficiency,

$$W_{T(\text{actual})} = 0.8 \times W_T = 0.8 \times 970.41 = 776.328 \text{ kJ/kg}$$

$$W_{\text{pump (actual)}} = 0.8 \times W_{\text{pump}} = 0.8 \times 2.15 = 1.72 \text{ kJ/kg}$$

$$W_{\text{net (actual)}} = W_{T(\text{actual})} - W_{\text{pump (actual)}} = 776.328 - 1.72$$
  

$$= 774.61 \text{ kJ/kg}$$

$$\eta_{\text{cycle (actual)}} = \frac{W_{\text{net (actual)}}}{Q_1} = \frac{774.61}{2981.97} = 0.2597 = 25.97 \%$$

6. Percentage reduction in net work

$$= \frac{W_{\text{net}} - W_{\text{net (actual)}}}{W_{\text{net}}} = \frac{968.26 - 774.61}{968.26} = 20 \%$$

7. Percentage reduction in cycle efficiency

$$= \frac{\eta_{\text{cycle}} - \eta_{\text{cycle (actual)}}}{\eta_{\text{cycle}}} = \frac{32.4 - 25.97}{32.4}$$
  

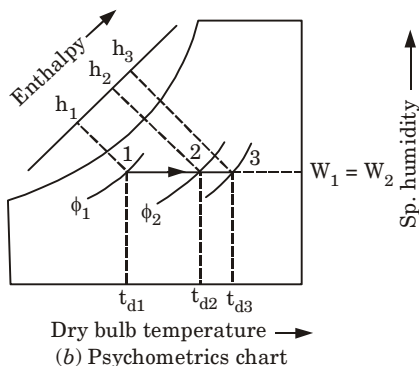
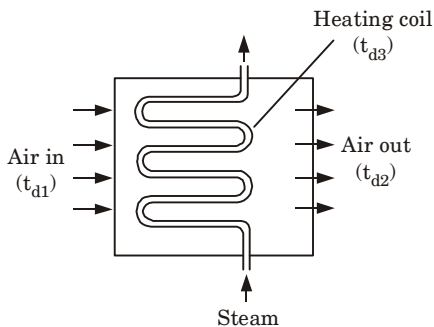
$$= 19.84 \%$$

**b. Explain the following processes and show them on psychrometric chart :**

- i. Sensible heating and cooling.
- ii. Heating and humidification.
- iii. Cooling and dehumidification.

**Ans.****A. Sensible Heating :**

1. The heating of air, without any change in its specific humidity is known as sensible heating. Thus the heating can be achieved by passing the air over heating coil like electric resistance heating coils or steam coils.
2. The heat absorbed by the air during sensible heat is obtained from the psychrometric chart by the enthalpy difference ( $h_2 - h_1$ ) and the specific humidity during the sensible heating remains constant *i.e.*,  $W_1 = W_2$
3. Let air at temperature  $t_{d1}$  passes over a heating coil of temperature  $t_{d3}$  and the temperature of air leaving the heating coil  $t_{d2}$  will be less than  $t_{d3}$ . The amount of heat added during sensible heating may be obtain by the relation :

**Fig. 10. Sensible heating.**

4. Heat added,

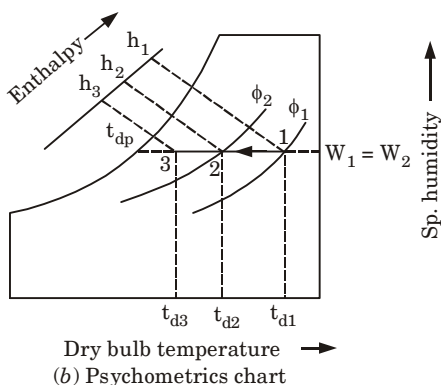
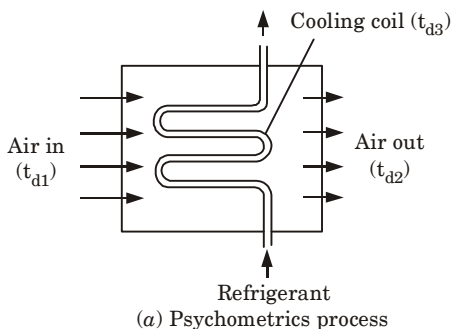
$$\begin{aligned}
 q &= h_2 - h_1 \\
 &= c_{pa} (t_{d2} - t_{d1}) + W c_{ps} (t_{d2} - t_{d1}) \\
 &= (c_{pa} + W c_{ps}) (t_{d2} - t_{d1}) \\
 &= c_{pm} (t_{d2} - t_{d1})
 \end{aligned}$$

Then term  $(c_{pa} + W c_{ps})$  is called humid specific heat ( $c_{pm}$ ) and its value is taken as 1.022 kJ/kg-K.

$\therefore$  Heat added ( $q$ ) = 1.022 ( $t_{d2} - t_{d1}$ ) kJ/kg

### B. Sensible Cooling :

1. The cooling of air, without any change in its specific humidity is known as sensible cooling.
2. Thus the sensible cooling can be achieved by passing the air over cooling coil like evaporating coil of the refrigeration cycle or secondary brine coil.



**Fig. 11.** Sensible cooling.

3. The heat rejected by air during sensible cooling is obtained from the psychrometric chart by the enthalpy difference  $(h_1 - h_2)$ .

4. Let air at temperature  $t_{d1}$  passes over a cooling coil of temperature  $t_{d3}$  and the temperature of air leaving the cooling coil ( $t_{d2}$ ) will be more than  $t_{d3}$ . The specific humidity during the sensible cooling remains constant i.e.,  $W_1 = W_2$ .
5. The dry bulb temperature reduces from  $t_{d1}$  to  $t_{d2}$  and relative humidity increases from  $\phi_1$  to  $\phi_2$ .
6. The amount of heat rejected during sensible cooling is obtained from the relation :
  - i. Heat rejected,

$$q = h_1 - h_2 = c_{pa} (t_{d1} - t_{d2}) + W c_{ps} (t_{d1} - t_{d2})$$

$$= (c_{pa} + W c_{ps}) (t_{d1} - t_{d2}) = c_{pm} (t_{d1} - t_{d2})$$

$$\therefore \text{Heat rejected } q = 1.022 (t_{d1} - t_{d2}) \text{ kJ/kg}$$

- ii. For air conditioning purposes, the sensible heat per minute is given by,

$$SH = m_a c_{pm} \Delta t \quad (\because m_a = V\rho)$$

$$= V\rho c_{pm} \Delta t \text{ kJ/min} \quad \dots(1)$$

where

$V$  = rate of dry air flowing in  $\text{m}^3/\text{min}$ ,

$\rho$  = density of moist air at  $20^\circ\text{C}$  and 50 % relative humidity

=  $1.2 \text{ kg/m}^3$  of dry air,

$c_{pm}$  = humid specific heat

=  $1.022 \text{ kJ/kg-K}$ , and

$\Delta t = t_{d1} - t_{d2}$  = difference of dry bulb temperatures between the entering and leaving conditions of air in  $^\circ\text{C}$ .

- iii. Putting the value of  $\rho$  and  $c_{pm}$  in eq. (1), we get

$$SH = V \times 1.2 \times 1.022 \times \Delta t$$

$$= 1.2264 V \times \Delta t \text{ kJ/min}$$

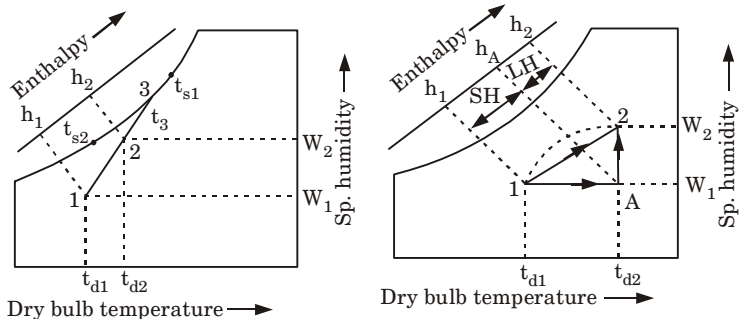
$$= \frac{1.2264 V \times \Delta t}{60} = 0.02044 V \times \Delta t \text{ kJ/s}$$

## C. Heating and Humidification :

1. This process is reverse process of cooling and dehumidification.
2. When air is passed through a humidifier having spray water temperature higher than the dry bulb temperature of the entering air, the unsaturated air will reach the condition of saturation and thus the air becomes hot.
3. The heat of vaporization of water is absorbed from the spray water itself and hence it gets cooled.
4. In this way, the air becomes heated and humidified.
5. In this process, the dry bulb temperature as well as specific humidity of air increases and the final relative humidity of the air can be lower or higher than that of the entering air.
6. The total heat added to the air during heating and humidification is,

where

$$\begin{aligned}
 q &= h_2 - h_1 = (h_2 - h_A) + (h_A - h_1) \\
 &= q_L + q_S \\
 q_L &= (h_2 - h_A) = \text{latent heat of vaporization of the} \\
 &\quad \text{increased moisture content } (W_2 - W_1), \text{ and} \\
 q_S &= (h_A - h_1) = \text{sensible heat added}
 \end{aligned}$$



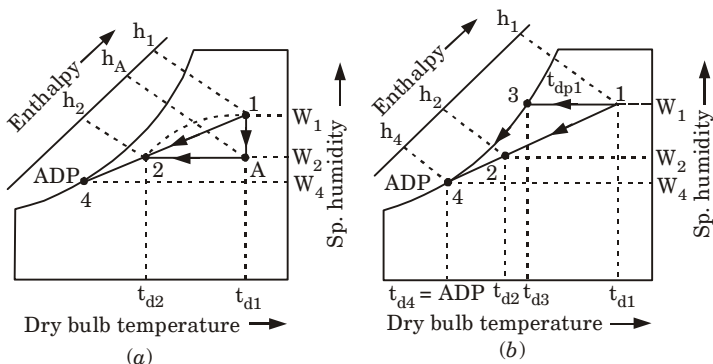
**Fig. 12.** Heating and humidification.

7. We know that sensible heat factor,

$$\text{SHF} = \frac{\text{sensible heat}}{\text{total heat}} = \frac{q_S}{q} = \frac{q_S}{q_S + q_L} = \frac{h_A - h_1}{h_2 - h_1}$$

#### D. Cooling and Dehumidification :

1. In this process, the dry bulb temperature as well as the specific humidity of air decreases and the final relative humidity of the air is generally higher than that of the entering air.



**Fig. 13.** Cooling and dehumidification.

2. The dehumidification of air is only possible when the effective surface temperature of the cooling coil is less than the dew point temperatures of the air entering the coil (i.e.  $t_{dp1}$ ).
3. The effective surface temperature of the coil is known as apparatus dew point (ADP).

4. The process of cooling and dehumidification is shown below :

- i. Let  $t_{d1}$  = Dry bulb temperature of air entering the coil,  
 $t_{dp1}$  = Dew point temperature of the entering air  
 $= t_{d3}$ , and  
 $t_{d4}$  = Effective surface temperature or ADP of the coil.

ii. Under ideal conditions, the dry bulb temperature of the air leaving the cooling coil (*i.e.*  $t_{d4}$ ) should be equal to the surface temperature of the cooling coil (*i.e.*, ADP), which is never possible due to inefficiency of the cooling coil. Thus, the resulting condition of air coming out of the coil is shown by a point 2 on the line 1 – 4.

iii. The total heat removed from the air during the cooling and dehumidification process is,

$$q = h_1 - h_2 = (h_1 - h_A) + (h_A - h_2) \\ = LH + SH$$

where  $LH = h_1 - h_A$  = latent heat removed due to condensation of vapour of the reduced moisture content ( $W_1 - W_2$ ), and

$$SH = h_A - h_2 = \text{sensible heat removed.}$$

iv. We know that sensible heat factor,

$$SHF = \frac{\text{sensible heat}}{\text{total heat}} = \frac{SH}{LH + SH} = \frac{h_A - h_2}{h_1 - h_2}$$

7. Attempt any **one** part of the following :

(7 × 1 = 7)

a. **Explain the vapour compression cycle with the help of  $T$ - $s$  and  $p$ - $h$  diagram.**

**Ans.**

1. The four process of the cycle is shown on  $T$ - $s$  and  $p$ - $h$  diagrams in Fig. 14(a) and (b).

**i. Compression Process :**

1. The vapour refrigerant at low pressure  $p_1$  and temperature  $T_1$  is compressed isentropically to dry saturated vapour as shown by the vertical line 1-2 on  $T$ - $s$  diagram and by the curve 1-2 on  $p$ - $h$  diagram.

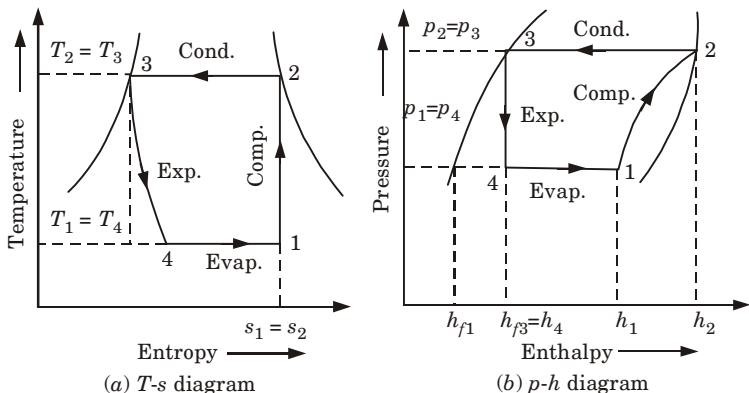
2. Work done during isentropic compression per kg is given by,

$$W = h_2 - h_1$$

Where  $h_1$  = Enthalpy of vapour refrigerant at temperature  $T_1$  (*i.e.*, at suction of the compressor), and

$h_2$  = Enthalpy of the vapour refrigerant at temperature  $T_2$  (*i.e.*, at discharge of the compressor).





**Fig. 14.** Theoretical vapour compression cycle with dry saturated vapour after compression.

### ii. Condensing Process :

1. The high temperature and pressure vapour refrigerant from the compressor is passed through the condenser where it is completely condensed at constant pressure  $p_2$  and temperature  $T_2$  as shown by the horizontal line 2-3 on  $T$ - $s$  and  $p$ - $h$  diagrams.
2. The vapour refrigerant is changed into liquid refrigerant.

### iii. Expansion Process :

1. The liquid refrigerant at pressure  $p_3 = p_2$  and temperature  $T_3 = T_2$  is expanded by throttling process through the expansion valve to a low pressure  $p_4 = p_1$  and temperature  $T_4 = T_1$ , as shown by the curve 3-4 on  $T$ - $s$  diagram and by the vertical line 3-4 on  $p$ - $h$  diagram.
2. During the throttling process, no heat is absorbed or rejected by the liquid refrigerant.

### iv. Evaporation Process :

1. The liquid vapour mixture of the refrigerant at pressure  $p_4 = p_1$  and temperature  $T_4 = T_1$  is evaporated and changed into vapour refrigerant at constant pressure and temperature, as shown by the horizontal line 4-1 on  $T$ - $s$  and  $p$ - $h$  diagrams.
2. During evaporation, the liquid vapour refrigerant absorbs its latent heat of vapourization from the medium (*i.e.*, air, water or brine) which is to be cooled and the process of vaporization continues up to point 1 which is the starting point and thus the cycle is completed.
3. The heat absorbed or extracted by the liquid vapour refrigerant during evaporation per kg of refrigerant is given by

$$R_E = h_1 - h_4 = h_1 - h_{f3} \quad (\because h_{f3} = h_4)$$

Where  $h_{f3}$  = Sensible heat at temperature  $T_3$  (*i.e.*, enthalpy of liquid refrigerant leaving the condenser)

4. It may be noticed from the cycle that the liquid vapour refrigerant has extracted heat during evaporation and the work will be done by the compressor for isentropic compression of the high pressure and temperature vapour refrigerant.
5. Therefore, coefficient of performance is given by,

$$\text{COP} = \frac{\text{Refrigeration effect}}{\text{Work done}}$$

$$= \frac{h_1 - h_4}{h_2 - h_1} = \frac{h_1 - h_{f3}}{h_2 - h_1}$$

- b. A refrigerator operates on ideal vapour compression cycle between 0.14 MPa and 0.8 MPa. If the mass flow rate of the refrigerant is 0.06 Kg/s, determine : (a) the rate of heat removal from the refrigerated space, (b) the power input to the compressor, (c) the heat rejection rate in the condenser and (d) the COP.**

**Ans.**

**Given :**  $p_1 = p_4 = 0.14 \text{ MPa} = 1.4 \text{ bar}$ ,  $p_2 = p_3 = 0.8 \text{ MPa} = 8 \text{ bar}$ ,

$\dot{m} = 0.06 \text{ kg/s}$

**To Find :** i. Rate of heat removal from refrigerated space.  
 ii. Power input to the compressor.  
 iii. Heat rejection rate in the condenser.  
 iv. COP.

**Note :** Here, refrigerant is not mentioned so we are letting it *R-717 (i.e., ammonia)*.

1. The *T-s* and *p-h* diagram are shown in Fig. 15(a) and Fig. 15(b) respectively.
2. Various properties of *R-717* are as follows :
  - i. At 1.4 bar :  $h_{f1} = 81.5 \text{ kJ/kg}$ ,  $h_{g1} = 1428.7 \text{ kJ/kg}$ ,  
 $s_{f1} = 0.5465 \text{ kJ/kg-K}$   
 $s_{g1} = 5.9974 \text{ kJ/kg-K}$
  - ii. At 8 bar :  $h_{f3} = h_4 = 284.8 \text{ kJ/kg}$ ,  $h_{g2} = h_2 = 1478.3$ ,  
 $s_{f2} = 1.2963 \text{ kJ/kg-K}$   
 $s_{g2} = s_2 = 5.3971 \text{ kJ/kg-K}$
3. We know that, entropy at point 1,
 
$$s_1 = s_{f1} + x_1(s_{g1} - s_{f1})$$

$$s_1 = 0.5465 + x_1(5.9974 - 0.5465)$$

$$s_1 = 0.5465 + x_1 \times 5.4509$$
4. Also the entropy at point 1 and point 2 are same, therefore equating the two, we get

$$0.5465 + x_1 \times 5.4509 = 5.3771$$

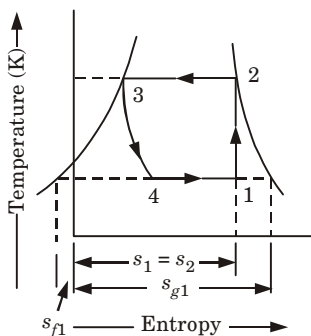
$$x_1 = 0.89$$

5. Now, enthalpy at point 1,

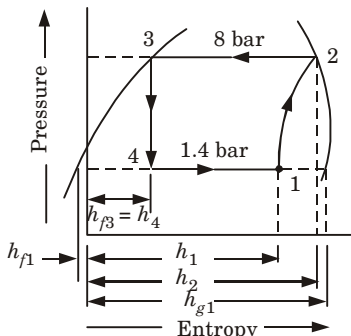
$$\begin{aligned} h_1 &= h_{f1} + x_1(h_{g1} - h_{f1}) \\ &= 81.5 + 0.89(1428.7 - 81.5) = 1280.51 \text{ kJ/kg} \end{aligned}$$

6. Heat removed from refrigerated space,

$$\begin{aligned} &= \dot{m}(h_1 - h_{f3}) \\ &= 0.06 \times (1280.51 - 284.8) \\ &= 59.74 \text{ kJ/s} \end{aligned}$$



(a)  $T$ - $s$  diagram.



(b)  $p$ - $h$  diagram.

**Fig. 15.**

7. Power input to compressor =  $\dot{m}(h_2 - h_{f1})$   
 $= 0.06(1478.3 - 1280.51) = 11.86 \text{ kW}$

8. Heat rejection rate in condenser =  $\dot{m}(h_2 - h_{f3})$   
 $= 0.06(1478.3 - 284.8) = 71.61 \text{ kW}$

9. 
$$\text{COP} = \frac{h_1 - h_{f3}}{h_2 - h_1} = \frac{1280.51 - 284.8}{1478.3 - 1280.51} = 5.03$$



**B.Tech.****(SEM. III) ODD SEMESTER THEORY  
EXAMINATION, 2019-20  
THERMODYNAMICS****Time : 3 Hours****Max. Marks : 100**

**Note : 1.** Attempt **all** sections. If require any missing data; then choose suitably.

**Section-A**

1. Attempt **all** questions in brief. (2 × 7 = 14)
- a. What is critical point and triple point ?
- b. State two limitations of first law of thermodynamics.
- c. Explain Carnot theorem.
- d. State the third law of thermodynamics.
- e. Distinguish between Helmholtz and Gibbs function.
- f. What do you understand by 1 ton of refrigeration ?
- g. What are the causes of irreversibility of a process ?
- h. Draw  $p$ - $T$  diagram of pure substance.
- i. What is the effect of decrease in evaporator pressure and superheating on refrigeration effect and COP of vapour compression refrigeration cycle ?
- j. What is inversion curve ?
2. Attempt any **three** of the following : (10 × 3 = 30)
- a. Derive steady flow energy equation (SFEE). Also write the steady flow energy equation for heat exchanger, nozzle, turbine, pump and boiler with suitable assumptions.
- b. 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 :

- The heat rejected by engine *B*,
- The temperature at which heat is rejected by engine *A*, and
- The work done during the process by engines *A* and *B* respectively.

If engines *A* and *B* deliver equal work, determine :

- The amount of heat taken in by engine *B*, and
- The efficiencies of engines *A* and *B*.

c. Prove that :  $C_p - C_v = -T \left( \frac{\partial V}{\partial T} \right)_T^2 \left( \frac{\partial p}{\partial V} \right)_T$

- Explain simple Rankine cycle with neat sketch, *p*-*V* and *T*-*s* diagram. If 5 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 change in volume, enthalpy, internal energy and entropy.

- Explain the desirable properties required for an ideal refrigerant. Name some commonly used refrigerants and also explain their properties.

- Attempt any **one** part of the following : (10 × 1 = 10)

- A gas undergoes a thermodynamic cycle consisting of three processes beginning at an initial state where  $p_1 = 1$  bar,  $V_1 = 1.5 \text{ m}^3$  and  $U_1 = 512 \text{ kJ}$ .

The processes are as follows :

- Process 1-2 : Compression with  $pV = \text{constant}$  to  $p_2 = 2$  bar,  $U_2 = 690 \text{ kJ}$ ,
- Process 2-3 :  $W_{23} = 0$ ,  $Q_{23} = -150 \text{ kJ}$ , and
- Process 3-1 :  $W_{31} = + 50 \text{ kJ}$ . Neglecting KE and PE changes, Determine the heat interactions  $Q_{12}$  and  $Q_{31}$ .

- 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 ?

- Attempt any **one** part of the following : (10 × 1 = 10)

- 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/kgK.

- i. 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 ?
- ii. If the cycle operates in steady flow with a power output of 20 kW, what is the steam flow rate ?

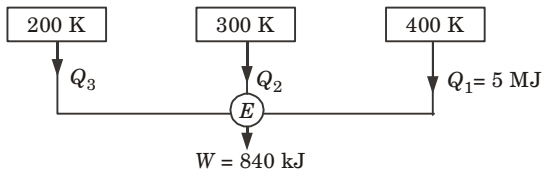


Fig. 1.

- b. Establish the equivalence of Kelvin Plank and Clausius statement. Show that efficiency of a reversible heat engine operating between the same temperature limits is same.
5. Attempt any **one** part of the following : (10 × 1 = 10)
    - a. Discuss the Clapeyron equation and also explain the Joule-Kelvin effect with help of inversion curve and inversion temperature.
    - b. Heat is supplied reversibly from a heat source to a reversible engine and during this process, the temperature of the working fluid increases from 525 K to 875 K. Taking water equivalent as 100 kJ/K and presuming that heat rejection during the cycle takes place at ambient temperature of 290 K, determines the total heat abstracted, availability and the loss of available work.
  6. Attempt any **one** part of the following : (10 × 1 = 10)
    - a. A steam turbine working on a Rankine cycle is supplied with dry saturated steam at 25 bar and the exhaust takes place at 0.2 bar. For a steam flow rate of 10 kg/s, determine :
      - i. Quality of steam at the end of expansion,
      - ii. Turbine shaft work,
      - iii. Power required to drive the pump,
      - iv. Work ratio,
      - v. Rankine efficiency, and
      - vi. Heat flow in the condenser.
    - b. Define and explain the following terms :
      - i. Dry bulb temperature, wet bulb temperature and dew point temperature.

7. Attempt any **one** part of the following : (10 × 1 = 10)
- a. **Explain the vapour compression refrigeration cycle and find out its COP with the help of  $T-s$ ,  $p-h$ , and flow diagram. Can this cycle be reversible ? If not, why ?**
- b. **The air supplied to an air conditioned room is noted to be at temperature 20 °C and specific humidity 0.0085. Corresponding to these conditions, determine the partial pressure of vapour, relative humidity and dew point temperature. Take barometric or total pressure = 1.0132 bar.**



**SOLUTION OF PAPER (2019-20)**

**Note :** 1. Attempt **all** sections. If require any missing data; then choose suitably.

**Section-A**

1. Attempt **all** questions in brief.

(2 × 7 = 14)

**a. What is critical point and triple point ?**

**Ans.** **Critical Point :** Critical point is the point where distinction between the entropy of water and the entropy of dry steam disappears.

**Triple Point :** Triple point is defined as a point at which pressure and temperature are such that all the three states (solid, liquid and vapour) of a substance co-exist in equilibrium.

**b. State two limitations of first law of thermodynamics.**

**Ans.**

1. The first law fixes the exchange rate between heat and work and puts no restrictions on the direction of change.
2. The first law of thermodynamics provides a necessary but not a sufficient condition for a process to take place.

**c. Explain Carnot theorem.**

**Ans.** Carnot theorem states that of all heat engines operating between a given constant temperature source and a given constant temperature sink, none has a higher efficiency than a reversible engine.

**d. State the third law of thermodynamics.**

**Ans.** Third law of thermodynamics states that the entropy of a perfect crystal is zero at the absolute zero of temperature and it represents the maximum degree of order.

**e. Distinguish between Helmholtz and Gibbs function.**

**Ans.**

S. No.	Helmholtz Function	Gibbs Function
1.	It is useful for controlled temperature and volume.	It is useful for controlled temperature and pressure.
2.	It is used for closed system.	It is used for open system.

**f. What do you understand by 1 ton of refrigeration ?**



**Ans.** It is defined as the amount of refrigeration effect produced by the uniform melting of one tonne (1000 kg) of ice and at  $0^{\circ}\text{C}$  in 24 hours.

Practically,

$$1 \text{ TR} = 210 \text{ kJ / min}$$

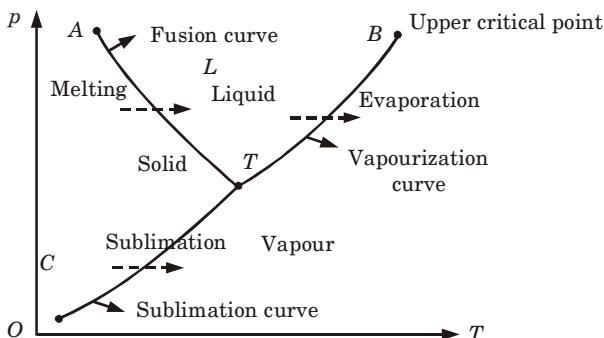
**g. What are the causes of irreversibility of a process ?**

**Ans.** Following are the main causes of irreversibility of a process :

1. Lack of equilibrium during the process.
2. Involvement of dissipative effects.

**h. Draw  $p$ - $T$  diagram of pure substance.**

**Ans.**



**Fig. 1.**

**i. What is the effect of decrease in evaporator pressure and superheating on refrigeration effect and COP of vapour compression refrigeration cycle ?**

**Ans.** **Effect of Decrease in Evaporator Pressure :** The COP of the refrigerating system will be decreased for the same amount of refrigerant flow. So, the refrigerating capacity of the system will decrease and the refrigeration cost will increase.

**Effect of Superheating :**

1. Increases the work of compression.
2. Increases the heat rejection in the condenser.
3. May increase or decrease COP.

**j. What is inversion curve ?**

**Ans.** The curve passing through the maxima of isenthalpes is called the inversion curve.

**2. Attempt any three of the following : (10 × 3 = 30)**

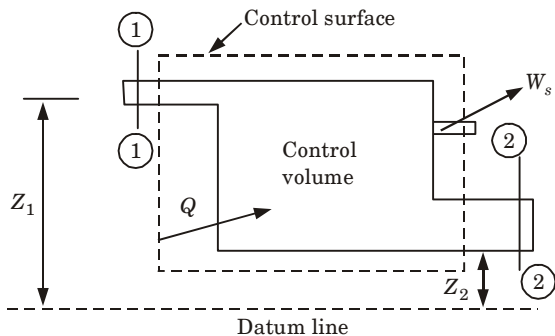
**a. Derive steady flow energy equation (SFEE). Also write the steady flow energy equation for heat exchanger, nozzle, turbine, pump and boiler with suitable assumptions.**

**Ans.****A. Assumptions Made in the Analysis of SFEE :**

1. There is no accumulation or decrease of mass in the control volume at any time *i.e.*, there is no other source or sink of mass in the control volume.
2. Rate of mass flow in and out of the control volume is equal and constant with respect to time.
3. State, velocity and elevation of fluid mass entering and leaving the surface do not change with time.
4. Rate of heat and work transfers across the control volume is constant.

**B. General Energy Equation For Steady Flow Processes :**

1. Let's consider the flow of a fluid through a control volume as shown in Fig. 2. In the time interval " $dt$ ", there occurs a flow (or flux) of mass and energy into the control volume.
2. Section 1-1 is the inlet side and section 2-2 is the outlet side.
3. At the inlet side (section 1-1) to control volume following are the fluid parameters :

Average velocity =  $C_1$ Pressure =  $p_1$ Specific volume =  $v_1$ Internal energy =  $u_1$ **Fig. 2.**

4. At the outlet (section 2-2), following are fluid parameters :

Velocity =  $C_2$ Pressure =  $p_2$ Specific volume =  $v_2$ Internal energy =  $u_2$ 

5. During the flow of fluid through the control volume, heat ' $Q$ ' and mechanical work ' $W_s$ ' are also supposed to cross the control surface. While writing the energy balance equation on the sides of the control volume, following energies are taken into consideration :
  - a. Internal energy stored in the fluid.

- b. Potential energy and kinetic energy.
- c. Flow energy (or flow work) required to push the fluid in or out of control volume.
- d. Heat and shaft (mechanical) work which may cross the control volume.
6. Since the energy is conserved therefore energy balance for the control volume mentioned above can be written in the following form

$$m_1 \left[ u_1 + p_1 v_1 + \frac{C_1^2}{2} + gZ_1 \right] + Q = m_2 \left[ u_2 + p_2 v_2 + \frac{C_2^2}{2} + gZ_2 \right] + W_s \dots (1)$$

7. The eq. (1) is a general energy equation and can be applied to all fluids compressible or incompressible, ideal or real fluids, liquids and gases.

### C. SFEE for Nozzle :

1. The flow through a nozzle is characterized by following features :
  - i. Shaft work is zero *i.e.*,  $W_s = 0$
  - ii. If the flow is reversible adiabatic manner, then  $Q = 0$ .
  - iii. If the nozzle is horizontal, change in elevation, *i.e.*,  $dZ$  will be zero  
 $\therefore Z_1 = Z_2$ .
2. Under these features, SFEE for a nozzle / diffuser is reduced to

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$

$$\text{or} \quad h_1 - h_2 = \frac{C_2^2}{2} - \frac{C_1^2}{2}$$

3. For a nozzle  
Enthalpy drop = Increase in kinetic energy

### D. SFEE for Heat Exchanger :

1. A heat exchanger is characterized by the following features :
  - i. Shaft work is zero,  $W_s = 0$
  - ii. Change in KE = 0
  - iii. Change in PE = 0
- iv. It is a perfectly insulated system *i.e.*, no external heat interaction.
2. From energy balance equation, we can write,  
Energy given by fluid A = Energy gained by fluid B

### E. SFEE for Turbine :

1. A steam or gas turbine has following features :
  - i.  $\Delta KE$  or  $d$  (kinetic energy) = 0
  - ii.  $\Delta PE$  or  $d$  (potential energy) = 0
  - iii.  $Q = 0$  since walls are insulated.
2. Therefore, SFEE for a turbine is reduced to

$$mh_1 = mh_2 + W_s$$

$$\text{or} \quad W_s = m(h_1 - h_2)$$

Obviously the work is done by the turbine at the expense of enthalpy.

**F. SFEE for Boiler :**

1. A boiler has following features :

i. Shaft work is zero,  $W_s = 0$ .

ii. Change in kinetic energy is negligible,  $\frac{C_2^2 - C_1^2}{2} = 0$ .

iii. Change in elevation between inlet and outlet point is negligible,  
 $Z_1 = Z_2$ .

2. Therefore SFEE is reduced to

$$mh_1 + Q = mh_2 \Rightarrow Q = m(h_2 - h_1)$$

**G. SFEE for Pump :**

1. For a pump,  $Q = 0$ ,  $dU = 0$

(Since there is no change in the temperature of water)

2. Work is negative since it is done on the system.

3. SFEE for a pump is reduced to

$$m \left[ p_1 v_1 + \frac{C_1^2}{2} + gZ_1 \right] = m \left[ p_2 v_2 + \frac{C_2^2}{2} + gZ_2 \right] - W$$

**b. 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.**

**Given :**  $T_H = 1000 \text{ K}$ ,  $T_L = 100 \text{ K}$ ,  $(Q_s)_A = 1680 \text{ kJ}$ ,  $\eta_A = \eta_B$

1. For equal efficiencies median temperature,

$$T_M = \sqrt{T_H T_L} = \sqrt{1000 \times 100} = 316.23 \text{ K}$$

So, the temperature at which heat is rejected by engine A,  
 $T_M = 316.23 \text{ K}$

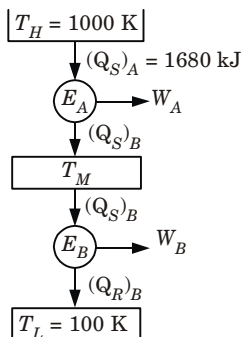


Fig. 3.

2. Efficiency of engine A,

$$\eta_A = (T_H - T_M)/T_H = ((Q_S)_A - (Q_S)_B)/(Q_S)_A$$

( $\because$  Heat rejected by engine A = Heat received by engine B)

$$1 - (T_M/T_H) = 1 - ((Q_S)_B/(Q_S)_A)$$

$$T_M/T_H = (Q_S)_B/(Q_S)_A$$

$$316.23/1000 = (Q_S)_B/1680$$

$$(Q_S)_B = 531.266 \text{ kJ}$$

3. Efficiency of engine B,  $\eta_B = (T_M - T_L)/T_M = ((Q_S)_B - (Q_R)_B)/(Q_S)_B$
- $$T_L/T_M = (Q_R)_B/(Q_S)_B$$
- $$100/316.23 = (Q_R)_B/531.266$$

So, heat rejected by engine B,  $(Q_R)_B = 168 \text{ kJ}$

4. Work done by engine A,  $W_A = (Q_S)_A - (Q_S)_B = 1680 - 531.266$
- $$W_A = 1148.734 \text{ kJ}$$
5. Work done by engine B,  $W_B = (Q_S)_B - (Q_R)_B = 531.266 - 168$
- $$W_B = 363.266 \text{ kJ}$$

6. For  $W_A = W_B$
- $$T_H - T_M = T_M - T_L$$
- (For Carnot engine, work done =  $Q_H - Q_L = T_H - T_L$ )
- $$T_M = (1000 + 100)/2 = 550 \text{ K}$$

7. Now efficiency of engine A,  $\eta_A = 1 - (T_M/T_H) = 1 - (Q_S)_B/(Q_S)_A$
- $$550/1000 = (Q_S)_B/1680$$

So, the amount of heat taken in by engine B,  $(Q_S)_B = 924 \text{ kJ}$

8. Efficiency of engine A,  $\eta_A = 1 - \frac{T_M}{T_H} = 1 - \frac{550}{1000} = 0.45 = 45 \%$

9. Efficiency of engine B,  $\eta_B = 1 - \frac{T_L}{T_M} = 1 - \frac{100}{550} = 0.81818 = 81.82 \%$

c. Prove that :  $C_p - C_v = -T \left( \frac{\partial V}{\partial T} \right)_T^2 \left( \frac{\partial p}{\partial V} \right)_T$

**Ans.**

1. We know that,

$$i. \text{ First } Tds \text{ equation is given as, } Tds = C_v dT + T \left( \frac{\partial p}{\partial T} \right)_v dV \quad \dots(1)$$

$$ii. \text{ Second } Tds \text{ equation is given as, } Tds = C_p dT - T \left( \frac{\partial V}{\partial T} \right)_p dp \quad \dots(2)$$

2. Equating eq. (1) and eq. (2) we have

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

$$3. \quad (C_p - C_v)dT = T \left( \frac{\partial p}{\partial T} \right)_v dV + T \left( \frac{\partial V}{\partial T} \right)_p dp$$

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

$$4. \quad dT = \left( \frac{\partial T}{\partial V} \right)_p dV + \left( \frac{\partial T}{\partial p} \right)_v dp$$

$$\text{Where, } \frac{T \left( \frac{\partial p}{\partial T} \right)_v}{C_p - C_v} = \left( \frac{\partial T}{\partial V} \right)_p \text{ and } \frac{T \left( \frac{\partial V}{\partial T} \right)_p}{C_p - C_v} = \left( \frac{\partial T}{\partial p} \right)_v$$

$$5. \text{ Both these equations give } C_p - C_v = T \left( \frac{\partial p}{\partial T} \right)_v \left( \frac{\partial V}{\partial T} \right)_p$$

$$6. \text{ But } \left( \frac{\partial p}{\partial T} \right)_v \left( \frac{\partial T}{\partial V} \right)_p \left( \frac{\partial V}{\partial p} \right)_T = -1$$

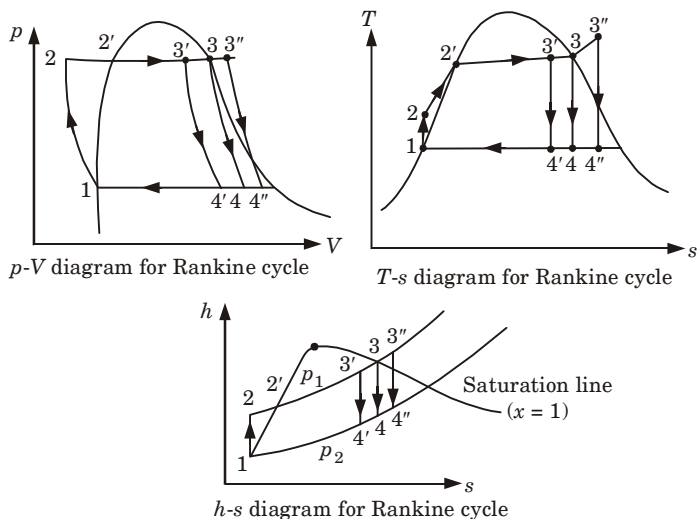
$$\therefore C_p - C_v = -T \left( \frac{\partial V}{\partial T} \right)_T^2 \left( \frac{\partial p}{\partial V} \right)_T$$

**d. Explain simple Rankine cycle with neat sketch,  $p$ - $V$  and  $T$ - $s$  diagram. If 5 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 change in volume, enthalpy, internal energy and entropy.**

**Ans.****A. Rankine Cycle :**

1. Professor Rankine modified the Carnot cycle and presented a technically feasible cycle known as Rankine cycle. It is also a reversible cycle and it differs from Carnot cycle in following aspects :
  - i. The process of condensation is allowed to proceed to completion, i.e., exhaust steam from the steam turbine or steam engine is condensed back to liquid water. At the end of condensation process, the working substance is only liquid (water) and not a mixture of liquid and vapour.
  - ii. Pressure of water can be easily raised to the boiler pressure by means of a small sized feed pump.

Moreover, the steam can be superheated in the boiler so as to obtain the exhaust steam of high quality. It prevents pitting and erosion of turbine blades.



**Fig. 4.**

2. Various process of Rankine cycle are as follows :

**i. Process (1-2) :**

1. Pumping of feed water to the boiler from back (or condenser pressure)  $p_b$  to boiler pressure  $p_1$ .
2. Compression process is a reversible adiabatic process.

**ii. Process (2-3) :**

1. Feed water is converted into steam at constant pressure (boiler pressure  $p_1$ ).
2. Heat added during the process (2-3) is  $q_s$ .

**iii. Process (3-4) :**

1. Process 3-4 refers to reversible adiabatic expansion of steam in the turbine from boiler pressure ' $p_1$ ' to condenser (or back) pressure ' $p_b$ '.
2. During the process 3-4, there is an enthalpy drop which is equal to the work done ' $W_T$ ' by turbine.

**iv. Process (4-1) :**

1. Exhaust steam from the steam turbine is condensed back to liquid form at constant pressure in the condenser.

2. The steam rejects its latent heat of vapourization to the cooling water. It is denoted by  $q_r$ .

**B. Numerical :**

**Given :**  $m = 5 \text{ kg}$ ,  $p = 10 \text{ bar}$ ,  $T_1 = 45^\circ\text{C} = 318 \text{ K}$ ,

$T_2 = 300^\circ\text{C} = 573 \text{ K}$

**To Find :**

- Change in volume,
- Change in enthalpy,
- Change in internal energy, and
- Change in entropy.

1. We know that,

$$W = p(V_2 - V_1) = mR(T_2 - T_1)$$

$$10 \times \Delta V = 5 \times 0.462 \times (573 - 318)$$

$$[\because R = 0.462 \text{ kJ/kgK}]$$

$$\Delta V = 59 \text{ m}^3$$

2. Change in enthalpy,

$$\Delta h = mC_p(T_2 - T_1)$$

$$= 5 \times 4.187 \times (573 - 318) [\because C_p = 4.187 \text{ kJ/kgK}]$$

$$= 5338.425 \text{ kJ/kg}$$

3. Change in internal energy,

$$\Delta U = mC_v(T_2 - T_1)$$

$$= 5 \times (4.187 - 0.462) (573 - 318)$$

$$[\because C_p - C_v = R]$$

$$= 4749.375 \text{ kJ}$$

4. Change in entropy,

$$\Delta s = mC_p \ln \left( \frac{T_2}{T_1} \right)$$

$$= 5 \times 4.187 \times \ln \left( \frac{573}{318} \right)$$

$$= 12.33 \text{ kJ/K}$$

- e. Explain the desirable properties required for an ideal refrigerant. Name some commonly used refrigerants and also explain their properties.

**Ans.**

**A. Desirable Properties of an Ideal Refrigerant :**

- Low boiling point.
- Low specific heat of liquid.
- Low specific volume of vapour.



4. Low cost.
5. High critical temperature.
6. High latent heat of vapourization.
7. Non-corrosive to metal.
8. Non-flammable and non-explosive.
9. Non-toxic.
10. Easy to liquefy at moderate pressure and temperature.

**B. Commonly used Refrigerants :**

**a. Air (*R-729*) :**

**i. Properties :**

1. No cost involved, easily available.
2. Completely non-toxic.
3. Completely safe.

**b. Ammonia (*R-717*) :**

**i. Properties :**

1. It is highly toxic, flammable, irritating and food destroying.
2. It has excellent thermal properties.
3. It has the highest refrigerating effect per kg of refrigerant.

**c. *R-12* (Dichlorodifluoromethane) or Freon-12 ( $\text{CCl}_2\text{F}_2$ ) :**

**i. Properties :**

1. It is non-toxic, non-flammable, non-explosive and non-corrosive therefore, it is most suitable refrigerant.
2. It is fully oil miscible therefore it simplifies the problem of oil return.
3. It does not break even under the extreme operating conditions.

**d. *R-22* (Monochlorodifluoromethane) or Freon-22 ( $\text{CHClF}_2$ )**

1. The compressor displacement per tonne of refrigeration with *R-22* is 60 % less than the compressor displacement with *R-12* as refrigerant.
2. *R-22* is miscible with oil at condenser temperature.
3. The latent heat at  $-15^\circ\text{C}$  is low and is 218.1 kJ/kg.

**e. *R-113* (Trichlorotrifluoroethane) or Freon-13 ( $\text{CCl}_2\text{FCClF}_2$  or  $\text{C}_2\text{Cl}_3\text{F}_3$ ) :**

**i. Properties :**

1. It has a boiling point of  $47.6^\circ\text{C}$  at atmospheric pressure.
2. It remains liquid at room temperatures and pressures and as such it can be carried in sealed tins rather than cylinders.

**3. Attempt any one part of the following : (10 × 1 = 10)**

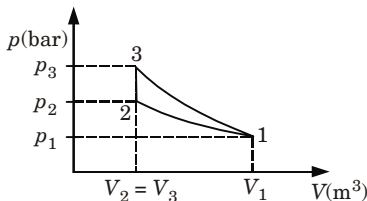
**a. A gas undergoes a thermodynamic cycle consisting of three processes beginning at an initial state where  $p_1 = 1$  bar,  $V_1 = 1.5 \text{ m}^3$  and  $U_1 = 512 \text{ kJ}$ .**

The processes are as follows :

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

**Ans.**

**Given :**  $p_1 = 1 \text{ bar} = 100 \text{ kPa}$ ,  $V_1 = 1.5 \text{ m}^3$ ,  $U_1 = 512 \text{ kJ}$ ,  $p_2 = 2 \text{ bar}$ ,  
 $U_2 = 690 \text{ kJ}$ ,  $W_{23} = 0$ ,  $Q_{23} = -150 \text{ kJ}$ ,  $W_{31} = 50 \text{ kJ}$   
**To Find :** Heat interactions  $Q_{12}$  and  $Q_{31}$ .

**Fig. 5.**

1. For process 1-2, from first law of thermodynamics,

$$Q_{12} = (U_2 - U_1) + p_1 V_1 \ln(p_1/p_2)$$

$$= (690 - 512) + 100 \times 1.5 \ln(1/2)$$

$$Q_{12} = 74.03 \text{ kJ}$$

2. For process 2-3,  $Q_{23} = U_3 - U_2 + W_{23}$

$$-150 = U_3 - 690 + 0$$

$$U_3 = 540 \text{ kJ}$$

3. For process 3-1,  $Q_{31} = (U_1 - U_3) + W_{31} = 512 - 540 + 50 = 22 \text{ kJ}$

- b. 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.**

**Given :**  $p_1 = 1.2 \text{ MPa}$ ,  $T_1 = 188 \text{ °C}$ ,  $h_1 = 2785 \text{ kJ/kg}$ ,  $C_1 = 33.3 \text{ m/s}$   
 $z_1 = 3 \text{ m}$ ,  $p_2 = 20 \text{ kPa}$ ,  $h_2 = 2512 \text{ kJ/kg}$ ,  $C_2 = 100 \text{ m/s}$

$z_2 = 0 \text{ m}$ ,  $Q = -0.29 \text{ kJ/s}$ ,  $\dot{m} = 0.42 \text{ kg/s}$

**To Find :** Power output of turbine ( $W$ ).

1. SFEE for turbine,

$$\dot{m} \left( h_1 + \frac{C_1^2}{2} + z_1 g \right) + Q = \dot{m} \left( h_2 + \frac{C_2^2}{2} + z_2 g \right) + W$$

$$W = \dot{m} \left[ (h_1 - h_2) + \frac{C_1^2 - C_2^2}{2} + (z_1 - z_2)g \right] + Q$$

$$= 0.42 \left[ (2785 - 2512) + \frac{(33.3)^2 - (100)^2}{2 \times 1000} + \frac{(3 - 0) 9.81}{1000} \right] + (-0.29)$$

$$= 0.42 [273 - 4.445 + 0.0294] - 0.29$$

$$W = -112.51 \text{ kJ/s}$$

4. Attempt any **one** part of the following : (10 × 1 = 10)
- a. 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/kgK.
- i. 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 ?
- ii. If the cycle operates in steady flow with a power output of 20 kW, what is the steam flow rate ?

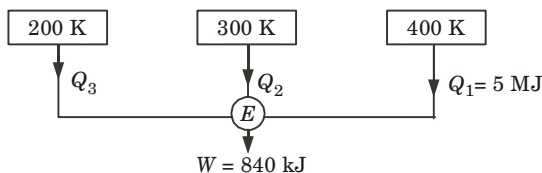


Fig. 6.

**Ans.**

**Given :**  $T_S = 350^\circ\text{C} = 623 \text{ K}$ ,  $T_R = 27^\circ\text{C} = 300 \text{ K}$ ,  $T_w = 350^\circ\text{C} = 623 \text{ K}$ ,  $\Delta s = 1.44 \text{ kJ/kgK}$

**Data Assumed :**  $C_w = 4.187 \text{ kJ/kgK}$

**To Find :** i. For  $m_w = 1 \text{ kg}$ , work done per cycle and heat supplied ( $Q_s$ )

ii. For 20 kW power output, steam flow rate ( $\dot{m}_s$ )

- Entropy change,  $\Delta s = (\text{Heat supplied } (Q_s))/T_w$   
 $Q_s = T_w \Delta s = 623 \times 1.44 = 897.12 \text{ kJ/kg}$   
 Heat supplied,  $Q_s = 1 \times 897.12 = 897.12 \text{ kJ}$  ( $\because m_w = 1 \text{ kg}$ )
- Heat available  $= m_w C_w (T_S - T_R) = 1 \times 4.187(623 - 300) = 1352.40 \text{ kJ}$
- Work done per cycle = Heat available – Heat supplied  
 $= 1352.40 - 897.12 = 455.281 \text{ kJ}$
- Power output  $= \dot{m}_s \left( \frac{\text{Heat available}}{\text{kg}} - \frac{\text{Heat supplied}}{\text{kg}} \right)$   
 $20 = \dot{m}_s [1352.40 - 897.12]$

$\therefore$  Steam flow rate,  $\dot{m}_s = 0.044 \text{ kg/s}$

- b. Establish the equivalence of Kelvin Planck and Clausius statement. Show that efficiency of a reversible heat engine operating between the same temperature limits is same.

**Ans.**

**A. Equivalence of Kelvin Planck and Clausius Statement :**

- Both Kelvin Planck and Clausius statements appear to be different but both are interlinked and are complementary to each other.

2. Equivalence of these two statements can be proved by showing that violating one statement leads to the violation of other statement and vice-versa.
- a. **Violating Kelvin Planck Statement Leads to Violation of Clausius Statement :**
  1. Let's consider a heat engine which violates Kelvin Planck statement by absorbing heat from source at  $T_1$  and converts it completely into work.
 
$$\therefore W = Q_1$$
  2. Now let's introduce a refrigerator which gets work input from the engine.
  3. The refrigerator extracts  $Q_2$  from the low temperature heat reservoir and rejects heat  $Q_1 + Q_2$  to the high temperature heat reservoir.
  4. Combining the engine the refrigerator into one system working between same temperature limits, we observe that the sole effect of combined system is to transfer  $Q_2$  from low temperature heat reservoir  $T_2$  to high temperature heat reservoir without any work input thus violating the Clausius statement Fig. 7.

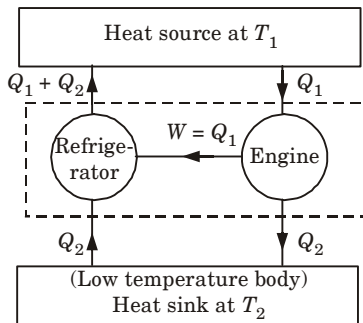


Fig. 7.

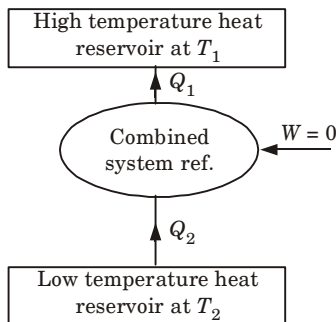


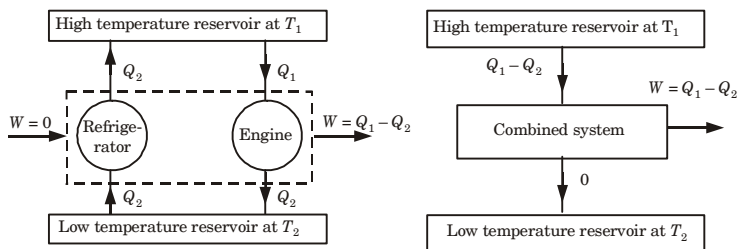
Fig. 8. Combined system (refrigerator) violates Clausius statement.

**b. Violation of Clausius Statement Leads to Violation of Kelvin Planck Statement :**

1. Let's consider a refrigerator which violates Clausius statement as shown in the Fig. 9(a).
2. Refrigerator absorbs heat  $Q_2$  from low temperature heat reservoir and rejects the same to the high temperature reservoir without the aid of any external work *i.e.*,  $W = 0$ .
3. Let's introduce a heat engine which receives heat  $Q_1$  ( $Q_1 > Q_2$ ) from the high temperature reservoir and rejects heat  $Q_2$  and produces work,

$$W = Q_1 - Q_2.$$

4. Now combining the refrigerator and heat engine into one system. We observe that the combined system operates as a heat engine, which receives heat from a single high temperature reservoir as  $Q_1 - Q_2$  and converts the same into equal amount of work energy without any heat rejection.



(a) Violation of Clausius statement. (b) Combined system (engine) violates Kelvin Planck statement.

**Fig. 9.**

5. This violates the Kelvin Planck statement of second law of thermodynamics.

**B. Proof :**

1. "The efficiency of all reversible heat engines operating between the same temperature levels is the same".
2. From Fig. 8, let both the heat engines  $HE_A$  and  $HE_B$  be reversible and  $\eta_A > \eta_B$ . Let the rates of working of the engines be such that

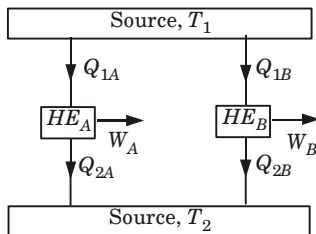
$$Q_{1A} = Q_{1B} = Q_1$$

3. Since

$$\eta_A > \eta_B$$

$$\frac{W_A}{Q_{1A}} > \frac{W_B}{Q_{1B}}$$

$$W_A > W_B$$



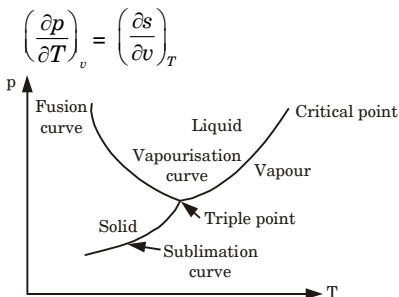
**Fig. 10.** The cyclic heat engines HEA and HEB operating between the same source and sink.

4. If  $HE_B$  is reversed to run say, as a heat pump using some part of the work output ( $W_A$ ) of engine  $HE_A$ , we see that the combined system of heat pump  $HE_B$  and engine  $HE_A$ , becomes a PMM2.
5. So  $\eta_A$  cannot be greater than  $\eta_B$ . Similarly, if we assume  $\eta_B > \eta_A$  and reverse the engine  $HE_A$ , we observe that  $\eta_B$  cannot be greater than  $\eta_A$ ,  
 $\therefore \eta_A = \eta_B$
6. Since the efficiencies of all reversible engines operating between the same heat reservoirs are the same, the efficiency of a reversible engine is independent of the nature or amount of the working substance undergoing the cycle.
5. Attempt any **one** part of the following : (10 × 1 = 10)
- a. **Discuss the Clapeyron equation and also explain the Joule-Kelvin effect with help of inversion curve and inversion temperature.**

**Ans.**

**A. Clapeyron Equation :**

1. The Clausius-Clapeyron equation is one such equation which is used to determine the enthalpy change associated with a phase change.
2. Consider the Maxwell relation,



**Fig. 11.**

3. During the phase change the pressure is the saturation pressure, which depends on the temperature. Therefore the partial pressure derivative ( $dp/dT$ ) is expressed by

$$[s_g - s_f] = \left( \frac{dp}{dT} \right) \cdot [v_g - v_f]$$

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f}$$

Where,

$s_g$  = specific entropy of saturated vapour,  
 $s_f$  = specific entropy of saturated vapour liquid,  
 $v_g$  = specific volume of saturated vapour, and  
 $v_f$  = specific volume of saturated liquid.

4. During this process the pressure also remains constant.

$$\frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f} = \frac{s_{fg}}{v_{fg}} = \frac{h_{fg}}{T \cdot v_{fg}}$$

Where,

$s_{fg}$  = increase in specific entropy,  
 $v_{fg}$  = increase in specific volume, and  
 $h_{fg}$  = latent heat added during evaporation.

$$\left( \frac{dp}{dT} \right) = \frac{h_{fg}}{T v_{fg}}$$

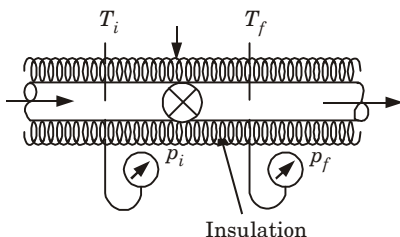
5. Which is called the Clapeyron equation.  
 6. The Clapeyron equation is applicable to any phase change process that occurs at constant pressure and temperature. It can be expressed by following relation in general form,

$$\left( \frac{dp}{dT} \right) = \frac{h_{12}}{T \cdot v_{12}}$$

Where 1 and 2 shows the two phases.

### B. Joule-Kelvin Effect :

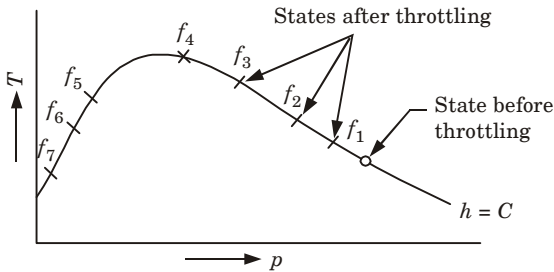
1. A gas is made to undergo continuous throttling process by a valve as shown in Fig. 12.



**Fig. 12.** Joule-Thomson expansion.

2. The pressures and temperatures of the gas in the insulated pipe upstream and downstream of the valve are measured with suitable manometers and thermometers.  
 3. Let  $p_i$  and  $T_i$  be the arbitrarily chosen pressure and temperature before throttling and let them be kept constant.

4. By operating the valve manually, the gas is throttled successively to different pressures and temperatures  $p_{f1}, T_{f1}; p_{f2}, T_{f2}; p_{f3}, T_{f3}$  and so on. These are then plotted on the  $T$ - $p$  coordinates as shown in Fig. 13.



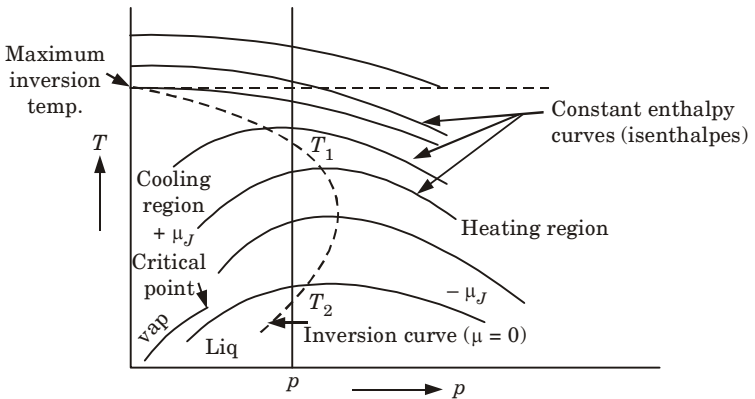
**Fig. 13.** Isenthalpic states of a gas.

5. All the points represent equilibrium states of some constant mass of gas, say, 1 kg, at which the gas has the same enthalpy.
6. The curve passing through all these points is an isenthalpic curve. It is not the graph of a throttling process, but the graph through points of equal enthalpy.
7. The initial temperature and pressure of the gas (before throttling) are then set to new values, and by throttling to different states, a family of isenthalpes is obtained for the gas, as shown in Fig. 13.
8. The curve passing through the maxima of these isenthalpes is called the inversion curve.
9. The numerical value of the slope of an isenthalpe on a  $T$ - $p$  diagram at any point is called the Joule-Kelvin coefficient and is denoted by  $\mu_J$ .
10. Thus the locus of all points at which  $\mu_J$  is zero is the inversion curve. The region inside the inversion curve where  $\mu_J$  is positive is called the cooling region and the region outside where  $\mu_J$  is negative is called the heating region.

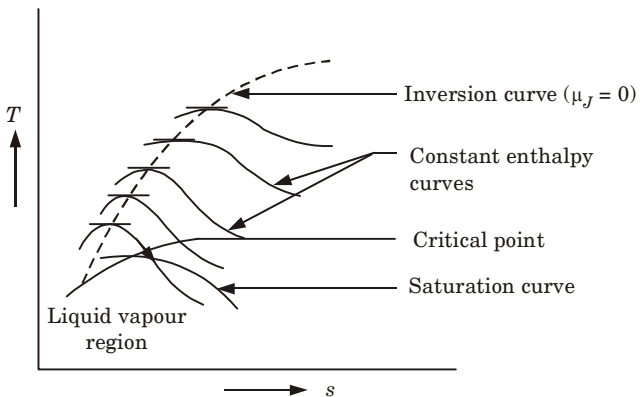
So, 
$$\mu_J = \left( \frac{\partial T}{\partial p} \right)_h$$

11. For achieving the effect of cooling by Joule-Kelvin expansion, the initial temperature of the gas must be below the point where the inversion curve intersects the temperature axis, i.e., below the maximum inversion temperature.
12. For nearly all substances, the maximum inversion temperature is above the normal ambient temperature and hence cooling can be obtained by the Joule-Kelvin effect.





**Fig. 14.** Isenthalpic curves and the inversion curve.



**Fig. 15.** Inversion and saturation curves on  $T$ - $s$  plot.

- b. Heat is supplied reversibly from a heat source to a reversible engine and during this process, the temperature of the working fluid increases from 525 K to 875 K. Taking water equivalent as 100 kJ/K and presuming that heat rejection during the cycle takes place at ambient temperature of 290 K, determines the total heat abstracted, availability and the loss of available work.**

**Ans.****Given :**  $T_1 = 525 \text{ K}$ ,  $T_2 = 875 \text{ K}$ ,  $(mc)_{\text{water}} = 100 \text{ kJ/K}$ ,  $T = 290 \text{ K}$ **To Find :**  
i. Total heat abstracted ( $Q$ ),  
ii. Availability ( $W$ ), and  
iii. The loss of available work ( $W_L$ ).

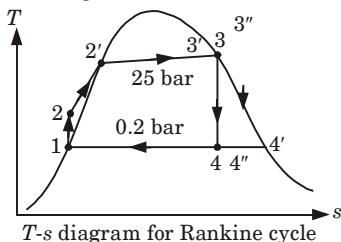
- Total heat abstracted,  $Q = (mc)_{\text{water}} (T_Q - T_1)$   
 $= 100[875 - 525] = 35000 \text{ kJ}$
- Entropy change of working fluid,  
 $\Delta s = (mc)_{\text{water}} \ln (T_2/T_1) = 100 \ln (875/525) = 51.0826 \text{ kJ/K}$
- Irreversibility,  $I_R = T_0(\Delta s) = 290 \times 51.0826 = 14813.954 \text{ kJ}$
- Availability,  $W = Q - I_R = 35000 - 14813.954 = 20186.046 \text{ kJ}$
- The loss of available work,  
 $W_L = Q - W = 35000 - 20186.046 = 14813.954 \text{ kJ}$

**6. Attempt any one part of the following : (10 × 1 = 10)**

- a. A steam turbine working on a Rankine cycle is supplied with dry saturated steam at 25 bar and the exhaust takes place at 0.2 bar. For a steam flow rate of 10 kg/s, determine :**
- Quality of steam at the end of expansion,
  - Turbine shaft work,
  - Power required to drive the pump,
  - Work ratio,
  - Rankine efficiency, and
  - Heat flow in the condenser.

**Ans.****Given :**  $\dot{m}_s = 10 \text{ kg/s}$ ,  $p_1 = 0.2 \text{ bar}$ ,  $p_2 = 25 \text{ bar}$ 

- From steam table,  
 i. At 25 bar,  $h_2' = 962.0 \text{ kJ/kg}$ ,  $h_3 = 2800.9 \text{ kJ/kg}$   
 $s_2' = 2.5543 \text{ kJ/kgK}$ ,  $s_3 = 6.2536 \text{ kJ/kgK}$   
 ii. At 0.2 bar,  $h_1 = 251.5 \text{ kJ/kg}$ ,  $h_4' = 2609.9 \text{ kJ/kg}$   
 $s_1 = 0.8321 \text{ kJ/kgK}$ ,  $s_4' = 7.9094 \text{ kJ/kgK}$   
 $V_1 = 0.001017 \text{ m}^3/\text{kg}$

**Fig. 16.**

- We know that,  $s_3 = s_4$ ,  $s_3 = s_1 + x(s_4' - s_1)$   
 $6.2536 = 0.8321 + x(7.9094 - 0.8321)$

So, quality of steam,  $x = 0.766$

$$3. \text{ Also, } h_4 = h_1 + x(h_4' - h_1) = 251.5 + 0.766(2609.9 - 251.5) \\ h_4 = 2058.034 \text{ kJ/kg}$$

$$4. \text{ Turbine shaft work, } W_T = \dot{m}_s (h_3 - h_4) = 10(2800.9 - 2058.034) \\ W_T = 7428.66 \text{ kW}$$

5. Power required to drive the pump,

$$W_P = \dot{m}_s V_1 (p_2 - p_1) = 10 \times 0.001017 \times (25 - 0.2) \times 100 \\ W_P = 25.222 \text{ kW}$$

$$6. \text{ Work ratio, } W_R = \frac{W_{\text{net}}}{W_T} = \frac{W_T - W_P}{W_T} = \frac{7428.66 - 25.222}{7428.66}$$

$$W_R = 0.9966$$

$$7. \text{ For pump work, } h_2 - h_1 = V_1 (p_2 - p_1) \\ h_2 = 251.5 + 0.001017(25 - 0.2) \times 100 \\ h_2 = 254.022 \text{ kJ/Kg}$$

$$8. \text{ Heat supplied, } Q_S = \dot{m}_s (h_3 - h_2) = 10(2800.9 - 254.022) \\ Q_S = 25468.78 \text{ kW}$$

$$9. \text{ Rankine efficiency, } \eta = W_{\text{net}}/Q_S = (W_T - W_P)/Q_S \\ = 7403.438/25468.78 = 0.29069 = 29.07 \%$$

$$10. \text{ Heat flow in the condenser, } Q_C = \dot{m}_s (h_4 - h_1) \\ = 10(2058.034 - 251.5) = 18070.65 \text{ kW}$$

**b. Define and explain the following terms :**

**i. Dry bulb temperature, wet bulb temperature and dew point temperature.**

**Ans.**

**A. DBT :** Dry bulb temperature (DBT) is the temperature, recorded by an ordinary thermometer whose reading is not affected by moisture present in the air or by thermal radiation.

**B. WBT :** Wet bulb temperature is the temperature recorded by a thermometer whose bulb is covered with a wet cloth and exposed to current of moving air (atmospheric air).

**C. DPT :** Dew point temperature (DPT) is the temperature at which the water vapour present in the moist air just begins to condense when the mixture of moist air is cooled at constant pressure.

**ii. Relative humidity and specific humidity.**

**Ans.**

**A. Relative Humidity :** Relative humidity is defined as the ratio between actual amount of water vapour *i.e.*, present in a given volume of mixture and the maximum amount of water vapour that could be present in the same volume at the same temperature when the mixture is saturated.

It is denoted by *RH* or  $\phi$ .

**B. Specific Humidity :** Specific humidity is defined as the amount of water vapour in kg present along with 1 kg of dry air in a mixture of dry air and water vapour. It is also called humidity ratio or humidity. And it is denoted by  $\omega$ .

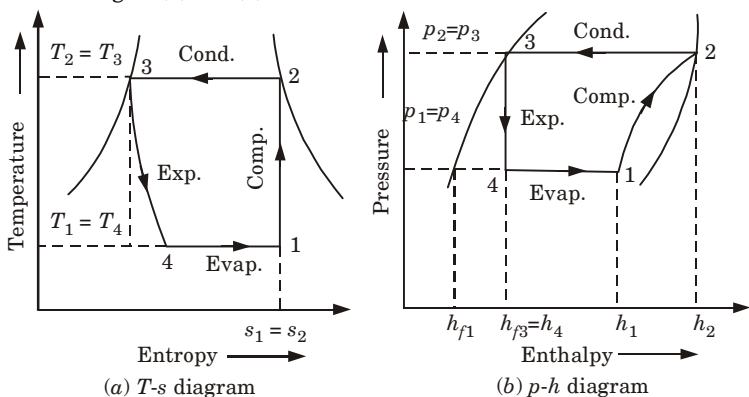
It is expressed in terms of kg per kg of dry air.

7. Attempt any **one** part of the following : (10 × 1 = 10)

a. **Explain the vapour compression refrigeration cycle and find out its COP with the help of  $T$ - $s$ ,  $p$ - $h$ , and flow diagram. Can this cycle be reversible ? If not, why ?**

**Ans.**

1. The four process of the cycle is shown on  $T$ - $s$  and  $p$ - $h$  diagrams in Fig. 17(a) and (b).



**Fig. 17.** Theoretical vapour compression cycle with dry saturated vapour after compression.

### i. Compression Process :

1. The vapour refrigerant at low pressure  $p_1$  and temperature  $T_1$  is compressed isentropically to dry saturated vapour as shown by the vertical line 1-2 on  $T$ - $s$  diagram and by the curve 1-2 on  $p$ - $h$  diagram.
2. Work done during isentropic compression per kg is given by,

$$W = h_2 - h_1$$

Where

$h_1$  = Enthalpy of vapour refrigerant at temperature  $T_1$  (i.e., at suction of the compressor), and

$h_2$  = Enthalpy of the vapour refrigerant at temperature  $T_2$  (i.e., at discharge of the compressor).

### ii. Condensing Process :

1. The high temperature and pressure vapour refrigerant from the compressor is passed through the condenser where it is completely condensed at constant pressure  $p_2$  and temperature  $T_2$  as shown by the horizontal line 2-3 on  $T$ - $s$  and  $p$ - $h$  diagrams.
2. The vapour refrigerant is changed into liquid refrigerant.

**iii. Expansion Process :**

1. The liquid refrigerant at pressure  $p_3 = p_2$  and temperature  $T_3 = T_2$  is expanded by throttling process through the expansion valve to a low pressure  $p_4 = p_1$  and temperature  $T_4 = T_1$ , as shown by the curve 3-4 on  $T$ - $s$  diagram and by the vertical line 3-4 on  $p$ - $h$  diagram.
2. During the throttling process, no heat is absorbed or rejected by the liquid refrigerant.

**d. Evaporation Process :**

1. The liquid vapour mixture of the refrigerant at pressure  $p_4 = p_1$  and temperature  $T_4 = T_1$  is evaporated and changed into vapour refrigerant at constant pressure and temperature, as shown by the horizontal line 4-1 on  $T$ - $s$  and  $p$ - $h$  diagrams.
2. During evaporation, the liquid vapour refrigerant absorbs its latent heat of vapourization from the medium (*i.e.*, air, water or brine) which is to be cooled and the process of vaporization continues up to point 1 which is the starting point and thus the cycle is completed.
3. The heat absorbed or extracted by the liquid vapour refrigerant during evaporation per kg of refrigerant is given by

$$R_E = h_1 - h_4 = h_1 - h_{f3} \quad (\because h_{f3} = h_4)$$

Where  $h_{f3}$  = Sensible heat at temperature  $T_3$  (*i.e.*, enthalpy of liquid refrigerant leaving the condenser)

4. It may be noticed from the cycle that the liquid vapour refrigerant has extracted heat during evaporation and the work will be done by the compressor for isentropic compression of the high pressure and temperature vapour refrigerant.
5. Therefore, coefficient of performance is given by,

$$\text{COP} = \frac{\text{Refrigeration effect}}{\text{Work done}}$$

$$= \frac{h_1 - h_4}{h_2 - h_1} = \frac{h_1 - h_{f3}}{h_2 - h_1}$$

6. The compression refrigeration cycle is not reversible cycle, since it involves throttling which is an irreversible process.

- b. The air supplied to an air conditioned room is noted to be at temperature 20 °C and specific humidity 0.0085. Corresponding to these conditions, determine the partial pressure of vapour, relative humidity and dew point temperature. Take barometric or total pressure = 1.0132 bar.**

**Ans.**

**Given :**  $t_{db} = 20^\circ\text{C}$ ,  $w = 0.0085$ ,  $p_b = 1.0132 \text{ bar} = 101.32 \text{ kPa}$

**To Find :** i. Partial pressure of vapour ( $p_v$ ).

ii. Relative humidity ( $\phi$ ).

iii. Dew point temperature ( $t_{dp}$ ).

1. We know that, specific humidity,  $w = 0.622 (p_v)/(p_b - p_v)$   
 $0.0085 = 0.622 (p_v)/(101.32 - p_v)$   
 $73.1765 p_v = 101.32 - p_v$   
 $74.176 p_v = 101.32$

So, partial pressure of vapour,  $p_v = 1.366 \text{ kPa}$

2. Since, saturation pressure is the pressure corresponding to the dry bulb temperature. So, from steam table at  $t_{db} = 20^\circ\text{C}$ ,  
 $p_s = 0.0234 \text{ bar} = 2.34 \text{ kPa}$
3. Relative humidity,  $\phi = p_v/p_s = 1.366/2.34 = 0.58376 = 58.376 \%$
4. Since, dew point temperature is the temperature corresponding to the partial vapour pressure. So, from steam table at  $p_v = 1.366 \text{ kPa}$ ,  
 $t_{dp} = 10^\circ\text{C}$

