

**KARPAGAM ACADEMY OF HIGHER EDUCATION****(Deemed to be University)****(Established Under Section 3 of UGC Act 1956)****Pollachi Main Road, Eachanari (Po),****COIMBATORE – 21****FACULTY OF ENGINEERING****DEPARTMENT OF MECHANICAL ENGINEERING****SUBJECT NAME: ENGINEERING
THERMODYNAMICS****SUBJECT CODE : 16BEME403**

L	T	P	C
3	2	0	4

OBJECTIVE

1. To familiarize the students to understand the fundamentals of thermodynamics and to perform thermal analysis on their behavior and performance.

UNIT I BASIC CONCEPTS AND FIRST LAW**12**

Basic concepts - Classical and Statistical approaches - Thermodynamic systems - closed, open, isolated. Property – State - Process-adiabatic - Quasi-static process – Cycle - Point and Path function – Energy - Work transfer - Concept of temperature and heat- Zeroth law of thermodynamics - Concept of ideal gases - First law of thermodynamics –PMM1, internal energy, specific heat capacities, enthalpy, and its application to closed system and open system-steady flow energy equation.

UNIT II SECOND LAW AND ENTROPY**12**

Physical description of the second law - Kelvin-Planck and Clausius statements –Equivalence - Reversible processes and cycles- Carnot cycle – Corollaries - Absolute temperature scale – Clausius Theorem, inequality - Entropy- Principle, transfer, generation, balance - Third law of thermodynamics

UNIT III PROPERTIES OF PURE SUBSTANCE AND GAS MIXTURES**12**

Pure substance - Phase change process - Property diagrams - PVT surface - Steam – types, dryness fraction - Avogadro's law - Ideal Gas - Equations of state-Vander Waal's equation - Real Gas - Compressibility and its chart - Mixtures of Gases – Properties.

UNIT IV THERMODYNAMIC AVAILABILITY AND RELATIONS**12**

Basics-Dead state, quality of energy, degradation of energy - Reversible processes – Maximum work - Exergy – Closed system - Steady flow system – Irreversibility - Exergy Balance - Second law efficiency – Exact differentials - Tds Relations - Maxwell's Relation – Clausius – Clapeyron Equation - Joule-Thompson Coefficient.

UNIT V PSYCHROMETRY**12**

Psychrometry - Psychrometric charts - Property calculations of air vapour mixtures- Psychrometric process- Adiabatic mixing - Evaporative cooling.

TOTAL**60**

(Permitted to use standard thermodynamic table, Mollier diagram, and Psychometric chart in the examination)

TEXT BOOKS

S. No.	Author(s) Name	Title of the book	Publisher	Year of Publication
1	Nag P K	Engineering Thermodynamics	Tata McGraw-Hill, New Delhi	2013
2	Cengel	Thermodynamics-An Engineering Approach	Tata McGraw-Hill, New Delhi	2014

REFERENCES

S. No.	Author(s) Name	Title of the book	Publisher	Year of Publication
1	Holman J P	Thermodynamics	McGraw-Hill, New Delhi	1988
2	Venwylen and Sontag	Classical Thermodynamics	Wiley Eastern, New Delhi	1994
3.	Kothandaraman C P and Domkundwar S	Engineering Thermodynamics	Dhanpatrai & Sons, New Delhi	2004

WEB REFERENCES

1. http://nptel.iitm.ac.in/courses/Webcourse-contents/IIT%20Guwahati/engg_mechanics/index.htm
2. <http://nptel.iitm.ac.in/video.php?subjectId=112103108>
3. <http://web.mit.edu/emech/dontindex-build/index.html>
4. <http://www.indiabix.com/engineering-mechanics/questions-and-answers/>

**KARPAGAM ACADEMY OF HIGHER EDUCATION****(Deemed to be University)****(Established Under Section 3 of UGC Act 1956)****Pollachi Main Road, Eachanari (Po),****COIMBATORE – 21****FACULTY OF ENGINEERING****DEPARTMENT OF MECHANICAL ENGINEERING****LESSON PLAN**
Subject Name : Engineering Thermodynamics Subject Code : 16BEME403

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
<u>UNIT – I : BASIC CONCEPTS AND FIRST LAW</u>			
1.	1	Introduction to subject- basic concepts-classical and statistical approaches, scope and limitation	T[1], T[2]
2.	1	Thermodynamic systems – closed, open, isolated and adiabatic– property, state, process	T[1], T[2]
3.	1	Quasi–static process, cycle, point and path function, work, energy	T[1], T[2], W[1]
4.	1	Zeroth law of thermodynamics, Concept of temperature and heat	T[1], T[2]
5.	1	Concept of ideal and real gases, First law of thermodynamics, PMM1	T[1], T[2]
6.	1	Internal energy, specific heat capacities, enthalpy	T[1], T[2]
7.	1	Tutorial-1: General Problems in First Law of thermodynamics	T[1], R[1]
8.	1	Application to closed and open systems, Isometric, Isobaric, Isothermal process	T[1], T[2]
9.	1	Isentropic, Polytrophic, Free expansion process – work done & heat transfer	T[1], T[2]
10.	1	Steady flow energy equation – engineering applications, problems	T[1], W[1], J[1]
11.	1	Tutorial-2: General Problems in Non-Flow & Steady Flow Processes	T[1], R[1]
12.	1	Discussion on Competitive Examination related Questions / University previous year questions	GATE, ESE QP
Total No. of Hours Planned for Unit - I			12

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
<u>UNIT – II : SECOND LAW AND ENTROPY</u>			
13.	1	Heat engines, Heat pumps	T[1], T[2], W[1]
14.	1	Second law of thermodynamics – Kelvin Planck statement and Clausius statement	T[1], T[2]
15.	1	Equivalence. Reversible processes, cycles	T[1], T[2]

16.	1	Carnot cycle, reversed Carnot cycle, Efficiency of Heat engines & COP of Heat pumps.	T[1], T[2]
17.	1	Tutorial-3: Problems Related to Second Law & Carnot cycle	T[1], R[3]
18.	1	Corollaries of second law of thermodynamics and Absolute temperature scale	T[1], T[2]
19.	1	Concept of Entropy, Entropy of fluids and gases	T[1], T[2], W[1]
20.	1	Clausius theorem, absolute entropy, Clausius inequality,	T[1], T[2]
21.	1	Entropy- Principle, transfer, generation, balance - Third law of thermodynamics,	T[1], T[2]
22.	1	Problems in Clausius inequality	T[1], T[2]
23.	1	Tutorial-4: Problems Related to Carnot theorem and Clausius inequality	T[1], R[1], W[4]
24.	1	Discussion on Competitive Examination related Questions / University previous year questions	GATE, ESE QP
Total No. of Hours Planned for Unit - II			12

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
<u>UNIT – III : PROPERTIES OF PURE SUBSTANCE AND GAS MIXTURES</u>			
25.	1	Properties of pure substances in solid, liquid and vapour phases, phase change process	T[1], T[2]
26.	1	Property diagrams, Formation of steam, pVT diagram	T[1], T[2], W[1]
27.	1	Steam – types, dryness fraction, Avagadro’s law. Equation of state. Vander Waals’ equation	T[1], T[2]
28.	1	Virial expansions, Law of corresponding states, compressibility and its chart.	T[1], T[2]
29.	1	Problems solved on pure substances	T[1], T[2]
30.	1	Tutorial-5: Problems Related to Pure Substances	T[1], R[1]
31.	1	Real gas - compressibility and its chart	T[1], T[2], W[1]
32.	1	Mixture of gases, properties	T[1], T[2]
33.	1	Dalton’s law of partial pressure, exact differentials.	T[1], T[2]
34.	1	Problems solved on pure substances	T[1], T[2]
35.	1	Tutorial-6: Problems Related to Gas Mixtures	T[1], R[3], W[4]
36.	1	Discussion on Competitive Examination related Questions / University previous year questions	GATE, ESE QP
Total No. of Hours Planned for Unit - III			12

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
<u>UNIT – IV : THERMODYNAMIC AVAILABILITY AND RELATIONS</u>			
37.	1	Basics-Dead state, quality of energy	T[1], T[2]
38.	1	degradation of energy - Reversible processes	T[1], T[2]
39.	1	Maximum work - Exergy – Closed system - Steady flow system	T[1], T[2], J[1]
40.	1	Irreversibility - Exergy Balance	T[1], T[2], W[1]
41.	1	Second law efficiency – Exact differentials	T[1], T[2]
42.	1	Tutorial-5: Problems Related to Non Flow Systems	T[1], R[1]
43.	1	Tds Relations	T[1], T[2]
44.	1	Maxwell’s Relation	T[1], T[2]

45.	1	Clausius – Clapeyron Equation	T[1], T[2], W[1]
46.	1	Joule-Thompson Coefficient	T[1], T[2]
47.	1	Tutorial-6: Problems Related to steady Flow process & entropy	T[1], R[1], W[4]
48.	1	Discussion on Competitive Examination related Questions / University previous year questions	GATE, ESE QP
Total No. of Hours Planned for Unit - IV			12

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
<u>UNIT – V : PSYCHROMETRY</u>			
49.	1	Psychrometry and psychrometric properties.	T[1], T[2]
50.	1	Use of psychrometric chart and property calculation of Air vapour mixture.	T[1], T[2], W[1]
51.	1	Psychrometric processes, Sensible heating and cooling.	T[1], T[2]
52.	1	Latent heat, Sensible heat factor (SHF)	T[1], T[2]
53.	1	Problems by using Psychrometric chart and processes	T[1], T[2]
54.	1	Tutorial-9: Problems Related to Psychrometric Processes	T[1], R[3], W[4]
55.	1	Adiabatic mixing of air streams	T[1], T[2]
56.	1	Evaporative cooling	T[1], T[2]
57.	1	Application of psychrometry in air conditioning	T[1], T[2], W[1]
58.	1	Problems by using Psychrometry	T[1], T[2]
59.	1	Tutorial-10: Problems Related to Psychrometric Processes	T[1], R[1]
60.	1	Discussion on Competitive Examination related Questions / University previous year questions	GATE, ESE QP
Total No. of Hours Planned for Unit - V			12

TEXT BOOKS

T [1] – Nag.P.K, 2017, Engineering Thermodynamics, Tata McGraw–Hill, New Delhi.

T [2] – Cengel, 2017, Thermodynamics-An Engineering Approach, Tata McGraw–Hill, New Delhi.

REFERENCES

R [1] - Holman.J.P, 2017, Thermodynamics, McGraw–Hill, NewDelhi.

R [2] - Venwylen and Sontag, 1994, Classical Thermodynamics, Wiley Eastern, New Delhi

R [3] - Kothandaraman C.P. and Domkundwar S, 2004, Engineering Thermodynamics, Dhanpatrai and sons, New Delhi

WEBSITES

W [1] - http://nptel.iitm.ac.in/courses/Webcourse-contents/IIT%20Guwahati/engg_thermodynamics/index.htm

W [2] - <http://nptel.iitm.ac.in/video.php?subjectId=112103108>

W [3] - <http://web.mit.edu/emech/dontindex-build/index.html>

W [4] - <http://www.indiabix.com/engineering-thermodynamics/questions-and-answers/>

JOURNALS

J [1] – Journal of Thermal Sciences

J [2] – Journal of Heat and Mass Transfer

TOTAL NUMBER OF COURSE HOURS : 60 Hrs

PREPARED BY : P.PARANTHAMAN AP / MECH / FOE / KAHE

UNIT - I

BASIC CONCEPTS & FIRST LAW

LECTURE NOTES

Basic concepts - Classical and Statistical approaches - Thermodynamic systems - closed, open, isolated. Property - State - Process-adiabatic - Quasi-static process - Cycle - Point and Path function - Energy - Work transfer - Concept of temperature and heat- Zeroth law of thermodynamics - Concept of ideal gases - First law of thermodynamics -PMM1, internal energy, specific heat capacities, enthalpy, and its application to closed system and open system-steady flow energy equation.

1. Thermodynamics

Thermodynamics can be defined as the science of energy. The name thermodynamics stems from the Greek words therme (heat) and dynamis (power), which is most descriptive of the early efforts to convert heat into power.

1.1 Classical Thermodynamics (Macroscopic) & Statistical Thermodynamics (Microscopic)

- It is well-known that a substance consists of a large number of particles called molecules. The properties of the substance naturally depend on the behavior of these particles.
- For example, the pressure of a gas in a container is the result of momentum transfer between the molecules and the walls of the container.
- However, one does not need to know the behavior of the gas particles to determine the pressure in the container. It would be sufficient to attach a pressure gage to the container.
- This macroscopic approach to the study of thermodynamics that does not require knowledge of the behavior of individual particles is called **classical thermodynamics**.
- Thermodynamic approach by considering average behavior of large number of particles is termed as **Statistical Thermodynamics**.

1.2 Application of Thermodynamics:

- Thermodynamics is commonly encountered in many engineering systems and other aspects of life, and one does not need to go very far to see some application areas of it.
- Many ordinary household utensils and appliances are designed, in whole or in part, by using the principles of thermodynamics.
- Some examples include the electric or gas range, the heating and air-conditioning systems, the refrigerator, the humidifier, the pressure cooker, the water heater, the shower, the iron, and even the computer and the TV.
- On a larger scale, thermodynamics plays a major part in the design and analysis of automotive engines, rockets, jet engines, and conventional or nuclear power plants, solar collectors, and the design of vehicles from ordinary cars to airplanes.

1.3 Measuring Mass, Length, Time, and Force

- A unit is any specified amount of a quantity by comparison with which any other quantity of the same kind is measured.
- For example, meters, centimeters, kilometers, feet, inches, and miles are all units of length. Seconds, minutes, and hours are alternative time units.
- Because physical quantities are related by definitions and laws, a relatively small number of physical quantities suffice to conceive of and measure all others. These may be called primary dimensions.
- The others may be measured in terms of the primary dimensions and are called secondary.
- For example, if length and time were regarded as primary, velocity and area would be secondary.
- Let us illustrate these ideas by considering briefly the SI system of units.

Quantity	SI		
	Unit	Dimension	Symbol
mass	kilogram	M	kg
length	meter	L	m
time	second	t	s

1.3.1 Density (ρ)

Density is defined as the ratio of mass of the object to its volume occupied.

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{V}, kg/m^3$$

1.3.2 Specific volume (v)

It is defined as the inverse of density that is volume occupied by an object per unit mass of the same.

$$v = \frac{1}{\rho}, m^3/kg$$

1.3.3 Specific gravity (SG)

Sometimes the density of a substance is given relative to the density of a well-known substance. Then it is called specific gravity, or relative density, and is defined as the ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C, for which $\rho_{H_2O} = 1000 \text{ kg/m}^3$).

$$SG = \frac{\rho}{\rho_{H_2O}}$$

1.3.4 Velocity (V)

The rate of change of distance of an object with respect to time is defined as velocity. m/sec is the unit of velocity and it is expressed as

$$V = \frac{\text{Change in Distance}}{\text{Time Taken}}, \quad m/sec$$

1.3.5 Acceleration (a)

The rate of change of velocity of an object with respect to time is defined as acceleration. m/sec^2 is the unit of acceleration. The acceleration due to gravity effect of our earth's atmosphere is termed as acceleration due to gravity (g) and its value is 9.81 m/sec^2 .

1.3.6 Force (F)

According to Newton's second law (The rate of change of momentum is directly proportional to force) is expressed as the equality

$$F = ma$$

The newton, N, is the force required to accelerate a mass of 1 kilogram at the rate of 1 meter per second per second.

$$1 \text{ N} = (1 \text{ kg})(1 \text{ m/s}^2) = 1 \text{ kg} \cdot \text{m/s}^2$$

Quantity	Dimensions	Units	Symbol	Name
Velocity	Lt^{-1}	m/s		
Acceleration	Lt^{-2}	m/s^2		
Force	MLt^{-2}	kg m/s^2	N	newtons
Pressure	$\text{ML}^{-1} \text{t}^{-2}$	$\text{kg m/s}^2 (\text{N/m}^2)$	Pa	pascal
Energy	$\text{ML}^2 \text{t}^{-2}$	$\text{kg m}^2/\text{s}^2 (\text{N m})$	J	joule
Power	$\text{ML}^2 \text{t}^{-3}$	$\text{kg m}^2/\text{s}^3 (\text{J/s})$	W	watt

1.4 Pressure (p)

- Pressure** is defined as a normal force exerted by a fluid per unit area. pressure is defined as force per unit area, it has the unit of newtons per square meter (N/m^2), which is called a **pascal** (Pa). That is, $1 \text{ Pa} = 1 \text{ N/m}^2$

$$1 \text{ kPa} = 10^3 \text{ N/m}^2$$

$$1 \text{ bar} = 10^5 \text{ N/m}^2$$

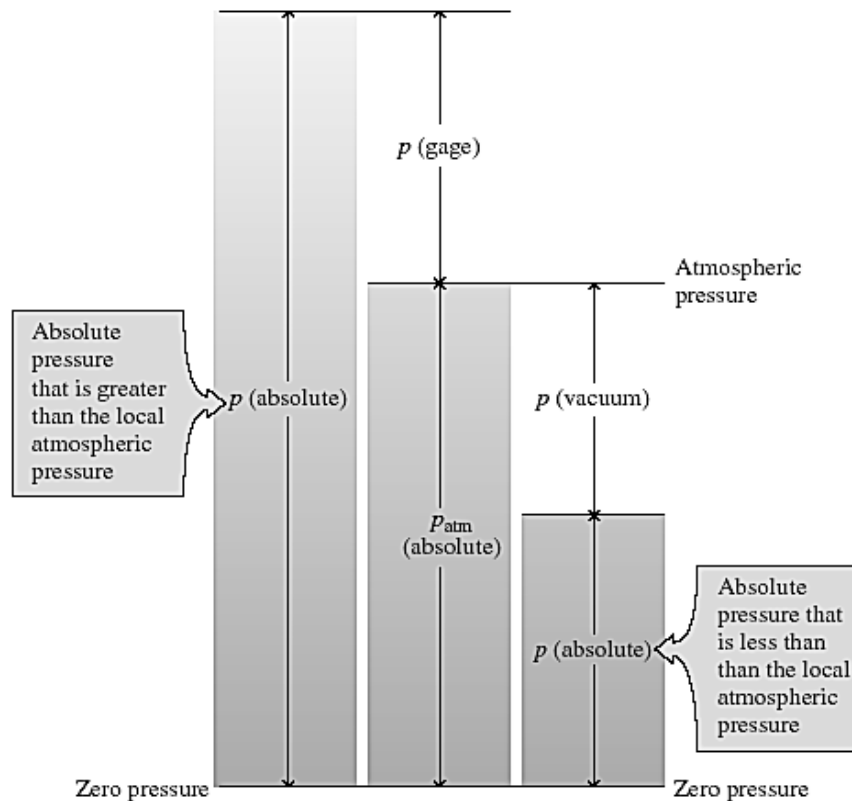
$$1 \text{ MPa} = 10^6 \text{ N/m}^2$$

$$1 \text{ standard atmosphere (atm)} = 1.01325 \times 10^5 \text{ N/m}^2$$

- The actual pressure at a given position is called the absolute pressure, and it is measured relative to absolute vacuum (i.e., absolute zero pressure).
- The difference between the absolute pressure and the local atmospheric pressure is called the gage pressure P_{gage} . It can be positive or negative, but pressures below atmospheric pressure are sometimes called vacuum pressures

$$p(\text{gage}) = p(\text{absolute}) - p_{\text{atm}}(\text{absolute})$$

$$p(\text{vacuum}) = p_{\text{atm}}(\text{absolute}) - p(\text{absolute})$$



- The pressure at a point in a fluid has the same magnitude in all directions. The variation of pressure with elevation is given by

$$\frac{dP}{dz} = -\rho g$$

- Where the positive z direction is taken to be upward. When the density of the fluid is constant, the pressure difference across a fluid layer of thickness Δz is

$$\Delta P = P_2 - P_1 = \rho g \Delta z$$

- The absolute and gage pressures in a liquid open to the atmosphere at a depth h from the free surface

$$P = P_{atm} - \rho g h \quad \text{or} \quad P_{gage} = \rho g h$$

- The atmospheric pressure is measured by a barometer and is given by

$$P_{atm} = \rho g h$$

- Where h is the height of the liquid column.

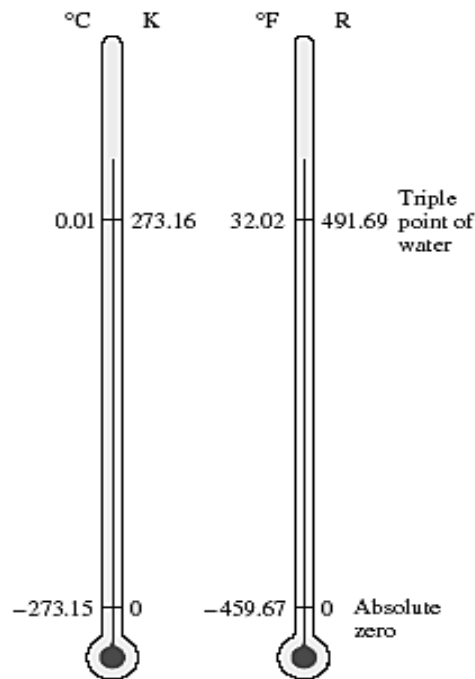
1.5 Temperature (T)

- We are familiar with temperature as a measure of "hotness" or "coldness," it is not easy to give an exact definition for it. Based on our physiological sensations, we express the level of temperature qualitatively with words like freezing cold, cold, warm, hot, and red-hot.

1.6 Zeroth Law of Thermodynamics

- When a body A is in thermal equilibrium with a Body B and also separately with a body C, then B & C will be in thermal equilibrium with each other. This is known as the Zeroth law of Thermodynamics.

- It is the basis of temperature measurement.



Relation between temperature scales

(T_c – Celsius Scale)

(T_k – Kelvin Scale)

(T_F – Fahrenheit Scale)

(T_R – Rankine Scale)

$$T(K) = T(^{\circ}C) + 273.15$$

$$T(R) = T(^{\circ}F) + 459.67$$

$$T(R) = 1.8 T(K)$$

1.7 Energy

- Although everybody has a feeling of what energy is, it is difficult to give a precise definition for it. Energy can be viewed as the ability to cause changes. Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear, and their sum constitutes the **total energy** E (or e on a unit mass basis) of a system.
- The international unit of energy is joule (J) or kilojoule (1 kJ = 1000 J). In the English system, the unit of energy is the British thermal unit (Btu),
- In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups: macroscopic and microscopic.
- The **macroscopic** forms of energy are those a system possesses as a whole with respect to some outside reference frame, such as **kinetic and potential energies**. The **microscopic** forms of energy are those related to the molecular structure of a system and the degree of the molecular activity,

and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the **internal energy** of a system and is denoted by U.

- The term energy was coined in 1807 by Thomas Young, and its use in thermodynamics was proposed in 1852 by Lord Kelvin.
- The term internal energy and its symbol U first appeared in the works of Rudolph Clausius and William Rankine in the second half of the nineteenth century, and it eventually replaced the alternative terms inner work, internal work, and intrinsic energy commonly used at the time.
- The macroscopic energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity, and surface tension.
- The energy that a system possesses as a result of its motion relative to some reference frame is called **kinetic energy** (KE). When all parts of a system move with the same velocity, the kinetic energy is expressed as

$$KE = m \frac{V^2}{2} \text{ (kJ)}$$

$$PE = m g z \text{ (kJ)}$$

- The energy that a system possesses as a result of its elevation in a gravitational field is called **potential energy** (PE) and is expressed as
- Energy can cross the boundary of a closed system in two distinct forms: heat and work

1.8 Basic Thermodynamic Concepts:

- Thermodynamic System

A system is defined as a quantity of matter or a region in space chosen for study.

- Surroundings

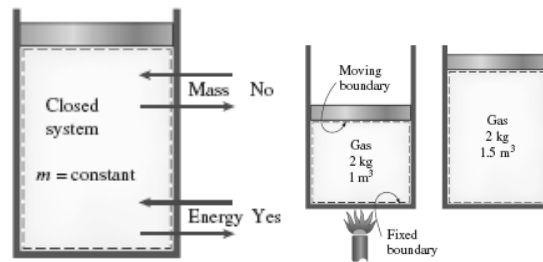
The mass or region outside the system is called the surroundings.

- Boundary

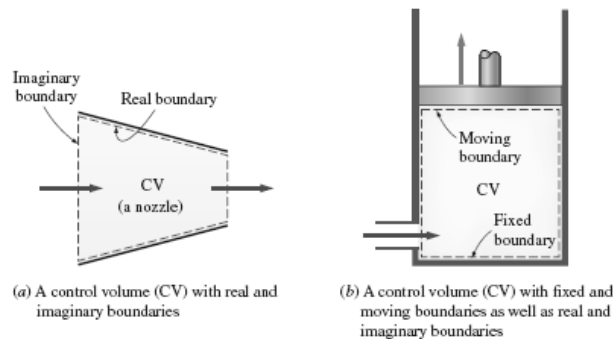
The real or imaginary surface that separates the system from its surroundings is called the boundary. The boundary of a system can be fixed or movable.



- Systems may be considered to be closed or open, depending on whether a fixed mass or a fixed volume in space is chosen for study.
- A closed system (also known as a control mass or just system when the context makes it clear) consists of a fixed amount of mass, and no mass can cross its boundary. That is, no mass can enter or leave a closed system, as shown in figure.



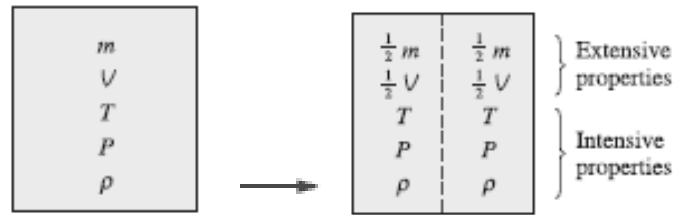
- But energy, in the form of heat or work, can cross the boundary; and the volume of a closed system does not have to be fixed.
- If, as a special case, even energy is not allowed to cross the boundary, that system is called an isolated system.
- An open system, or a control volume, as it is often called, is a properly selected region in space. It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Flow through these devices is best studied by selecting the region within the device as the control volume. Both mass and energy can cross the boundary of a control volume.
- A large number of engineering problems involve mass flow in and out of a system and, therefore, are modeled as control volumes.
- A water heater, a car radiator, a turbine, and a compressor all involve mass flow and should be analyzed as control volumes (open systems) instead of as control masses (closed systems).



- The boundaries of a control volume are called a control surface, and they can be real or imaginary.

1.9 Thermodynamic Properties

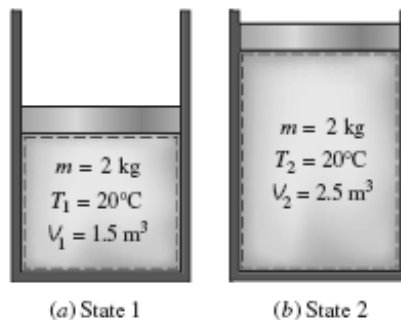
- Any characteristic of a system is called a **property**.
- Some familiar properties are pressure P , temperature T , volume V , and mass m . It also include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.
- Properties are considered to be either **intensive or extensive**.
- **Intensive properties** are those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties** are those whose values depend on the size – or extent – of the system. Total mass, total volume, and total momentum are some examples of extensive properties.



- Extensive properties per unit mass are called **specific properties**. Some examples of specific properties are specific volume, specific gravity and specific total energy.
- Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes known as a **continuum**.
- **Point Functions** are the thermodynamic properties, it results in an idealization concept known as **continuum**

1.10 Thermodynamic State

- Consider a system not undergoing any change. At this point, all the properties can be measured or calculated throughout the entire system, which gives us a set of properties that completely describes the condition, or **the state**, of the system. At a given state, all the properties of a system have fixed values.



1.11 Thermodynamic equilibrium

- Thermodynamics deals with equilibrium states. The word **equilibrium implies a state of balance**.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- A system in equilibrium experiences no changes when it is isolated from its surroundings.
- There are many types of equilibrium, and a system is not in thermodynamic equilibrium unless the conditions of all the relevant types of equilibrium are satisfied.
- For example, a system is in **thermal equilibrium** if the temperature is the same throughout the entire system. That is, the system involves no temperature differential, which is the driving force for heat flow.
- **Mechanical equilibrium** is related to pressure, and a system is in mechanical equilibrium if there is no change in pressure at any point of the system with time.
- If a system involves two phases, it is in **phase equilibrium** when the mass of each phase reaches an equilibrium level and stays there.

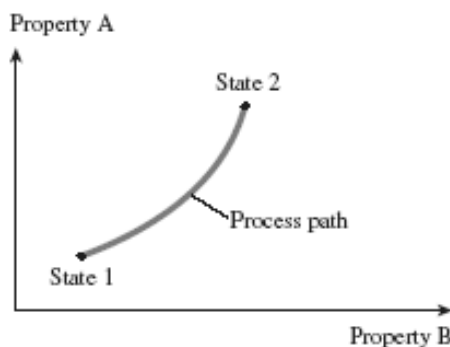
- Finally, a system is in **chemical equilibrium** if its chemical composition does not change with time, that is, no chemical reactions occur.
- The number of properties required to fix the state of a system is given by the state postulate:
- The state of a simple compressible system is completely specified by two independent, intensive properties.



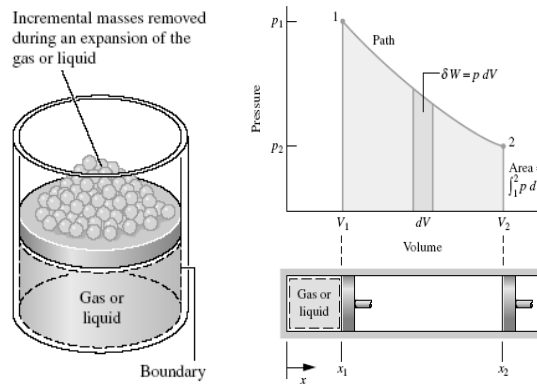
The state of nitrogen is fixed by two independent, intensive properties.

1.12 Process:

- Any change that a system undergoes from one equilibrium state to another is called a **process**, and the series of states through which a system passes during a process is called the **path of the process**.
- To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings.



- When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called a **quasi-static, or quasi-equilibrium, process**.
- A **quasi-equilibrium process** can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.



- A system is said to have undergone a **cycle** if it returns to its initial state at the end of the process. That is, for a cycle the initial and final states are identical.

1.13 First law of Thermodynamics

- The first law of thermodynamics, also known as the conservation of energy principle, provides a sound basis for studying the relationships among the various forms of energy and energy interactions. Based on experimental observations, the first law of thermodynamics states that energy can be neither created nor destroyed during a process; it can only change forms.

1.14 Energy Balance

- In the light of the preceding discussions, the conservation of energy principle can be expressed as follows: The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

$$\left(\begin{array}{c} \text{Total energy entering} \\ \text{the system} \end{array} \right) - \left(\begin{array}{c} \text{Total energy leaving} \\ \text{the system} \end{array} \right) = \left(\begin{array}{c} \text{change in the total} \\ \text{energy of the system} \end{array} \right)$$

Or

$$E_{in} - E_{out} = \Delta E_{sys}$$

1.15 Energy Change of a System, ΔE_{system}

- The determination of the energy change of a system during a process involves the evaluation of the energy of the system at the beginning and at the end of the process, and taking their difference. That is,

$$\text{Energy change} = \text{Energy at final state} - \text{Energy at initial state}$$

or

$$\Delta E = E_{final} - E_{initial} = E_2 - E_1$$

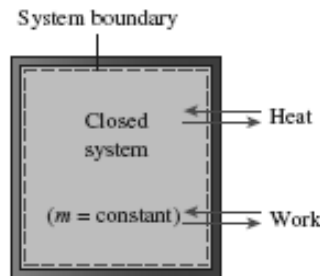
1.16 Mechanisms of Energy Transfer, E_{in} And E_{out}

- Energy can be transferred to or from a system in three forms: heat, work, and mass flow.
- Energy interactions are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.

- The only two forms of energy interactions associated with a fixed mass or closed system are heat transfer and work.

1.17 Heat (Q)

- Heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference. That is, an energy interaction is heat only if it takes place because of a temperature difference.



- A process during which there is no heat transfer is called an adiabatic process
- The amount of heat transferred during the process between two states (states 1 and 2) is denoted by Q_{12} , or just Q & heat has energy units, kJ (or Btu). Heat transfer *per unit mass* of a system is denoted by q and is determined from

$$q = \frac{Q}{m}, \quad \text{kJ/kg}$$

- Sign Convention,**

$Q > 0$ (+ve value): heat transfer to the system

$Q < 0$ (-ve value): heat transfer from the system

1.18 Work (W)

- Work, like heat, is an energy interaction between a system and its surroundings. Energy can cross the boundary of a closed system in the form of heat or work. Therefore, if the energy crossing the boundary of a closed system is not heat, it must be work.

Forms of Work:

- Mechanical form of work
Example: Shaft work, Spring work, Work Done on Elastic Solid Bars, Work Associated with the Stretching of a Liquid Film, Work Done to Raise or to Accelerate a Body,
- Non mechanical form of work
Example: Electrical work, Magnetic work, magnetic polarization work
- Sign Convention

$W > 0$ (+ve value): work done by the system

$W < 0$ (-ve value): work done on the system

(compressible fluid)	$W = \int_1^2 p dV$		
Electrical work	$W = \int_1^2 E dC = \int_1^2 EI d\tau$	Surface film	$W = - \int_1^2 \sigma dA$
Shaft work	$W = \int_1^2 T d\theta$	Stretched wire	$W = - \int_1^2 \mathcal{F} dL$
Magnetised solid			$W = - \int_1^2 H dI$

1.19 Power

The rate of energy transfer by work is called power and denoted by P . The unit for power is Watt (W).

The energy balance can be written more explicitly as

$$= (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{sys}$$

- For a closed system undergoing a cycle, the initial and final states are identical, and thus

$$\Delta E_{sys} = E_2 - E_1 = 0$$

$$W_{net,out} = Q_{net,in} \text{ (for a cycle)}$$

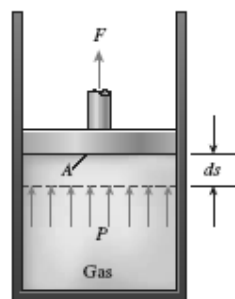
- The energy balance relation for a closed system undergoing a process (i.e. from state 1 to state 2) becomes

$$Q_{net,in} - W_{net,out} = \Delta E_{sys} \text{ (or) } Q - W = \Delta E$$

1.20 Moving boundary work

- Consider the gas enclosed in the piston-cylinder device shown in Fig. 4-2. The initial pressure of the gas is P , the total volume is V , and the cross sectional area of the piston is A .
- If the piston is allowed to move some distance ds in a quasi-equilibrium manner, the differential work done during this process is

$$\delta W_b = F ds = PA ds = P dV$$



A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount ds .

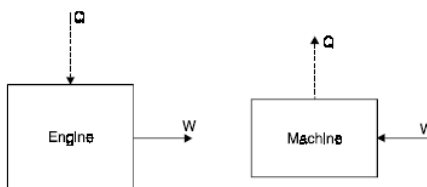
- The total boundary work done during the entire process as the piston moves is obtained by adding all the differential works from the initial state to the final state:

$$W_b = \int_1^2 P dV, \quad kJ$$

- The compression or expansion process can occur with keeping any one of the thermodynamic properties constant and such processes are given name starting with iso. (Isothermal, Isobaric, Isochoric etc.)

1.21 Perpetual Motion Machine of the First Kind – PMM 1

- The first law of thermodynamics 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 form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM 1. A PMM 1 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.



1.22 The Characteristic Equation of State

- At temperatures that are considerably in excess of critical temperature of a fluid, and also at very low pressure, the vapour of fluid tends to obey the equation

$$\frac{PV}{T} = \text{constant} = R$$

- In practice, no gas obeys this law rigidly, but many gases tend towards it.
- An imaginary ideal gas which obeys this law is called a perfect gas, and the equation

$$\frac{PV}{T} = R$$

is called the characteristic equation of a state of a perfect gas. The constant R is called the gas constant. Each perfect gas has a different gas constant.

- Units of R are Nm/kg K or kJ/kg K .
- Usually, the characteristic equation is written as

$$Pv = RT$$

or for, m kg, occupying $V \text{ m}^3$

$$PV = mRT$$

- The characteristic equation in another form can be derived by using kilogram-mole as a unit.
- The kilogram-mole is defined as a quantity of a gas equivalent to M kg of the gas, where M is the molecular weight of the gas (e.g., since the molecular weight of oxygen is 32, then 1 kg mole of oxygen is equivalent to 32 kg of oxygen).
- As per definition of the kilogram-mole, for m kg of a gas, we have

$$m = nM$$

- Where n = number of moles.
- Since the standard of mass is the kg, kilogram-mole will be written simply as mole.

$$PV = nMRT$$

- According to Avogadro's hypothesis the volume of 1 mole of any gas is the same as the volume of 1 mole of any other gas, when the gases are at the same temperature and pressure.
- Therefore, $\frac{V}{n}$ is the same for all gases at the same value of p and T . That is the quantity $\frac{pV}{nT}$ is a constant for all gases. This constant is called universal gas constant, and is given the symbol, R_u .

$$\text{i.e., } MR = R_u = PV/nT$$

or

$$PV = nR_uT$$

- Since $MR = R_u$, then

$$R = \frac{R_u}{M}$$

1.23 Types of process:

1.23.1 Reversible and Irreversible Processes

a) Reversible process

A reversible process (also sometimes known as quasi-static process) is one which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states.

This process has the following characteristics:

1. It must pass through the same states on the reversed path as were initially visited on the forward path.
2. This process when undone will leave no history of events in the surroundings.
3. It must pass through a continuous series of equilibrium states.

No real process is truly reversible but some processes may approach reversibility, to close approximation.

b) Irreversible process

An irreversible process is one in which heat is transferred through a finite temperature.

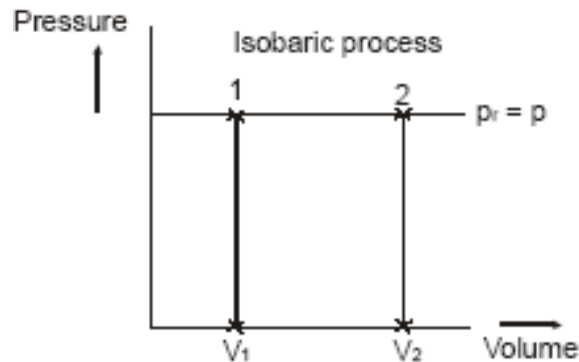
An irreversible process is usually represented by a dotted (or discontinuous) line joining the end states to indicate that the intermediate states are indeterminate.

Irreversibility's are of two types:

1. External irreversibility's. These are associated with dissipating effects outside the working fluid.
Example. Mechanical friction occurring during a process due to some external source.
2. Internal irreversibility's. These are associated with dissipating effects within the working fluid.

1.23.2 Constant Pressure Process or Isobaric Process:

It refers to the thermodynamic process in which there is no change in pressure during the process. Such types of processes are also known as isobaric processes.



It refers to the thermodynamic process in which there is no change in pressure during the process. Such types of processes are also known as isobaric processes.

The P-v-T relation of an ideal gas for such a process becomes

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$$

And since pressure remains constant in this process ($P_1 = P_2$), therefore

$$\frac{v_1}{T_1} = \frac{v_2}{T_2}$$

Heat transfer & work transfer is given as

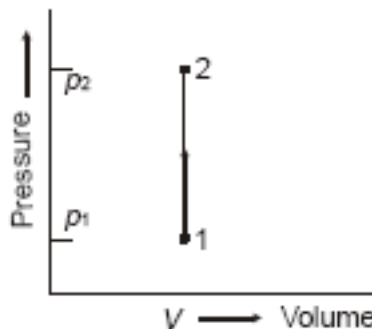
$$Q = m c_p \Delta T \quad \& \quad W = P (V_2 - V_1), \text{ kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = m c_v \Delta T \quad \& \quad \Delta H = m c_p \Delta T, \text{ kJ}$$

1.23.3 Constant Volume Process or Isochoric Process:

When a fluid undergoes a thermodynamic process in a fixed enclosed space such that the process occurs at constant volume, then the process is called constant volume process or isochoric process.



It refers to the thermodynamic process in which there is no change in volume during the process. Such types of processes are also known as isochoric processes.

The P-v-T relation of an ideal gas for such a process becomes

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$$

And since pressure remains constant in this process ($v_1 = v_2$), therefore

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Heat transfer & work transfer is given as

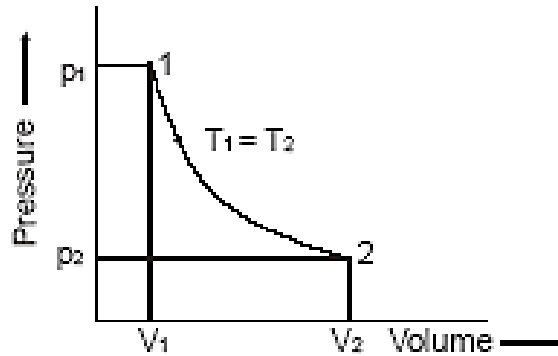
$$Q = m c_v \Delta T, \text{ kJ} \quad \& \quad W = 0, \text{ kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = m c_v \Delta T \quad \& \quad \Delta H = m c_p \Delta T, \text{ kJ}$$

1.23.4 Constant Temperature Process or Isothermal Process:

Thermodynamic process in which the temperature remains constant is called constant temperature or isothermal process.



It refers to the thermodynamic process in which there is no change in temperature during the process. Such types of processes are also known as isothermal processes.

The P-v-T relation of an ideal gas for such a process becomes

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$$

And since temperature remains constant in this process ($T_1 = T_2$), therefore

$$P_1 v_1 = P_2 v_2 = \text{constant}$$

Heat transfer & work transfer is given as

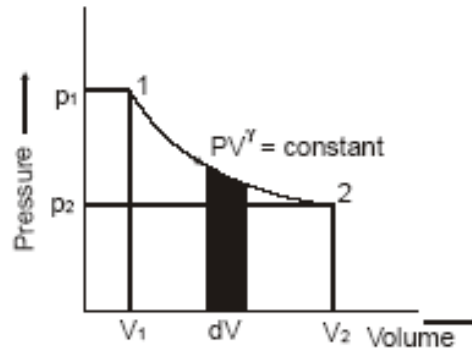
$$Q = W = P_1 V_1 \ln \left(\frac{V_2}{V_1} \right) = m R T \ln \left(\frac{V_2}{V_1} \right), \text{ kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = 0 \quad \& \quad \Delta H = 0, \text{ kJ}$$

1.23.5 Adiabatic Process:

An adiabatic process is the thermodynamic process in which there is no heat interaction during the process, i.e. during the process, $Q = 0$. The adiabatic process follows the law $PV^\gamma = \text{constant}$ where γ is called adiabatic index and is given by the ratio of two specific heats.



An adiabatic process is the thermodynamic process in which there is no heat interaction during the process, i.e. during the process, $Q = 0$. The adiabatic process follows the law $PV^\gamma = \text{constant}$ where γ is called adiabatic index and is given by the ratio of two specific heats.

The P-v-T relation of an ideal gas for such a process becomes

$$P_1 v_1^\gamma = P_2 v_2^\gamma \leftrightarrow \frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^\gamma$$

Also

$$\frac{T_2}{T_1} = \frac{P_2}{P_1} \times \frac{v_2}{v_1} = \left(\frac{v_2}{v_1}\right)^{-\gamma} \times \frac{v_2}{v_1} = \left(\frac{v_2}{v_1}\right)^{1-\gamma} \leftrightarrow \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}$$

Heat transfer & work transfer is given as

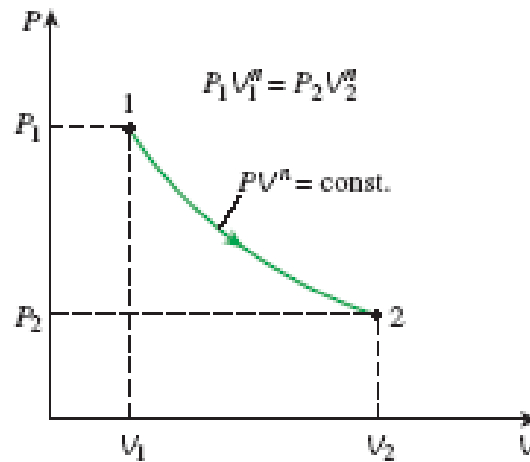
$$Q = 0 \text{ \& } W = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{m R (T_1 - T_2)}{\gamma - 1}, \text{ kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = m c_v \Delta T \text{ \& } \Delta H = m c_p \Delta T, \text{ kJ}$$

1.23.6 Polytropic Process:

Polytropic process is the most commonly used process in practice. In this, the thermodynamic process is said to be governed by the law $PV^n = \text{constant}$ where n is the index which can vary from $-\infty$ to $+\infty$.



Polytropic process is the most commonly used process in practice. In this, the thermodynamic process is said to be governed by the law $PV^n = \text{constant}$ where n is the index which can vary from $-\infty$ to $+\infty$.

The P-v-T relation of an ideal gas for such a process becomes

$$P_1 v_1^n = P_2 v_2^n \leftrightarrow \frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^n$$

Also

$$\frac{T_2}{T_1} = \frac{P_2}{P_1} \times \frac{v_2}{v_1} = \left(\frac{v_2}{v_1}\right)^{-n} \times \frac{v_2}{v_1} = \left(\frac{v_2}{v_1}\right)^{1-n} \leftrightarrow \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{n-1}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{n-1/n}$$

Heat transfer & work transfer is given as

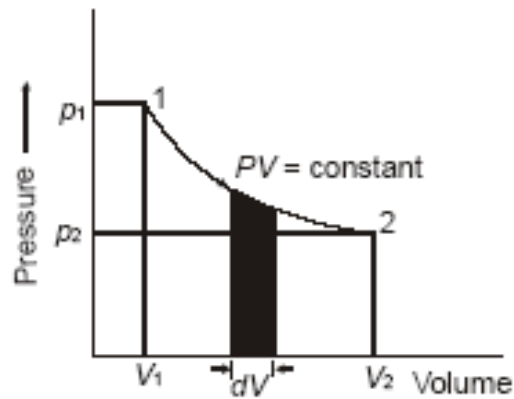
$$Q = W \times \left(\frac{\gamma - n}{\gamma - 1}\right) \text{ \& } W = \frac{P_1 V_1 - P_2 V_2}{n - 1} = \frac{m R (T_1 - T_2)}{n - 1}, \text{ kJ}$$

And the change in internal energy & enthalpy is given as

$$\Delta U = m c_v \Delta T \text{ \& } \Delta H = m c_p \Delta T, \text{ kJ}$$

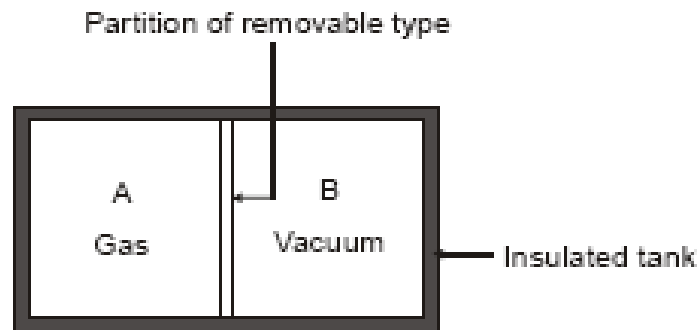
1.23.7 Hyperbolic Process:

Hyperbolic process is the one in which product of pressure and volume remains constant during the process. The curve for such an expansion process is a rectangular hyperbola and hence this is known as hyperbolic expansion.



1.23.8 Free Expansion:

Free expansion, as the name implies refers to the unrestrained expansion of a gas.



1.24 Enthalpy

Enthalpy (H) of a substance at any point is quantification of energy content in it, which could be given by summation of internal energy and flow energy. Enthalpy is very useful thermodynamic property for the analysis of engineering systems.

Mathematically, it is given as,

$$H = U + PV$$

On unit mass basis, the specific enthalpy could be given as,

$$h = u + Pv$$

1.25 Specific Heats

The specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree. In general, this energy depends on how the process is executed.

In thermodynamics, we are interested in two kinds of specific heats: specific heat at constant volume c_v and specific heat at constant pressure c_p .

Physically, the specific heat at constant volume c_v can be viewed as the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

The energy required to do the same as the pressure is maintained constant is the specific heat at constant pressure c_p . The specific heat at constant pressure c_p is always greater than c_v because at

constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system.

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v \quad \& \quad c_p = \left(\frac{\partial h}{\partial T} \right)_p$$

Using the definition of enthalpy and the equation of state of an ideal gas, we have

$$\left. \begin{array}{l} h = u + Pv \\ Pv = RT \end{array} \right\} h = u + RT$$

Since R is constant and $u = u(T)$, it follows that the enthalpy of an ideal gas is also a function of temperature only

$$h = h(T)$$

Since u and h depend only on temperature for an ideal gas, the specific heats c_v and c_p also depend, at most, on temperature only. Therefore, at a given temperature, u, h, c_v , and c_p of an ideal gas have fixed values regardless of the specific volume or pressure. The differential changes in the internal energy and enthalpy of an ideal gas can be expressed as

$$du = c_v(T) dT \quad \& \quad dh = c_p(T) dT$$

The change in internal energy or enthalpy for an ideal gas during a process from state 1 to state 2 is determined by integrating these equations

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T) dT = c_v(T_2 - T_1)$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T) dT = c_p(T_2 - T_1)$$

1.26 Specific Heat Relations of Ideal Gases

A special relationship between c_p and c_v for ideal gases can be obtained by differentiating the relation $h = u + RT$, which yields

$$dh = du + R dT$$

Replacing dh by $c_p dT$ and du by $c_v dT$ and dividing the resulting expression by dT , we obtain

$$c_p - c_v = R$$

This is an important relationship for ideal gases since it enables us to determine c_v from a knowledge of c_p and the gas constant R. At this point, we introduce another ideal-gas property called the specific heat ratio γ , defined as

$$\gamma = \frac{c_p}{c_v}$$

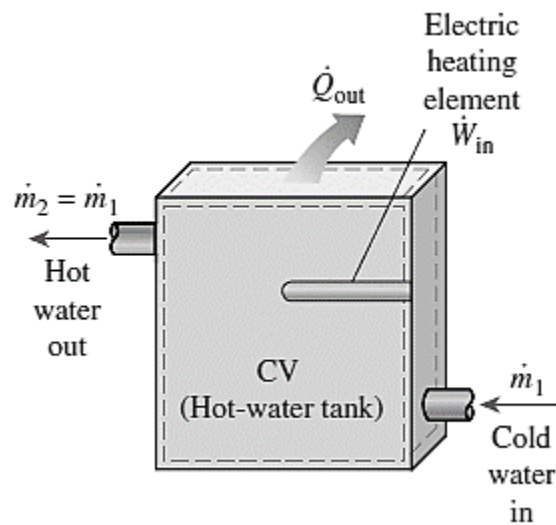
The specific ratio also varies with temperature, but this variation is very mild. For monatomic gases, its value is essentially constant at 1.667. Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

1.27 Path Function

Work & heat are termed as path functions and it is not a thermodynamic property since it does not depend on the particular state of the system but it depends on the path taken by the system undergoing a process from state 1 to state 2. Hence heat and work are considered as inexact or imperfect differentials.

1.28. Mass Flow, \dot{m}

- Mass flow in and out of the system serves as an additional mechanism of energy transfer. When mass enters a system, the energy of the system increases because mass carries energy with it (in fact, mass is energy).
- Likewise, when some mass leaves the system, the energy contained within the system decreases because the leaving mass takes out some energy with it.



The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

1.29 Mass and Volume Flow Rates

- The amount of mass flowing through a cross section per unit time is called the **mass flow rate** and is denoted by \dot{m} . The dot over a symbol is used to indicate time rate of change.

$$\dot{m} = \rho V A$$

- The volume of the fluid flowing through a cross section per unit time is called the volume flow rate \dot{V}

$$\dot{V} = V A \quad m^3/s$$

- The mass and volume flow rates are related by

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$

- Where v is the specific volume. This relation is analogous to $m = \rho V = V/v$, which is the relation between the mass and the volume of a fluid in a container.

1.30 Conservation of Mass Principle

- The conservation of mass principle for a control volume can be expressed as: The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) of the total mass within the control volume during Δt . That is,

$$\left(\begin{array}{c} \text{Total mass entering} \\ \text{the CV during } \Delta t \end{array} \right) - \left(\begin{array}{c} \text{Total mass leaving} \\ \text{the CV during } \Delta t \end{array} \right) = \left(\begin{array}{c} \text{Net change of mass} \\ \text{within the CV during } \Delta t \end{array} \right)$$

$$m_{in} - m_{out} = \Delta m_{CV} \quad kg$$

OR

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{CV} \quad kg/s$$

1.31 Mass Balance for Steady-Flow Processes

- During a steady-flow process, the total amount of mass contained within a control volume does not change with time ($m_{CV} = \text{constant}$).
- When dealing with steady-flow processes, we are not interested in the amount of mass that flows in or out of a device over time; instead, we are interested in the amount of mass flowing per unit time, that is, the mass flow rate \dot{m} . The conservation of mass principle for a general steady flow system with multiple inlets and outlets is expressed in rate form as

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (kg/s)$$

- It states that the total rate of mass entering a control volume is equal to the total rate of mass leaving it. Many engineering devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet).
- For single-stream steady-flow systems,

$$\dot{m}_1 = \dot{m}_2 \rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

1.32 Flow Work and The Energy of a Flowing Fluid

- Unlike closed systems, control volumes involve mass flow across their boundaries, and some work is required to push the mass into or out of the control volume. This work is known as the flow work, or flow energy, and is necessary for maintaining a continuous flow through a control volume.

1.33 Total Energy of a Flowing Fluid

- the total energy of a simple compressible system consists of three parts: internal, kinetic, and potential energies. On a unit-mass basis, it is expressed as

$$e = u + ke + pe = u + \frac{V^2}{2} + g z \quad , \quad kJ/kg$$

- Where V is the velocity and z is the elevation of the system relative to some external reference point.
- The fluid entering or leaving a control volume possesses an additional form of energy, the flow energy Pv . Then the total energy of a flowing fluid on a unit-mass basis (denoted by u) becomes

$$\theta = Pv + e = Pv + u + ke + pe$$

- But the combination $Pv + u$ has been previously defined as the enthalpy h .

$$\theta = h + ke + pe = h + \frac{V^2}{2} + g z, \quad kJ/kg$$

- By using the enthalpy instead of the internal energy to represent the energy of a flowing fluid, one does not need to be concerned about the flow work. The energy associated with pushing the fluid into or out of the control volume is automatically taken care of by enthalpy.

1.34 Energy Analysis of Steady-Flow Systems

- A large number of engineering devices such as turbines, compressors, and nozzles operate for long periods of time under the same conditions once the transient start-up period is completed and steady operation is established, and they are classified as **steady-flow devices**
- During a steady-flow process, no intensive or extensive properties within the control volume change with time. Thus, the volume V , the mass m , and the total energy content E of the control volume remain constant
- The fluid properties at an inlet or exit remain constant during a steady flow process.
- Also, the heat and work interactions between a steady-flow system and its surroundings do not change with time.
- Thus, the power delivered by a system and the rate of heat transfer to or from a system remains constant during a steady-flow process.
- The mass balance for a single-stream (one-inlet and one-outlet) steady-flow system is given as

$$\dot{m}_1 = \dot{m}_2 \rightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

- Where the subscripts 1 and 2 denote the inlet and the exit states, respectively, ρ is density, V is the average flow velocity in the flow direction, and A is the cross-sectional area normal to flow direction.
- During a steady-flow process, the total energy content of a control volume remains constant ($E_{CV} = \text{constant}$), and thus the change in the total energy of the control volume is zero ($\Delta E_{CV} = 0$).
- Therefore, the amount of energy entering a control volume in all forms (by heat, work, and mass) must be equal to the amount of energy leaving it.
- Then the rate form of the general energy balance reduces for a steady-flow process to

$$E_{in} - E_{out} = \Delta E_{CV} = 0 \text{ for steady flow process}$$

$$\therefore E_{in} = E_{out}$$

- for a general steady-flow system can also be written more explicitly as

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m} \left(h + \frac{V^2}{2} + g z \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m} \left(h + \frac{V^2}{2} + g z \right)$$

Based on the first law expression for a process

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m} \left(h + \frac{V^2}{2} + g z \right) - \sum_{in} \dot{m} \left(h + \frac{V^2}{2} + g z \right)$$

For a single stream steady flow process

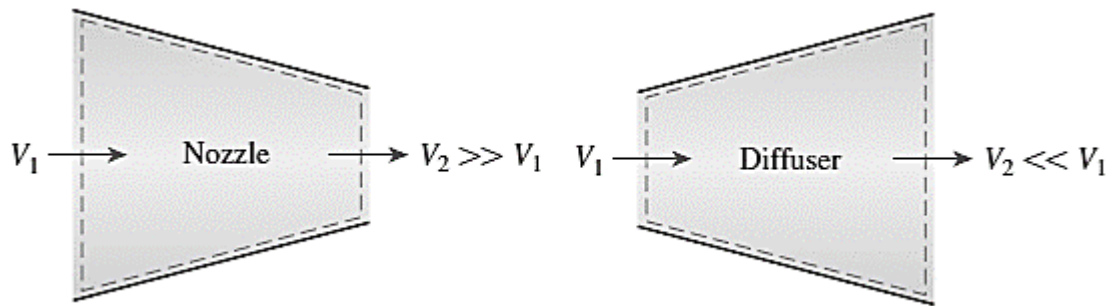
$$\dot{Q} - \dot{W} = \dot{m} \left\{ \left(h_2 + \frac{V_2^2}{2} + g z_2 \right) - \left(h_1 + \frac{V_1^2}{2} + g z_1 \right) \right\}$$

1.35 Steady-Flow Engineering Devices

- Some common steady-flow devices are described, and the thermodynamic aspects of the flow through them are analyzed. The conservation of mass and the conservation of energy principles for these devices are illustrated with examples.

1.35.1 Nozzles and Diffusers

- Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses.
- A nozzle is a device that increases the velocity of a fluid at the expense of pressure.
- A diffuser is a device that increases the pressure of a fluid by slowing it down.
- That is, nozzles and diffusers perform opposite tasks.



- The rate of heat transfer between the fluid flowing through a nozzle or a diffuser and the surroundings is usually very small ($\dot{Q} \approx 0$) since the fluid has high velocities, and thus it does not spend enough time in the device for any significant heat transfer to take place.
- Nozzles and diffusers typically involve no work ($\dot{W} = 0$) and any change in potential energy is negligible ($\Delta p_e \approx 0$).
- as a fluid passes through a nozzle or diffuser, it experiences large changes in its velocity and hence the change in kinetic energy is not equal to zero ($\Delta ke \neq 0$).

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} + g z_1 \right) = \dot{m} \left(h_2 + \frac{V_2^2}{2} + g z_2 \right)$$

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

1.35.2 Turbines and Compressors

- In steam, gas, or hydroelectric power plants, the device that drives the electric generator is the **turbine**. As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft. As a result, the shaft rotates, and the turbine produces work.
- Compressors**, as well as pumps and fans, are devices used to increase the pressure of a fluid. Work is supplied to these devices from an external source through a rotating shaft. Therefore, compressors involve work inputs.
- Even though these three devices function similarly, they do differ in the tasks they perform.
- A **fan** increases the pressure of a gas slightly and is mainly used to mobilize a gas.
- A **compressor** is capable of compressing the gas to very high pressures.
- Pumps** work very much like compressors except that they handle liquids instead of gases.

- Note that turbines produce power output whereas compressors, pumps, and fans require power input. ($\dot{W} \neq 0$)
- Heat transfer from turbines is usually negligible ($\dot{Q} \cong 0$) since they are typically well insulated.
- Heat transfer is also negligible for compressors unless there is intentional cooling.
- Potential energy changes are negligible for all of these devices ($\Delta pe \cong 0$).
- The velocities involved in these devices, with the exception of turbines and fans, are usually too low to cause any significant change in the kinetic energy ($\Delta ke \cong 0$).
- The fluid velocities encountered in most turbines are very high, and the fluid experiences a significant change in its kinetic energy. However, this change is usually very small relative to the change in enthalpy, and thus it is often disregarded.
- For a compressor, the energy balance equation becomes

$$\dot{W}_{in} + \dot{m} \left(h_1 + \frac{V_1^2}{2} + g z_1 \right) = \dot{Q}_{out} + \dot{m} \left(h_2 + \frac{V_2^2}{2} + g z_2 \right)$$

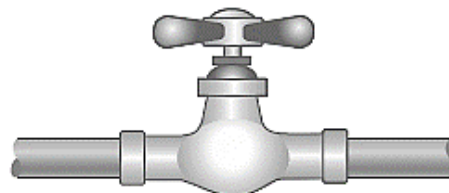
- For a turbine, the energy balance equation becomes

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} + g z_1 \right) = \dot{W}_{out} + \dot{Q}_{out} + \dot{m} \left(h_2 + \frac{V_2^2}{2} + g z_2 \right)$$

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} + g z_1 \right) = \dot{W}_{out} + \dot{m} \left(h_2 + \frac{V_2^2}{2} + g z_2 \right) \quad \text{if } \dot{Q} = 0$$

1.35.3 Throttling Valves

- Throttling valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid. Some familiar examples are ordinary adjustable valves, capillary tubes, and porous plugs.



(a) An adjustable valve



(b) A porous plug



(c) A capillary tube

- Unlike turbines, they produce a pressure drop without involving any work. The pressure drop in the fluid is often accompanied by a large drop in temperature, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications.
- Throttling valves are usually small devices, and the flow through them may be assumed to be adiabatic ($\dot{q} \cong 0$) since there is neither sufficient time nor large enough area for any effective heat

transfer to take place. Also, there is no work done ($\dot{w} = 0$), and the change in potential energy, if any, is very small ($\Delta pe \cong 0$).

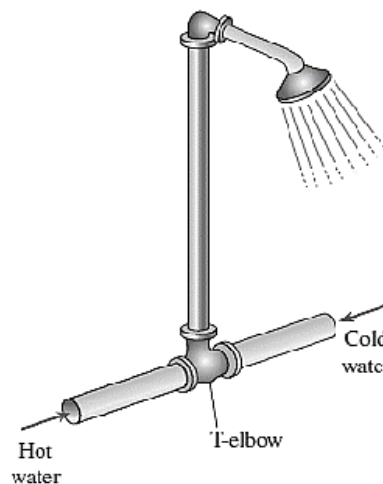
- Even though the exit velocity is often considerably higher than the inlet velocity, in many cases, the increase in kinetic energy is insignificant ($\Delta ke \cong 0$).
- Then the conservation of energy equation for this single-stream steady-flow device reduces to

$$h_1 = h_2$$

1.35.4 Mixing Chambers

- In engineering applications, mixing two streams of fluids is not a rare occurrence. The section where the mixing process takes place is commonly referred to as a mixing chamber. The mixing chamber does not have to be a distinct “chamber.” An ordinary T-elbow or a Y-elbow in a shower, for example, serves as the mixing chamber for the cold- and hot-water streams (Fig. 5–35).
- The conservation of mass principle for a mixing chamber requires that the sum of the incoming mass flow rates equal the mass flow rate of the outgoing mixture.
- Mixing chambers are usually well insulated ($\dot{q} \cong 0$) and usually do not involve any kind of work ($\dot{w} = 0$).
- Also, the kinetic and potential energies of the fluid streams are usually negligible ($ke \cong 0$, $pe \cong 0$).
- Then all there is left in the energy equation is the total energies of the incoming streams and the outgoing mixture.
- The conservation of energy principle requires that these two equals each other.
- Therefore, the conservation of energy equation becomes analogous to the conservation of mass equation for this case.

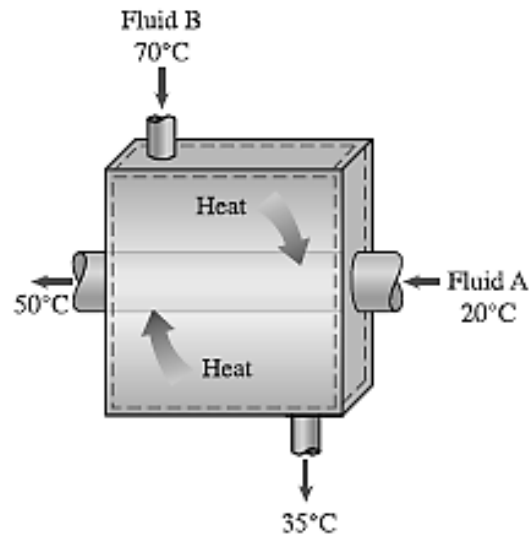
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$



1.35.5 Heat Exchangers

- heat exchangers are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various industries, and they come in various designs.
- The simplest form of a heat exchanger is a double-tube (also called tube-and-shell) heat exchanger.

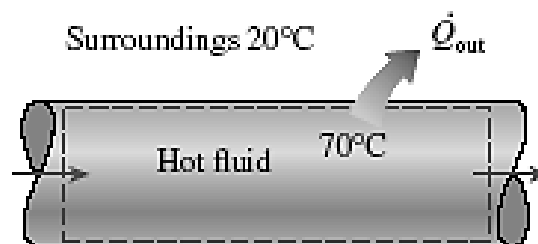
- The conservation of mass principle for a heat exchanger in steady operation requires that the sum of the inbound mass flow rates equal the sum of the outbound mass flow rates. This principle can also be expressed as follows:



- Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.
- Heat exchangers typically involve no work interactions ($\dot{w} = 0$) and negligible kinetic and potential energy changes ($\Delta ke \cong 0$, $\Delta pe \cong 0$) for each fluid stream.

1.35.6 Pipe and Duct Flow

- The transport of liquids or gases in pipes and ducts is of great importance in many engineering applications. Flow through a pipe or a duct usually satisfies the steady-flow conditions and thus can be analyzed as a steady flow process.



TWO MARK QUESTION AND ANSWERS

1. What is open system?

ANS: When a system has both mass and energy transfer it is called as open system.

Example: Air Compressor.

2. State PMM-I.

ANS : PMM of its first kind delivers work continuously without any input. It violates first law of thermodynamics. It is impossible to construct an engine working with this principle.

3. Define process.

ANS: It is defined as the change of state undergone by a gas due to energy flow.

4. Define cycle.

ANS: When a system undergoes a series of processes and return to its initial condition, it is known as cycle.

5. What is closed system?

ANS: When a system has only heat and work transfer, but there is no mass transfer, it is called as closed system. Example: Piston and cylinder arrangement.

6. Define first law of thermodynamics.

ANS : When a system undergoes a cyclic process then the net heat transfer is equal to net work transfer.

7. What is a steady flow process?

ANS: During the process the rate of flow of mass and energy across the boundary remains constant, is known as steady flow process.

8. State Kelvin Planck statement of second law of thermodynamics.

ANS : Kelvin planck statement says, "It is not possible to have a heat engine which can produce work by interacting with single thermal reservoir.

9. What is refrigerator?

ANS: A refrigerator is a device which operating in a cyclic process, maintains the temperature of a cold body at a temperature lower than the temperature of the surroundings.

10. Define the term COP.

ANS: Co-efficient of performance is defined as the ratio of heat extracted or rejected to work input.

$$\text{COP} = \text{Heat extracted or rejected} / \text{work input}$$

11. Define the term entropy

ANS: Entropy is an index of unavailability or degradation of energy.

PROBLEMS:

- The internal energy of a certain substance is given by the following equation $u = 3.56pv + 84$, where u is given in kJ/kg, p is in kPa, and v is in m^3/kg . A system composed of 3kg of this substance expands from an initial pressure of 500 kPa and a volume of 0.22 m^3 to a final pressure 100 kPa in a process in which pressure and volume are related by $pv^{1.2} = \text{constant}$. If the expansion is quasi-static, find Q , ΔU , and W for the process.

Solution:

According to the first law of thermodynamics, for a closed system undergoing a process

$$Q = \Delta U + W$$

Where

$$\Delta U = U_2 - U_1 = 3.56(P_2V_2 - P_1V_1)$$

We know that for a polytropic process with $n = 1.2$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n$$

On solving

$$V_2 = 0.056 \text{ m}^3$$

Therefore,

$$\Delta U = U_2 - U_1 = 3.56(100 \times 0.056 - 500 \times 0.22) = -371.66 \text{ kJ}$$

The work done during a polytropic process is given as

$$W = \frac{P_1 V_1 - P_2 V_2}{n - 1} = \frac{500 \times 0.22 - 100 \times 0.056}{1.2 - 1} = 522 \text{ kJ}$$

Therefore,

$$Q = \Delta U + W$$

$$Q = -371.66 + 522 = 150.34 \text{ kJ}$$

2. A piston and cylinder machine contains a fluid system which passes through a complete cycle of four processes. During a cycle, the sum of all heat transfers is -170 kJ. The system completes 100 cycles per minute. Complete the following table showing the method for each item and compute the net rate of work output in kW.

Process	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a-b	0	2170	-----
b-c	21000	0	-----
c-d	-2100	-----	-36600
d-a	-----	-----	-----

Solution:

According to the first law of thermodynamics, for a closed system undergoing a process

$$Q = \Delta E + W$$

Therefore, for process 1-2

$$Q_{1-2} = \Delta E_{1-2} + W_{1-2}$$

$$\Delta E_{1-2} = -2170 \text{ kJ/min}$$

For process 2-3

$$Q_{2-3} = \Delta E_{2-3} + W_{2-3}$$

$$\Delta E_{2-3} = 21000 \text{ kJ/min}$$

For process, 3-4

$$Q_{3-4} = \Delta E_{3-4} + W_{3-4}$$

$$W_{3-4} = 35500 \text{ kJ/min}$$

We know that, according to first law of thermodynamics for a closed system undergoing a cyclic process,

$$\sum Q = \sum W = -170 \times 100 = -17000 \text{ kJ/min}$$

Therefore,

$$Q_{1-2} + Q_{2-3} + Q_{3-4} + Q_{4-1} = -17000$$

$$Q_{4-1} = -35900 \text{ kJ/min}$$

Also

$$W_{1-2} + W_{2-3} + W_{3-4} + W_{4-1} = -17000$$

$$W_{4-1} = -54670 \text{ kJ/min}$$

We also know that

$$\oint \Delta E = 0$$

Therefore,

$$\Delta E_{1-2} + \Delta E_{2-3} + \Delta E_{3-4} + \Delta E_{4-1} = 0$$

$$\Delta E_{4-1} = 17770 \text{ kJ/min}$$

The net work done during the cycle in Kw is

$$W = -\frac{17000}{60} = 283.33 \text{ kW}$$

3. A fluid is confined in a cylinder by a spring loaded frictionless piston. Show the pressure in the fluid is a linear function of the volume ($p = a+bV$). The internal energy of the fluid is given by the following equation $U = 34 + 3.15pV$ where U is in kJ, p is in kPa and V in m^3 . If the fluid changes from an initial state of 170 kPa, 0.03 m^3 to a final state of 4000 kPa, 0.06 m^3 with no work other than that done on the piston, find the direction and magnitude of the work and heat transfer.

Solution:

According to the first law of thermodynamics, for a closed system undergoing a process

$$Q = \Delta U + W$$

Where

$$\Delta U = U_2 - U_1 = 3.15(P_2V_2 - P_1V_1)$$

$$\Delta U = U_2 - U_1 = 3.15(4000 \times 0.06 - 170 \times 0.03) = 740 \text{ kJ}$$

The work done during this process is only PdV work, therefore

$$W = \int_1^2 PdV = \int_1^2 (a + bV)dV$$

On integrating the above equation, we get

$$W = a(V_2 - V_1) + b\left(\frac{V_2^2 - V_1^2}{2}\right)$$

To find the constants a & b

$$P = a + bV$$

For state 1

$$170 = a + 0.03b$$

$$4000 = a + 0.06b$$

On solving the above simultaneous equation, we get

$$a = -3660$$

$$b = 127666.67$$

On substituting a & b values in the integrated equation, we get

$$W = -3660(0.03) + 127666.67\left(\frac{0.06^2 - 0.03^2}{2}\right)$$

$$W = 62.55 \text{ kJ}$$

Therefore,

$$Q = 740 + 62.55 = 802.55 \text{ kJ}$$

4. A fluid undergoes a reversible adiabatic compression from 0.5 MPa, 0.2 m³ to 0.05 m³ according to the law, $PV^{1.3} = C$. Determine the change in enthalpy, internal energy, the heat transfer and work transfer during the process. Assume $R = 0.287 \text{ kJ/kg K}$ and $c_p = 1 \text{ kJ/kg K}$, $c_v = 0.72 \text{ kJ/kg K}$.

Solution:

To find the final pressure for the given process,

$$\frac{P_2}{P_1} = \left(\frac{V_2}{V_1}\right)^n$$

$$P_2 = 0.83 \text{ MPa}$$

To find work done,

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n - 1}$$

$$W_{1-2} = \frac{500 \times 0.2 - 830 \times 0.05}{1.3 - 1}$$

$$W_{1-2} = 195 \text{ kJ}$$

In order to find the other data's, we should find the initial and final temperature we can use PVT relation

$$\frac{P_1}{P_2} = \left(\frac{T_2}{T_1}\right)^{n/n-1}$$

$$T_2 = \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}} \times T_1$$

$$T_2 = \left(\frac{0.5}{0.83}\right)^{\frac{1.3-1}{1.3}} \times T_1$$

$$T_2 = 0.89 T_1$$

We know that the heat transfer is given as

$$Q_{1-2} = W \times \left(\frac{\gamma - n}{\gamma - 1}\right) = 195 \times \frac{1.4 - 1.3}{1.4 - 1} = 48.75 \text{ kJ}$$

From the first law of thermodynamics for a process

$$Q_{1-2} = W_{1-2} + \Delta U_{1-2}$$

Therefore, the change internal energy

$$\Delta U_{1-2} = Q_{1-2} - W_{1-2} = 48.75 - 195 = -146.25 \text{ kJ}$$

We also know that

$$\Delta U_{1-2} = m c_v \Delta T$$

Therefore,

$$m \Delta T = \frac{146.25}{0.72} = 203.13 \text{ kg.K}$$

We know that, the change in enthalpy is given as

$$\Delta H_{1-2} = m c_p \Delta T = 1 \times 203.13 = 203.15 \text{ kJ}$$

5. 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: $W_{23} = 0$, $Q_{23} = -150 \text{ kJ}$
 - Process 3-1: $W_{31} = +50 \text{ kJ}$. Neglecting KE and PE changes determine the heat interactions Q_{12} and Q_{31} .

Solution:

According to the first law of thermodynamics, for a closed system undergoing a process

$$Q = \Delta U + W$$

Therefore, for process 1-2

$$Q_{1-2} = \Delta U_{1-2} + W_{1-2}$$

Where

$$\Delta U_{1-2} = U_2 - U_1 = 690 - 512 = 178 \text{ kJ}$$

For a process with $PV = \text{constant}$,

$$V_2 = \frac{P_1 V_1}{P_2} = \frac{1 \times 1.5}{2} = 0.75 \text{ m}^3$$

the work done is given as

$$W_{1-2} = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = 1 \times 10^2 \times \ln\left(\frac{0.75}{1.5}\right) = -69.32 \text{ kJ}$$

Therefore,

$$Q_{1-2} = 178 - 69.32 = 108.68 \text{ kJ}$$

We know that for a cyclic process

$$\begin{aligned} \sum Q &= \sum W \\ \sum W &= W_{1-2} + W_{2-3} + W_{3-1} = -69.32 + 0 + 50 = -19.32 \text{ kJ} \\ \sum Q &= Q_{1-2} + Q_{2-3} + Q_{3-1} = -19.32 \\ Q_{3-1} &= -19.32 - 108.68 + 150 = 22 \text{ kJ} \end{aligned}$$

6. In a Gas turbine installation, the gases enter the turbine at the rate of 5 kg/sec with a velocity of 50 m/sec and enthalpy of 900 kJ/kg and leave the turbine with 150 m/sec and enthalpy of 400 kJ/kg . The loss of heat from the gases to the surroundings is 25 kJ/kg . Assume $R = 0.285 \text{ kJ/kg K}$, $c_p = 1.004 \text{ kJ/kg K}$ and inlet conditions to be at 100 kPa and 27°C . Determine the work done and diameter of the inlet pipe.

Solution:

According to the first law of thermodynamics for an open system undergoing steady flow process, the steady flow energy equation is

$$E_{in} = E_{out}$$

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} + gz_1 \right) = \dot{m} \left(h_2 + \frac{V_2^2}{2} + gz_2 \right) + \dot{Q} + \dot{W}$$

Neglecting P.E. changes and rearranging the equation, we get

$$\dot{W} = \dot{m} \left([h_1 - h_2] + \frac{(V_1^2 - V_2^2)}{2} \right) - \dot{Q}$$

$$\dot{W} = 5 \left([900 - 400] \times 10^3 + \frac{(50^2 - 150^2)}{2} \right) - 25 \times 10^3$$

$$\dot{W} = 465 \text{ kW}$$

According to the continuity equation, we have

$$\dot{m} = \frac{A_1 V_1}{v_1}$$

We know that according to equation of state

$$P_1 v_1 = RT_1$$

Therefore,

$$v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 300}{100} = 0.861 \text{ m}^3/\text{kg}$$

Hence,

$$A_1 = \frac{\dot{m} \times v_1}{V_1} = \frac{5 \times 0.861}{50} = 0.0861 \text{ m}^2$$

$$A_1 = \frac{\pi}{4} d_1^2 = 0.0861$$

$$d_1 = 0.331 \text{ m}$$

7. Air flows steadily at the rate of 0.5 Kg/s through an air compressor, entering at 7m/s velocity, 100Kpa pressure, and 0.95 m³/kg volume, and leaving at 5m/s, 700Kpa, and 0.19 m³/kg. the internal energy of the air leaving is 90 KJ/kg greater than that of air entering. Cooling water in the compressor jackets absorbs heat from the air at the rate of 58 KW. (a) compute the rate of shaft work input to the air in KW. (b) find the ratio of the inlet pipe diameter to outlet pipe diameter.

Solution:

According to the first law of thermodynamics for an open system undergoing steady flow process, the steady flow energy equation is

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} + gz_1 \right) + \dot{W} = \dot{m} \left(h_2 + \frac{V_2^2}{2} + gz_2 \right) + \dot{Q}$$

We know that, $h = u + Pv$

$$\dot{m} \left([u_1 + P_1 v_1] + \frac{V_1^2}{2} + gz_1 \right) + \dot{W} = \dot{m} \left([u_2 + P_2 v_2] + \frac{V_2^2}{2} + gz_2 \right) + \dot{Q}$$

Neglecting P.E. changes and rearranging the equation, we get

$$\dot{W} = \dot{m} \left([(u_2 - u_1) + (P_2 v_2 - P_1 v_1)] + \frac{(V_2^2 - V_1^2)}{2} \right) + \dot{Q}$$

$$\dot{W} = 0.5 \left([(90) + (700 \times 0.19 - 100 \times 0.95)] \times 10^3 + \frac{(5^2 - 7^2)}{2} \right) + 58 \times 10^3$$

$$\dot{W} = 122 \text{ kW}$$

According to the continuity equation, we have

$$\frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2}$$

$$\frac{A_1}{A_2} = \frac{v_1 V_2}{v_2 V_1} = \frac{0.95 \times 5}{0.19 \times 7} = 3.571$$

$$\frac{\frac{\pi}{4} d_1^2}{\frac{\pi}{4} d_2^2} = 3.571$$

$$\frac{d_1}{d_2} = \sqrt{3.571} = 1.89$$

8. A nozzle is a device for increasing the velocity of the steadily flowing steam. At the inlet of the nozzle the enthalpy of the fluid passing is 3000 KJ/kg and 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 the exit of the nozzle. (b) If the inlet area is 0.1m² and specific volume at the inlet is 0.187 m³/kg. Find the mass flow rate. (c) If the specific volume at the nozzle exit is 0.498 m³/kg, find the exit area of the nozzle.

Solution:

According to the first law of thermodynamics for an open system undergoing steady flow process, the steady flow energy equation is

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} + gz_1 \right) = \dot{m} \left(h_2 + \frac{V_2^2}{2} + gz_2 \right) + \dot{Q} + \dot{W}$$

Neglecting K.E & P.E. changes and rearranging the equation, we get

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$3000 \times 10^3 + \frac{60^2}{2} = 2762 \times 10^3 + \frac{V_2^2}{2}$$

On solving

$$V_2 = 692.53 \text{ m/s}$$

Mass flow rate,

$$\dot{m} = \frac{A_1 V_1}{v_1} = \frac{0.1 \times 60}{0.187} = 32.09 \text{ kg/s}$$

Exit area of the nozzle

$$A_2 = \frac{\dot{m} \times v_2}{V_2} = \frac{32.09 \times 0.498}{692.53} = 0.023 \text{ m}^2$$

9. A turbine operates under steady flow conditions, receiving steam at the flowing 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 flowing 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.

Solution:

According to the first law of thermodynamics for an open system undergoing steady flow process, the steady flow energy equation is

$$E_{in} = E_{out}$$

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} + gz_1 \right) = \dot{m} \left(h_2 + \frac{V_2^2}{2} + gz_2 \right) + \dot{Q} + \dot{W}$$

Neglecting P.E. changes and rearranging the equation, we get

$$\dot{W} = \dot{m} \left([h_1 - h_2] + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2) \right) - \dot{Q}$$

$$\dot{W} = 0.42 \left([2785 - 2512] \times 10^3 + \frac{(33.3^2 - 100^2)}{2} + g(3 - 0) \right) - 0.29 \times 10^3$$

$$\dot{W} = 112.52 \text{ kW}$$

MULTIPLE CHOISE QUESTIONS

Questions	opt1	opt2	opt3	opt4	answer
Thermodynamics is the science of	Earth	Energy	Temperature	Environment	Energy
Statistical thermodynamics is following _____ approach	Zeroth law	Macroscopic	First law	Microscopic	Microscopic
If the heat transfer in a process is zero, then it is called as	Isothermal process	Polytrophic process	Adiabatic process	Isobaric process	Adiabatic process
The work done in _____ process is zero.	isothermal	Polytrophic	Isochoric	Isobaric	Isochoric
Both _____ constitute universe	Temperature & heat	System & surrounding	Heat & work	Enthalpy & entropy	System & surrounding
In an open system _____ will cross the boundary	Mass alone	Energy alone	Both mass and energy	Nothing	Both mass and energy
In a closed system _____ will cross the boundary	Mass alone	Energy alone	Both mass and energy	Nothing	Energy alone
Which one of the following is the path function?	Heat	Temperature	Pressure	Volume	Heat
Which one of the following is the point function?	Heat	Work	Temperature	None of these	Temperature
Which one of the following is the path function?	Heat	Work	Temperature	None of these	None of these
Intensive property is independent of the _____ of the system.	Weight	Mass	Gravity	Inertia	Mass
Extensive property is dependent on the _____ of the system.	Weight	Mass	Gravity	Inertia	Mass
The system is free from any unbalanced forces then it is said to be in a state of	Closed system	Isolated system	Quasi-static	Mechanical equilibrium	Mechanical equilibrium
If there is no temperature change within the system then it is said to be in a state of	Closed system	Isolated system	Thermal equilibrium	Mechanical equilibrium	Thermal equilibrium
If the initial and end state of a process is same then it is known as	State	Process	Cycle	Property	Cycle
When temperature is constant through out the process then it is known as	Isoba ric		Adiabatic	Isentropic	Isothermal

When entropy is constant through out the process then it is known as	Isobaric	Isothermal	Isochoric	Isentropic	Isentropic
When pressure is constant through out the process then it is known as	Isobaric	Isothermal	Polytrophic	Isentropic	Isobaric
When volume is constant through out the process then it is known as	Isobaric	Isochoric	Adiabatic	Polytrophic	Isochoric
When a system existing in single phase only then it is known as	Open system	Homogeneous system	Heterogeneous system	Isolated system	Homogeneous system
When a system existing in more than one phase then it is known as	Open system	Homogeneous system	Heterogeneous system	Isolated system	Heterogeneous system
A device which is used to increase the velocity and decrease the pressure is known as	compressor	blower	nozzle	diffuser	nozzle
A device which is used to increase the pressure and decrease the velocity is known as	compressor	Blower	Nozzle	Diffuser	Diffuser
The work done in free expansion process is	Zero	less than zero	Greater than zero	Unpredictable	Zero
Flow through a pipe is the example for	Isolated system	Closed system	Adiabatic system	Open system	Open system
Flask is the example for	Isolated system	Closed system	Open system	None of these	Isolated system
Steady flow energy equation can be applied to the following situation	Battery	Flask	Nozzle	Cold storage plant	Nozzle
The energy possessed by a body because of its height above the ground level, is known as	Internal energy	Released energy	Potential energy	Standby energy	Potential energy
The energy possessed by a body because of its molecular motion alone, is known as	Internal energy	Released energy	Potential energy	Standby energy	Internal energy
Adiabatic process is a process in which no	Change of pressure	Change of heat	Change of temperature	Change of entropy	Change of heat
Both heat transfer and work transfer are	Positive functions	Path functions	Point functions	Negative functions	Path functions

UNIT II

SECOND LAW & ENTROPY

LECTURE NOTES

Physical description of the second law - Kelvin-Planck and Clausius statements -Equivalence - Reversible processes and cycles- Carnot cycle - Corollaries - Absolute temperature scale - Clausius Theorem, inequality - Entropy- Principle, transfer, generation, balance - Third law of thermodynamics

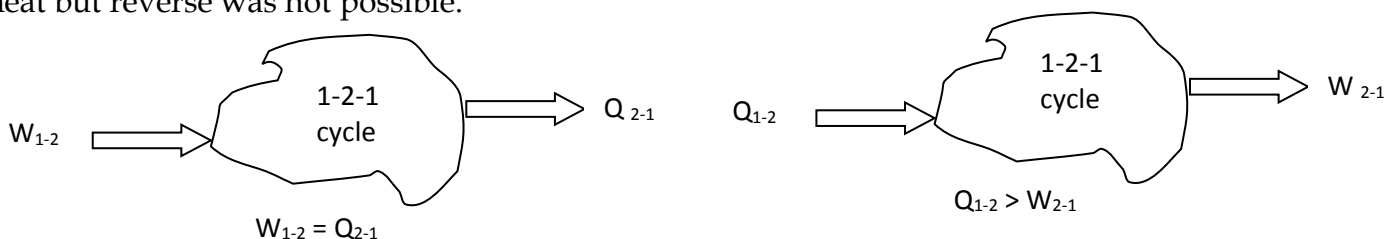
2.1 Introduction:

The first law of thermodynamics explained that the energy is a conserved property and any process to happen should satisfy the first law.

Now let us consider some examples like transfer of heat from hot coffee to the surrounding air, an electric heater converting the supplied electricity into equal amount of heat and a paddle wheel mechanism where the potential energy lost by the mass is stored as internal energy inside the system, all these processes obeys the first law and reverse is possible as per the first law. But in actual case the reversing of the above processes is not possible. Hence it can be concluded that energy transfer happens in certain direction only.

This explanation related to the energy transfer is missing in the first law and also to explain that energy is not just a quantity but it has quality too and it happens in certain direction. The second law of thermodynamics helps to explain the same.

Second law helps to determine the quality of energy as well as the degradation of energy. The quality of energy is broadly classified into two types, Low grade energy and High grade energy. The work transfer (W) is considered as High grade energy and heat as low grade energy. To prove this Joule conducted an experiment and it showed that work can be completely converted into heat but reverse was not possible.



Also it proved that complete conversion of low grade energy into high grade energy in one cycle is not possible.

Therefore, for a process to occur it has to satisfy both first law of thermodynamics and second law of thermodynamics.

2.2 Thermal energy reservoirs:

Thermal energy reservoirs are hypothetical bodies which have large thermal capacity and it can supply or absorb finite amount of heat without any change in its temperature. Examples: ocean, river, atmosphere, large water bodies etc.

In thermodynamics, the thermal energy reservoirs are classified into two types, source & sink. A TER which supplies heat is known as source or high temperature reservoir (HTR) and TER which absorbs heat is termed as sink or low temperature reservoir (LTR).

2.3 Heat Engine:

A heat engine is a device that used to convert heat into work. These devices do not work on thermodynamic cycle instead they work on mechanical cycle. Example: Turbines, IC engines etc. The figure 2 & 3 shows the pictorial representation of a heat engine

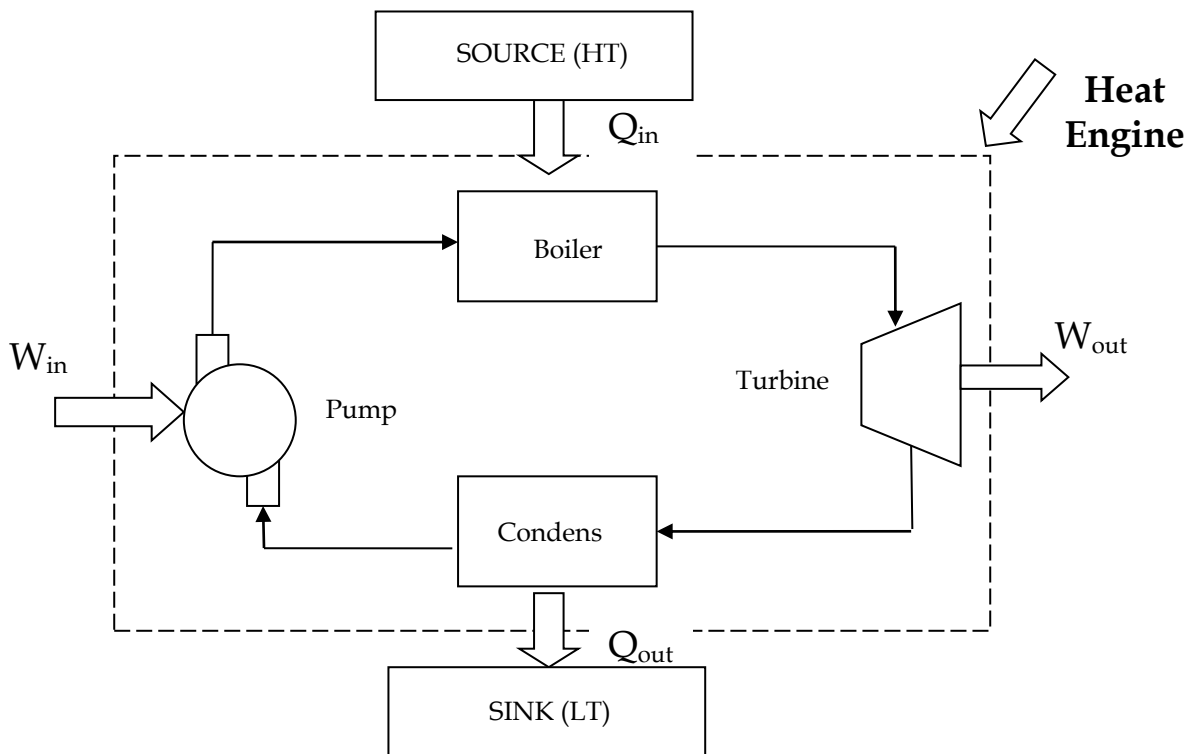


Fig. 2 Steam Power Plant

The steam power plant shown in the fig.2 is a best example for heat engine, the energy balance for this plant can be written as

$$W_{net,out} = W_{out} - W_{in} \text{ \& } Q_{net,out} = Q_{in} - Q_{out}$$

Also we know that according to first law of thermodynamics, a closed system undergoing a cyclic process,

$$W_{net,out} = Q_{net,out} = Q_{in} - Q_{out}$$

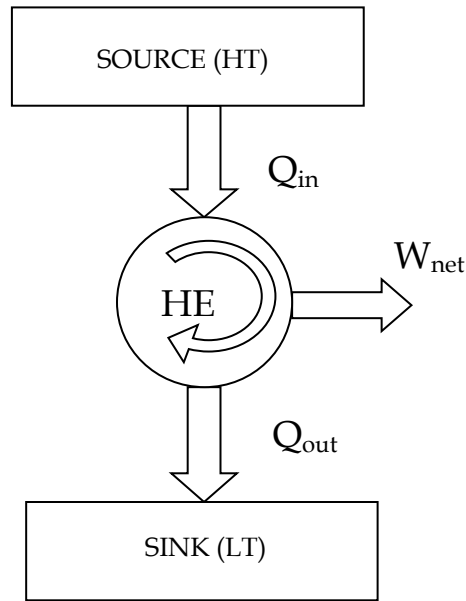


Fig.3 Heat Engine

The performance of a heat engine is the measure of fraction of heat input that is converted into work output. This measurement of a heat engine is known as Thermal efficiency, η_{ther}

$$\begin{aligned}\eta_{therm} &= \frac{\text{Net work output}}{\text{Total heat input}} \\ &= \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} \\ \eta_{therm} &= 1 - \frac{Q_{out}}{Q_{in}} \text{ or } 1 - \frac{Q_2}{Q_1} \text{ or } 1 - \frac{Q_L}{Q_H}\end{aligned}$$

The thermal efficiency is always less than unity since the entire heat energy cannot be converted into work.

2.4 Refrigerators & Heat pump:

We know that heat always flows from higher level to lower level and this occurs naturally. But reverse cannot happen naturally hence it requires external aid.

A device which transfers heat from low temperature reservoir (sink) to high temperature reservoir (Source) and operating in a cycle will maintain the systems temperature lower than that of the surroundings is known as Refrigerator. The working fluid in a refrigerator is called as Refrigerant.

A device which transfers heat from low temperature reservoir (sink) to high temperature reservoir (Source) and operating in a cycle will maintain the systems temperature higher than that of the surroundings is known as Heat Pump.

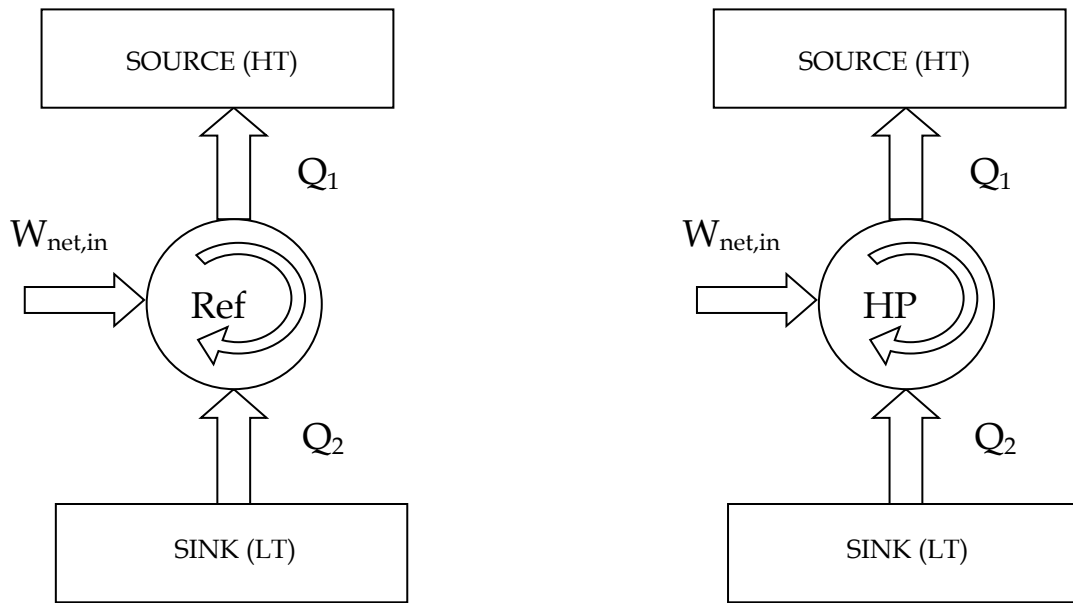


Fig. 4 Refrigerator & Heat pump

The performance of a refrigerator is the measure of fraction of desired output (Q_2) to the required work input and it is known as coefficient of performance (COP).

$$COP_{ref} = \frac{\text{Desired Output}}{\text{Desired Input}} = \frac{Q_2}{W_{net,in}} = \frac{Q_2}{Q_1 - Q_2}$$

The COP of the refrigerator is always greater than unity since the amount of heat removed is greater than that of the work input.

The performance of a heat pump is the measure of fraction of desired output (Q_1) to the required work input and it is known as coefficient of performance (COP).

$$COP_{HP} = \frac{\text{Desired Output}}{\text{Desired Input}} = \frac{Q_1}{W_{net,in}} = \frac{Q_1}{Q_1 - Q_2}$$

$$COP_{HP} = COP_{ref} + 1$$

2.5 Second law of Thermodynamics:

The second law has two different statements; one is Kelvin Planck statement & the other is the Clausius statement.

2.5.1 Kelvin Planck Statement:

According to Kelvin Planck statement, it is impossible to construct a heat engine that will continuously supply work output by exchanging heat with single heat reservoir with fixed temperature.

2.5.2 Clausius Statement:

According to Clausius's statement, it is impossible to construct a device operating in a cycle will produce no effect other than the transfer of heat from LTR to HTR.

2.6 Equivalence of the Two Statements:

The Kelvin-Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics. Any device that violates the Kelvin-Planck statement also violates the Clausius statement, and vice versa. This can be demonstrated as follows.

Consider the heat-engine-refrigerator combination shown in Fig. 5a, operating between the same two reservoirs.

The heat engine is assumed to have, in violation of the Kelvin-Planck statement, a thermal efficiency of 100 percent, and therefore it converts all the heat Q_1 it receives to work W .

This work is now supplied to a refrigerator that removes heat in the amount of Q_2 from the low-temperature reservoir and rejects heat in the amount of $Q_2 + Q_1$ to the high-temperature reservoir.

During this process, the high-temperature reservoir receives a net amount of heat Q_2 (the difference between $Q_2 + Q_1$ and Q_1).

Thus, the combination of these two devices can be viewed as a refrigerator, as shown in Fig. 5b, that transfers heat in an amount of Q_2 from a cooler body to a warmer one without requiring any input from outside. This is clearly a violation of the Clausius statement.

Therefore, a violation of the Kelvin-Planck statement results in the violation of the Clausius statement.

It can also be shown in a similar manner that a violation of the Clausius statement leads to the violation of the Kelvin-Planck statement.

Therefore, the Clausius and the Kelvin-Planck statements are two equivalent expressions of the second law of thermodynamics.

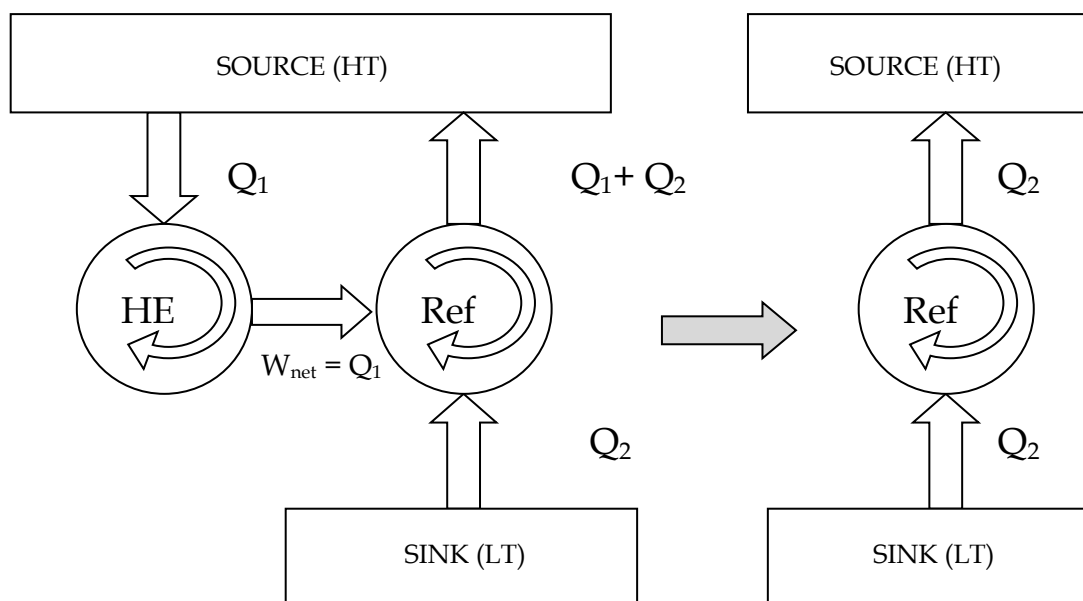


Fig. 5a & 5b Kelvin Clausius Statement equivalence

2.7 Reversible process

A reversible process (also sometimes known as quasi-static process) is one which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states.

This process has the following characteristics:

1. It must pass through the same states on the reversed path as were initially visited on the forward path.
2. This process when undone will leave no history of events in the surroundings.
3. It must pass through a continuous series of equilibrium states.

No real process is truly reversible but some processes may approach reversibility, to close approximation.

2.8 Irreversible process

An irreversible process is one in which heat is transferred through a finite temperature.

An irreversible process is usually represented by a dotted (or discontinuous) line joining the end states to indicate that the intermediate states are indeterminate.

Irreversibility's are of two types:

1. External irreversibility's. These are associated with dissipating effects outside the working fluid. Example. Mechanical friction occurring during a process due to some external source.
2. Internal irreversibility's. These are associated with dissipating effects within the working fluid.

2.9 Carnot Cycle:

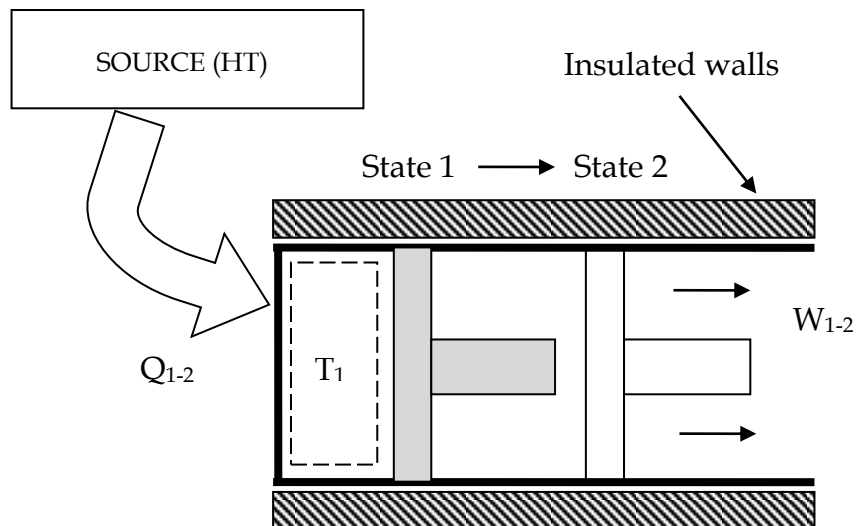
A Carnot cycle is a reversible cycle which is an ideal hypothetical cycle in which all the processes involved are reversible. It was proposed by Sadi Carnot in the year 1824. And a heat engine working on such Carnot cycle is known as Carnot Engine,

The Carnot engine consists of four reversible processes, in which two of them are reversible isothermal processes & other two are reversible adiabatic processes.

Consider a simple compressible system like a gas confined inside a piston cylinder device. The cylinder is completely insulated in the sides and bottom of the cylinder has a detachable covers made of adiabatic & diathermic materials.

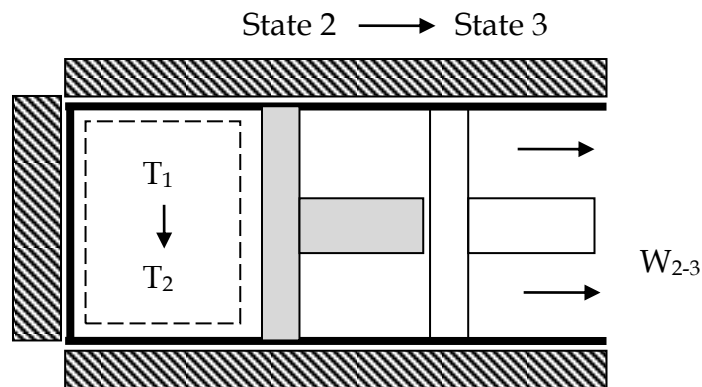
Process 1-2: Reversible isothermal Expansion Process

During this process, Q_{1-2} amount of heat is supplied to the system from the source at T_1 °C, the supplied heat increases the internal energy of the system thereby some work W_{1-2} is done on the surrounding due to expansion of the gas in the system.



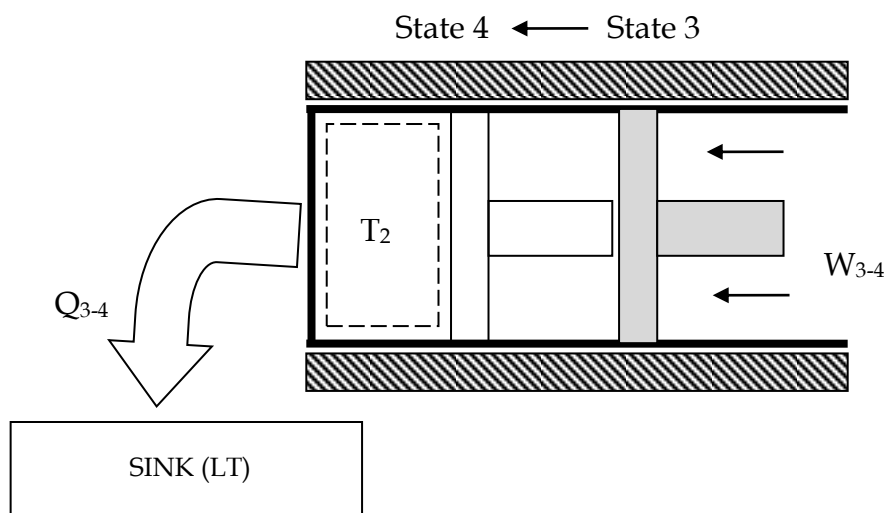
Process 2-3: Reversible Adiabatic Expansion Process

During this process, the gas again does work (W_{2-3}) on the surrounding by slow expansion of the gas with temperature decreasing from T_1 to T_2 .



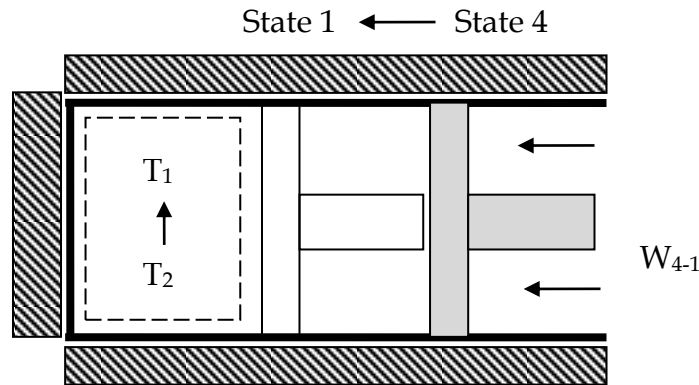
Process 3-4: Reversible Isothermal Compression Process

During this process, the gas is compressed isothermally by rejecting Q_{3-4} amount of heat to the sink by expense of work (W_{3-4}).



Process 4-1: Reversible Adiabatic Compression Process

During this process, the gas is again compressed adiabatically which increases the temperature from T_2 to T_1 by the expense of work W_{4-1}



Let us apply the first law of thermodynamics to the above process,
For Process 1-2:

$$Q_{1-2} = \Delta U_{1-2} + W_{1-2}$$

For process 2-3:

$$0 = \Delta U_{2-3} + W_{2-3}$$

For process 3-4:

$$-Q_{3-4} = \Delta U_{3-4} - W_{3-4}$$

For process 4-1:

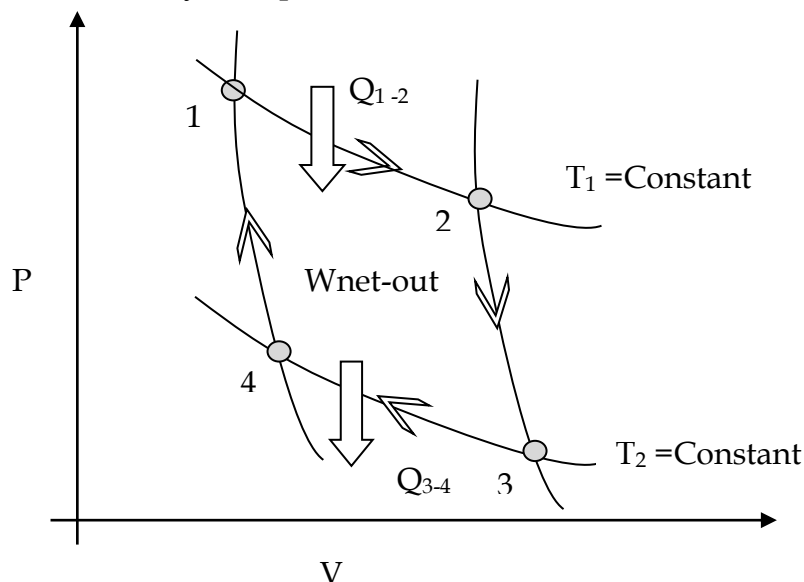
$$0 = \Delta U_{4-1} - W_{4-1}$$

For cycle 1-2-3-4-1:

$$\sum Q = \sum W$$

$$Q_{1-2} - Q_{3-4} = (W_{1-2} + W_{2-3}) - (W_{3-4} + W_{4-1}) = W_{net,out}$$

The P-V diagram for the Carnot cycle is plotted as shown below

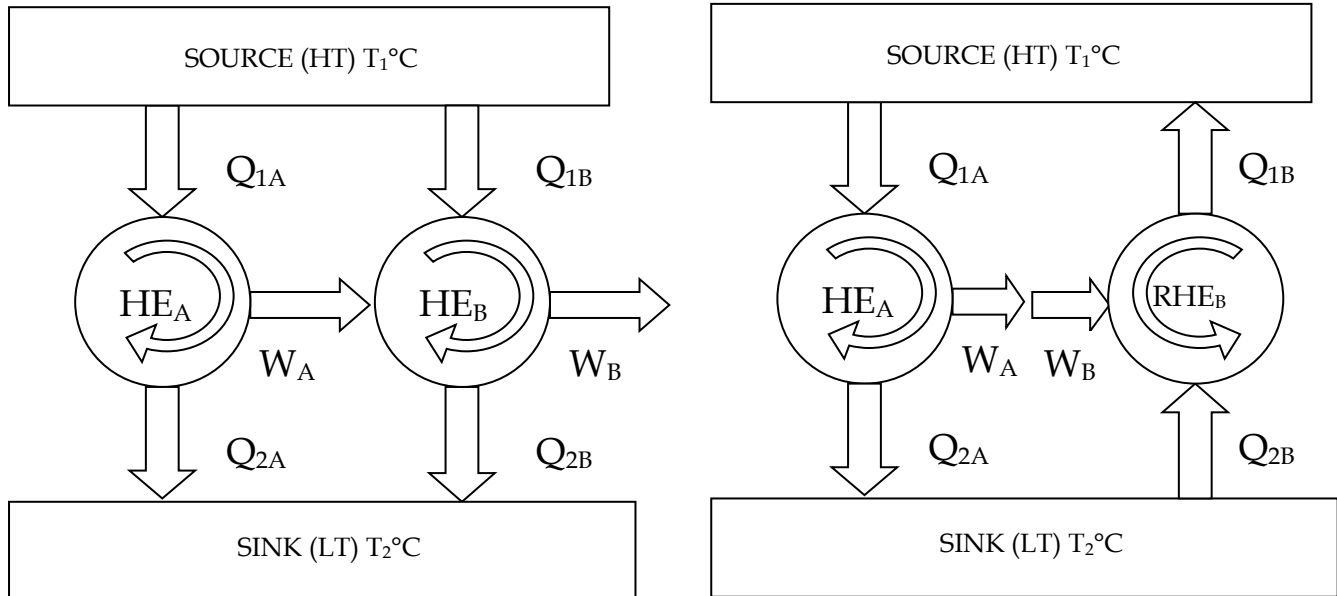


2.10 Carnot Theorem:

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

Proof:

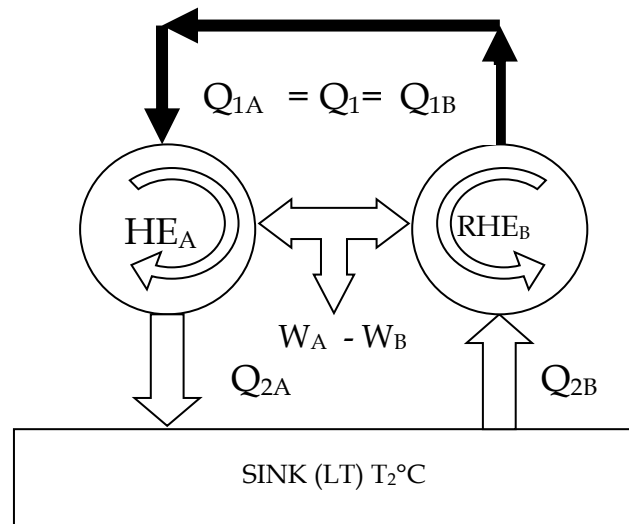
Consider two heat engines operating between same reservoirs as shown in the figure, in the engines A & B, engine B is reversible and Engine A is irreversible and they are supplied with same amount of heat input Q_1 . That is $Q_{1A} = Q_{1B}$.



Let us assume that

$$\begin{aligned}\eta_A &> \eta_B \\ \frac{W_A}{Q_{1A}} &> \frac{W_B}{Q_{1B}} \\ W_A &> W_B\end{aligned}$$

- Now let us reverse the Engine B, that is the magnitude of Q & W remains same but the direction is reversed.
- Since $W_A > W_B$, some part of the work of W_A is fed to drive the reversed engine B.
- Since $Q_{1A} = Q_{1B} = Q_1$, heat discharged by the reversed engine B may be supplied to engine A as input. Thus eliminating the source.
- The engine A and the Reversed Engine B together constitutes a heat engine operating in a cycle producing a net work $W_A - W_B$, while exchanging heat with sink at T_2 .



- This violates the Kelvin Planck statement. Hence $\eta_A > \eta_B$ is wrong.
- Therefore, $\eta_B \geq \eta_A$ and hence proved.

Carnot Theorem Corollaries:

1. The efficiency of all reversible heat engines operating between same temperature reservoirs are the same.
2. The efficiency of a reversible heat engine is independent of the nature of amount of working substance undergoing the cycle.

2.11 Absolute Thermodynamic Temperature Scale:

A temperature scale which is independent of the properties of the substances that are used to measure temperature is called as thermodynamic temperature scale.

According to Carnot corollaries, the thermal efficiency of all heat engines operating between same temperature reservoirs are the same and it is independent of the working fluid & its properties. Hence the thermal efficiency of reversible heat engine becomes a function of reservoir temperatures only.

$$\eta_{therm} = g(T_1, T_2)$$

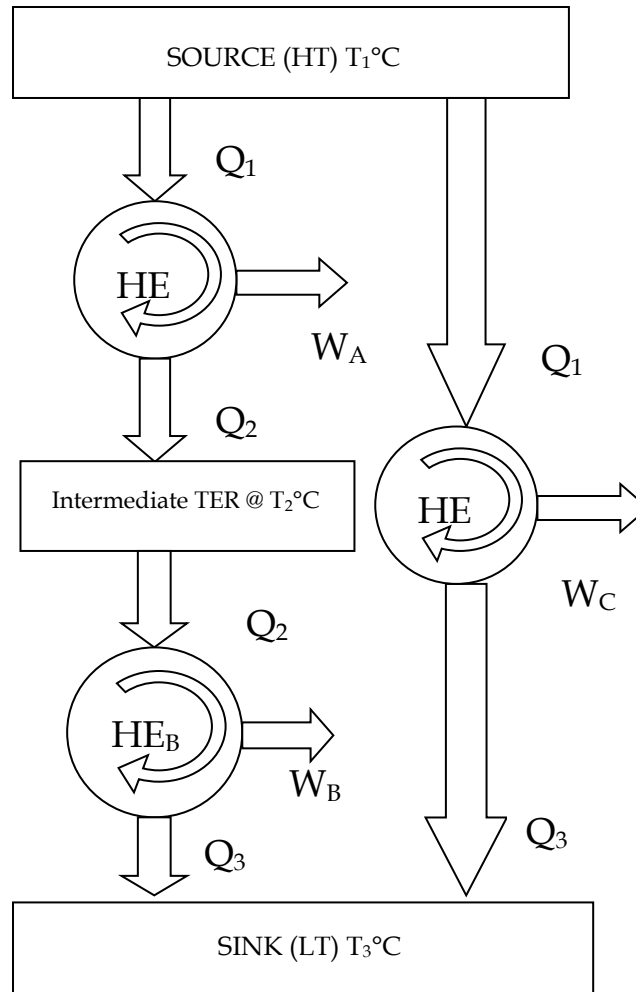
We know that,

$$\eta_{therm} = 1 - \frac{Q_2}{Q_1} = g(T_1, T_2)$$

Or

$$\frac{Q_1}{Q_2} = f(T_1, T_2)$$

The above functional form can be explained with help of the heat engines arranged as shown in the figure below



- Engines A and C are supplied with same amount of heat from the HTR at $T_1^\circ\text{C}$
- Engine C rejects Q_3 amount of heat to the LTR at $T_3^\circ\text{C}$
- Engine B gets Q_2 amount of heat rejected by engine A as its input at $T_2^\circ\text{C}$.

As per the Carnot corollary, the heat rejected by engines B & C must be the same in order to have same thermal efficiency.

Therefore, the functional form for these engines can be written as

$$\frac{Q_1}{Q_2} = f(T_1, T_2), \quad \frac{Q_2}{Q_3} = f(T_2, T_3), \quad \frac{Q_1}{Q_3} = f(T_1, T_3)$$

$$\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2} \times \frac{Q_2}{Q_3}$$

$$f(T_1, T_3) = f(T_1, T_2) \cdot f(T_2, T_3)$$

The LHS of the above equation is a function of T_1 & T_3 and hence RHS should also be a function of T_1 & T_3 . To meet the above stated condition, let us rewrite the functions as

$$f(T_1, T_2) = \frac{\phi(T_1)}{\phi(T_2)}, \quad f(T_2, T_3) = \frac{\phi(T_2)}{\phi(T_3)}$$

$$\therefore f(T_1, T_3) = \frac{\phi(T_1)}{\phi(T_2)} \times \frac{\phi(T_2)}{\phi(T_3)}$$

$$f(T_1, T_3) = \frac{\phi(T_1)}{\phi(T_3)}$$

Therefore, the heat engine operating between two thermal reservoirs of temperatures T_1 & T_2 can be written as

$$\frac{Q_1}{Q_2} = \frac{\phi(T_1)}{\phi(T_2)}$$

Lord Kelvin proposed taking $\phi(T) = T$ to define the thermodynamic temperature scale as

$$\left(\frac{Q_1}{Q_2}\right)_{rev} = \frac{T_1}{T_2}$$

This temperature scale is known as Kelvin Scale or Absolute thermodynamic temperature scale and the temperatures on this scale are known as absolute temperatures. This scale varies from 0 to infinity. The magnitude of a Kelvin is defined as 1/ 273.16 of temperature interval between zero & triple point of water (273.16 K or 0°C).

Carnot Heat engine:

A heat engine operating on a Carnot cycle is known as Carnot heat engine and its thermal efficiency is given as

$$\eta_{ther,rev} = \eta_{max} = 1 - \left(\frac{Q_2}{Q_1}\right)_{rev} = 1 - \frac{T_2}{T_1}$$

Similarly, a refrigerator and heat pump working on reversed Carnot cycle has its COP as

$$(COP_{ref})_{rev} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

$$(COP_{HP})_{rev} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_1}{T_1 - T_2}$$

2.12 Clausius Inequality:

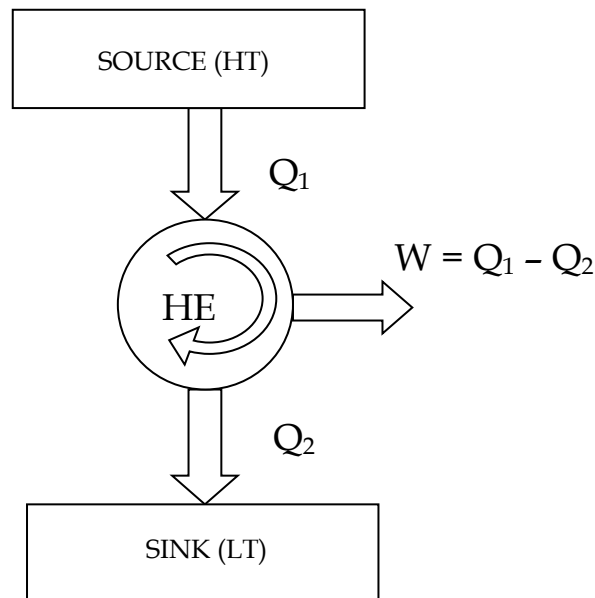
Consider a reversible heat engine as shown in the figure, the thermal efficiency of the reversible heat engine is given as

$$\eta_{therm} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

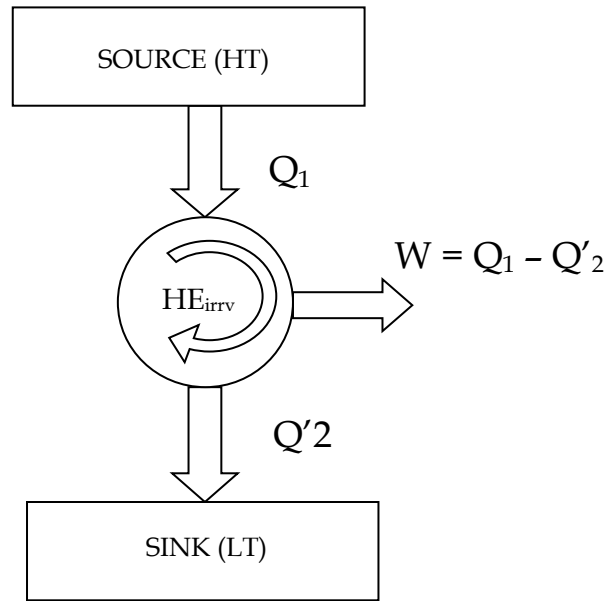
$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$$

$$\frac{Q_1}{T_1} - \frac{Q_2}{T_2} = 0$$

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



Now let us consider an irreversible heat engine, according to Carnot theorem, the efficiency of irreversible engine is less than the reversible engine, in the sense the work delivered by the irreversible engine is less than the reversible engine



$$W_{irrev} < W_{rev}$$

$$Q_1 - Q'_2 < Q_1 - Q_2$$

$$Q_1 - Q'_2 < T_1 - T_2$$

$$\frac{Q_1}{T_1} - \frac{Q'_2}{T_2} < 0$$

Therefore, for an irreversible engine

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

Therefore, in general

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

This is known as the Clausius Inequality.

Also, if the

$$\oint \frac{\delta Q}{T} = 0, \quad \text{Reversible system or process}$$

$$\oint \frac{\delta Q}{T} < 0, \quad \text{Irreversible system or process}$$

$$\oint \frac{\delta Q}{T} > 0, \quad \text{Impossible process}$$

2.13 Entropy:

Entropy is another thermodynamic property, which defines the degree of randomness or disorderliness of the systems process.

As it is already stated that the cyclic integral of a quantity becomes zero, then it depends only on the state of the system hence it can be concluded that the quantity is a point function. Also, the

point functions are properties of the system. Therefore, Clausius stated this differential quantity as a new property known as Entropy.

$$dS = \left(\frac{\delta Q}{T} \right)_{rev}$$

By integrating the above equation over the initial state to final state, change in entropy of the system during a process is obtained

$$\Delta S = \int_1^2 \left(\frac{\delta Q}{T} \right)_{rev}$$

2.14 Increase in Entropy Principle:

Consider a cycle consisting of two process 1-2 & 2-1, let process 1-2 be a normal process & process 2-1 a reversible one, then according to Clausius inequality,

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

$$\int_1^2 \frac{\delta Q}{T} + \int_2^1 \left(\frac{\delta Q}{T} \right)_{rev} \leq 0$$

$$\int_1^2 \frac{\delta Q}{T} + [dS]_2^1 \leq 0$$

$$\int_1^2 \frac{\delta Q}{T} + S_1 - S_2 \leq 0$$

Or

$$S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

In the differential form

$$dS \geq \frac{\delta Q}{T}$$

This relation states that the entropy change of a closed system is always greater than that of a system undergoing an irreversible process.

During an irreversible process some entropy is generated or produced, hence

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

Such entropy generated during such process is known as entropy generation and this value is always greater than zero or equal to zero for the limiting case of the process. Hence this is not a property of the system.

The entropy of an isolated system (Adiabatic closed system) in which the heat transfer is zero is always greater than or equal to zero.

$$\Delta S_{iso} \geq 0$$

This is known as increase in entropy principle.

The total change in entropy of a system, boundary & its surrounding is known to be Change in entropy of a universe.

$$S_{gen} = \Delta S_{univ} = \Delta S_{sys} + \Delta S_{surr} \geq 0$$

The increase in entropy principle states that

$$S_{gen} \begin{cases} > 0, & \text{Irreversible process} \\ = 0, & \text{reversible process} \\ < 0, & \text{impossible process} \end{cases}$$

Conclusions:

1. Processes can occur in certain direction only, also it must proceed in the direction of increasing entropy.
2. Entropy is a non-conserved property.
3. Entropy generated during a process acts as a measure of degree of irreversibility's present in the system

2.14.1 Change in Entropy of a Closed System:

For a closed system undergoing a reversible process is given as

$$Q = \Delta U + W$$

In the differential form

$$\delta Q = dU + \delta W$$

We know that,

$$dS = \frac{\delta Q}{T} \leftrightarrow \delta Q = T \cdot dS$$

$$\delta W = PdV$$

Therefore

$$T \cdot dS = PdV + dU, \quad kJ$$

$$T \cdot ds = Pdv + du, \quad kJ/kg$$

The above equation is known as T. dS or Gibb's equation.

Also

$$dh = du + d(Pv) = du + Pdv + vdP$$

$$du + Pdv = dh - vdP$$

Therefore

$$T \cdot ds = dh - vdP, \quad kJ/kg$$

Then the change in entropy is given as

$$ds = \frac{du}{T} + P \frac{dv}{T} \text{ or } ds = \frac{dh}{T} - v \frac{dP}{T}$$

By integrating the above equation from initial state to final state of a process for an ideal gas,

$$du = c_v dT, \quad dh = c_p dT, \quad Pv = RT$$

$$ds = c_v \frac{dT}{T} + \frac{RT}{v} \frac{dv}{T} \text{ or } ds = c_p \frac{dT}{T} - \frac{RT}{P} \frac{dP}{T}$$

$$ds = c_v \frac{dT}{T} + R \frac{dv}{v} \text{ or } ds = c_p \frac{dT}{T} - R \frac{dP}{P}$$

$$\int_1^2 ds = \int_1^2 c_v \frac{dT}{T} + \int_1^2 R \frac{dv}{v} \text{ or } \int_1^2 ds = \int_1^2 c_p \frac{dT}{T} - \int_1^2 R \frac{dP}{P}$$

$$s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

or

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} + R \ln \frac{P_2}{P_1}, \quad \text{kJ/kgK}$$

Similarly, the change in entropy of solids and liquids, the specific heat $c_p = c_v = c$ and the specific volume does not change, $dv = 0$.

$$s_2 - s_1 = c \ln \frac{T_2}{T_1}$$

2.14.2 Entropy Balance for closed system:

For a closed system, the entropy transfer is possible only by heat transfer since there is no mass flow. The entropy balance is given as

$$\sum \frac{Q_k}{T_k} + S_{gen} = S_2 - S_1 = \Delta S$$

If the closed system is adiabatic ($Q=0$) then

$$S_{gen} = S_2 - S_1 = \Delta S$$

2.14.3 Entropy Balance for steady flow processes (Open System):

For a steady flow process, entropy transfer takes place by the way of heat transfer as well as mass flow across the systems boundary of a control volume. The general expression for entropy balance is given as

$$\sum \frac{Q_k}{T_k} + \sum \dot{m}_{in} s_{in} - \sum \dot{m}_{out} s_{out} + S_{gen} = (S_2 - S_1)_{CV} = \Delta S$$

For steady flow systems like turbines, compressors, nozzles, ducts, pipes, heat exchangers, diffusers, mixing chambers etc., there is no change in the state of the working fluid and hence the change in entropy of a control volume becomes zero.

$$(S_2 - S_1)_{CV} = 0$$

Therefore,

$$S_{gen} = \sum \dot{m}_{out} s_{out} - \sum \dot{m}_{in} s_{in} - \sum \frac{Q_k}{T_k}$$

Also for a steady flow process, $\dot{m}_{in} = \dot{m}_{out}$

$$S_{gen} = \dot{m}(s_{out} - s_{in}) - \sum \frac{Q_k}{T_k}$$

If the steady flow device is adiabatic and reversible, then there is no entropy generation, hence the entropy of the control volume remains unchanged.

$$s_{out} = s_{in}$$

TWO MARK QUESTIONS

1. What is meant by heat engine?

ANS : When the system is in cyclic heat engine process means it must give heat as an input and work as an output.

2. What is meant by sink?

ANS: Sink is a thermal reservoir, which takes the heat from the system.

3. Explain the term “Reversibility”.

ANS : The system regains his original position without any changes in atmosphere and it follows the same path.

It is in thermal equilibrium condition.

It is quasistatic process.

4. Define the term entropy generation.

ANS: The entropy increase due to internal irreversibility is called entropy generation.

5. What is meant by source?

ANS: Source is a thermal reservoir, which supplies heat to the system

6. State Kelvin Planck statement of second law of thermodynamics.

ANS : Kelvin planck statement says, “It is not possible to have a heat engine which can produce work by interacting with single thermal reservoir.

7. What are the processes involved in Carnot cycle?

ANS: Adiabatic Compression

Isothermal Expansion

Adiabatic Expansion
Isothermal Compression

8. Define - PMM of second kind.

ANS: A heat engine, which converts whole of the heat energy into mechanical work is known as Perpetual motion machine of the second kind.

9. State Clausius statement of second law of thermodynamics.

ANS: It states that heat can flow from hot body to cold without any external aid but heat cannot flow from cold body to hot body without any external aid.

10. What is refrigerator?

ANS: A refrigerator is a device which operating in a cyclic process, maintains the temperature of a cold body at a temperature lower than the temperature of the surroundings.

11. State Carnot's theorem.

ANS : Carnot theorem states that no heat engine working in a cycle between two constant temperature reservoirs can be more efficient than a reversible engine working between the same reservoirs.

OR

It means that all the engines operating between a given constant temperature source and a given constant temperature sink, none, has a higher efficiency than a reversible engine.

12. What is meant by quality of energy?

ANS: The quality of energy is defined as the relative amount of mechanical work that can be generated in a theoretical conversion process.

13. What is meant by high grade energy?

ANS: An energy source that can be fully converted in to another form of energy is called high grade energy.

For example electrical energy is called a high-grade energy, as it is very easy to convert almost all of it into other energy forms such as thermal energy.

14. Define heat.

ANS: Heat is the energy crossing the boundary due to the temperature difference between the system and surroundings

15. Define the term COP.

ANS: Co-efficient of performance is defined as the ratio of heat extracted or rejected to work input.

$$\text{COP} = \text{Heat extracted or rejected} / \text{work input}$$

16. What is difference between a heat pump and refrigerator?

ANS: Heat pump is a device which operating in cyclic process, maintains the temperature of a hot body at a temperature higher than the temperature of surroundings.

A refrigerator is a device which operating in a cyclic process, maintains the temperature of a cold body at a temperature lower than the temperature of the surroundings.

17. Define the term entropy

ANS: Entropy is an index of unavailability or degradation of energy.

18. State the directional law of nature.

ANS : Heat is always flow from higher gradient to lower gradient is called the directional law of nature

19. Define second law efficiency

ANS: It is defined as the ratio of minimum available energy which must be consumed to do work by the actual amount of energy consumed in performing the same work.

20. What is meant by low grade energy?

ANS: An energy source which is not fully converted in to another form of energy is called low grade energy. it is not possible to convert thermal energy completely into electrical energy

21. What is meant by reversed Carnot engine?

ANS: An air conditioning device is working on a reverse Carnot cycle between the inside of a room at temperature T_2 and the outside at temperature T_1 . T_2 is always greater than T_1 .

22. Write the two kinds of energy

ANS:

- Potential energy
- Kinetic energy

23. Write some examples for high grade energy

ANS:

- Mechanical work
- Water powewind power
- Electrical energy
- Kinetic energy of a jet
- Tidal energy

PROBLEMS:

1. Establish the equivalence of Kelvin - Planck and Clausius statements.
2. A reversible engine is supplied with heat from two constant temperature sources at 900 K and 600 K and rejects heat to a constant temperature sink at 300 K. The engine develops work equivalent to 90 kJ/s and rejects heat at the rate of 56 kJ/s. Estimate the heat supplied by each source and the thermal efficiency of the engine.

Given Data:

$$T_{1A} = 900 \text{ K}, T_{1B} = 600 \text{ K}, T_2 = 300 \text{ K}, W_{\text{net}} = 90 \text{ kJ/s}, Q_2 = 56 \text{ kJ/s}$$

To Find:

$$Q_{1A} \text{ \& } Q_{1B}, \eta_{\text{ther}}$$

Solution:

We know that,

For a reversible heat engine, the work delivered by the engine is given as

$$W = (Q_{1A} + Q_{1B}) - Q_2$$

Therefore, on substitution of values,

$$Q_{\text{sup}} = Q_{1A} + Q_{1B} = W + Q_2 = 90 + 56 = 146 \frac{\text{kJ}}{\text{s}} \dots \dots \dots (1)$$

We also know that, the thermal efficiency is given as

$$\eta = \frac{W}{Q_{\text{sup}}} = \frac{90}{146} = 61.6 \%$$

According to Clausius inequality

$$\frac{Q_{\text{sup}}}{T_{\text{source}}} - \frac{Q_{\text{rej}}}{T_{\text{sink}}} = 0, \text{ for an reversible engine}$$

Therefore,

$$\begin{aligned} \frac{Q_{1A}}{T_{1A}} + \frac{Q_{1B}}{T_{1B}} - \frac{Q_2}{T_2} &= 0 \\ \frac{Q_{1A}}{900} + \frac{Q_{1B}}{600} - \frac{56}{300} &= 0 \\ 0.0011Q_{1A} + 0.00167Q_{1B} &= 0.187 \dots \dots \dots (2) \end{aligned}$$

On solving equation (1) & (2), we get

$$Q_{1A} = 99.68 \frac{\text{kJ}}{\text{s}} \quad \& \quad Q_{1B} = 46.32 \frac{\text{kJ}}{\text{s}}$$

3. A household refrigerator that has a power input of 450 W and a COP of 1.5 is to cool 5 large watermelons, 10 kg each, to 8°C. If the watermelons are initially at 28°C, determine how long it will take for the refrigerator to cool them. The watermelons can be treated as water whose specific heat is 4.2 kJ/kg °C. Is your answer realistic or optimistic? Explain.

Given Data:

$$W_{\text{in}} = 450 \text{ W}, \text{ COP} = 1.5, m = 5 \times 10 = 50 \text{ kg}, T_1 = 28^\circ\text{C}, T_2 = 8^\circ\text{C}, c_p = 4.2 \text{ kJ/kg}^\circ\text{C}$$

To Find:

Time taken to cool the watermelons, t = ?

Solution:

The total amount of heat to be removed is,

$$Q = m c_p \Delta T = 50 \times 4.2 \times (28 - 8)$$

$$Q = 4200 \text{ kJ}$$

The COP of a reversible refrigerator is,

$$COP = \frac{\text{heat Removed}}{\text{Work Input}} = \frac{Q_R}{W_{in}}$$

$$1.5 = \frac{Q_R}{450}$$

$$Q_R = 675 \text{ W} = 675 \text{ J/s}$$

For 1 second 540 J of heat is removed, therefore total time taken for removing 4200 kJ is

$$t = \frac{4200 \times 10^3}{675} = 6222.2 \text{ s} = 103.7 \text{ min}$$

4. A Carnot heat engine receives heat at 900 K and rejects the waste heat to the environment at 300 K. The entire work output of the heat engine is used to drive a Carnot refrigerator that removes heat from the cooled space at -15°C at a rate of 250 kJ/min and rejects it to the same environment at 300 K. Determine (a) the rate of heat supplied to the heat engine and (b) the total rate of heat rejection to the environment.

Given Data:

$$T_1 = 900 \text{ K}, T_2 = 300 \text{ K}, T_3 = 258 \text{ K}, Q_{2R} = 250 \text{ kJ/min}$$

To Find:

$$Q_{1E} = ? \quad Q_{2E} \& Q_{1R} = ?$$

Solution:

The COP of a reversible refrigerator is,

$$COP = \frac{\text{heat Removed}}{\text{Work Input}} = \frac{Q_{2R}}{W_{in}}$$

$$COP = \frac{T_3}{T_2 - T_3} = \frac{258}{300 - 258}$$

$$COP = 6.143$$

Therefore

$$W_{in} = \frac{Q_{2R}}{COP} = \frac{250}{6.143} = 40.7 \text{ kJ/min}$$

Also we know that,

$$W_{in} = W_{net,out} = Q_{1E} - Q_{2E}$$

For a reversible heat engine,

$$\eta_{therm} = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{900} = 66.7\%$$

$$\text{Also, } \eta_{therm} = 1 - \frac{Q_{2E}}{Q_{1E}} = \frac{W_{net,out}}{Q_{1E}}$$

$$Q_{1E} = \frac{W_{net,out}}{\eta_{therm}} = \frac{40.7}{0.667}$$

$$Q_{1E} = 61.02 \text{ kJ/min}$$

5. A heat pump receives heat from a lake that has an average winter time temperature of 6°C and supplies heat into a house having an average temperature of 23°C . (a) If the house loses heat to the atmosphere at the rate of 52,000 kJ/h, determine the minimum power supplied to the heat

pump, in kW. (b) A heat exchanger is used to transfer the energy from the lake water to the heat pump. If the lake water temperature decreases by 5°C as it flows through the lake water-to-heat pump heat exchanger, determine the minimum mass flow rate of lake water, in kg/s. Neglect the effect of the lake water pump.

Given Data:

$$T_2 = 6^\circ\text{C} = 279 \text{ K}, T_1 = 23^\circ\text{C} = 296 \text{ K}, Q_1 = Q_H = 52000 \text{ kJ/h} = 14.4 \text{ kJ/s}, \Delta T = 5^\circ\text{C}$$

To find:

$$\dot{W}_{in} = ?, \dot{m} = ?$$

Solution:

The COP of a reversible Heat pump is given as

$$COP = \frac{\text{heat to be added}}{\text{Work Input}} = \frac{\dot{Q}_H}{\dot{W}_{in}}$$

$$COP = \frac{T_1}{T_1 - T_2} = \frac{296}{296 - 279} = 17.4$$

Therefore,

$$\dot{W}_{in} = \frac{\dot{Q}_H}{COP} = \frac{14.4}{17.4} = 0.83 \text{ kJ/s}$$

Also

$$\dot{W}_{in} = \dot{Q}_H - \dot{Q}_L \rightarrow \dot{Q}_L = 14.4 - 0.83 = 13.57 \text{ kJ/s}$$

We know that,

$$\dot{Q}_L = \dot{m} c_p \Delta T$$

$$\dot{m} = \frac{\dot{Q}_L}{c_p \Delta T} = \frac{13.57}{4.18 \times 5} = 0.65 \text{ kg/s}$$

6. A reversible heat engine operates between two reservoirs at 820°C and 27°C. Engine drives a reversible refrigerator which operates between reservoirs at temperatures of 27°C and -15°C. The heat transfer to the engine is 2000 kJ and net work available for the combined cycle is 300 kJ. How much heat is transferred to the refrigerant and also determine the total heat rejected to the reservoir at 27°C. If the efficiency of the heat engine and COP of the refrigerator are each 40% of their maximum values, determine heat transfer to the refrigerator and also heat rejected to the reservoir at 27°C.

Given data:

$$T_1 = 820^\circ\text{C} = 1093 \text{ K}, T_2 = 27^\circ\text{C} = 300 \text{ K}, T_3 = -15^\circ\text{C} = 258 \text{ K}, Q_{1E} = 2000 \text{ kJ}, W_{\text{net}} = 300 \text{ kJ} = W_{\text{out}} - W_{\text{in}}$$

$$\eta_{\text{therm}} \& COP = 40\% \text{ of } \eta_{\text{therm,rev}} \& COP_{\text{rev}}$$

To Find:

Heat transferred to refrigerant, $Q_{2R} = ?$

Total heat rejected to LTR, $Q_{\text{sink}} = Q_{2E} + Q_{1R} = ?$

Find the same if $\eta_{\text{therm}} \& COP = 40\% \text{ of } \eta_{\text{therm,rev}} \& COP_{\text{rev}}$

Solution:

For a reversible heat engine,

$$\eta_{\text{therm}} = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{1093} = 72.6\%$$

$$\text{Also, } \eta_{\text{therm}} = 1 - \frac{Q_{2E}}{Q_{1E}} = \frac{W_{\text{out}}}{Q_{1E}}$$

$$W_{\text{out}} = \eta_{\text{therm}} \times Q_{1E} = 0.726 \times 2000$$

$$W_{\text{out}} = 1451 \text{ kJ}$$

Also it is given that

$$W_{\text{net}} = W_{\text{out}} - W_{\text{in}}$$

$$300 = 1451 - W_{\text{in}}$$

$$W_{\text{in}} = 1151 \text{ kJ}$$

For a reversible refrigerator,

$$COP = \frac{\text{heat Removed}}{\text{Work Input}} = \frac{Q_{2R}}{W_{\text{in}}}$$

$$COP = \frac{T_3}{T_2 - T_3} = \frac{258}{300 - 258}$$

$$COP = 6.143$$

Therefore

$$Q_{2R} = W_{\text{in}} \times COP = 1151 \times 6.143 = 7070.9 \text{ kJ}$$

Also we know that,

$$W_{\text{out}} = Q_{1E} - Q_{2E}$$

$$Q_{2E} = 2000 - 1451 = 549 \text{ kJ}$$

$$W_{\text{in}} = Q_{1R} - Q_{2R}$$

$$Q_{1R} = 1151 + 7070 = 8221.9 \text{ kJ}$$

Total heat rejected to the LTR is

$$Q = Q_{2E} + Q_{1R} = 549 + 8221.9$$

$$Q = 8770.9 \text{ kJ}$$

if η_{therm} & $COP = 40\%$ of $\eta_{\text{therm,rev}}$ & COP_{rev} , then

$$W_{\text{out}} = 40\% \eta_{\text{therm}} \times Q_{1E} = 0.4 \times 0.726 \times 2000$$

$$W_{\text{out}} = 581 \text{ kJ}$$

Also it is given that

$$W_{\text{net}} = W_{\text{out}} - W_{\text{in}}$$

$$300 = 581 - W_{\text{in}}$$

$$W_{\text{in}} = 281 \text{ kJ}$$

For a reversible refrigerator,

$$COP = \frac{\text{heat Removed}}{\text{Work Input}} = \frac{Q_{2R}}{W_{\text{in}}}$$

Therefore

$$Q_{2R} = W_{\text{in}} \times 40\%COP = 281 \times 0.4 \times 6.143 = 690.5 \text{ kJ}$$

Also we know that,

$$W_{\text{out}} = Q_{1E} - Q_{2E}$$

$$Q_{2E} = 2000 - 581 = 1419 \text{ kJ}$$

$$W_{\text{in}} = Q_{1R} - Q_{2R}$$

$$Q_{1R} = 690.5 + 281 = 971.5 \text{ kJ}$$

Total heat rejected to the LTR is

$$Q = Q_{2E} + Q_{1R} = 1419 + 971.5$$

$$Q = 2390.5 \text{ kJ}$$

7. A reversible heat engine operates between two reservoirs at temperatures of 600°C and 40°C. The engine drives a reversible refrigerator which operates between reservoirs at temperatures of 40°C and -20°C. The heat transfer to the heat engine is 2000kJ and the network output of the combined engine refrigerator plant is 360kJ. (a) Evaluate the heat transfer to the refrigerant and the net heat transfer to the reservoir at 40°C. (b) Reconsider (a) given that the efficiency of the heat engine and the COP of the refrigerator are each 40% of their maximum possible values.

Given Data:

$$T_1 = 600^\circ\text{C} = 873\text{ K}, T_2 = 40^\circ\text{C} = 313\text{ K}, T_3 = -20^\circ\text{C} = 263\text{ K}, Q_{1E} = 2000\text{ kJ}, W_{\text{net}} = 360\text{ kJ} = W_{\text{out}} - W_{\text{in}}$$

$$\eta_{\text{therm}} \& \text{COP} = 40\% \text{ of } \eta_{\text{therm, rev}} \& \text{COP}_{\text{rev}}$$

To Find:

Heat transferred to refrigerant, $Q_{2R} = ?$

Total heat rejected to LTR, $Q_{\text{sink}} = Q_{2E} + Q_{1R} = ?$

Find the same if $\eta_{\text{therm}} \& \text{COP} = 40\% \text{ of } \eta_{\text{therm, rev}} \& \text{COP}_{\text{rev}}$

Solution:

For a reversible heat engine,

$$\eta_{\text{therm}} = 1 - \frac{T_2}{T_1} = 1 - \frac{313}{873} = 64.15\%$$

$$\text{Also, } \eta_{\text{therm}} = 1 - \frac{Q_{2E}}{Q_{1E}} = \frac{W_{\text{out}}}{Q_{1E}}$$

$$W_{\text{out}} = \eta_{\text{therm}} \times Q_{1E} = 0.642 \times 2000$$

$$W_{\text{out}} = 1283\text{ kJ}$$

Also it is given that

$$W_{\text{net}} = W_{\text{out}} - W_{\text{in}}$$

$$300 = 1283 - W_{\text{in}}$$

$$W_{\text{in}} = 983\text{ kJ}$$

For a reversible refrigerator,

$$\text{COP} = \frac{\text{heat Removed}}{\text{Work Input}} = \frac{Q_{2R}}{W_{\text{in}}}$$

$$\text{COP} = \frac{T_3}{T_2 - T_3} = \frac{263}{313 - 263}$$

$$\text{COP} = 5.26$$

Therefore

$$Q_{2R} = W_{\text{in}} \times \text{COP} = 983 \times 5.26 = 5170.6\text{ kJ}$$

Also we know that,

$$W_{\text{out}} = Q_{1E} - Q_{2E}$$

$$Q_{2E} = 2000 - 1283 = 717\text{ kJ}$$

$$W_{\text{in}} = Q_{1R} - Q_{2R}$$

$$Q_{1R} = 983 + 5170.6 = 6153.6\text{ kJ}$$

Total heat rejected to the LTR is

$$Q = Q_{2E} + Q_{1R} = 717 + 6153.6$$

$$Q = 6870.6\text{ kJ}$$

if $\eta_{\text{therm}} \& \text{COP} = 40\% \text{ of } \eta_{\text{therm, rev}} \& \text{COP}_{\text{rev}}$, then

$$W_{out} = 40\% \eta_{therm} \times Q_{1E} = 0.4 \times 0.642 \times 2000$$

$$W_{out} = 513.6 \text{ kJ}$$

Also it is given that

$$W_{net} = W_{out} - W_{in}$$

$$300 = 513.6 - W_{in}$$

$$W_{in} = 213.6 \text{ kJ}$$

For a reversible refrigerator,

$$COP = \frac{\text{heat Removed}}{\text{Work Input}} = \frac{Q_{2R}}{W_{in}}$$

Therefore

$$Q_{2R} = W_{in} \times 40\%COP = 213.6 \times 0.4 \times 5.26 = 449.4 \text{ kJ}$$

Also we know that,

$$W_{out} = Q_{1E} - Q_{2E}$$

$$Q_{2E} = 2000 - 513.6 = 1486.4 \text{ kJ}$$

$$W_{in} = Q_{1R} - Q_{2R}$$

$$Q_{1R} = 213.6 + 449.4 = 663 \text{ kJ}$$

Total heat rejected to the LTR is

$$Q = Q_{2E} + Q_{1R} = 1486.4 + 663$$

$$Q = 2149.4 \text{ kJ}$$

8. State and derive the processes of Carnot cycle with p-v diagram.
9. Air of mass 0.5 kg as an ideal gas executes a Carnot cycle having a thermal efficiency of 50%. The heat transfer to the air during the isothermal expansion is 40 kJ. At the beginning of isothermal expansion, the pressure is 7 bar and the volume is 0.12 m³. Determine a) the maximum and minimum temperatures for the cycle, b) the volume at the end of isothermal expansion, c) the work and heat transfer for each of the four processes.

Given Data:

$$m = 0.5 \text{ kg}, \eta_{therm} = 50\%, Q_{1-2} = 40 \text{ kJ}, P_1 = 7 \text{ bar} = 700 \text{ kPa}, V_1 = 0.12 \text{ m}^3$$

To find:

a) $T_1 = ?$ $T_2 = ?$ b) $V_2 = ?$ c) W & Q for processes 1-2, 2-3, 3-4, 4-1

Solution:

To find the initial temperature of the system, T_1

$$= mRT_1$$

$$T_1 = \frac{P_1 V_1}{mR} = \frac{700 \times 0.12}{0.5 \times 0.287}$$

$$T_1 = 585.4 \text{ K}$$

To find the final temperature of the system, T_2

$$\eta_{therm} = 1 - \frac{T_2}{T_1}$$

$$0.5 = 1 - \frac{T_2}{585.4}$$

$$T_2 = 292.7 \text{ K}$$

To find the final volume at the end of isothermal expansion process

$$W_{1-2} = Q_{1-2} = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right)$$

$$\ln\left(\frac{V_2}{V_1}\right) = \frac{40}{700 \times 0.12} = 0.4761$$

Therefore,

$$V_2 = V_1 \times e^{0.4761} = 0.12 \times e^{0.4761}$$

$$V_2 = 0.193 \text{ m}^3$$

To find the Q & W for the four processes

Process 1-2:

$$W_{1-2} = Q_{1-2} = 40 \text{ kJ}$$

Process 2-3:

$$Q_{2-3} = 0, \quad \text{since adiabatic process}$$

$$W_{2-3} = \Delta U_{2-3} = m c_v \Delta T = 0.5 \times 0.718 \times (585.4 - 292.7)$$

$$W_{2-3} = 107.5 \text{ kJ}$$

Process 3-4:

$$\frac{Q_{3-4}}{Q_{1-2}} = \frac{Q_2}{Q_1} = \frac{T_2}{T_1}$$

$$Q_{3-4} = Q_2 = \frac{T_2}{T_1} \times Q_1 = \frac{292.5}{585.4} \times 40$$

$$Q_{3-4} = 20 \text{ kJ} = W_{3-4}$$

Process 4-1:

$$Q_{4-1} = 0, \quad \text{since adiabatic process}$$

$$W_{4-1} = \Delta U_{4-1} = m c_v \Delta T = 0.5 \times 0.718 \times (292.7 - 585.4)$$

$$W_{2-3} = -107.5 \text{ kJ}$$

Entropy

10. A 30-kg iron block and a 40-kg copper block, both initially at 80°C, are dropped into a large lake at 15°C. Thermal equilibrium is established after a while as a result of heat transfer between the blocks and the lake water. Determine the total entropy change for this process. Take specific heat of iron and copper as 0.45 & 0.386 kJ/kg°C.

Given Data:

$$m_{\text{iron}} = 30 \text{ kg}, m_{\text{cu}} = 40 \text{ kg}, T_1 = 80^\circ\text{C}, T_2 = 15^\circ\text{C}, c_{\text{iron}} = 0.45 \text{ kJ/kg}^\circ\text{C}, c_{\text{cu}} = 0.386 \text{ kJ/kg K}$$

To Find:

Entropy generated or Change in Entropy of universe

Solution:

We know that, the change in entropy of solids is given as

$$\Delta S_{\text{iron}} = m_{\text{iron}} c_{\text{iron}} \ln \frac{T_2}{T_1} = 30 \times 0.45 \times \ln \frac{288}{353}$$

$$\Delta S_{\text{iron}} = -2.75 \text{ kJ/K}$$

$$\Delta S_{\text{cu}} = m_{\text{cu}} c_{\text{cu}} \ln \frac{T_2}{T_1} = 40 \times 0.386 \times \ln \frac{288}{353}$$

$$\Delta S_{\text{cu}} = -3.14 \text{ kJ/K}$$

The heat lost by the blocks is the heat gained by the lake, as the blocks & lake together makes a closed system,

$$Q_{out} = \Delta U + W$$

Since no work is done, $W = 0$

Therefore,

$$Q_{out} = \Delta U_{iron} + \Delta U_{cu} = m_{iron}c_{iron}(T_1 - T_2) + m_{cu}c_{cu}(T_1 - T_2)$$

$$Q_{out} = 30 \times 0.45 \times (353 - 288) + 40 \times 0.386 \times (353 - 288)$$

$$Q_{out} = 1881.1 \text{ kJ}$$

The change in entropy of the lake is given as

$$\Delta S_{lake} = \frac{Q_{gain}}{T_{lake}} = \frac{1881.1}{288} = 6.53 \text{ kJ/K}$$

Therefore, the total change in entropy of the system is

$$\Delta S_{tot} = \Delta S_{iron} + \Delta S_{cu} + \Delta S_{lake}$$

$$\Delta S_{tot} = -2.75 - 3.14 + 6.53$$

$$\Delta S_{tot} = 0.642 \text{ kJ/K}$$

11. Chickens with an average mass of 2.2 kg and average specific heat of 3.54 kJ/kg°C are to be cooled by chilled water that enters a continuous-flow-type immersion chiller at 0.5°C and leaves at 2.5°C. Chickens are dropped into the chiller at a uniform temperature of 15°C at a rate of 250 chickens per hour and are cooled to an average temperature of 3°C before they are taken out. The chiller gains heat from the surroundings at 25°C at a rate of 150 kJ/h. Determine (a) the rate of heat removal from the chickens, in kW, and (b) the rate of entropy generation during this chilling process.

Given Data:

$$m_{chk} = 2.2 \text{ kg}, c_{chk} = 3.54 \text{ kJ/kg}^\circ\text{C}, T_{1w} = 0.5^\circ\text{C}, T_{2w} = 2.5^\circ\text{C}$$

$$\text{mass flow rate of chicken, } \dot{m}_{chk} = m_{chk} \times 250 \text{ chicks per hour} = 2.2 \times \frac{250}{3600} = 0.153 \text{ kg/s}$$

$$T_{1c} = 15^\circ\text{C}, T_{2c} = 3^\circ\text{C}, T_{sur} = 25^\circ\text{C} = 298 \text{ K}, Q_{sur} = 150 \text{ kJ/h} = 0.042 \text{ kJ/s}$$

To Find:

Rate of heat removal from chicken, $Q_{chk}=?$

Entropy generation, $\Delta S_{tot}=?$

Solution:

The rate of heat removal from the chickens is given as

$$\dot{Q}_{chk} = \dot{m}_{chk} \times c_{chk} \times (T_{1c} - T_{2c}) = 0.153 \times 3.54 \times (15 - 3)$$

$$\dot{Q}_{chk} = 6.5 \text{ kJ/s} = 6.5 \text{ kW}$$

Entropy generation,

$$\Delta S_{tot} = \Delta S_{chk} + \Delta S_w + \Delta S_{sur}$$

The change in entropy of the chicken is given as

$$\Delta S_{chk} = \dot{m}_{chk} c_{chk} \ln \frac{T_{2c}}{T_{1c}} = 0.153 \times 3.54 \times \ln \frac{276}{288}$$

$$\Delta S_{chk} = -0.0231 \text{ kW/K}$$

The change in entropy of the water is given as

$$\Delta S_w = \dot{m}_w c_{pw} \ln \frac{T_{2w}}{T_{1w}}$$

To find the mass flow rate of water and total heat gained by the water is

$$\dot{Q}_w = Q_{chk} + Q_{in} = 6.5 + 0.042 = 6.542 \text{ kW}$$

Also

$$\begin{aligned} \dot{Q}_w &= \dot{m}_w \times c_{pw} \times (T_{2w} - T_{1w}) \\ \dot{m}_w &= \frac{\dot{Q}_w}{c_{pw}(T_{2w} - T_{1w})} = \frac{6.542}{4.18 \times (2.5 - 0.5)} = 0.771 \text{ kg/s} \end{aligned}$$

Therefore,

$$\begin{aligned} \Delta S_w &= 0.771 \times 4.18 \times \ln \frac{275.5}{273.5} \\ \Delta S_w &= 0.0235 \text{ kW/K} \end{aligned}$$

The change in entropy of the surroundings is

$$\begin{aligned} \Delta S_{sur} &= -\frac{\dot{Q}_{sur}}{T_{sur}} = \frac{0.042}{298} \\ \Delta S_{sur} &= -0.00014 \text{ kW/K} \end{aligned}$$

Therefore, entropy generation is,

$$\begin{aligned} \Delta S_{tot} &= \Delta S_{chk} + \Delta S_w + \Delta S_{sur} \\ \Delta S_{tot} &= -0.0231 + 0.0235 - 0.00014 \\ \Delta S_{tot} &= 0.00026 \text{ kW/K} \end{aligned}$$

12. Carbon-steel balls ($\rho = 7833 \text{ kg/m}^3$ and $c_p = 0.465 \text{ kJ/kg}^\circ\text{C}$) 8 mm in diameter are annealed by heating them first to 900°C in a furnace and then allowing them to cool slowly to 100°C in ambient air at 35°C . If 2500 balls are to be annealed per hour, determine (a) the rate of heat transfer from the balls to the air and (b) the rate of entropy generation due to heat loss from the balls to the air.

Given data:

Diameter of steel balls, $d = 8 \text{ mm} = 8 \times 10^{-3} \text{ m}$

Volume of steel balls, $V = 4/3\pi r^3 = 2.68 \times 10^{-7} \text{ m}^3$

Mass of the steel ball, $m = \rho V = 7833 \times 2.68 \times 10^{-7} = 2.1 \times 10^{-3} \text{ kg}$

Mass flow rate of steel balls annealed, $\dot{m} = (2500 \times 2.1 \times 10^{-3})/3600 = 1.46 \times 10^{-3} \text{ kg/s}$

$T_{1b} = 900^\circ\text{C}$, $T_{2b} = 100^\circ\text{C}$, $T_{sur} = 35^\circ\text{C}$

Solution:

The rate of heat transfer from the balls is,

$$\begin{aligned} \dot{Q} &= \dot{m} c_p \Delta T = 1.46 \times 10^{-3} \times 0.465 \times (900 - 100) \\ \dot{Q} &= 0.54 \text{ kJ/s} \end{aligned}$$

The rate of entropy generation,

$$\Delta S_{tot} = \Delta S_{balls} + \Delta S_{sur} = \dot{m}_{ball} c_{pball} \ln \frac{T_{2b}}{T_{1b}} + \frac{\dot{Q}}{T_{sur}}$$

$$\Delta S_{tot} = 1.46 \times 10^{-3} \times 0.465 \times \ln \frac{373}{1173} + \frac{0.54}{308}$$

$$\Delta S_{tot} = -7.52 \times 10^{-4} + 1.753 \times 10^{-3}$$

$$\Delta S_{tot} = 0.001 \text{ kW/K}$$

13. 1 kg of ice at -5°C is exposed to the atmosphere which is at 20°C . The ice melts and comes into thermal equilibrium with the atmosphere. (i) Determine the entropy increase of the universe; (ii) what is the minimum amount of work necessary to convert the water back into ice at -5°C ? c_p of ice is 2093 J/kg K and the latent heat of fusion of ice is 333.3 kJ/kg .

Given Data:

$m = 1 \text{ kg}$, $T_1 = -5^\circ\text{C} = 268 \text{ K}$, $T_2 = 20^\circ\text{C} = 293 \text{ K}$, $c_p = 2093 \text{ J/kgK}$, $h_{fg} = 333.3 \text{ kJ/kg}$

To Find:

Entropy increase of Universe

Work input required to convert water back to ice

Solution:

The total entropy changes of the system or the Entropy generation or Increase in Entropy of the universe is

$$\Delta S_{univ} = \Delta S_1 + \Delta S_2 + \Delta S_3 + \Delta S_{sur}$$

The change in entropy during ice being converted from ice at -5°C to water at 0°C

$$\Delta S_1 = mc_p \ln \frac{273}{T_1} = 1 \times 2093 \times \ln \frac{273}{268} = 38.69 \text{ J/K}$$

The entropy change or increase during phase change,

$$\Delta S_2 = \frac{Q}{273} = \frac{m \times h_{fg}}{273} = \frac{1 \times 333.3}{273} = 1220.9 \text{ J/K}$$

The entropy change or increase during water rising from 0°C to 20°C

$$\Delta S_3 = mc_{pw} \ln \frac{T_2}{273} = 1 \times 4187 \times \ln \frac{293}{273} = 296.02 \text{ J/K}$$

The change in entropy of the surrounding,

$$\Delta S_{sur} = -\frac{Q_{gain}}{T_2}$$

Heat lost by the surrounding,

$$Q_{lost} = mc_p(273 - T_1) + m \times h_{fg} + mc_p(T_2 - 273)$$

$$Q_{lost} = \{1 \times 2093 \times (273 - 268)\} + (1 \times 333.3 \times 10^3) + \{1 \times 4187 \times (293 - 273)\}$$

$$Q_{lost} = 427505 \text{ J}$$

$$\Delta S_{sur} = -\frac{Q_{lost}}{T_2} = -\frac{427505}{293} = -1459.06 \text{ J/K}$$

Therefore,

$$\Delta S_{univ} = 38.69 + 1220.9 + 296.02 - 1459.06 = 96.55 \text{ J/K}$$

In order to convert water back into ice, an external device, refrigerator is to be used. The amount of heat to be removed from water is 427505 J and the minimum amount of work needed to be supplied to the refrigerator can be found using increase in entropy principle

$$\Delta S_{univ} \geq 0$$

$$-(\Delta S_1 + \Delta S_2 + \Delta S_3) + \Delta S_{sur} \geq 0$$

$$-(\Delta S_1 + \Delta S_2 + \Delta S_3) + \frac{Q_{lost} + W}{T_2} \geq 0$$

$$\begin{aligned}
 -(38.69 + 1220.9 + 296.02) + \frac{427505 + W}{293} &\geq 0 \\
 -(1555.6) + \frac{427505 + W}{293} &\geq 0 \\
 \frac{427505 + W}{293} &\geq 1555.6 \\
 W &\geq (1555.6 \times 293) - 427505 \\
 W &\geq 28288.7 \text{ J} \\
 W_{min} &= 28288.7 \text{ J}
 \end{aligned}$$

14. One kg of ice at -10°C is allowed to melt in atmosphere at 30°C . The ice melts and the water so formed rises in temperature to that of atmosphere. Determine the entropy change of ice, entropy change of surrounding and the entropy changes of universe. The specific heat of ice is 2 kJ/kgK and its latent heat is 335 kJ/kg .

Given Data:

$$m = 1 \text{ kg}, T_1 = -10^\circ\text{C} = 263 \text{ K}, T_2 = 30^\circ\text{C} = 303 \text{ K}, c_p = 2 \text{ kJ/kgK}, h_{fg} = 335 \text{ kJ/kg}$$

To Find:

Entropy increase of Universe

Work input required to convert water back to ice

Solution:

The total entropy changes of the system or the Entropy generation or Increase in Entropy of the universe is

$$\Delta S_{univ} = \Delta S_1 + \Delta S_2 + \Delta S_3 + \Delta S_{sur}$$

The change in entropy during ice being converted from ice at -5°C to water at 0°C

$$\Delta S_1 = mc_p \ln \frac{273}{T_1} = 1 \times 2 \times \ln \frac{273}{263} = 0.075 \text{ kJ/K}$$

The entropy change or increase during phase change,

$$\Delta S_2 = \frac{Q}{273} = \frac{m \times h_{fg}}{273} = \frac{1 \times 335}{273} = 1.227 \text{ kJ/K}$$

The entropy change or increase during water rising from 0°C to 20°C

$$\Delta S_3 = mc_{pw} \ln \frac{T_2}{273} = 1 \times 4.187 \times \ln \frac{303}{273} = 0.437 \text{ kJ/K}$$

The change in entropy of the surrounding,

$$\Delta S_{sur} = -\frac{Q_{lost}}{T_2}$$

Heat lost by the surrounding,

$$\begin{aligned}
 Q_{lost} &= mc_p(273 - T_1) + m \times h_{fg} + mc_p(T_2 - 273) \\
 Q_{lost} &= \{1 \times 2 \times (273 - 263)\} + (1 \times 335) + \{1 \times 4.187 \times (303 - 273)\} \\
 Q_{lost} &= 480.6 \text{ kJ} \\
 \Delta S_{sur} &= -\frac{Q_{lost}}{T_2} = -\frac{480.6}{303} = -1.586 \text{ kJ/K}
 \end{aligned}$$

Therefore,

$$\Delta S_{univ} = 0.075 + 1.227 + 0.437 - 1.586 = 0.153 \text{ kJ/K}$$

In order to convert water back into ice, an external device, refrigerator is to be used. The amount of heat to be removed from water is 480.6 kJ and the minimum amount of work needed to be supplied to the refrigerator can be found using increase in entropy principle

$$\begin{aligned}
 \Delta S_{univ} &\geq 0 \\
 -(\Delta S_1 + \Delta S_2 + \Delta S_3) + \Delta S_{sur} &\geq 0 \\
 -(\Delta S_1 + \Delta S_2 + \Delta S_3) + \frac{Q_{lost} + W}{T_2} &\geq 0 \\
 -(0.075 + 1.227 + 0.437) + \frac{480.6 + W}{303} &\geq 0 \\
 -(1.739) + \frac{480.6 + W}{303} &\geq 0 \\
 \frac{480.6 + W}{303} &\geq 1.739 \\
 W &\geq (1.739 \times 303) - 480.6 \\
 W &\geq 46.32 \text{ kJ} \\
 W_{min} &= 46.32 \text{ kJ}
 \end{aligned}$$

15. A system has a heat capacity at constant volume $c_v = AT^2$ where $A = 0.042 \text{ J/K}^3$. The system is originally at 200 K, and a thermal reservoir at 100 K is available. What is the maximum amount of work that can be covered as the system is cooled down to the temperature of the reservoir?

Given Data:

$$c_v = AT^2, A = 0.042 \text{ J/K}^3, T_1 = 200 \text{ K}, T_2 = 100 \text{ K}$$

Solution:

Maximum amount of work, W

Solution:

Let us consider a reversible heat engine is used to convert the heat from the system to work, by using increase in entropy principle

$$\Delta S_{univ} \geq 0$$

The change in entropy of the universe is given as sum of change in entropy of the system, heat engine & the thermal reservoir

$$\begin{aligned}
 \Delta S_{univ} &= \Delta S_{sys} + \Delta S_{HE} + \Delta S_{res} \\
 \Delta S_{sys} &= \int_{T_1}^{T_2} c_v \frac{dT}{T} = \int_{T_1}^{T_2} A T^2 \frac{dT}{T} = \int_{200}^{100} 0.042 \times T dT = -630 \text{ J/K} \\
 \Delta S_{HE} &= 0 \\
 \Delta S_{res} &= \frac{Q_1 - W}{T_2}
 \end{aligned}$$

Heat transferred by the system is given as

$$Q_1 = \int_{T_1}^{T_2} c_v dT = \int_{T_1}^{T_2} A T^2 dT = \int_{200}^{100} 0.042 \times T^2 dT = -98 \text{ kJ}$$

Therefore,

$$\begin{aligned}
 -630 + 0 + \frac{98000 - W}{100} &\geq 0 \\
 \frac{98000 - W}{100} &\geq 630 \\
 W &\leq 98000 - (630 \times 100)
 \end{aligned}$$

$$W \leq 350 \text{ kJ}$$

$$W_{\max} = 350 \text{ kJ}$$

16. 2 kg of an ideal gas is compressed polytropically from a pressure of $1.5 \times 10^5 \text{ N/m}^2$ and at a temperature of 16°C to a pressure of $7.5 \times 10^5 \text{ N/m}^2$. According to the law $p v^{1.3} = \text{constant}$. Determine initial volume, final temperature, work done, change in internal energy, change in enthalpy, heat transfer, change in entropy. Assume $R = 0.287 \text{ kJ/kg K}$ and $c_p = 1 \text{ kJ/kg K}$, $c_v = 0.72 \text{ kJ/kg K}$.

Given Data:

$m = 2 \text{ kg}$, $P_1 = 150 \text{ kPa}$, $T_1 = 16^\circ\text{C} = 289 \text{ K}$, $P_2 = 750 \text{ kPa}$, $p v^{1.3} = \text{constant}$, $R = 0.287 \text{ kJ/kg K}$ and $c_p = 1 \text{ kJ/kg K}$, $c_v = 0.72 \text{ kJ/kg K}$.

To Find:

$V_1 = ?$, $T_2 = ?$, $W_{1-2} = ?$, $\Delta U_{1-2} = ?$, $\Delta H_{1-2} = ?$, $Q_{1-2} = ?$, $\Delta S_{1-2} = ?$

Solution:

We know that, for an ideal gas

$$PV = mRT$$

For initial state,

$$P_1 V_1 = mRT_1$$

$$V_1 = \frac{2 \times 0.287 \times 289}{150} = 1.11 \text{ m}^3$$

To find the final temperature, we can use PVT relation

$$\frac{P_1}{P_2} = \left(\frac{T_2}{T_1} \right)^{n/n-1}$$

$$T_2 = \left(\frac{P_1}{P_2} \right)^{\frac{n-1}{n}} \times T_1$$

$$T_2 = \left(\frac{150}{750} \right)^{\frac{1.3-1}{1.3}} \times 289$$

$$T_2 = 199.3 \text{ K}$$

To find work done,

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n - 1}$$

To find the final volume,

$$P_2 V_2 = mRT_2$$

$$V_2 = \frac{2 \times 0.287 \times 199.3}{750} = 0.153 \text{ m}^3$$

Therefore,

$$W_{1-2} = \frac{150 \times 1.11 - 750 \times 0.153}{1.3 - 1}$$

$$W_{1-2} = 172.5 \text{ kJ}$$

To find change in internal energy,

$$\Delta U_{1-2} = m c_v \Delta T = 2 \times 0.72 \times (199.3 - 289)$$

$$\Delta U_{1-2} = -129.2 \text{ kJ}$$

Heat transferred,

$$Q_{1-2} = W_{1-2} + \Delta U_{1-2}$$

$$Q_{1-2} = 172.5 - 129.2$$

$$Q_{1-2} = 43.3 \text{ kJ}$$

To find the change in enthalpy,

$$\Delta H_{1-2} = m c_p \Delta T = 2 \times 1 \times (199.3 - 289)$$

$$\Delta H_{1-2} = -179.4 \text{ kJ}$$

To find the change in entropy,

$$\Delta S_{1-2} = m c_v \ln \frac{T_2}{T_1} + m R \ln \frac{V_2}{V_1}$$

$$\Delta S_{1-2} = \left\{ 2 \times 0.72 \times \ln \frac{199.3}{289} \right\} + \left\{ 2 \times 0.287 \times \ln \frac{0.153}{1.11} \right\}$$

$$\Delta S_{1-2} = -1.672 \text{ kJ/K}$$

MULTIPLE CHOICE QUESTIONS

Questions	opt1	opt2	opt3	opt4	answer
The displacement work is given by	$\int p.ds$	$\int T.ds$	$\int p.dv$	$\int p. dT$	$\int p.dv$
The change in internal energy is zero in _____ process	Isobaric	Isothermal	polytrophic	Isochoric	Isothermal
The polytropic law is given by	$pV = \text{constant}$	$pV^\gamma = \text{constant}$	$pV^n = \text{constant}$	$p/T = \text{constant}$	$pV^n = \text{constant}$
The isentropic law is given by	$pV = \text{constant}$	$pV^\gamma = \text{constant}$	$pV^n = \text{constant}$	$p/T = \text{constant}$	$pV^\gamma = \text{constant}$
The energy required to raise the temperature of the unit mass of a substance by one degree at constant volume is known as	super heat	specific heat at constant volume	Degree of heat	Specific heat at constant pressure	specific heat at constant volume
The energy required to raise the temperature of the unit mass of a substance by one degree at constant pressure is known as	Super heat	Specific heat at constant volume	Degree of heat	Specific heat at constant pressure	Specific heat at constant pressure
The fluid pressure is reduced from higher pressure to lower pressure at constant enthalpy then the process is known as	Isentropic process	Throttling process	Isobaric process	Adiabatic process	Throttling process
The ratio of specific heat (?) for air is approximately equal to	1	0.287	1.4	2.5	1.4
The efficiency of Carnot cycle with $T_1 = 1000\text{ K}$ and $T_2 = 100\text{ K}$ is approximately	10%	50%	90%	0%	90%
The efficiency of a heat engine is equal to	Work output X Heat input	Work output / Heat input	Heat input + Work output	Heat input - Work output	Work output / Heat input
The efficiency of an actual engine is	less than carnot engine	greater than carnot engine	equal to carnot engine	None of these	less than carnot engine
It is impossible to construct an engine which produces work output by exchanging heat between a single thermal reservoir	Carnot theorm	Kelvin-plank statement	Clausius statement	Clausius inequality	Kelvin-plank statement
Entropy is a	positive function	negative function	point function	path function	point function
PMM - II violates	Clausius statement	Carnot theorem	Clausius inequality	Kelvin Planck statement	Kelvin Planck statement
If cyclic integral of $dQ/T < 0$, then the cycle	irreversible and	irreversible and	reversible and	reversible and	irreversible and

is	possible	impossible	possible	impossible	possible
Free expansion is an example for	reversible process	irreversible process	adiabatic process	throttling process	irreversible process
Reversible process occurs with	rapid rate	friction motion	infinitesimal rate	None of these	infinitesimal rate
A system undergoing reversible process has _____ efficiency	minimum	maximum	zero	None of these	maximum
In perfect gas the change in density is directly related to the change of	Pressure and temperature	temperature and volume	volume and density	density and entropy	Pressure and temperature
The ideal gas laws relates _____	PVT	SVT	ABT	TVS	PVT
The Individual Gas Constant R depends on the particular gas and the is related to the _____ of the gas .	Cp	Molecular	Cv	Temperature	Molecular
The value of Ru is _____	mR	nR	Rn	mn	mR
The formula for air density is _____	$P = p/RT$	$p=P/RT$	$R=P / pR$	$T = p/PR$	$P = p/RT$
The weight of air is the product of _____	$p \text{ g V}$	$P \text{ g V}$	$R \text{ g V}$	$T \text{ g V}$	$p \text{ g V}$
_____ is the measure of the heat energy required to raise the temperature of unit quantity of substance by unit interval .	heat	entropy	Specific heat	Enthalpy	Specific heat
Internal energy depends on _____	Enthalpy	entropy	temperature	molecular mass	temperature
Intermolecular forces of gas particles depend on _____	Pressure	Temperature	Volume	Velocity	Pressure
Molar volume of an ideal gas is _____	One mole of an ideal gas occupies 22.4 liters (dm ³) at STP	M ³	Volume at STP	Volume at NTP	Volume at STP
Van der waals equation of state is _____	$(P+a/V^2)(V_m-a)=RT$	$(P+a/V^2)(V_m-c)=RT$	$(P+a/V^2)(V_m-d)=RT$	$(P+a/V^2)(V_m-b)=RT$	$(P+a/V^2)(V_m-b)=RT$
STP is _____	0 C and 1.01325 bar	15 C and 760 mm of Hg	25 C and 760 mm of Hg	20 C and 1.01325 bar	20 C and 1.01325 bar

UNIT III

PROPERTIES OF PURE SUBSTANCE & GAS MIXTURES

LECTURE NOTES

Pure substance - Phase change process - Property diagrams - PVT surface - Steam – types, dryness fraction - Avogadro's law - Ideal Gas - Equations of State-Vander Waal's equation - Real Gas - Compressibility and its chart - Mixtures of Gases – Properties.

3.1 Introduction:

If a substance has a fixed chemical composition throughout, then such substances are called as pure substances. Examples: Oxygen, Carbon dioxide, water, Nitrogen etc. Also it need not have to be a single chemical compound or element, maybe a mixture of them can be considered as pure substances until they are homogeneous. The mixture of two or more phases of a pure substance as long as the chemical composition of them is the same.

3.2. Phase of a substance:

A phase is a distinct arrangement of molecules such that they are differentiable from the rest of them with a boundary surface. A substance can exist in three different phases viz solid, liquid & gas. In a solid phase, the molecules are at relatively fixed in position. In liquid phase, group of molecules move about each other whereas in a gaseous phase, the molecules move about at random.

3.3. Compressed liquid & saturated liquid:

The conditions at which water exists as liquid phase is called as compressed or subcooled liquid.

A liquid which is about to change to gaseous phase is called as saturated liquid.

3.4. Saturated Vapour & Superheated vapour:

A vapour which is about to condense back into liquid is known as saturated vapour. And if the same vapour which is not going to condense back into liquid is known as superheated vapour.

The boiling point of a liquid depends on the pressure. Hence the boiling temperature is fixed if the pressure is fixed. At a given pressure if the pure substance changes its phase, then the temperature at which it happens is called as saturation temperature (T_{sat}). Similarly, at a given temperature, the pressure at which the phase change happens is known as saturation pressure (P_{sat}).

3.5. Latent heat:

The amount of heat energy required to cause a phase change is called as latent heat (h_{fg}). The amount of energy absorbed while melting process is known as latent heat of fusion and this is equivalent to the energy released during freezing. The amount of energy absorbed during a vapourization is called as latent heat of vapourization and it is equivalent to heat released during condensation.

3.6. Property Diagrams:

The properties of a substance vary while it undergoes a phase change process. Such variations occurring during a phase change process can be better understood with the help of property diagrams.

(i) T-v diagram:

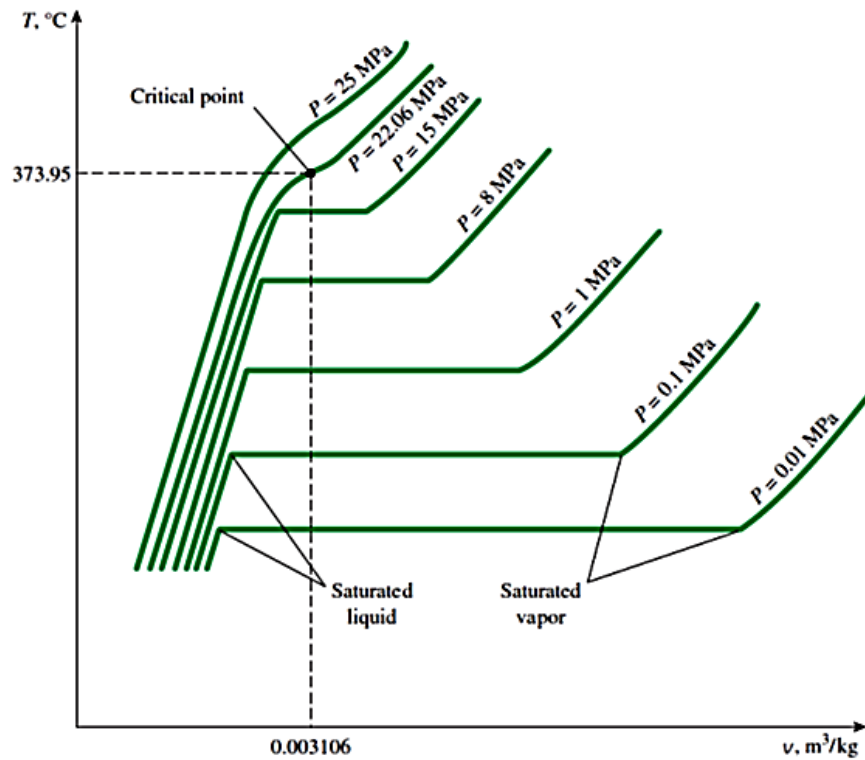


Fig. 3.1 T- v plot

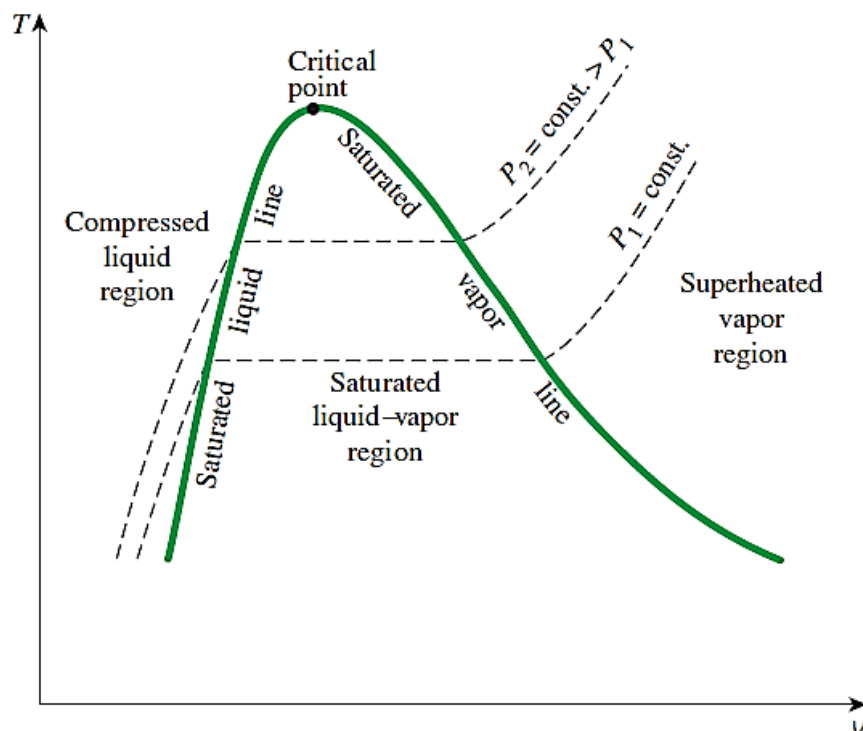


Fig. 3.2. T-v diagram

The point at which the saturated liquid and saturated vapour states are identical is called as critical point. The corresponding temperature, specific volume & pressure at critical point are called as the critical temperature, critical specific volume & critical pressure respectively. For water, the critical pressure is 22.06 MPa & the critical temperature & specific volume is 373.95°C & 0.0003106 m³/kg.

The connection of all saturated liquid points by a line forms the saturated liquid line. Similarly, the connecting line of all saturated vapour points is called as saturated vapour line.

(ii) P-v Diagram

It is similar in resemblance to the T-v diagram but in the P-v diagram the constant temperature lines are having a downward trend.

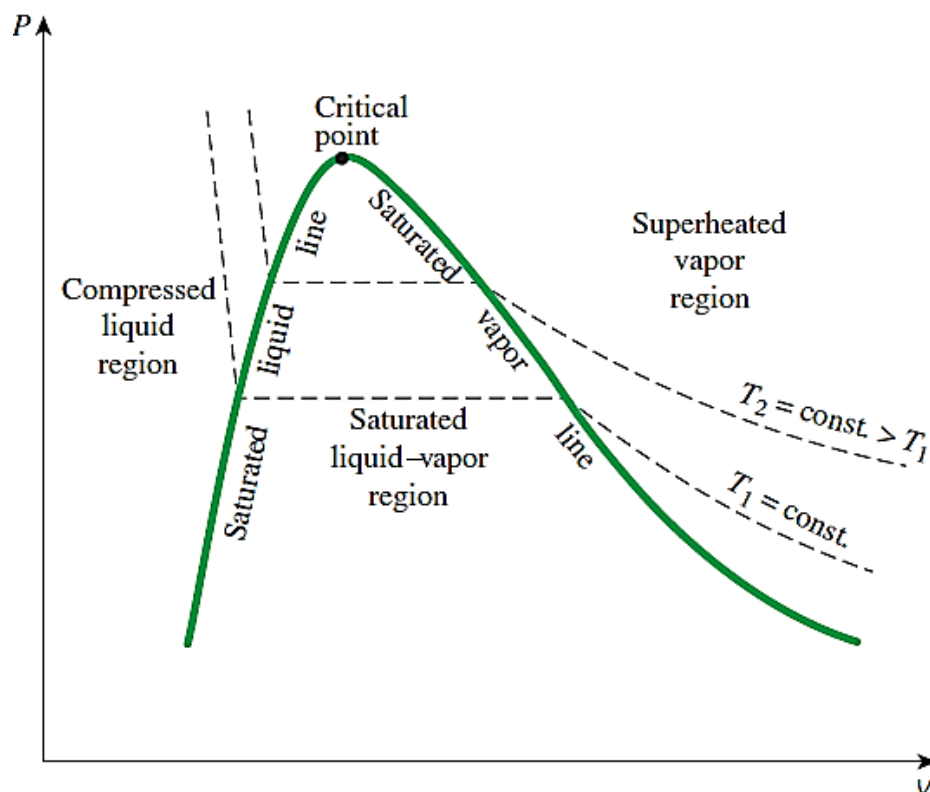


Fig. 3.3. P-v diagram

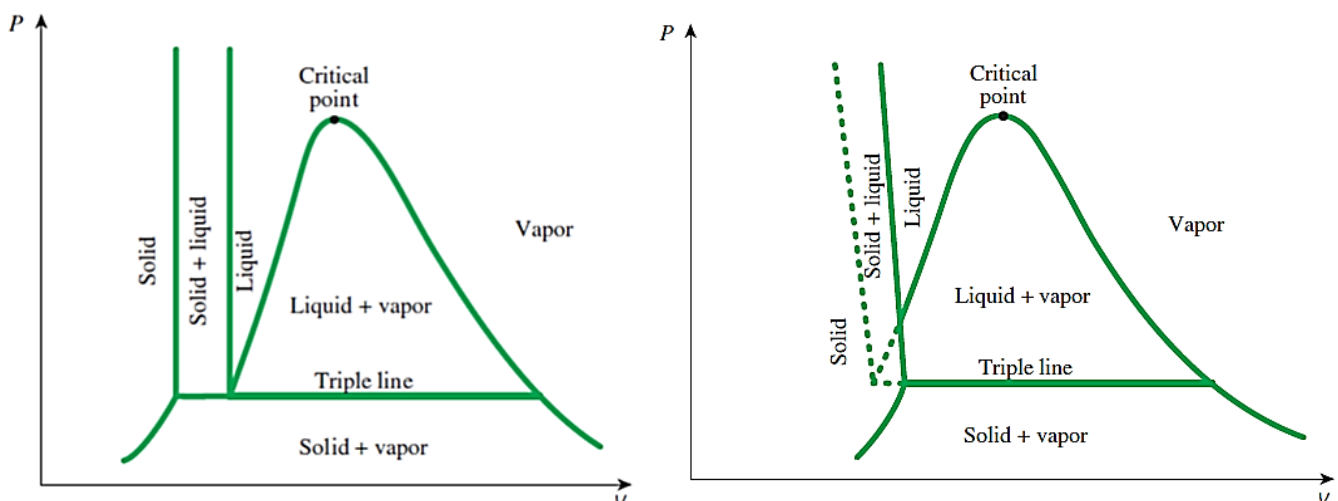


Fig. 3.4. P-v Diagram of a substance that contracts on freezing & the other expanding on freezing

Most of the substances contracts on solidification but the water on freezing expands in order to make the ice lighter so that it can float.

The condition at which all the three principal phases of a substance coexists in equilibrium is called as triple phase state and the line connecting those points is known as Triple line.

(iii) P-T Diagram (Phase Diagram)

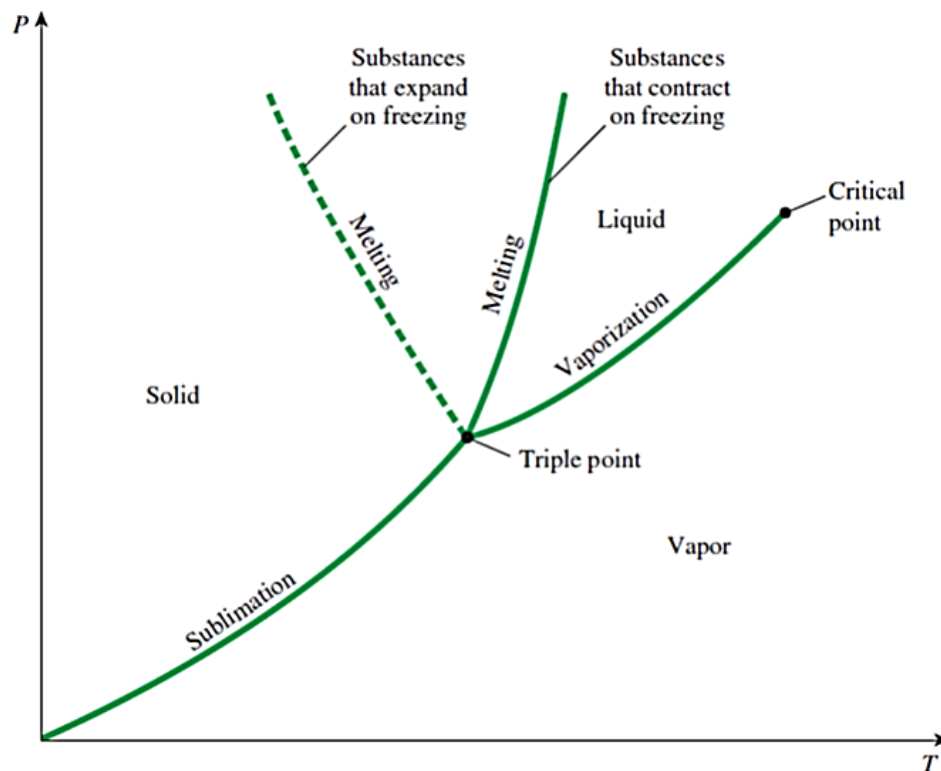


Fig. 3.5. P-T Diagram

The P-T diagram shows the various phase change transitions, sublimation (solid phase to vapour phase directly) line separates the solid & vapour region. The vapourization line separates the liquid and vapour region. The melting line separates the solid & liquid region. The point at which all three phases coexists in equilibrium is known as triple point.

(iv) T-s Diagram

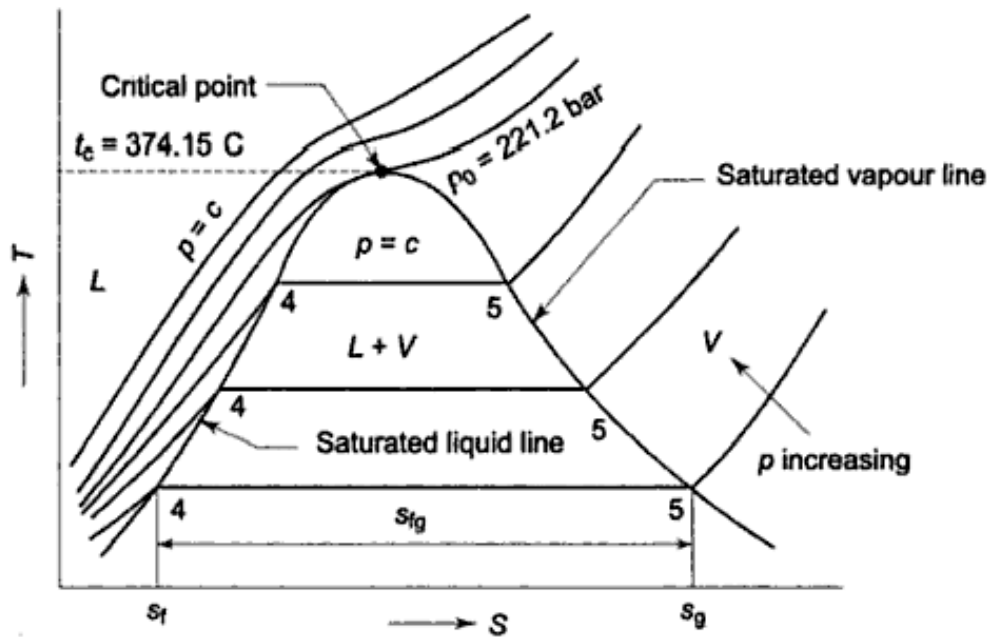


Fig. 3.6 T-s Diagram

The T-s diagram is obtained by joining the saturated liquid & vapour points of the isobars obtained for different pressures. The change in entropy during a phase change process at the particular pressure is the difference between the specific entropy of saturated vapour (s_g) to the specific entropy of saturated water (s_f). This s_{fg} decreases with increase in the pressure and becomes zero at the critical point.

(v) h-s Diagram (Mollier Diagram)

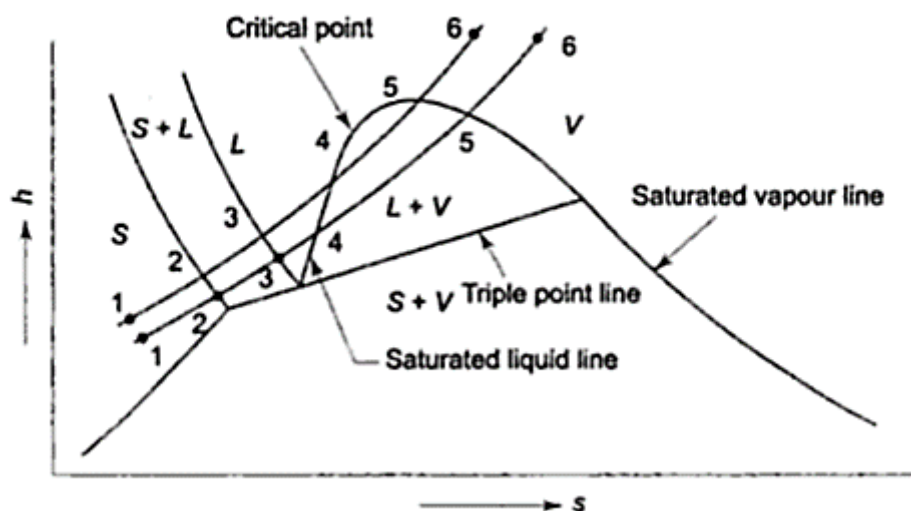


Fig. 3.7. h-s diagram

The h-s phase equilibrium diagram indicated above shows the various phases and transition zones. The slope of the isobar in the h-s diagram is equal to the absolute saturation temperature at that pressure.

$$\left(\frac{\partial h}{\partial s}\right)_{p=\text{const}} = T$$

Based on the above relation, the slope of the isobar remains constant if the temperature remains constant and it increases with increase in the temperature.

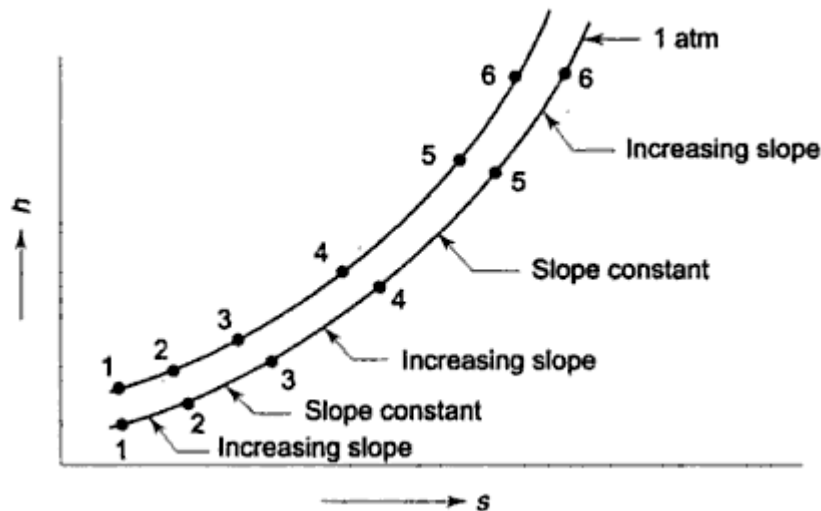


Fig. 3.8 h-s Isobars

The latent heat of vapourization (h_{fg}) is the difference between the specific enthalpy of saturated vapour (h_g) to the specific enthalpy of saturated water (h_f).

3.7. P-v-T surface:

The state of a simple compressible substance is fixed by any two independent intensive properties. Once the two appropriate properties are fixed, the other properties become dependent one. It is known that two independent variables of the form $z = f(x, y)$ can be represented as a surface in space. Thereby, P-v-T are the independent properties which can be represented as a surface in space. This results in P-v-T surfaces which shows the phase equilibrium of various phases of a substance.

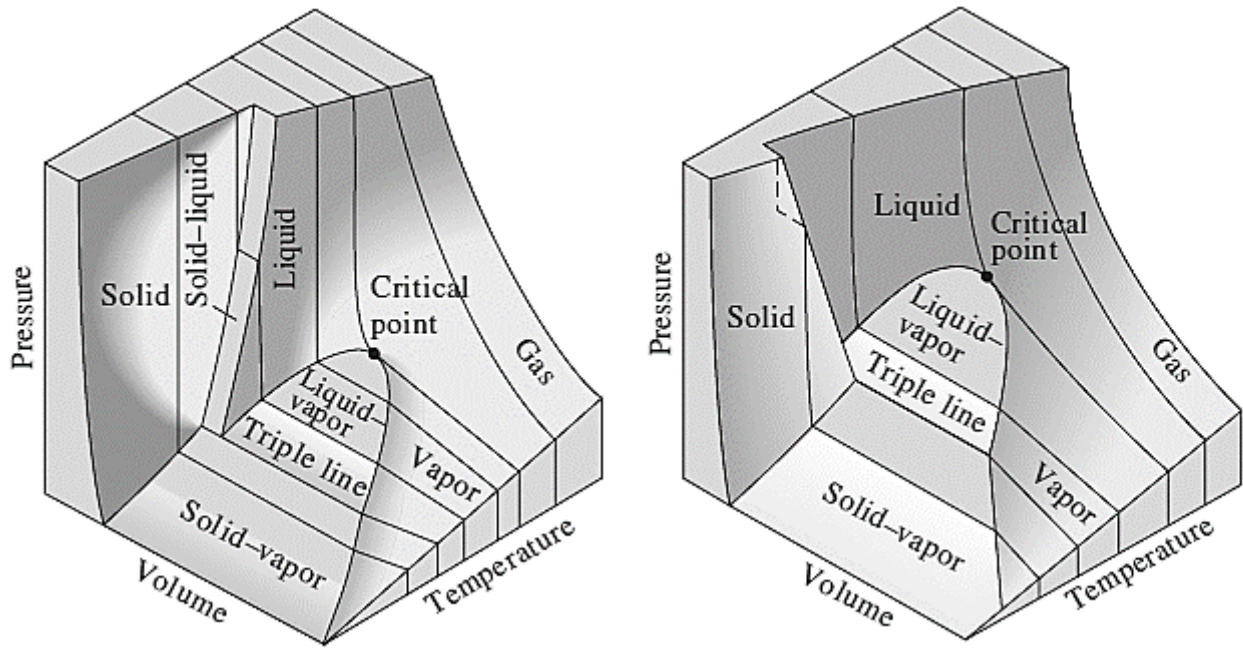


Fig. 3.9. P-v-T surface of a substance that contracts & expands on freezing

3.8. Quality or Dryness Fraction:

It is defined as the ratio of mass of vapour present in the total mass of liquid vapour mixture.

$$x = \frac{m_g}{m_f + m_g} = \frac{m_g}{m}$$

Total volume of the mixture is given as

$$V = V_f + V_g$$

$$m v = m_f v_f + m_g v_g$$

$$m v = (m - m_g) v_f + m_g v_g$$

$$v = \left(1 - \frac{m_g}{m}\right) v_f + \frac{m_g}{m} v_g$$

$$v = (1 - x) v_f + x v_g$$

$$v = v_f - x v_f + x v_g$$

$$v = v_f + x(v_g - v_f) = v_f + x v_{fg}$$

Similarly, the other properties are expressed in the same pattern to obtain the respective property of a liquid vapour mixture.

$$u = u_f + x(u_g - u_f) = u_f + x u_{fg}$$

$$h = h_f + x(h_g - h_f) = h_f + x h_{fg}$$

$$s = s_f + x(s_g - s_f) = s_f + x s_{fg}$$

3.9. Avogadro's Law:

It states that the volume of a kg mole of all gases at the pressures of 760 mm Hg (Standard atmospheric pressure) and temperature of 0°C is same and it equals to 22.4 litres. Therefore 1 kg mole of a gas has a volume of 22.4 m³ at normal temperature & pressure.

A mole of a substance has a mass numerically equal to the molecular weight of the substance. 1 kg mole of oxygen has 32 kg of mass, 1 kg mole of a nitrogen has a mass of 28 kg, etc.

If m is the mass in kg & M is molecular weight of certain gas, then the number of kg moles of the gas, n is expressed as

$$n = \frac{m}{M} = \frac{kg}{kg/kgmole} = kg \text{ mole}$$

The molar volume of certain gas with a total volume of V , kg is given as

$$v = \frac{V}{n} \text{ m}^3/kg \text{ mole}$$

3.10. Ideal Gas Equation of state:

The characteristic gas equation for an ideal gas is given as

$$P v = R T \text{ or } P V = m R T$$

$$P v = n R_u T \text{ or } P v = N K T$$

Where, n – number of kg mole of a gas, R_u – Universal Gas constant (8.314 kJ/kg mole K) and R is the characteristic gas constant, $R = R_u/M$.

N is the total number of molecules, $N = n A$.

A – Avogadro's number = 6.023×10^{26} molecules/kg mole.

K – Boltzmann constant = $R_u / A = 8314.3 / 6.023 \times 10^{26} = 1.38 \times 10^{-23}$ J/molecule K

The above ideal gas equation is applicable to limited range because of its simplicity. In order to have a wide range of application with no limitations it is desirable to have an equation of state that meets the same to represent the P-v-T behaviour of substances.

There are several equations proposed to meet the above condition and they are as follows,

- i. Vander Waals equation of state
- ii. Beattie – Bridgeman equation of state
- iii. Benedict – Webb – Rubin equation of state
- iv. Virial Equation of state

3.11. Vander Waals equation of state:

Vander Waal proposed an improvised form of equation of state in 1873 by considering two constants that accounts for the intermolecular attraction forces and the volume occupied by the molecules themselves. The improved equation of state is given as

$$\left(P + \frac{a}{v^2}\right) (v - b) = R T$$

The term a/v^2 accounts for the intermolecular forces, and b accounts for the volume occupied by the gas molecules.

In a room at atmospheric pressure and temperature, the volume actually occupied by molecules is only about one-thousandth of the volume of the room. As the pressure increases, the volume occupied by the molecules becomes an increasingly significant part of the total volume. Van der Waals proposed to correct this by replacing v in the ideal-gas relation with the quantity $v - b$, where b represents the volume occupied by the gas molecules per unit mass.

The determination of the two constants appearing in this equation is based on the observation that the critical isotherm on a P - v diagram has a horizontal inflection point at the critical point, the first and the second derivatives of P with respect to v at the critical point must be zero. That is,

$$\left(\frac{\partial P}{\partial v}\right)_{T_{cr}=T=const} = 0 \quad \& \quad \left(\frac{\partial^2 P}{\partial v^2}\right)_{T_{cr}=T=const} = 0$$

By performing differentiation and eliminating the v_{cr} , the constants a & b can be determined as

$$a = \frac{27 R^2 T_{cr}^2}{6 P_{cr}} \quad \& \quad b = \frac{R T_{cr}}{8 P_{cr}}$$

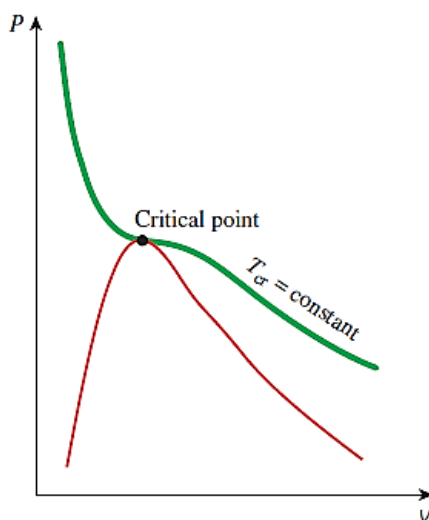


Fig. 3.10. Critical Isotherm

The accuracy of the Vander Waals equation of state solely depends on the values of the constants a & b that are found for a wide range of ideal gas behaviours.

3.12. Compressibility factor (Z):

The behaviour of a real gas deviates from that of an ideal gas near the saturation region and critical points. This deviation can be accounted in the ideal gas equation by introducing a correction factor known as compressibility factor, z

$$z = \frac{P v}{R T} \quad \text{or} \quad P v = z R T$$

Where $z = 1$ for ideal gases and it is less than or greater than 1 for real gases.

Gases behave differently at a given temperature and pressure but their behaviour looks alike at temperatures and pressures with respect to their critical temperature and pressure. And this ratio is known to be reduced temperature, pressure & specific volume.

$$P_R = \frac{P}{P_{cr}}, \quad T_R = \frac{T}{T_{cr}} \quad \& \quad v_R = \frac{v}{v_{cr}}$$

The compressibility factor, z is same for all real gases at same reduced properties. This condition is known to be principle of corresponding states.

The compressibility factor chart for various gases shown in the figure 3.11. shows that

- At very low pressures ($P_R \ll 1$) gases behave as an ideal gas regardless of the temperatures.
- At high temperatures ($T_R \gg 2$) the ideal gas behaves like an ideal gas with good accuracy regardless of the pressure (except for $P_R \gg 1$).
- The behaviour of the ideal gas is deviating more in the vicinity of the critical points.

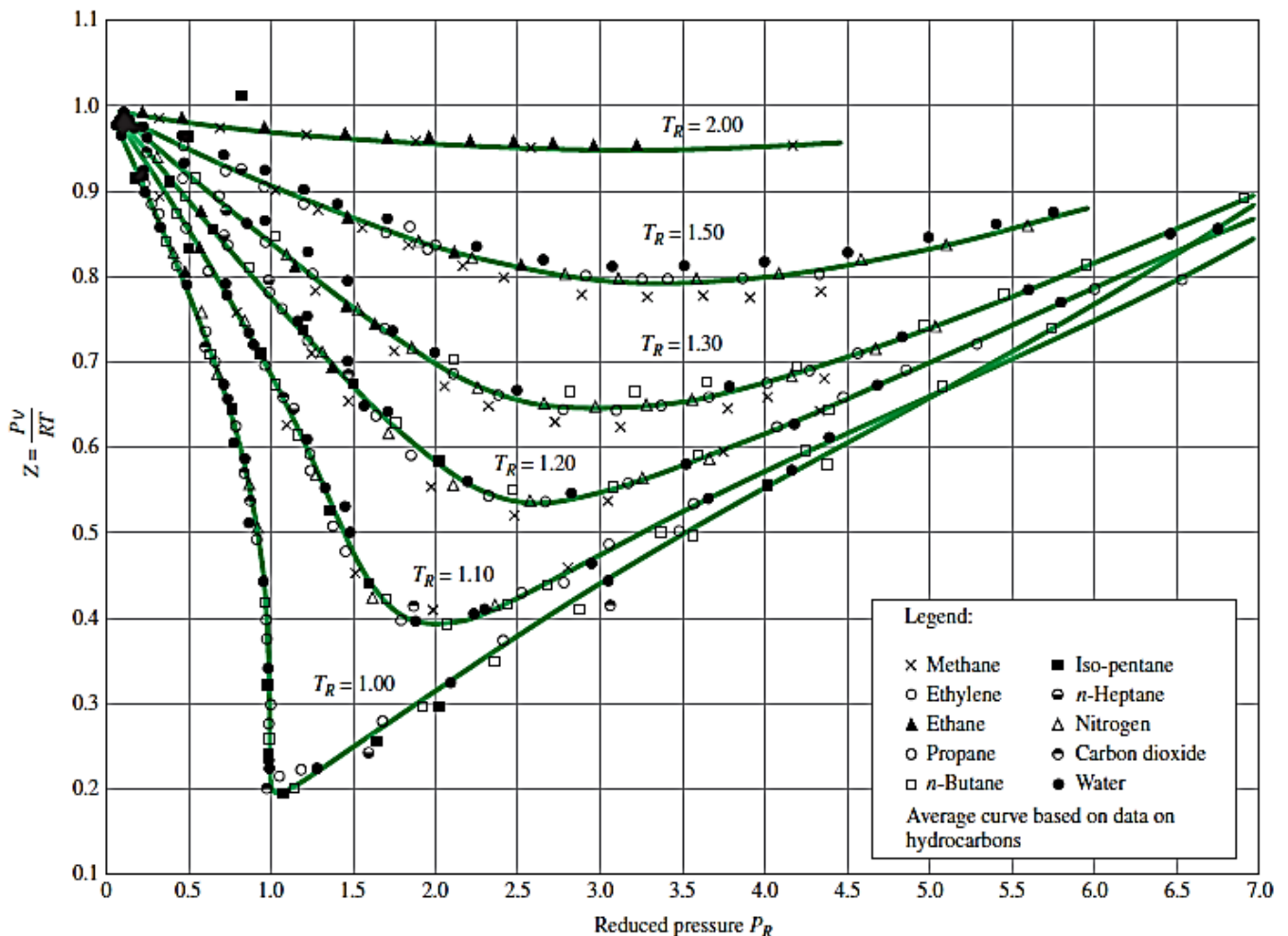


Fig. 3.11. Compressibility Chart

3.13. Gas Mixtures:

Mixture of various gases in certain proportion is known to be gas mixtures. In general, the atmospheric air is a gas mixture, that has certain composition of different gases like Nitrogen, oxygen, CO₂ etc.

The composition of gas mixtures can be specified with number of moles of each component called molar analysis or by specifying the mass of each component in the gas mixture, called gravimetric analysis.

The mixture of gases does not undergo any chemical reaction, the equilibrium state can be expressed with

$$P V = (n_1 + n_2 + n_3 + \dots + n_c) R_u T$$

Where, n_1 to n_n are the number of kg moles of different components of the gas mixture.

$$P = \frac{n_1 R_u T}{V} + \frac{n_2 R_u T}{V} + \frac{n_3 R_u T}{V} + \dots + \dots + \frac{n_c R_u T}{V}$$

In the above expression ($n_i R_u T / V$) represents the pressure of i^{th} gas of the mixture that would exert if it alone occupies a volume V at that temperature T . This pressure is known as the partial pressure of i^{th} gas and it is denoted as

$$P_1 = \frac{n_1 R_u T}{V} \quad P_2 = \frac{n_2 R_u T}{V} \quad P_3 = \frac{n_3 R_u T}{V} \quad \dots \dots \dots P_n = \frac{n_c R_u T}{V}$$

And $P = P_1 + P_2 + \dots + P_c$

This is known as Dalton's law of partial pressure stating that the total pressure of the mixture is equal to sum of their partial pressures of individual components in the gas mixture.

In the same manner, the total volume of a gas mixture is equal to sum of the partial volumes of each individual components of the gas mixture (partial volume is the volume occupied by the i^{th} gas of the mixture that would occupy a volume if it existed alone at the mixture temperature & pressure. This is known as Amagat's Law of partial volume.

$$V_1 = \frac{n_1 R_u T}{P} \quad V_2 = \frac{n_2 R_u T}{P} \quad V_3 = \frac{n_3 R_u T}{P} \quad \dots \dots \dots V_n = \frac{n_c R_u T}{P}$$

And $V = V_1 + V_2 + \dots + V_c$

The mass of the gas mixture, m is equal to the sum of the mass of individual components in the gas mixture and similarly, the mole number of the gas mixture, n is the sum of all the mole numbers of the individual components in the mixture.

$$m = \sum_{i=1}^c m_i \quad n = \sum_{i=1}^c n_i$$

The ratio of mass of a component to the mass of the mixture is known as mass fraction, m_f

$$m_{fi} = \frac{m_i}{\sum_{i=1}^c m_i} = \frac{m_i}{m}$$

Also the sum of all the mass fraction is equal to 1

$$m_f = \sum_{i=1}^c m_{fi} = 1$$

Similarly, the ratio of mole number of a component of gas mixture to the total mole number of a mixture is known as mole fraction, x_{fi}

$$x_{fi} = \frac{n_i}{\sum_{i=1}^c n_i} = \frac{n_i}{n}$$

Also the sum of all the mass fraction is equal to 1

$$x_f = 1$$

The gas constant of the mixture is equal to the sum of gas constant of the individual components

$$R_m = \frac{m_1 R_1 + m_2 R_2 + \dots + m_c R_c}{m_1 + m_2 + \dots + m_c}$$

The equivalent molecular weight, M of the gas mixture is given as

$$M = \sum_{i=1}^c x_{fi} M_i$$

The average molar mass of the gas mixture and the average gas constant is given as

$$M_i = \frac{m_i}{n_i} \quad M_m = \frac{m}{n} \quad R_m = \frac{R_u}{M_m}$$

Internal energy, Enthalpy & specific heats of the gas mixtures is also taken as sum of the partial values of the same.

Average internal energy, $U_m = m u_m$

$$U_m = m u_m = \frac{m_1 u_1 + m_2 u_2 + \dots + m_c u_c}{m_1 + m_2 + \dots + m_c}$$

Average enthalpy, $H_m = m h_m$

$$H_m = m h_m = \frac{m_1 h_1 + m_2 h_2 + \dots + m_c h_c}{m_1 + m_2 + \dots + m_c}$$

Specific heats of the gas mixture,

$$c_{vm} = \frac{m_1 c_{v1} + m_2 c_{v2} + \dots + m_c c_{vc}}{m_1 + m_2 + \dots + m_c}$$

$$c_{pm} = \frac{m_1 c_{p1} + m_2 c_{p2} + \dots + m_c c_{pc}}{m_1 + m_2 + \dots + m_c}$$

Also the change in entropy of the gas mixture due to diffusion is given as

$$\Delta S = \sum_{i=1}^c m_i R_i \ln(x_{fi})$$

Since, mole fraction is equal to ratio of partial pressure of i^{th} gas to the pressure of gas mixture

$$x_{fi} = \frac{n_i}{n} = \frac{P_i}{P}$$

TWO MARK QUESTIONS

1. What is available energy?

ANS: Available energy is the maximum thermal useful work under ideal condition.

2. What is anergy?

ANS: The product of entropy and environmental temperature is called “anergy”, which implies dispersed energy and the anergy balance equation becomes,

$$[\text{Anergy input}] + [\text{Anergy generated}] = [\text{Anergy output}]$$

3. State Gouy Stodola’s theorem.

ANS: The rate of loss of exergy in a process is proportional to the rate of entropy generation.

$$I = T_0 (\Delta S)_{\text{universe}} = T_0 S_{\text{generation}}$$

4. What is exergy?

ANS: Exergy is defined as a measure of the actual potential of a system to do work.

5. What is unavailable energy?

ANS: The energy present in the system which cannot be converted into work, is known as unavailable energy.

6. State the law of degradation of energy

ANS: The principle that during any irreversible process the total energy available to do work decreases.

7. What is dead state?

ANS: The state of a system when it is in thermodynamic equilibrium with its environment. Also it has no potential and kinetic energy. And it is chemically inert (no reaction with the environment)

8. Give exergy balance for a steady flow system.

$$\text{ANS: } \Psi_1 - \Psi_2 = H_1 + (mV_1^2)/2 + mgZ_1 - T_0 S_1 - (H_2 + (mV_2^2)/2 + mgZ_2 - T_0 S_2)$$

9. What is useful work?

ANS: The quantity of energy transferred from one system to another without an accompanying transfer of entropy.

10. What is the availability function for a closed system?

$$\text{ANS: } W_{\text{max}} \text{ or Availability} = U_1 - U_2 + p_0 (V_1 - V_2) - T_0 (S_1 - S_2)$$

11. What is saturation pressure?

ANS: It is the pressure at which phase change begins or ends at a specified temperature.

$$P_{\text{Sat}} = P_{\text{Sat}}(T)$$

12. What is saturation temperature?

ANS: Temperature at which phase change (liquid-vapour) begins or ends at a given pressure

$$T_{\text{Sat}} = T_{\text{Sat}}(P)$$

13. Write the useful work equation for closed system.

$$\begin{aligned} \text{ANS: } W_{\text{act or useful}} &= Q - \Delta U \\ &= T_0 (S_2 - S_1) \end{aligned}$$

14. What is the availability function for a steady flow system?

$$\text{ANS: } W_{\text{max}} \text{ or Availability} = (H_1 - T_0 S_1) - (H_2 - T_0 S_2)$$

Problems:

1. A vessel of volume 0.04 m^3 contains a mixture of saturated water and saturated steam at a temperature of 250°C . The mass of the liquid present is 9 kg . Find the pressure, the mass, the specific volume, the enthalpy, the entropy, and the internal energy.

Given Data:

$$V = 0.04 \text{ m}^3, T_{\text{sat}} = 250^\circ\text{C}, m_f = 9 \text{ kg}$$

To Find:

$$m = ?, P = ?, v = ?, h = ?, s = ?, u = ?$$

Solution:

We know that the given liquid vapour mixture is a saturated mixture, hence its saturation pressure at T_{sat} is taken from the steam tables along with other properties at saturated condition.

Saturated Water and Steam (Temperature) Tables

(t)	(p)	(v _f)	(v _g)	(h _f)	(h _{fg})	(h _g)	(s _f)	(s _{fg})	(s _g)	(t)
250	39.776	0.001 251	0.050 037	1 085.8	1 714.6	2 800.4	2.794	3.277	6.071	250
255	43.246	0.001 263	0.045 896	1 110.2	1 688.5	2 798.7	2.839	3.197	6.036	255
260	46.943	0.001 276	0.042 134	1 134.9	1 661.5	2 796.4	2.885	3.116	6.001	260
265	50.877	0.001 289	0.038 710	1 159.9	1 633.6	2 793.5	2.931	3.035	5.966	265
270	55.058	0.001 303	0.035 588	1 185.2	1 604.7	2 789.9	2.976	2.954	5.930	270

(i) Saturation pressure of the liquid vapour mixture

$$P_{\text{sat}} = 39.776 \text{ bar}$$

(ii) Mass of the saturated liquid vapour mixture

$$\text{volume of liquid, } V_f = m_f v_f = 9 \times 0.001251 = 0.011259 \text{ m}^3$$

$$\text{Total volume, } V = V_f + V_g$$

$$0.04 = 0.011259 + V_g$$

$$V_g = 0.028741 \text{ m}^3$$

We also know that,

$$\begin{aligned} \text{volume of vapour, } V_g &= m_g v_g \\ m_g &= \frac{V_g}{v_g} = \frac{0.028741}{0.050037} = 0.5744 \text{ kg} \end{aligned}$$

To find the dryness fraction, x

$$x = \frac{m_g}{m} = \frac{0.5744}{9.5744} = 0.06$$

(iii) specific volume, v

$$v = v_f + x(v_g - v_f) = 0.001251 + 0.06(0.050037 - 0.001251) = 0.004178 \text{ m}^3/\text{kg}$$

(iv) enthalpy, h $h = h_f + x(h_{fg}) = 1085.8 + 0.06(1714.6) = 1188.7 \text{ kJ/kg}$

(v) Entropy, s

$$s = s_f + x(s_{fg}) = 2.794 + 0.06(3.277) = 2.991 \text{ kJ/kgK}$$

(vi) Internal Energy, u

$$u = h - Pv = 1188.7 - (3977.6 \times 0.004178) = 1172.08 \text{ kJ/kg}$$

2. Steam initially at 0.3 MPa, 250°C is cooled at constant volume. (a) At what temperature will the steam become saturated vapour? (b) What is the quality at 80°C what is the heat transferred per kg of steam in cooling from 250°C to 80°C.

Given:

$$P = 0.3 \text{ MPa}, T = 250^\circ\text{C}$$

To Find:

i. $T_{\text{sat}} = ?$, ii. $x = ?$ At $T = 80^\circ\text{C}$ iii. $Q = ?$

Solution:

For the given pressure the actual saturation temperature is $T_{\text{sat}} = 133.55^\circ\text{C}$ and the given temperature is greater than the saturation temperature hence the steam is in superheated condition, from steam tables for super-heated steam

	$P = 200 \text{ kPa } (120.23)$				$P = 300 \text{ kPa } (133.55)$			
Sat.	0.88573	2529.5	2706.6	7.1271	0.60582	2543.6	2725.3	6.9918
150	0.95964	2576.9	2768.8	7.2795	0.63388	2570.8	2761.0	7.0778
200	1.08034	2654.4	2870.5	7.5066	0.71629	2650.7	2865.5	7.3115
250	1.19880	2731.2	2971.0	7.7085	0.79636	2728.7	2967.6	7.5165
300	1.31616	2808.6	3071.8	7.8926	0.87529	2806.7	3069.3	7.7022
400	1.54930	2966.7	3276.5	8.2217	1.03151	2965.5	3275.0	8.0329
500	1.78139	3130.7	3487.0	8.5132	1.18669	3130.0	3486.0	8.3250

Specific volume, $v = 0.7964 \text{ m}^3/\text{kg}$, enthalpy, $h_1 = 2967.6 \text{ kJ/kg}$, since the given process is a constant volume process, for the specific volume of $0.7964 \text{ m}^3/\text{kg}$, the saturation temperature is

From the steam tables, $v_g = 0.8919$ and $T_{\text{sat}} = 120^\circ\text{C}$ & $v_g = 0.7708$ for $T_{\text{sat}} = 125^\circ\text{C}$, therefore for $v = v_g = 0.7964 \text{ m}^3/\text{kg}$ by interpolation $T_{\text{sat}} = 123.9^\circ\text{C}$

The properties of steam at 80°C is taken from the steam tables

Temp. °C T	Pressure kPa, MPa P	Specific Volume, m ³ /kg		Internal Energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg K		
		Sat. Liquid v _f	Sat. Vapour v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapour u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapour h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapour s _g
0.01	0.6113	0.001000	206.132	0.00	2375.3	2375.3	0.00	2501.3	2501.3	0.0000	9.1562	9.1562
5	0.8721	0.001000	147.118	20.97	2361.3	2382.2	20.98	2489.6	2510.5	0.0761	8.9496	9.0257
10	1.2276	0.001000	106.377	41.99	2347.2	2389.2	41.99	2477.7	2519.7	0.1510	8.7498	8.9007
15	1.7061	0.001001	77.075	62.00	2322.1	2386.0	62.00	2465.0	2529.0	0.2245	8.5560	8.7805
75	38.578	0.001026	4.131	313.87	2162.0	2475.9	313.91	2321.4	2635.3	1.0154	6.6670	7.6824
80	47.390	0.001029	3.407	334.84	2147.4	2482.2	334.88	2308.8	2643.7	1.0752	6.5369	7.6121

specific volume, v

$$v = v_f + x(v_g - v_f)$$

$$0.7964 = 0.001029 + x(3.407 - 0.001029)$$

$$x = 0.234 \text{ Enthalpy of steam at } 80^\circ\text{C}$$

$$h_2 = h_f + x(h_{fg}) = 334.88 + 0.234(2308.8) = 875.9 \text{ kJ/kg}$$

From the first law of thermodynamics for a process,

$$Q = \Delta U + W$$

We also know that for a constant volume process, $W = 0$

$$\therefore Q = \Delta u = u_2 - u_1 = (h_2 - P_2 v_2) - (h_1 - P_1 v_1)$$

Since $v_1 = v_2 = v$ for a constant volume process

$$Q = (h_2 - h_1) - v(P_2 - P_1)$$

$$Q = (875.9 - 2967.6) - 0.7964(47.39 - 300)$$

$$Q = -1890.2 \text{ kJ/kg}$$

3. A piston-cylinder device contains 0.005 m³ of liquid water and 0.9 m³ of water vapour in equilibrium at 600 kPa. Heat is transferred at constant pressure until the temperature reaches 200°C. (a) What is the initial temperature of the water? (b) Determine the total mass of the water. (c) Calculate the final volume. (d) Show the process on a P-v diagram with respect to saturation lines.

Given Data:

$$V_f = 0.005 \text{ m}^3, V_g = 0.9 \text{ m}^3, P = 600 \text{ kPa}, T_2 = 200^\circ\text{C}$$

Find:

(i) initial temperature, $T_1 = ?$, (ii) $m = ?$, (iii) $V_2 = ?$

Solution:

The initial volume, V_1 is given as

$$V_1 = V_f + V_g = 0.005 + 0.9 = 0.905 \text{ m}^3$$

Since the given mixture is a liquid vapour mixture, hence the initial temperature of this would be the saturation temperature at $P = 600 \text{ kPa}$, therefore, from steam tables at $P = 600 \text{ kPa}$

$$T_1 = T_{sat} = 158.85^\circ\text{C}$$

From steam tables,

$$v_g = 0.316 \text{ m}^3/\text{kg}$$

$$v_f = 0.001101 \text{ m}^3/\text{kg}$$

We know that

$$V_f = m_f \times v_f$$

$$\therefore m_f = \frac{V_f}{v_f} = \frac{0.005}{0.001101} = 4.54 \text{ kg}$$

Similarly,

$$V_g = m_g \times v_g$$

$$\therefore m_g = \frac{V_g}{v_g} = \frac{0.9}{0.316} = 2.85 \text{ kg}$$

Total mass of the mixture in the container is

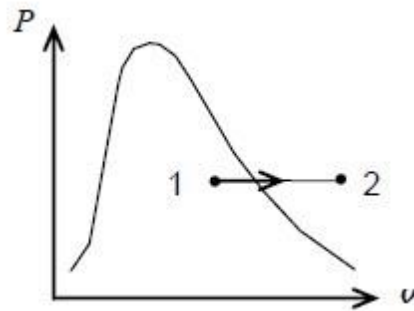
$$m = m_f + m_g = 4.54 + 2.85 = 7.4 \text{ kg}$$

At the final state the water vapour is superheated to a temperature of $T_2 = 200^\circ\text{C}$, at $P = 600 \text{ kPa}$, from steam tables, the specific volume is given as

$$v_2 = 0.352 \text{ m}^3/\text{kg}$$

Total final volume

$$V_2 = m \times v = 7.4 \times 0.352 = 2.605 \text{ m}^3$$



P-v Diagram

4. A large insulated vessel is divided into two chambers one containing 5 kg of dry saturated steam at 0.2 MPa and the other with 10 kg of steam at 80 % quality at 0.5 MPa. If the partition is removed and the steam is mixed thoroughly and allowed to settle, find the final pressure, steam quality and entropy change in the process.

Given Data:

$$m_{g1} = 5 \text{ kg}, P_1 = 0.2 \text{ MPa}, x_1 = 1 \text{ (Since dry steam)}$$

$$m_{g2} = 10 \text{ kg}, P_2 = 0.5 \text{ MPa}, x_2 = 0.8$$

To Find:

Final pressure, steam quality & entropy change

Solution:

Final pressure of the steam after the mixing process is the average of the pressures given

$$P_3 = \frac{200 + 500}{2} = 350 \text{ kPa}$$

The quality of the steam after mixing process is given as

$$x_3 = \frac{m_{g3}}{m_{f3} + m_{g3}}$$

Where the m_{gm} , m_{fm} are the mass of saturated liquid & mass of the saturated vapour in the mixture,

$$m_{f3} = m_{f1} + m_{f2} = 0 + m_{g2} \left(\frac{1 - x_2}{x_2} \right) = 10 \times \left(\frac{1 - 0.8}{0.8} \right) = 2.5 \text{ kg}$$

$$m_{g3} = m_{g1} + m_{g2} = 5 + 10 = 15 \text{ kg}$$

$$x_3 = \frac{15}{2.5 + 15} = 0.9$$

The entropy change during the mixing process is given as,

$$\Delta S = m_3 s_3 - (m_1 s_1 + m_2 s_2)$$

The entropy of the steam 1 at $P_1 = 200$ kPa is taken from property tables as

$$s_1 = s_g = 7.127 \text{ kJ/kgK}$$

The entropy of the steam 2 at $P_2 = 500$ kPa is taken from the property table as

$$s_2 = s_f + x_2 s_{fg} = 1.8604 + 0.8 \times 4.9603 = 5.8286 \text{ kJ/kgK}$$

The entropy of the steam 3 at $P_3 = 350$ kPa is taken from the property table as

$$s_3 = s_f + x_3 s_{fg} = 1.7274 + 0.9 \times 5.2128 = 6.4190 \text{ kJ/kgK}$$

Therefore, the entropy change during the process is

$$\Delta S = 15 \times 6.4190 - (5 \times 7.127 + 10 \times 5.8286) = 96.29 - 93.92 = 2.37 \text{ kJ/kgK}$$

$$\Delta S = 2.37 \text{ kJ/kgK}$$

5. Determine the specific volume of superheated water vapour at 15 MPa and 350°C, using (a) the ideal-gas equation, (b) the generalized compressibility chart, and (c) the steam tables. Also determine the error involved in the first two cases.

Given:

$$P = 15 \text{ MPa}, T = 350^\circ\text{C}$$

To Find:

Specific volume, $v = ?$ using (i) Ideal gas equation (ii) compressibility chart & (iii) steam tables

Solution:

From the thermodynamic table A-1, for water

$$R = 0.4615 \text{ kJ/kgK} \quad T_{cr} = 647.1 \text{ K} \quad P_{cr} = 22.06 \text{ MPa}$$

(i) ideal gas equation:

$$v = \frac{RT}{P} = \frac{0.4615 \times 623}{15000} = 0.01917 \text{ m}^3/\text{kg}$$

(ii) compressibility chart

$$P_R = \frac{P}{P_{cr}} = \frac{15}{22.06} = 0.68$$

$$T_R = \frac{T}{T_{cr}} = \frac{623}{647.1} = 0.96$$

From the compressibility chart, $z = 0.72$

$$v = 0.72 \times 0.01917 = 0.01380 \text{ m}^3/\text{kg}$$

(iii) from steam tables, for $P = 15$ MPa and $T = 350^\circ\text{C}$, from table A-6

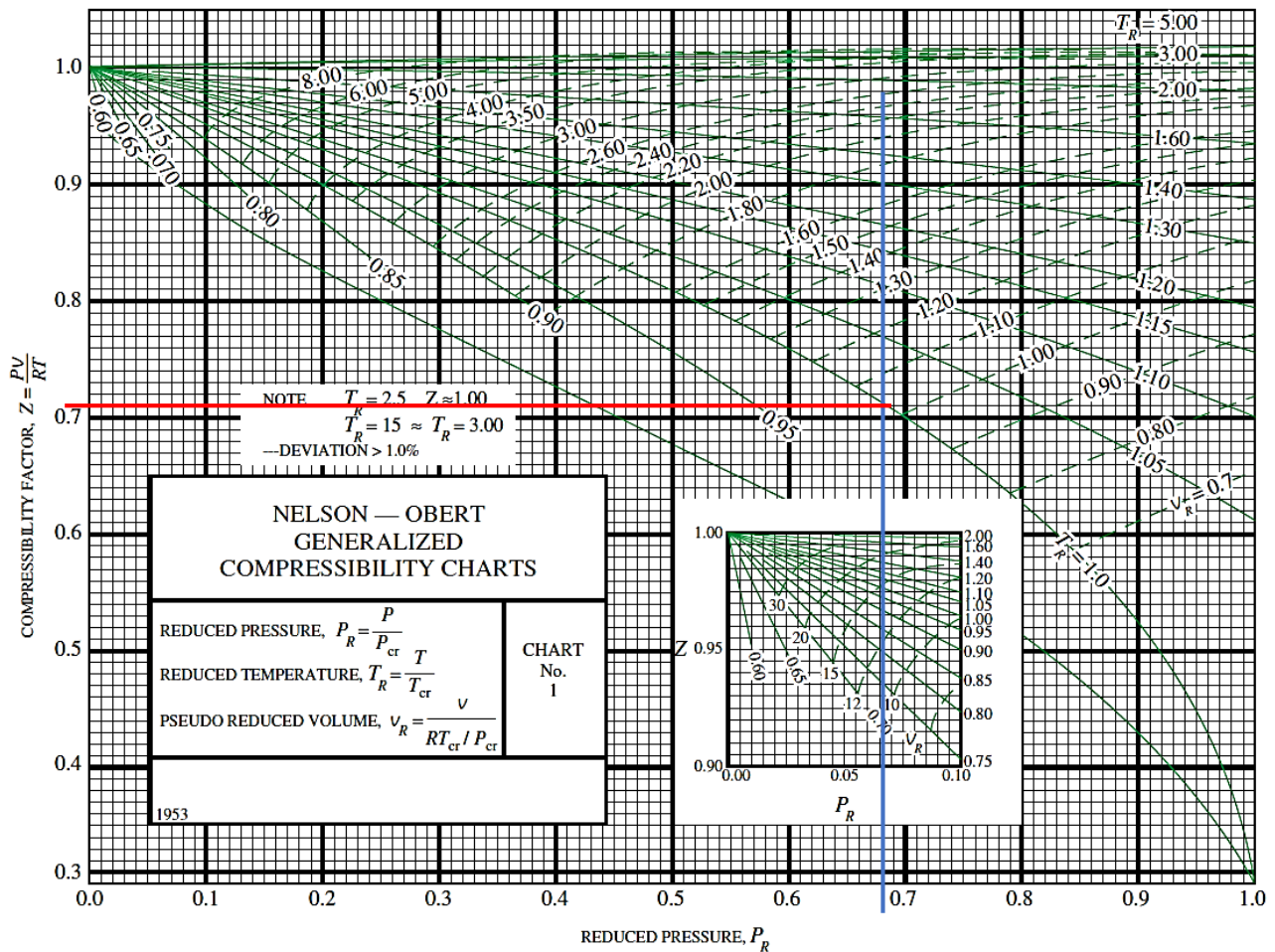
$$v = 0.011481 \text{ m}^3/\text{kg}$$

The percentage error involved in the case (i) & (iii)

$$40 \%$$

The percentage error involved in the case (ii) & (iii)

$$16.8 \%$$

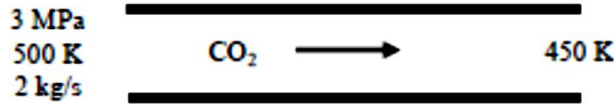
(a) Low pressures, $0 < P_R < 1.0$ 

6. Carbon dioxide gas enters a pipe at 3 MPa and 500 K at a rate of 2 kg/s. CO₂ is cooled at constant pressure as it flows in the pipe and the temperature of CO₂ drops to 450 K at the exit. Determine the volume flow rate and the density of carbon dioxide at the inlet and the volume flow rate at the exit of the pipe using (a) the ideal-gas equation and (b) the generalized compressibility chart. Also, determine (c) the error involved in the first case.

Properties The gas constant, the critical pressure, and the critical temperature of CO₂ are (Table A-1)

$$R = 0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}, \quad T_{cr} = 304.2 \text{ K}, \quad P_{cr} = 7.39 \text{ MPa}$$

Analysis



(a) From the ideal gas equation of state,

$$\dot{V}_1 = \frac{\dot{m}RT_1}{P_1} = \frac{(2 \text{ kg/s})(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(500 \text{ K})}{(3000 \text{ kPa})} = 0.06297 \text{ m}^3/\text{kg} \quad (2.1\% \text{ error})$$

$$\rho_1 = \frac{P_1}{RT_1} = \frac{(3000 \text{ kPa})}{(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(500 \text{ K})} = 31.76 \text{ kg/m}^3 \quad (2.1\% \text{ error})$$

$$\dot{V}_2 = \frac{\dot{m}RT_2}{P_2} = \frac{(2 \text{ kg/s})(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(450 \text{ K})}{(3000 \text{ kPa})} = 0.05667 \text{ m}^3/\text{kg} \quad (3.6\% \text{ error})$$

(b) From the compressibility chart (EES function for compressibility factor is used)

$$\left. \begin{aligned} P_R = \frac{P_1}{P_{cr}} &= \frac{3 \text{ MPa}}{7.39 \text{ MPa}} = 0.407 \\ T_{R,1} = \frac{T_1}{T_{cr}} &= \frac{500 \text{ K}}{304.2 \text{ K}} = 1.64 \end{aligned} \right\} Z_1 = 0.9791$$

$$\left. \begin{aligned} P_R = \frac{P_2}{P_{cr}} &= \frac{3 \text{ MPa}}{7.39 \text{ MPa}} = 0.407 \\ T_{R,2} = \frac{T_2}{T_{cr}} &= \frac{450 \text{ K}}{304.2 \text{ K}} = 1.48 \end{aligned} \right\} Z_2 = 0.9656$$

$$\text{Thus, } \dot{V}_1 = \frac{Z_1 \dot{m}RT_1}{P_1} = \frac{(0.9791)(2 \text{ kg/s})(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(500 \text{ K})}{(3000 \text{ kPa})} = 0.06165 \text{ m}^3/\text{kg}$$

$$\rho_1 = \frac{P_1}{Z_1 RT_1} = \frac{(3000 \text{ kPa})}{(0.9791)(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(500 \text{ K})} = 32.44 \text{ kg/m}^3$$

$$\dot{V}_2 = \frac{Z_2 \dot{m}RT_2}{P_2} = \frac{(0.9656)(2 \text{ kg/s})(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(450 \text{ K})}{(3000 \text{ kPa})} = 0.05472 \text{ m}^3/\text{kg}$$

7. 1-kg of carbon dioxide is compressed from 1 MPa and 200°C to 3 MPa in a piston-cylinder device arranged to execute a polytropic process for which $PV^{1.2} = \text{constant}$. Determine the final temperature treating the carbon dioxide as (a) an ideal gas and (b) a van der Waals gas.

Properties The gas constant, molar mass, critical pressure, and critical temperature of carbon dioxide are (Table A-1)

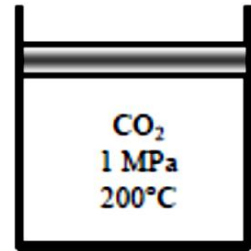
$$R = 0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}, \quad M = 44.01 \text{ kg/kmol}, \quad T_{cr} = 304.2 \text{ K}, \quad P_{cr} = 7.39 \text{ MPa}$$

Analysis (a) The specific volume at the initial state is

$$\nu_1 = \frac{RT_1}{P_1} = \frac{(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(473 \text{ K})}{1000 \text{ kPa}} = 0.08935 \text{ m}^3/\text{kg}$$

According to process specification,

$$\nu_2 = \nu_1 \left(\frac{P_1}{P_2} \right)^{1/n} = (0.08935 \text{ m}^3/\text{kg}) \left(\frac{1000 \text{ kPa}}{3000 \text{ kPa}} \right)^{1/1.2} = 0.03577 \text{ m}^3/\text{kg}$$



The final temperature is then

$$T_2 = \frac{P_2 \nu_2}{R} = \frac{(3000 \text{ kPa})(0.03577 \text{ m}^3/\text{kg})}{0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}} = 568 \text{ K}$$

(b) The van der Waals constants for carbon dioxide are determined from

$$a = \frac{27R^2 T_{cr}^2}{64P_{cr}} = \frac{(27)(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})^2 (304.2 \text{ K})^2}{(64)(7390 \text{ kPa})} = 0.1885 \text{ m}^6 \cdot \text{kPa}/\text{kg}^2$$

$$b = \frac{RT_{cr}}{8P_{cr}} = \frac{(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(304.2 \text{ K})}{8 \times 7390 \text{ kPa}} = 0.0009720 \text{ m}^3/\text{kg}$$

Applying the van der Waals equation to the initial state,

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

$$\left(1000 + \frac{0.1885}{\nu^2} \right) (\nu - 0.0009720) = (0.1889)(473)$$

Solving this equation by trial-error or by EES gives

$$\nu_1 = 0.08821 \text{ m}^3/\text{kg}$$

According to process specification,

$$\nu_2 = \nu_1 \left(\frac{P_1}{P_2} \right)^{1/n} = (0.08821 \text{ m}^3/\text{kg}) \left(\frac{1000 \text{ kPa}}{3000 \text{ kPa}} \right)^{1/1.2} = 0.03531 \text{ m}^3/\text{kg}$$

Applying the van der Waals equation to the final state,

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

$$\left(3000 + \frac{0.1885}{0.03531^2} \right) (0.03531 - 0.0009720) = (0.1889)T$$

Solving for the final temperature gives

$$T_2 = 573 \text{ K}$$

8. A mixture of gases consists of 0.4 kg of oxygen, 0.7 kg of carbon dioxide, and 0.2 kg of helium. This mixture is maintained at 100 kPa and 27°C. Determine the apparent molecular weight of this mixture, the volume it occupies, the partial volume of the oxygen, and the partial pressure of the helium.
9. A mixture of ideal gases consists of 5kg of nitrogen and 6kg of CO₂ at a pressure of 4bar and temperature of 27°C. Find (i) The mole fraction of each constituent, (ii) The equivalent molecular weight of mixture, (iii) The equivalent gas constant of the mixture, (iv) The partial pressures and partial volumes, (v) The volume and density of the mixture, (vi) The c_p and c_v of the mixture. Take γ for CO₂=1.286 and for N₂=1.4

Solution

(a) Since mole fraction $x_i = \frac{n_i}{\sum n_i}$

$$x_{N_2} = \frac{\frac{3}{28}}{\frac{3}{28} + \frac{5}{44}} = 0.485$$

$$x_{CO_2} = \frac{\frac{5}{44}}{\frac{3}{28} + \frac{5}{44}} = 0.515$$

Ans.

(b) Equivalent molecular weight of the mixture

$$\begin{aligned} M &= x_1 \mu_1 + x_2 \mu_2 \\ &= 0.485 \times 28 + 0.515 \times 44 \\ &= 36.25 \text{ kg/kg mol} \end{aligned}$$

Ans.

(c) Total mass,

$$m = m_{N_2} + m_{CO_2} = 3 + 5 = 8 \text{ kg}$$

Equivalent gas constant of the mixture

$$\begin{aligned} R &= \frac{m_{N_2} R_{N_2} + m_{CO_2} R_{CO_2}}{m} \\ &= \frac{3 \times \frac{8.3143}{28} + 5 \times \frac{8.3143}{44}}{8} = \frac{0.89 + 0.94}{8} \\ &= 0.229 \text{ kJ/kg K} \end{aligned}$$

Ans.

(d)

$$\begin{aligned} p_{N_2} &= x_{N_2} \cdot p = 0.485 \times 300 = 145.5 \text{ kPa} \\ p_{CO_2} &= x_{CO_2} \cdot p = 0.515 \times 300 = 154.5 \text{ kPa} \end{aligned}$$

$$V_{N_2} = \frac{m_{N_2} R_{N_2} T}{p} = \frac{3 \times \frac{8.3143}{28} \times 293}{300} = 0.87 \text{ m}^3$$

$$V_{CO_2} = \frac{m_{CO_2} R_{CO_2} T}{p} = \frac{5 \times \frac{8.3143}{44} \times 293}{300} = 0.923 \text{ m}^3$$

Ans.

(e) Total volume of the mixture

$$V = \frac{mRT}{p} = \frac{m_{N_2} R_{N_2} T}{p_{N_2}} = \frac{m_{CO_2} R_{CO_2} T}{p_{CO_2}}$$

$$\therefore V = \frac{8 \times 0.229 \times 293}{300} = 1.79 \text{ m}^3$$

Density of the mixture

$$\begin{aligned} \rho &= \rho_{N_2} + \rho_{CO_2} = \frac{m}{V} = \frac{8}{1.79} \\ &= 4.46 \text{ kg/m}^3 \end{aligned}$$

Ans.

(f) $c_{pN_2} - c_{vN_2} = R_{N_2}$

$$\begin{aligned} \therefore c_{vN_2} &= \frac{R_{N_2}}{\gamma - 1} = \frac{8.3143}{28 \times (1.4 - 1)} \\ &= 0.742 \text{ kJ/kg K} \end{aligned}$$

$$\begin{aligned} \therefore c_{pN_2} &= 1.4 \times 0.742 \\ &= 1.039 \text{ kJ/kg K} \end{aligned}$$

For CO_2 , $\gamma = 1.286$

$$\therefore c_{vCO_2} = \frac{R_{CO_2}}{\gamma - 1} = \frac{8.3143}{44 \times 0.286} = 0.661 \text{ kJ/kg K}$$

$$c_{pCO_2} = 1.286 \times 0.661 = 0.85 \text{ kJ/kg K}$$

For the mixture

$$\begin{aligned} c_p &= \frac{m_{N_2} c_{pN_2} + m_{CO_2} c_{pCO_2}}{m_{N_2} + m_{CO_2}} \\ &= \frac{3}{8} \times 1.039 + \frac{5}{8} \times 0.85 \\ &= 0.92 \text{ kJ/kg K} \end{aligned}$$

$$\begin{aligned} c_v &= \frac{m_{N_2} c_{vN_2} + m_{CO_2} c_{vCO_2}}{m} \\ &= \frac{3}{8} \times 0.742 + \frac{5}{8} \times 0.661 = 0.69 \text{ kJ/kg K} \end{aligned} \quad \text{Ans.}$$

If the mixture is heated at constant volume

$$\begin{aligned}
 U_2 - U_1 &= mc_v (T_2 - T_1) \\
 &= 8 \times 0.69 \times (40 - 20) \\
 &= 110.4 \text{ kJ} \\
 H_2 - H_1 &= mc_p (T_2 - T_1) \\
 &= 8 \times 0.92 \times 20 = 147.2 \text{ kJ} \\
 S_2 - S_1 &= mc_v \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1} \\
 &= mc_v \ln \frac{T_2}{T_1} = 8 \times 0.69 \times \ln \frac{313}{293} \\
 &= 0.368 \text{ kJ/kg K}
 \end{aligned}$$

Ans.

If the mixture is heated at constant pressure, ΔU and ΔH will remain the same.
The change in entropy will be

$$\begin{aligned}
 S_2 - S_1 &= mc_p \ln \frac{T_2}{T_1} - mR \ln \frac{p_2}{p_1} \\
 &= mc_p \ln \frac{T_2}{T_1} = 8 \times 0.92 \ln \frac{313}{293} \\
 &= 0.49 \text{ kJ/kg K}
 \end{aligned}$$

Ans.

10. A mass of air is initially at 260°C and 700 kPa and occupies 0.028 m³. The air is expanded at constant pressure to 0.084 m³. A polytropic process with $n = 1.5$ is then carried out, followed by a constant temperature process which completes a cycle. All the processes are reversible. Find the heat received and heat rejected in the cycle. Find the efficiency of the cycle.

Solution (a) The cycle is sketched on the p - v and T - s planes in Fig. Ex. 10.6.

Given

$$\begin{aligned}
 p_1 &= 700 \text{ kPa}, T_1 = 260 + 273 = 533 \text{ K} = T_3 \\
 V_1 &= 0.028 \text{ m}^3 \\
 V_2 &= 0.084 \text{ m}^3
 \end{aligned}$$

From the ideal gas equation of state

$$\begin{aligned}
 p_1 V_1 &= mRT_1 \\
 m &= \frac{700 \times 0.028}{0.287 \times 533} = 0.128 \text{ kg}
 \end{aligned}$$

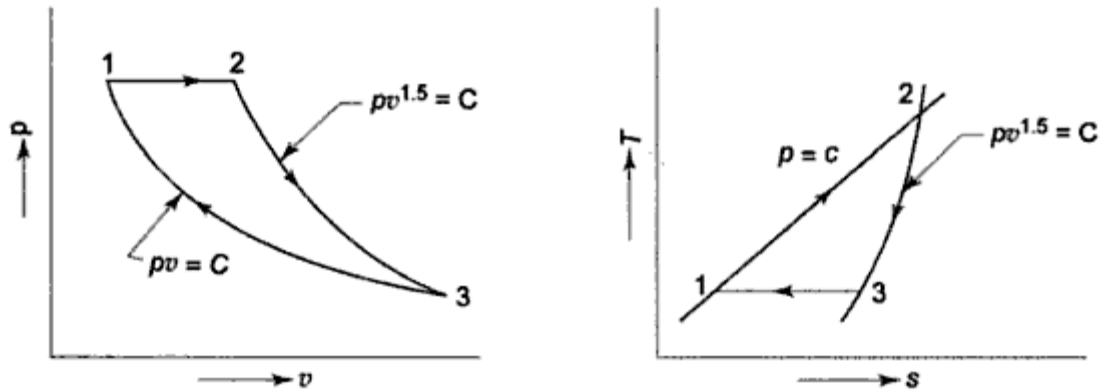


Fig. Ex. 10.6

Now
$$\frac{T_2}{T_1} = \frac{p_2 V_2}{p_1 V_1} = \frac{0.0084}{0.028} = 3$$

$\therefore T_2 = 3 \times 533 = 1599 \text{ K}$

Again
$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1} \right)^{n/(n-1)} = \left(\frac{1599}{533} \right)^{1.5/0.5} = (3)^3 = 27$$

Heat transfer in process 1-2

$$\begin{aligned} Q_{1-2} &= mc_p (T_2 - T_1) \\ &= 0.128 \times 1.005 (1599 - 533) \\ &= 137.13 \text{ kJ} \end{aligned}$$

Heat transfer in process 2-3

$$\begin{aligned} Q_{2-3} &= \Delta U + \int p dv \\ &= mc_v (T_3 - T_2) + \frac{mR(T_2 - T_3)}{n-1} \\ &= mc_v \frac{n-\gamma}{n-1} (T_3 - T_2) \\ &= 0.128 \times 0.718 \times \frac{1.5-1.4}{1.5-1} (533 - 1599) \\ &= 0.128 \times 0.718 \times \frac{0.1}{0.5} (-1066) \\ &= -19.59 \text{ kJ} \end{aligned}$$

For process 3-1

$$\delta Q = dU + \delta W = \delta W$$

$\therefore Q_{3-1} = W_{3-1} = \int_3^1 p dV = mRT_1 \ln \frac{V_1}{V_3}$

$$= mRT_1 \ln \frac{p_3}{p_1} = 0.128 \times 0.287 \times 533 \ln \left(\frac{1}{27} \right)$$

$$= -0.128 \times 0.287 \times 533 \times 3.2959$$

$$= -64.53 \text{ kJ}$$

(b) Heat received in the cycle

$$Q_1 = 137.13 \text{ kJ}$$

Heat rejected in the cycle

$$Q_2 = 19.59 + 64.53 = 84.12 \text{ kJ}$$

Ans.

(c) The efficiency of the cycle

$$\eta_{\text{cycle}} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{84.12}{137.13} = 1 - 0.61$$

$$= 0.39, \text{ or } 39\%$$

Ans.

11. 0.5 kg of air is compressed reversibly and adiabatically from 80kPa, 60°C to 0.4MPa, and is then expanded at constant pressure to the original volume. Sketch these properties on the p-v and t-s planes. Compute the heat transfer and work transfer for the whole path.

Solution The processes have been shown on the p - v and T - s planes in Fig. Ex. 10.5. At state 1

$$p_1 V_1 = mRT_1$$

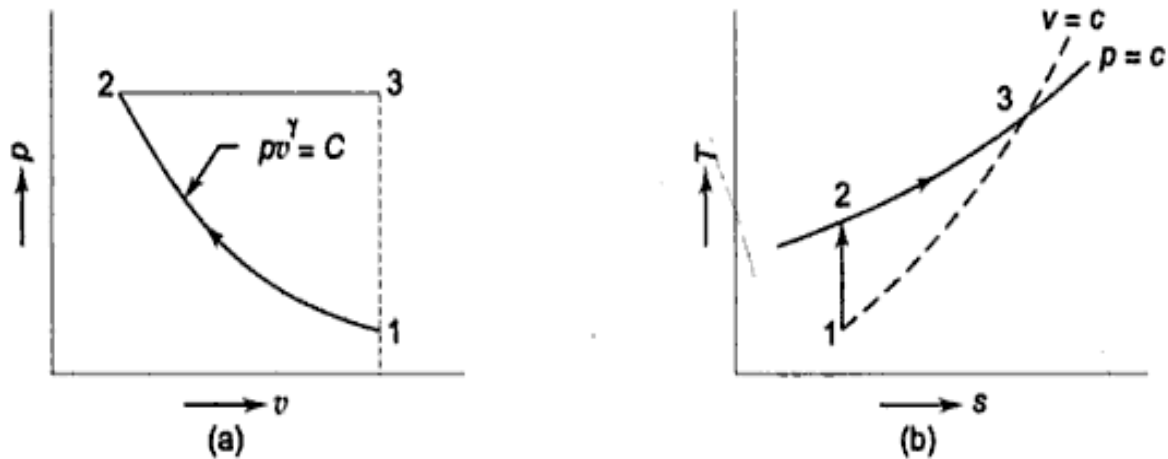


Fig. Ex. 10.5

\therefore

V_1 = volume of air at state 1

$$= \frac{m R T_1}{p_1} = \frac{1 \times 0.287 \times 333}{2 \times 80} = 0.597 \text{ m}^3$$

Since the process 1–2 is reversible and adiabatic

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma}$$

$$\therefore \frac{T_2}{T_1} = \left(\frac{400}{80} \right)^{(1.4-1)/1.4} = (5)^{2/7}$$

$$\therefore T_2 = 333 \times (5)^{2/7} = 527 \text{ K}$$

For process 1–2, work done

$$\begin{aligned} W_{1-2} &= \frac{p_1 V_1 - p_2 V_2}{\gamma - 1} = \frac{m R (T_1 - T_2)}{\gamma - 1} \\ &= \frac{1/2 \times 0.287 (333 - 527)}{0.4} \end{aligned}$$

$$= -69.6 \text{ kJ}$$

Again

$$p_1 v_1^\gamma = p_2 v_2^\gamma$$

$$\therefore \left(\frac{v_2}{v_1} \right)^\gamma = \frac{p_1}{p_2} = \frac{80}{400} = \frac{1}{5}$$

$$\therefore \frac{v_2}{v_1} = \left(\frac{1}{5} \right)^{1/1.4} = \frac{1}{3.162} = \frac{V_2}{V_1}$$

$$\therefore V_2 = \frac{0.597}{3.162} = 0.189 \text{ m}^3$$

For process 2–3, work done

$$\begin{aligned} W_{2-3} &= p_2 (V_1 - V_2) = 400 (0.597 - 0.189) \\ &= 163.2 \text{ kJ} \end{aligned}$$

\therefore Total work transfer

$$\begin{aligned} W &= W_{1-2} + W_{2-3} \\ &= -69.6 + 163.2 = 93.6 \text{ kJ} \end{aligned}$$

Ans.

For states 2 and 3

$$\frac{p_2 V_2}{T_2} = \frac{p_3 V_3}{T_3}$$

$$\therefore T_3 = T_2 \cdot \frac{V_3}{V_2} = 527 \times 3.162 = 1667 \text{ K}$$

Total heat transfer

$$\begin{aligned} Q &= Q_{1-2} + Q_{2-3} = Q_{2-3} = m c_p (T_3 - T_2) \\ &= 1/2 \times 1.005 (1667 - 527) \\ &= 527.85 \text{ kJ} \end{aligned}$$

Ans.

12. A mixture consisting of 1kg of He and 2.5 kg of N₂ at 25°C and 10 N/cm², compressed in a reversible adiabatic process to 70 N/cm². Calculate (i) The final partial pressure of constituents, (ii) The final

temperature and change in internal energy of mixture during the process. Take molecular weight of He = 4 kg/kg mole, C_v for N_2 = 0.743 kJ/kg K, He = 3.14 kJ/kg K, C_p for N_2 = 1.04 kJ/Kg K, He = 5.23 KJ/Kg K.

Given:

$$m_{He} = 1 \text{ kg}, m_{N_2} = 2.5 \text{ kg}, T_1 = 25^\circ\text{C}, P_1 = 100 \text{ kPa}, P_2 = 700 \text{ kPa}, c_{v,N_2} = 0.743 \frac{\text{kJ}}{\text{kg.K}}, c_{p,He} = 5.23 \frac{\text{kJ}}{\text{kg.K}}, c_{p,N_2} = 1.04 \frac{\text{kJ}}{\text{kg.K}}, M_{He} = 4 \text{ kg/kg.mole}$$

Solution:

To find the specific heat at constant volume & constant pressure for the given gas mixture,

$$c_v = \frac{m_{He} c_{v,He} + m_{N_2} c_{v,N_2}}{m_{He} + m_{N_2}} = 1.423 \frac{\text{kJ}}{\text{kg.K}}$$

$$c_p = \frac{m_{He} c_{p,He} + m_{N_2} c_{p,N_2}}{m_{He} + m_{N_2}} = 2.237 \frac{\text{kJ}}{\text{kg.K}}$$

We know that the specific heat ratio of the gas mixture is given as

$$\gamma = \frac{c_p}{c_v} = \frac{2.237}{1.423} = 1.572$$

The given process is a adiabatic compression process, hence the PvT relation

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = 605 \text{ K}$$

To find the partial pressure of the constituents at the end of the process,

$$x_{f,i} = \frac{P_i}{P}$$

Mole fraction of the helium & nitrogen are found as

$$x_{f,He} = \frac{n_{He}}{n} = \frac{\frac{m_{He}}{M_{He}}}{\frac{m_{He}}{M_{He}} + \frac{m_{N_2}}{M_{N_2}}} = 0.737$$

$$x_{f,N_2} = \frac{n_{N_2}}{n} = \frac{\frac{m_{N_2}}{M_{N_2}}}{\frac{m_{He}}{M_{He}} + \frac{m_{N_2}}{M_{N_2}}} = 0.263$$

Therefore, the partial pressures are given as

$$P_{2,He} = x_{f,He} P_2 = 515.9 \text{ kPa}$$

$$P_{2,N_2} = x_{f,N_2} P_2 = 184.1 \text{ kPa}$$

The change in internal energy of the gas mixture is given as

$$\Delta U = m C_v \Delta T = 3.5 \times 1.423 \times (605 - 298) = 1529.014 \text{ kJ}$$

13. A piston-cylinder device contains a mixture of 0.8 kg of H_2 and 1.2 kg of N_2 at 100 kPa and 300 K. Heat is now transferred to the mixture at constant pressure until the volume is doubled. Assuming constant specific heats at the average temperature, determine (a) the heat transfer and (b) the entropy change of the mixture.

Assumptions 1 Under specified conditions both H_2 and N_2 can be treated as ideal gases, and the mixture as an ideal gas mixture. 2 Kinetic and potential energy changes are negligible.

Properties The constant pressure specific heats of H_2 and N_2 at 450 K are 14.501 kJ/kg.K and 1.049 kJ/kg.K, respectively. (Table A-2b).

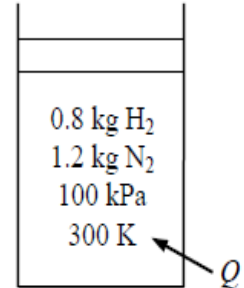
Analysis (a) Noting that $P_2 = P_1$ and $V_2 = 2V_1$,

$$\frac{P_2 V_2}{T_2} = \frac{P_1 V_1}{T_1} \longrightarrow T_2 = \frac{2V_1}{V_1} T_1 = 2T_1 = (2)(300 \text{ K}) = 600 \text{ K}$$

From the closed system energy balance relation,

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$$

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U \rightarrow Q_{\text{in}} = \Delta H$$



since W_b and ΔU combine into ΔH for quasi-equilibrium constant pressure processes.

$$\begin{aligned} Q_{\text{in}} = \Delta H &= \Delta H_{H_2} + \Delta H_{N_2} = [mc_{p,\text{avg}}(T_2 - T_1)]_{H_2} + [mc_{p,\text{avg}}(T_2 - T_1)]_{N_2} \\ &= (0.8 \text{ kg})(14.501 \text{ kJ/kg} \cdot \text{K})(600 - 300) \text{ K} + (1.2 \text{ kg})(1.049 \text{ kJ/kg} \cdot \text{K})(600 - 300) \text{ K} \\ &= \mathbf{3858 \text{ kJ}} \end{aligned}$$

(b) Noting that the total mixture pressure, and thus the partial pressure of each gas, remains constant, the entropy change of the mixture during this process is

$$\begin{aligned} \Delta S_{H_2} &= [m(s_2 - s_1)]_{H_2} = m_{H_2} \left(c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \right)_{H_2}^{\phi_0} = m_{H_2} \left(c_p \ln \frac{T_2}{T_1} \right)_{H_2} \\ &= (0.8 \text{ kg})(14.501 \text{ kJ/kg} \cdot \text{K}) \ln \frac{600 \text{ K}}{300 \text{ K}} \\ &= 8.041 \text{ kJ/K} \end{aligned}$$

$$\begin{aligned} \Delta S_{N_2} &= [m(s_2 - s_1)]_{N_2} = m_{N_2} \left(c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \right)_{N_2}^{\phi_0} = m_{N_2} \left(c_p \ln \frac{T_2}{T_1} \right)_{N_2} \\ &= (1.2 \text{ kg})(1.049 \text{ kJ/kg} \cdot \text{K}) \ln \frac{600 \text{ K}}{300 \text{ K}} \\ &= 0.8725 \text{ kJ/K} \end{aligned}$$

$$\Delta S_{\text{total}} = \Delta S_{H_2} + \Delta S_{N_2} = 8.041 \text{ kJ/K} + 0.8725 \text{ kJ/K} = \mathbf{8.91 \text{ kJ/K}}$$

MULTIPLE CHOICE QUESTIONS

Questions	opt1	opt2	opt3	opt4	answer
Energy Transfer as heat is always accompanied by a flow of _____	Internal energy	work	enthalpy	entropy	entropy
The Entropy generation is _____	a non negative term	may be negative or positive	zero for an irreversible process	none of these	a non negative term
for a closed system undergoing an irreversible process, the change in entropy is	reater than or equal to dQ/T	equal to dQ/T	greater than or equal to dQ/T_{sys}	equal to $dQ/T_{bou} + dS_{gen}$	equal to $dQ/T_{bou} + dS_{gen}$
Which of the statement is true	the quality of energy of a gas at 1500 K is superior to that at 300K	the quality of energy of a gas at 1500 K is inferior to that at 300K	the quality of energy of a gas at 300 K is superior to that at 1500K	the quality of energy of a gas at 1500 K is same to that at 300K	the quality of energy of a gas at 1500 K is superior to that at 300K
Which of the statement is true	The loss of available energy is less at 1500K than at 300K	The loss of available energy is more at 1500K than at 300K	The loss of available energy at 1500K is five times that at 300K	The loss of available energy at 1500K is equal at 300K	The loss of available energy is more at 1500K than at 300K
During a certain process $\Delta h = 7200 \text{ kJ/kg}$ $W_{max} = 4800 \text{ kJ/kg}$ and $\Delta s = 8 \text{ kJ/kgK}$. Therefore the temperature of the surroundings T_o is _____	100 K	200 K	300 K	400 K	300 K
A system is said to be in a dead state when its available energy is	zero	greater than zero	less than zero	unity	zero
Increase of entropy is proportional to _____	available energy	energy degradation	entropy generation	none of these	energy degradation
Availability refers to _____	maximum work potential	actual work	surrounding work	maximum possible useful work	maximum possible useful work
A system is said to be in a dead state when it is in	Thermal equilibrium	mechanical equilibrium	chemical equilibrium	thermodynamic equilibrium	thermodynamic equilibrium
Unavailable energy is the portion of the energy that	cannot be converted into	cannot be converted into	cannot be converted into	none of these	cannot be converted into work by a heat

	work by a heat engine	work even by a reversible heat engine	work by a heat engine as well as a reversible heat engine		engine as well as a reversible heat engine
second law of efficiency is _____	Exergy recovered / Exergy produced	Exergy recovered * Exergy produced	Exergy produced / Exergy recovered	none of these	Exergy recovered / Exergy produced
The exergy of an isolated system during a process _____	always increases	always decreases	always remains constant	none of these	always decreases
For systems that involve no actual work, the reversible work and irreversibility	are identical	may be identical	may not be identical	are not identical	are identical
Entropy is generated by	friction	chemical reaction	mixing of two fluids	All of these	All of these
In adiabatic flow with friction the stagnation temperature along a stream line	Increases	Decreases	Remains constant	Either increases or decreases	Remains constant
The heating of the gas constant is governed by	Boyle's law	Charles's law	Gaylussac's law	None	Charles's law
A process in which the gas is heated or expanded in such a way that the product of its pressure and volume remains constant is called _____	Isothermal process	Isobaric process	Adiabatic process	Polytropic process	Isothermal process
The hyperbolic process is governed by _____	Boyle's law	Charles's law	Gaylussac's law	None	Boyle's law
The heating of a gas at constant _____ is governed by Boyle's Law	Volume	Pressure	Temperature	None	Temperature
In isothermal process ,	Internal energy increases	Internal energy decreases	There is no change in internal energy	None	There is no change in internal energy
When the expansion or compression of the gas takes place according to the law $PV^n = \text{constant}$ then the process is known as _____	Isothermal process	Isobaric process	Adiabatic process	Polytropic process	Polytropic process

An adiabatic process is one in which _____	No heat enters or leave the gas	Temperature of gas changes	Change in internal energy equal to the work done	All of these	All of these
If the value of $n=0$ in the general law $PV^n = C$, the process is said to be hyperbolic, if n is equal to _____	Isothermal process	Isobaric process	Adiabatic process	Polytropic process	Isobaric process
The Carnot cycle has maximum efficiency for _____	Petrol engine	Diesel engine	Reversible engine	Irreversible engine	Reversible engine
The number of processes in a Rankine cycle is _____	3	4	5	6	5
The temperature of the gas when it is adiabatically decelerated to zero velocity at zero elevation is called _____	Stagnation temperature	Normal temperature	Standard temperature	Absolute temperature	Stagnation temperature
The enthalpy of a gas when it is adiabatically decelerated to zero velocity at zero elevation is called _____	Stagnation temperature	Normal temperature	Stagnation enthalpy	Stagnation density	Stagnation enthalpy
The pressure of a fluid when it is decelerated to zero velocity at zero elevation in a reversible adiabatic process is known as _____	Stagnation enthalpy	Standard temperature	Stagnation Pressure	Saturated Pressure	Stagnation Pressure

UNIT IV
THERMODYNAMIC AVAILABILITY AND RELATIONS
LECTURE NOTES

Basics - Dead state, quality of energy, degradation of energy - Reversible processes - Maximum work - Exergy - Closed system - Steady flow system - Irreversibility - Exergy Balance - Second law efficiency - Exact differentials - Tds Relations - Maxwell's Relation - Clausius - Clapeyron Equation - Joule-Thompson Coefficient.

4.1 Introduction:

From the first law of thermodynamics, the conservation of energy principle stated that energy cannot be created or destroyed but energy conversion is possible. Where as in the second law, it stated that energy is not just a quantity but it has quality as well. It also explained about the directional nature of the thermodynamic process.

In this chapter, let's have an insight on the concepts of availability. Availability or Exergy defined the maximum useful work that can be extracted from a system at a given state to specified environmental conditions.

Work done during a process is considered as a path function which depends on the initial, final state & the path followed, where as in the case of exergy, the initial condition is known and hence the work done during a process reduces to a function depending on its final state & the path followed.

Also, exergy is the maximum work potential that can be extracted from the thermodynamic system. The maximum work potential is possible if the process is reversible and the irreversibility's are neglected and the final state of the system reaching its surrounding condition (Dead State)

4.2. Dead State:

It is the state of the system at which the system is in thermodynamic equilibrium with its environment. The properties of the dead state are denoted along with a subscript 'o', i.e., P_o , T_o etc.,

4.3. Surrounding, Immediate surrounding & Environment:

Everything outside the systems boundary is known as surrounding, whereas the immediate surrounding is the region that is affected by the process that underwent in the system. The environment is the region beyond the immediate surrounding which does not get affected by the processes undergoing in a thermodynamic system.

4.4. Quality of Energy

The Joules experiment proved that the heat cannot be completely converted into work in finite number of cycles. This lead for the classification of energy into high grade and low grade energy. Mechanical work, electrical work, water power, tidal power are the examples of high grade energy and thermal energy, heat released during nuclear fission & fusion process & combustion of fossil fuels is accounted into low grade energy.

Second law provides the quality to energy possessed by the system under specified state. And this information helps to use the quality of energy effectively. The concepts of this chapter is useful in quantifying the quality of energy.

4.5. Degradation of Energy

According to first law of thermodynamics, energy is conserved but according to second law, energy is degraded. It is clear that when a high grade energy like work is converted to low grade energy heat, the quality of energy is degraded. Hence, the second law can also be called as law of degradation of energy.

4.4. Availability:

It is defined as the useful work potential delivered by a system undergoing a reversible process from a specified initial state to the state of dead. Also, it does not represent the actual work delivered by the system instead it gives a maximum limit up to which a system can deliver its work without violating the thermodynamic laws.

4.5. Useful work (W_u)

Useful work for a system with movable boundary is taken as the difference between the actual work (W) and work done on the surrounding (W_{sur}).

$$W_u = W - W_{sur} = W - P_o(v_2 - v_1)$$

4.6. Exergy or Availability of a closed system

Let us consider a closed system undergoing a process such that its temperature & pressure are in equilibrium with its environment. But it involves in doing some work on the surrounding. Thus the energy balance results in

$$\delta Q = \delta W + dE$$

$$T_o dS = \delta W_u + P_o V + dE$$

Where δW_u represents the availability of the system

$$\delta W_u = dE + P_o V - T_o dS$$

$$W_u = (E - E_o) + P_o (V - V_o) - T_o (S - S_o)$$

If the K.E & P.E changes are neglected, then the availability of a closed system is given as

$$A = \phi - \phi_o = (U - U_o) + P_o (V - V_o) - T_o (S - S_o)$$

If system changes from state 1 to state 2 during a process, the decrease in availability is the maximum useful work obtainable under given surrounding conditions.

$$A = (\phi_1 - \phi_o) - (\phi_2 - \phi_o) = (\phi_1 - \phi_2)$$

$$A = \{(U_1 - U_o) + P_o (V_1 - V_o) - T_o (S_1 - S_o)\} - \{(U_2 - U_o) + P_o (V_2 - V_o) - T_o (S_2 - S_o)\}$$

$$A = (U_1 - U_2) + P_o (V_1 - V_2) - T_o (S_1 - S_2)$$

4.7. Availability of an open system with steady flow

The exergy or availability of a steady flow system is given as

$$A = (\psi_1 - \psi_2) = (h_1 - h_2) - T_o(s_1 - s_2) + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)$$

The change in availability or the exergy represents the useful work or reversible work.

4.8. Decrease in exergy principle

The exergy or availability of an isolated system always decreases or in the limiting case remains constant for a reversible process. In simple words it can be understood as the available energy is destroyed during an actual process. This principle is known as decrease in exergy principle.

$$(\phi_1 - \phi_2)_{iso} \leq 0$$

4.9. Exergy Destruction or Irreversibility

The exergy destroyed is directly proportional to the entropy generated during a process. It also represents the lost work potential or unavailable energy or simply irreversibility.

$$I = T_o S_{gen} \geq 0$$

This above equation is known as Gouy-Stodola theorem.

4.10. Exergy Balance:

(a) Closed system:

exergy transfer by heat – exergy transfer by work – exergy destruction = change in exergy

$$\sum \left(1 - \frac{T_o}{T_k}\right) Q - [W - P_o(v_1 - v_2)] - T_o S_{gen} = \phi_1 - \phi_2$$

(b) Open system:

exergy transfer by heat – exergy transfer by work + exergy transfer by entering mass – exergy transfer by leaving mass – exergy destruction = change in exergy

$$\sum \left(1 - \frac{T_o}{T_k}\right) Q - [W - P_o(v_1 - v_2)] + \sum_{in} m \psi - \sum_{out} m \psi - T_o S_{gen} = \psi_1 - \psi_2$$

For a steady flow system, exergy entering is equal to sum of exergy leaving & the exergy destroyed.

$$\sum \left(1 - \frac{T_o}{T_k}\right) Q - [W - P_o(v_1 - v_2)] - T_o S_{gen} = \psi_1 - \psi_2$$

4.11. Second law efficiency:

It is defined as the ratio of actual thermal efficiency to the maximum thermal efficiency (reversible).

$$\eta_{II} = \frac{\eta_{actual}}{\eta_{max}} = \frac{W}{W_{rev}}$$

4.12. Exact Differentials

Let us consider a variable 'z' which depends on the independent variables 'x' & 'y' such that,

$$z = f(x, y)$$

The partial derivative of the above function is given as, (partial derivative is different from total derivative, since in partial case, the behaviour of dependent variable 'z' is found by varying one of the independent variable 'x' by keeping the other 'y' constant.)

$$dz = \left(\frac{\partial z}{\partial x}\right)_y dx + \left(\frac{\partial z}{\partial y}\right)_x dy$$

Let us consider

$$\left(\frac{\partial z}{\partial x}\right)_y = M, \quad \left(\frac{\partial z}{\partial y}\right)_x = N$$

Then partial derivative becomes,

$$dz = M dx + N dy$$

On differentiating M & N with respect to 'x' & 'y', it results in

$$\left(\frac{\partial M}{\partial y}\right)_x = \frac{\partial^2 z}{\partial x \partial y} \quad \left(\frac{\partial N}{\partial x}\right)_y = \frac{\partial^2 z}{\partial x \partial y}$$

This implies

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

The above condition of a function z depending on two independent variables 'x & y' resulted in a differential that is exact or perfect.

4.13. Maxwell's relations

A pure substance existing in a single phase has only two independent variables. In thermodynamics, we have eight such important variables like P, v, T, H, S, G (Gibbs function) & F (Helmholtz function). And it is possible to represent any one variable as dependent variable of other two. For pure substance, the following equations shows that for an infinitesimal reversible process.

1. $dU = TdS - PdV$
2. $dH = dU + PdV + VdP = T dS + V dP$
3. $dF = dU - T dS - S dT = -S dT - PdV$
4. $dG = dH - T dS - S dT = -S dT + V dP$

The above four equations resemble the PDE of the type,

$$dz = M dx + N dy$$

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

Let us substitute the values of M & N for each equations

For (1)

$$z = U, M = T, x = S, N = -P, y = V$$

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V \dots \dots \dots (a)$$

For (2)

$$z = H, M = T, x = S, N = V, y = P$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P \dots \dots \dots (b)$$

For (3)

$$z = F, M = -S, x = T, N = -P, y = V$$

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V \dots \dots \dots (c)$$

For (4)

$$z = G, M = -S, x = T, N = V, y = P$$

$$\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P \dots \dots \dots (d)$$

These are called the Maxwell relations. They are extremely valuable in thermodynamics because they provide a means of determining the change in entropy, which cannot be measured directly, by simply measuring the changes in properties P , v , and T . Note that the Maxwell relations given above are limited to simple compressible systems. However, other similar relations can be written just as easily for non-simple systems such as those involving electrical, magnetic, and other effects.

4.15. T dS Equations:

Let entropy, S be a function of (T, V) , then

$$dS = \left(\frac{\partial S}{\partial T}\right)_V dT + \left(\frac{\partial S}{\partial V}\right)_T dV$$

Multiplying by T on both sides,

$$T dS = T \left(\frac{\partial S}{\partial T}\right)_V dT + T \left(\frac{\partial S}{\partial V}\right)_T dV$$

Where,

$$T \left(\frac{\partial S}{\partial T}\right)_V = C_v, \quad \text{heat capacity at constant volume}$$

As per Maxwell relation (c)

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$$

On substituting these changes, the above equation becomes,

$$T dS = C_v dT + T \left(\frac{\partial P}{\partial T} \right)_V dV$$

The above equation is known as first TdS equation.

Let entropy, S be a function of (T, P), then

$$dS = \left(\frac{\partial S}{\partial T} \right)_P dT + \left(\frac{\partial S}{\partial P} \right)_T dP$$

Multiplying by T on both sides,

$$T dS = T \left(\frac{\partial S}{\partial T} \right)_P dT + T \left(\frac{\partial S}{\partial P} \right)_T dP$$

Where,

$$T \left(\frac{\partial S}{\partial T} \right)_P = C_P, \quad \text{heat capacity at constant pressure}$$

As per Maxwell relation (c)

$$\left(\frac{\partial S}{\partial P} \right)_T = - \left(\frac{\partial V}{\partial T} \right)_P$$

On substituting these changes, the above equation becomes,

$$T dS = C_P dT - T \left(\frac{\partial V}{\partial T} \right)_P dP$$

The above equation is known as second TdS equation.

4.16. Specific heat relation:

Let us consider the first & second TdS equations and its relations results in

$$T dS = C_v dT + T \left(\frac{\partial P}{\partial T} \right)_V dV \dots \dots (1)$$

$$T dS = C_P dT - T \left(\frac{\partial V}{\partial T} \right)_P dP \dots \dots \dots (2)$$

By considering (1) equal to (2)

$$(C_P - C_v) dT = T \left(\frac{\partial P}{\partial T} \right)_V dV + T \left(\frac{\partial V}{\partial T} \right)_P dP$$

$$dT = \frac{T \left(\frac{\partial P}{\partial T} \right)_V}{C_P - C_v} dV + \frac{T \left(\frac{\partial V}{\partial T} \right)_P}{C_P - C_v} dP$$

Now let us consider, $T = f(V, P)$, its perfect differential can be written as

$$dT = \left(\frac{\partial T}{\partial V} \right)_P dV + \left(\frac{\partial T}{\partial P} \right)_V dP$$

By relating the above two equations, it can be viewed that

$$\frac{T \left(\frac{\partial P}{\partial T} \right)_V}{C_P - C_v} = \left(\frac{\partial T}{\partial V} \right)_P \quad \text{and} \quad \frac{T \left(\frac{\partial V}{\partial T} \right)_P}{C_P - C_v} = \left(\frac{\partial T}{\partial P} \right)_V$$

On rearranging the above equation gives

$$C_P - C_v = T \left(\frac{\partial P}{\partial T} \right)_V \left(\frac{\partial V}{\partial T} \right)_P$$

By using the cyclic relation of the P-V-T variables, we have

$$\left(\frac{\partial P}{\partial T} \right)_V \left(\frac{\partial T}{\partial V} \right)_P \left(\frac{\partial V}{\partial P} \right)_T = -1$$

$$\left(\frac{\partial P}{\partial T} \right)_V = - \left(\frac{\partial V}{\partial T} \right)_P \left(\frac{\partial P}{\partial V} \right)_T$$

Substituting the above relation into the main equation results in

$$C_P - C_v = - T \left(\frac{\partial V}{\partial T} \right)_P^2 \left(\frac{\partial P}{\partial V} \right)_T$$

This relation can be expressed in terms of two other thermodynamic properties called the volume expansivity β and the isothermal compressibility α , which are defined as

$$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P$$

And

$$\alpha = -\frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_T$$

On substituting β and α in the above equation we have

$$C_P - C_v = \frac{V T \beta^2}{\alpha}$$

It is called the Mayer relation in honour of the German physician and physicist J. R. Mayer (1814–1878). We can draw several conclusions from this equation:

1. The isothermal compressibility α is a positive quantity for all substances in all phases. The volume expansivity could be negative for some substances (such as liquid water below 4°C), but its square is always positive or zero. The temperature T in this relation is thermodynamic temperature, which is also positive. Therefore, we conclude that the constant-pressure specific heat is always greater than or equal to the constant-volume specific heat:

$$c_p \geq c_v$$

2. The difference between c_p and c_v approaches zero as the absolute temperature approaches zero.

3. The two specific heats are identical for truly incompressible substances since $v = \text{constant}$. The difference between the two specific heats is very small and is usually disregarded for substances that are nearly incompressible, such as liquids and solids.

4.17. Clausius Clapeyron Equation:

This equation helps to determine the change in enthalpy during a phase change process, that is to find the enthalpy of vapourization or enthalpy of fusion from the basic thermodynamic properties P-v-T.

Let us consider the third Maxwell relation, and try to fetch an equation to find the desired quantity.

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$$

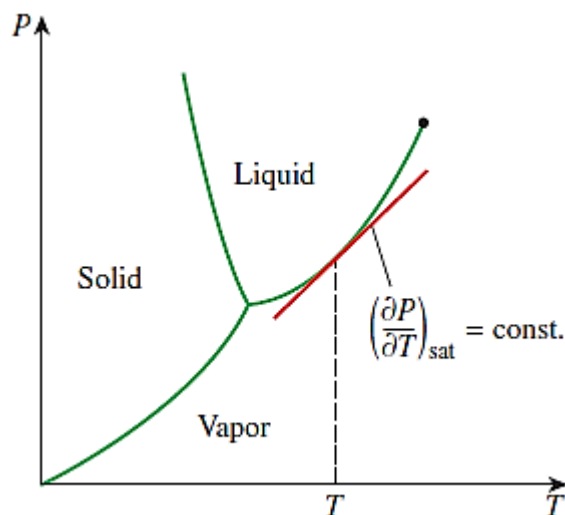
During the phase change process, the pressure is the saturation pressure and which is completely depending on the saturation temperature and independent of the volume, hence

$$P_{sat} = f(T_{sat})$$

And hence the partial derivative term in the Maxwell relation above can be represented as a total derivative

$$i.e., \left(\frac{\partial P}{\partial T}\right)_V \text{ as a total derivative like } \left(\frac{dP}{dT}\right)_{sat}$$

This total derivative quantity represents the slope of the saturation curve of P-T diagram. The slope is independent of the specific volume and it can be treated as a constant during the integration of the above Maxwell relation over the two saturation states at same temperature.



Therefore, for an isothermal liquid vapour phase change process,

$$\int_f^g \left(\frac{\partial P}{\partial T}\right)_V = \int_f^g \left(\frac{\partial S}{\partial V}\right)_T$$

On rearranging the above equation of integration,

$$\int_f^g \partial S = \int_f^g \left(\frac{dP}{dT} \right)_{sat} \cdot \partial v$$

$$s_g - s_f = s_{fg} = \left(\frac{dP}{dT} \right)_{sat} (v_g - v_f) = v_{fg} \left(\frac{dP}{dT} \right)_{sat}$$

On rearranging

$$\left(\frac{dP}{dT} \right)_{sat} = \frac{s_{fg}}{v_{fg}}$$

During the phase change process temperature remains constant and hence from the Gibb's equation, we have

$$dh = T ds + v dP$$

Where, the change in pressure dP tends to zero, hence

$$\int_f^g dh = \int_f^g T ds$$

$$h_{fg} = T s_{fg}$$

And

$$s_{fg} = \frac{h_{fg}}{T}$$

substituting the above value into the main equation, we have

$$\left(\frac{dP}{dT} \right)_{sat} = \frac{h_{fg}}{T v_{fg}}$$

The above equation is known as Clapeyron equation. This relation helps us to find the enthalpy of vapourization at a given temperature by knowing the slope of the saturation curve in P-T diagram and the change in specific volume during the phase change process.

This Clapeyron equation can be simplified for solid -vapour & liquid - vapour phase change process by simple approximations. At low pressures, the specific volume of vapour is greater than the specific volume of liquid, thus $v_{fg} \approx v_g$ and by treating the vapour as an ideal gas, we have

$$v_g = \frac{R T}{P}$$

Substituting the above value in Clapeyron equation we have

$$\left(\frac{dP}{dT} \right)_{sat} = \frac{P h_{fg}}{R T^2}$$

On rearranging the equation, we have

$$\left(\frac{dP}{P} \right)_{sat} = \frac{h_{fg}}{R} \left(\frac{dT}{T^2} \right)_{sat}$$

Also for small temperature differences, h_{fg} can be treated as constant at some average value. On integrating the above equation between the saturation states

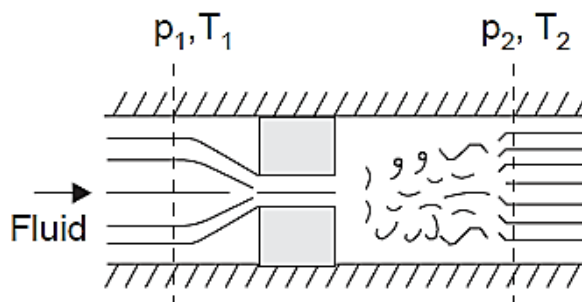
$$\int_1^2 \left(\frac{dP}{P} \right)_{sat} = \frac{h_{fg}}{R} \int_1^2 \left(\frac{dT}{T^2} \right)_{sat}$$

$$\ln \left(\frac{P_2}{P_1} \right)_{sat} = \frac{h_{fg}}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)_{sat}$$

The above equation is known as Clausius Clapeyron equation. It can be used to determine the variation of the saturation pressure with the temperature.

4.18. Joule Thompson Coefficient:

Consider the flow through a constricted passage like an orifice or porous plug or a valve, where the pressure of the flowing fluid decreases, also there is an appreciable increase or decrease in the temperature of the fluid leaving. The enthalpy during the throttling process remains constant. This forms the basis for the operation of the refrigeration & air conditioning systems.



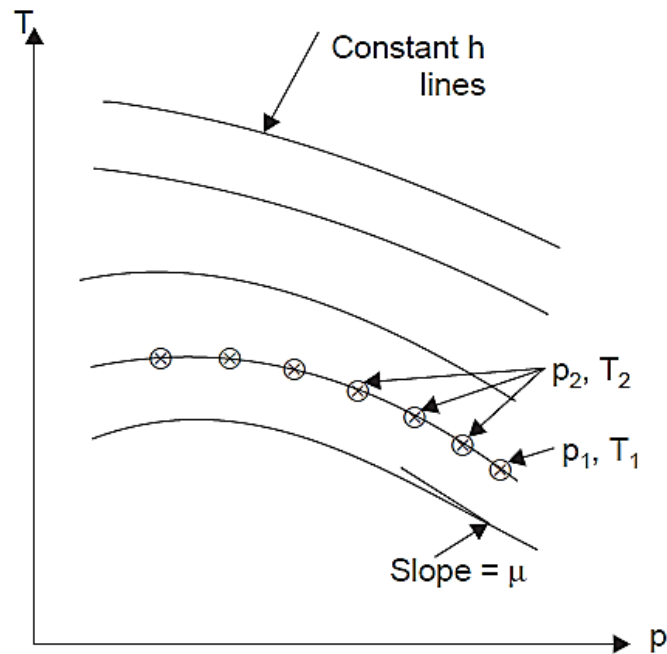
This behaviour of temperature while the fluid undergoes a throttling process can be well described by a coefficient known as Joule Thomson coefficient, μ

$$\mu = \left(\frac{\partial T}{\partial P} \right)_{h=const}$$

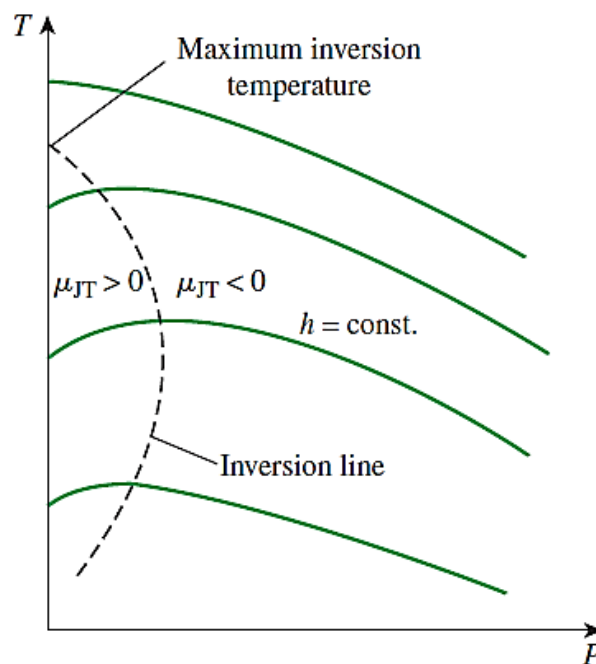
From the above expression, it is clear that the Joule Thomson coefficient is a measure of change in temperature with respect to the pressure during a constant enthalpy process.

$$\mu_{JT} \begin{cases} < 0 & \rightarrow \text{Temperature increases} \\ = 0 & \rightarrow \text{Temperature remains constant} \\ > 0 & \rightarrow \text{Temperature decreases} \end{cases}$$

Let us plot this behaviour of the fluid during the throttling process in a T-P plane. Let us fix the inlet pressure & temperature of the fluid and measure the outlet condition for different sizes of the porous plug. And plot these outlet conditions in the T-P plane for different set of input conditions.



In the plotted graph, we could see some of the constant enthalpy lines passes through zero slope or zero Joule Thomson coefficient.



And connection of these points gives the inversion line and the temperature corresponding to this point is called as inversion temperature. This inversion temperature plays an important role in deciding whether the throttling process results with increase or decrease in the fluid outlet temperature.

The temperature at the intersection of the $P=0$ line and the upper part of the inversion line is called as maximum inversion temperature.

The slope of the constant enthalpy lines has negative Joule Thomson coefficient ($\mu_{JT} < 0$) to the right side of the inversion line and it is positive ($\mu_{JT} > 0$) to the left of the inversion line. And it is equal to zero on the inversion line.

From the diagram it can be concluded the cooling effect cannot be achieved unless the fluid is below its maximum inversion temperature.

The maximum inversion temperature of hydrogen is -68°C and if we want to achieve any further cooling, it should be seen that the temperature is less than the maximum inversion temperature during the throttling process.

TWO MARK QUESTIONS

1. What is pure substance?

ANS: A [pure substance](#) is a material that has [constant chemical composition](#) (homogeneous in nature) and has consistent properties throughout the mass.

2. Define ideal gas.

ANS: It is defined as a gas having no forces of intermolecular attraction. These gases will follow the gas laws at all ranges of pressures and temperatures.

3. Define Joule-Thomson coefficient.

ANS: The rate of change of temperature T with respect to pressure P in a Joule–Thomson process (that is, at constant enthalpy H) is the *Joule–Thomson (Kelvin) coefficient* μ_{JT} . This coefficient can be expressed in terms of the gas's volume V , its heat capacity at constant pressure C_p , and its coefficient of thermal expansion α as:

$$\mu_{JT} \equiv \left(\frac{\partial T}{\partial P} \right)_H = \frac{V}{C_p} (\alpha T - 1)$$

4. What is Normal boiling point?

ANS: It is the temperature at which the liquid starts to change its state from liquid to vapour.

5. What is a Point function?

ANS: The quantity which is independent on the process or path followed by the system is known as point functions. Example: Pressure, volume, temperature, etc.,

6. Write the ideal gas equation.

ANS: $PV = mRT$

7. State Dalton's law of partial pressure.

ANS: The total pressure exerted in a closed vessel containing a number of gases is equal to the sum of the pressures of each gas and the volume of each gas equal to the volume of the vessel.

8. What is compressibility factor?

ANS: The gas equation for an ideal gas is given by $(PV/RT) = 1$, for real gas (PV/RT) is not equal to 1 ($PV/RT = Z$) for real gas is called the compressibility factor.

9. Define triple point.

ANS: Triple point is the state where all the three phases i.e. solid, liquid and vapour to exist in equilibrium.

10. State Boyle's law.

ANS: It states that volume of a given mass of a perfect gas varies inversely as the absolute pressure when temperature is constant.

11. What is meant by virial expansion?

ANS: Virial or virtual expansions are only applicable to gases of low and medium densities. The equation of state of a substance is given by

$$P = \frac{RT}{v} + \frac{a(T)}{v^2} + \frac{b(T)}{v^3} + \frac{c(T)}{v^4} + \frac{d(T)}{v^5} + \dots$$

The coefficient of $a(T)$, $b(T)$, $c(T)$, $d(T)$, ... are virial coefficients. The virial coefficient will vanish when the pressure becomes zero. Finally, the equation of state reduces to the ideal-gas equation.

12. State Avogadro's law.

ANS: The number of moles of any gas is proportional to the volume of gas at a given pressure and temperature.

13. Distinguish between ideal and real gas.

ANS: It is defined as a gas having no forces of intermolecular attraction. These gases will follow the gas laws at all ranges of pressures and temperatures.

It is defined, as a gas having the forces of attraction between molecules tends to be very small at reduced pressures and elevated temperatures.

14. What is the equation of state?

ANS: The relation between the independent properties such as pressure, specific volume and temperature for a pure substance is known as the equation of state.

15. State Charles's law.

ANS: It states that if any gas is heated at constant pressure, its volume changes directly as its absolute temperature.

$$V \propto T$$

16. What is critical point?

ANS: It represents the highest pressure and temperature at which the liquid and vapour phases coexist in equilibrium. At the critical point the liquid and vapour phases are indistinguishable i. e. Liquid directly converted into vapour.

17. State Joule's law.

ANS: Joule's law states, "The internal energy of a given quantity of a gas depends only on the temperature".

PROBLEMS:

1. Calculate the decrease in available energy when 25kg of water at 95°C mix with 35kg of water at 35°C, the pressure being taken as constant and the temperature of the surroundings being 15°C (c_p of water = 4.2 kJ/kg K).

Given:

Solution:

We know that for a system with heat transfer, the available energy or exergy is given as

$$d\chi_Q = \left(1 - \frac{T_o}{T_k}\right) Q$$

$$\chi_Q = \int_1^2 \left(1 - \frac{T_o}{T_k}\right) m c_p dT$$

$$\chi_Q = m c_p \int_1^2 \left(1 - \frac{288}{T_k}\right) dT$$

$$\chi_Q = m c_p \left\{ (T_2 - T_1) - 288 \ln \left(\frac{T_2}{T_1} \right) \right\}$$

Exergy in the 25 kg of water is given as

$$\chi_{25} = 25 \times 4.2 \times \left\{ (288 - 368) - 288 \ln \left(\frac{288}{368} \right) \right\}$$

$$\chi_{25} = -987.49 \text{ kJ}$$

Exergy in the 35 kg of water is given as

$$\chi_{35} = 35 \times 4.2 \times \left\{ (288 - 308) - 288 \ln \left(\frac{288}{308} \right) \right\}$$

$$\chi_{35} = -97.59 \text{ kJ}$$

To find the final temperature of the mixed water,

$$\text{heat lost by water at } 95^\circ\text{C} = \text{heat gained by water at } 35^\circ\text{C}$$

$$m_1 c_p (T_1 - T_3) = m_2 c_p (T_3 - T_2)$$

$$25 \times (368 - T_3) = 35 \times (T_3 - 308)$$

$$T_3 = 333 \text{ K}$$

Exergy in the 60 kg of mixed water is given as

$$\chi_{60} = 60 \times 4.2 \times \left\{ (288 - 333) - 288 \ln \left(\frac{288}{333} \right) \right\}$$

$$\chi_{60} = -803.27 \text{ kJ}$$

Therefore, the decrease in available energy is given as

$$\chi_{decreased} = (\chi_{25} + \chi_{35}) - \chi_{60} = -(987.49 + 97.59) - 803.27$$

$$\chi_{decreased} = 281.81 \text{ kJ}$$

2. Air expands through a turbine from 500 kPa, 527°C to 100 kPa, 307°C. During expansion 10 kJ/kg of heat is lost to the surroundings which is at 98 kPa, 27°C. Neglecting the K.E. and P.E. changes, determine per kg of air (a) the decrease in availability, (b) the minimum work and (c) the irreversibility. For air, take $c_p = 1.005$ kJ/kg K, $h = c_p T$ where c_p is constant. Take R is 0.287 kJ/kg K.

Solution From the property relation

$$T dS = dH - V dp$$

the entropy change of air in the expansion process is

$$\int_1^2 dS = \int_1^2 \frac{m c_p dT}{T} - \int_1^2 \frac{m R dp}{p}$$

or
$$S_2 - S_1 = m c_p \ln \frac{T_2}{T_1} - m R \ln \frac{p_2}{p_1}$$

For 1 kg of air,

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

From Eq. (8.30), the change in availability

$$\begin{aligned} \psi_1 - \psi_2 &= b_1 - b_2 \\ &= (h_1 - T_0 s_1) - (h_2 - T_0 s_2) \\ &= (h_1 - h_2) - T_0 (s_1 - s_2) \\ &= c_p (T_1 - T_2) - T_0 \left(R \ln \frac{p_2}{p_1} - c_p \ln \frac{T_2}{T_1} \right) \\ &= 1.005 (520 - 300) - 293 \left(0.287 \ln \frac{1}{5} - 1.005 \ln \frac{573}{793} \right) \\ &= 1.005 \times 220 - 293 (0.3267 - 0.4619) \\ &= 221.1 + 39.6 \\ &= 260.7 \text{ kJ/kg} \end{aligned}$$

Ans. (a)

The maximum work is

$$\begin{aligned} W_{\max} &= \text{change in availability} = \psi_1 - \psi_2 \\ &= 260.7 \text{ kJ/kg} \end{aligned}$$

Ans. (b)

From S.F.E.E.,

$$\begin{aligned} Q + h_1 &= W + h_2 \\ W &= (h_1 - h_2) + Q \\ &= c_p (T_1 - T_2) + Q \\ &= 1.005 (520 - 300) - 10 \\ &= 211.1 \text{ kJ/kg} \end{aligned}$$

The irreversibility

$$\begin{aligned} I &= W_{\max} - W \\ &= 260.7 - 211.1 \\ &= 49.6 \text{ kJ/kg} \end{aligned}$$

Ans. (c)

3. A mass of 1000 kg of fish initially at 1 bar, 300 K is to be cooled to -20°C. The freezing point of fish is -2.2°C and the specific heat of fish below and above the freezing point are 1.7 & 3.2

kJ/kgK respectively. The latent heat of fusion for the fish can be taken as 235 kJ/kg. Calculate the exergy produced in the chilling process. Take $T_o = 300$ K and $P_o = 1$ bar.

Solution

$$\text{Exergy produced} = H_2 - H_1 - T_o(S_2 - S_1)$$

With reference to Fig. Ex. 8.16,

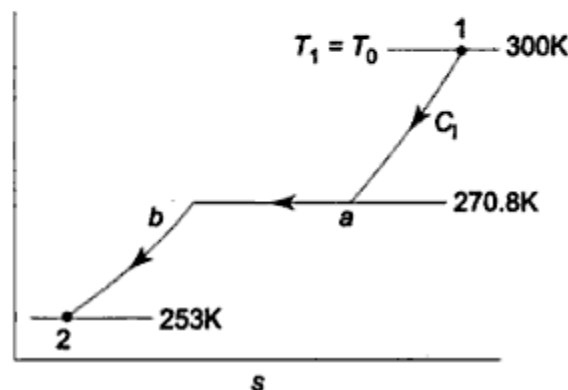


Fig. Ex. 8.16

$$\begin{aligned} H_1 - H_2 &= 1000 [1.7 (270.8 - 253) + 235 + 3.2(300 - 270.8)] \\ &= 1000 [1.7 \times 17.8 + 235 + 3.2 \times 29.2] \\ &= 1000 [30.26 + 235 + 93.44] = 358.7 \text{ MJ} \end{aligned}$$

$$H_2 - H_1 = -358.7 \text{ MJ}$$

$$\begin{aligned} S_1 - S_2 &= 1000 \left[1.7 \ln \frac{270.8}{253} + \frac{235}{270.8} + 3.2 \ln \frac{300}{270.8} \right] \\ &= -1000 [0.1156 + 0.8678 + 0.3277] \\ &= 1.311 \text{ MJ/K} \end{aligned}$$

$$S_2 - S_1 = -1.311 \text{ MJ/K}$$

$$\begin{aligned} \text{Exergy produced} &= -358.7 + 300 \times 1.311 \\ &= -358.7 + 393.3 \\ &= 34.6 \text{ MJ or } 9.54 \text{ kWh} \end{aligned}$$

Ans.

4. Steam enters a turbine at 30 bar, 400°C ($h=3230$ kJ/kg, $s = 6.9212$ kJ/kg K) and with a velocity of 160m/s. Steam leaves as saturated vapour at 100°C ($h = 2676.1$ kJ/kg, $s = 7.3549$ kJ/kgK) with a velocity of 100m/s. At steady state the turbine develops work at a rate of 540 kJ/kg. Heat transfer between the turbine and its surroundings occurs at an average outer surface temperature of 500K. Determine the irreversibility per unit mass. Give an energy balance and estimate the second law efficiency of the turbine. Take $P_o=1$ atm, $T_o=298$ K and neglect the PE effect.

Solution By exergy balance of the control volume (Fig. Ex. 8.18),

$$a_{f1} = W + Q \left(1 - \frac{T_o}{T_B} \right) + a_{f2} + I$$

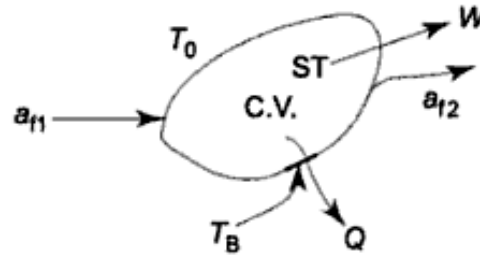


Fig. Ex. 8.18

$$\begin{aligned}
 I &= a_{f1} - a_{f2} - W - Q \left(1 - \frac{T_0}{T_B} \right) \\
 &= (h_1 - h_2) - T_0(s_1 - s_2) + \frac{V_1^2 - V_2^2}{2} - W - Q \left(1 - \frac{T_0}{T_B} \right) \\
 &= (3230.9 - 2676.1) - 298(6.9212 - 7.3549) + \frac{160^2 - 100^2}{2} \\
 &\quad \times 10^{-3} - 540 - Q \left(1 - \frac{298}{500} \right) \\
 &= 151.84 - Q(0.404) \tag{1}
 \end{aligned}$$

By SFEE,

$$\begin{aligned}
 h_1 + \frac{V_1^2}{2} &= W + h_2 + Q + \frac{V_2^2}{2} \\
 Q &= (h_1 - h_2) + \frac{V_1^2 - V_2^2}{2} - W \\
 &= (3230.9 - 2676.1) + \frac{160^2 - 100^2}{2} \times 10^{-3} - 540 \\
 &= 22.6 \text{ kJ/kg.}
 \end{aligned}$$

From Eq. (1),

$$I = 151.84 - 22.6 \times 0.404$$

$$= 42.71 \text{ kJ/kg}$$

Ans.

Net exergy transferred to turbine

$$a_{f_1} - a_{f_2} = 691.84 \text{ kJ/kg}$$

$$\text{Work} = 540 \text{ kJ/kg}$$

$$\text{Exergy destroyed} = I = 142.71 \text{ kJ/kg}$$

Exergy transferred out accompanying heat transfer

$$= 22.6 \times 0.404 = 9.13 \text{ kJ/kg}$$

Exergy Balance

Exergy transferred
691.84 kJ/kg

Exergy utilized
Work = 540 kJ/kg (78%)
Destroyed = 142.71 kJ/kg (20.6%)
Transferred with heat = 9.13 kJ/kg (1.3%)

691.84 kJ/kg

$$\text{Second law efficiency, } \eta_{II} = \frac{540}{691.84} = 0.78 \text{ or } 78\%$$

Ans.

5. A compressor operating at steady state takes in 1kg/s of air at 1bar and 25°C and compresses it to 8bar and 160°C. Heat transfer from the compressor to its surroundings occurs at a rate of 100 kW. (a) Determine the power input in kW. (b) Evaluate the second law efficiency for the compressor. Neglect KE and PE changes. Take $T_o = 25^\circ\text{C}$ and $P_o = 1\text{bar}$.

Solution SFEE for the compressor (Fig. Ex. 8.14) gives:

$$\begin{aligned}\dot{W} &= \dot{Q} + \dot{m}(h_1 - h_2) = -100 + 1 \times 1.005 (25 - 160) \\ &= -235.7 \text{ kW} \quad \text{Ans. (a)}\end{aligned}$$

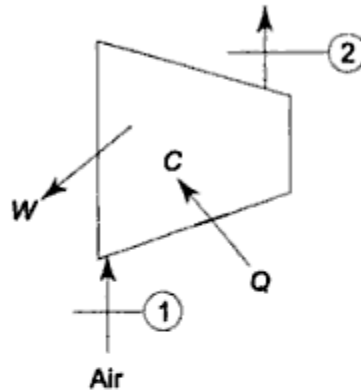


Fig. Ex. 8.14

Exergy balance for the compressor gives:

$$\begin{aligned}\dot{m}a_{f_1} + \dot{Q}\left(1 - \frac{T_0}{T}\right) - \dot{W} - \dot{m}a_{f_2} &= \dot{I} \\ -\dot{W} &= \dot{m}(a_{f_2} - a_{f_1}) - \dot{Q}\left(1 - \frac{T_0}{T}\right) + \dot{I} \\ \eta_{II} &= \frac{\dot{m}(a_{f_2} - a_{f_1})}{\dot{W}} \\ a_{f_2} - a_{f_1} &= h_2 - h_1 - T_0(s_2 - s_1) \\ &= c_p(T_2 - T_1) - T_0\left(c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}\right) \\ &= 1.005 (160 - 25) - 298 \left(1.005 \ln \frac{433}{298} - 0.287 \ln 8\right) \\ &= 200.95 \text{ kJ/kg} \\ \eta_{II} &= \frac{200.95}{235.7} = 0.853 \text{ or, } 85.3\% \quad \text{Ans. (b)}\end{aligned}$$

6. Derive the Maxwell's relation
7. Derive the first & second TdS equations, also derive an expression for the difference in heat capacities, c_p & c_v . Write down the significance of the expression.
8. Explain and derive the Joule Thompson coefficient.
9. Derive the Clausius Clapeyron equation.

MULTIPLE CHOISE QUESTIONS

Questions	opt1	opt2	opt3	opt4	answer
NTP is _____	0 C and 76 mm of Hg	0 C and 7600 mm of Hg	0 C and 760 mm of Hg	0 C and 760 cm of Hg	0 C and 760 mm of Hg
The system is free from any chemical reactions then it is said to be in a state of	Mechanical equilibrium	isolated system	quasi-static	chemical Equilibrium	chemical Equalbrium
S1) Work transfer is equal to heat transfer in case of isothermal process. S2) Work transfer is less than the heat transfer in case of isothermal process	S1 is correct	S2 is correct	Both S1 and S2 are correct	Both S1 and S2 are wrong	S1 is correct
The state of substance whose evaporation from its liquid state is complete , is known as _____	Steam	Vapour	Air	Perfect gas	Perfect gas
The characteristic equation of a gas is _____	$p_v = \text{constant}$	$P_v = mR$	$P_v = mRT$	$P_v = RT$	$P_v = mRT$
The value of the gas constant (R) is	287 J/KgK	28.7 J/KgK	2.87 J/KgK	0.287 J/KgK	287 J/KgK
The value of the universal gas constant (Ru) is _____	8.314 J/Kg K	83.14 J/Kg K	831.4 J/Kg K	8314 J/Kg K	8314 J/Kg K
The gas constant (R) is equal to the _____ of two specific heat	Sum	Difference	Product	Ratio	Difference
The specific heat at constant pressure is _____ than that of specific heat at constant volume	Equal to	Less than	More than	None	More than
The ratio of specific heat at constant pressure and the specific heat at constant volume is _____	Equal to one	Less than one	More than one	None	More than one
The value of C_p / C_v for air	1	1.4	1.8	2.5	1.4
When the gas is heated at constant pressure , then the heat supplied is _____	Raises the temperature of the gas	Increases the internal energy of the gas	Does some external work during expansion	Both b and c	Both b and c
When the real gas undergoes Joules Thomson expansion , the temperature	May remain constant	Always increases	May increase or decrease	Always decreases	Always increases
The pressure P of an ideal gas and its mean kinetic energy E per unit volume are related by the relation	$P=2E/3$	$P=3E/2$	$P=E/3$	$P=E/2$	$P=2E/3$

The inversion temperature T_i of a gas is related to Vander Wall's constant as	$T_i = 8a/27Rb$	$T_i = 27 Rb/8a$	$T_i = 2Rb/8a$	$T_i = 2a/Rb$	$T_i = 2a/Rb$
If Q_1 is the heat absorbed, Q_2 be the heat delivered and W be the work done on a carnot heat pump, the coefficient of performance is given by	$Q_1/(Q_1 - Q_2)$	$Q_2/(Q_1 - Q_2)$	Q_1/W	Q_2/W	Q_2/W
The vander waal's equation $(P+a/V^2)(V-b) = RT$. The greater the value of constant's	Closer the gas to the ideal condition	Lesser are the forces of cohesion	Easier is to liquefy the gas	Higher is the density of the gas	Lesser are the forces of cohesion
The entropy of the mixture of ideal gases is the sum of the entropies is the constituents evaluated at	Temperature and pressure of the mixture	Temperature of the mixture and the partial pressure of the constituents	Temperature and the volume of the mixture	Pressure and volume of the mixture	Temperature of the mixture and the partial pressure of the constituents
The system is said to be consisting of a pure substance when	It is homogeneous in composition	It is homogeneous and invariable chemical aggregation	It has only one phase	It has more than one phase	It is homogeneous and invariable chemical aggregation
In thermodynamic analysis, a pure substance is that which _____	Consist of only a single chemical species	Has no dissolved impurities	Behaves as a perfect gas	May have a number of chemical species but the composition may remain constant	May have a number of chemical species but the composition may remain constant
At its critical point of any substance will _____	Exist all the three phases simultaneously	Change directly from solid to vapour	Lose phase distinction between liquid and vapour	None	Lose phase distinction between liquid and vapour
If a closed system obey the following form of the first law equation, $dq = du + pdV$	It is a simple compressible system undergoing	It is a pure substance undergoing infinitesimal process	IT is undergoing an irreversible process	It is undergoing an isothermal process	It is a simple compressible system undergoing reversible process

	reversible process				
In a reversible isothermal process undergone by an ideal gas	Heat transfer is zero	Change in internal energy is zero	Work transfer is zero	Heat transfer is equal to work transfer	Heat transfer is equal to work transfer
For a pure substance at its triple point , a number of degrees of freedom is	0	1	2	None of these	0
The international standard atmosphere pressure and temperature at sea level are	1.0133 bar and 288.2 K	1.01325 bar and 273 K	quasi-static 1 bar and 0K	760 mm of Hg and 0K	1.0133 bar and 288.2 K
S1) The fluid in which the density remains constant is known as compressible fluid S2) The fluid in which the density remains constant is known as incompressible fluid	S1 is correct	S2 is correct	Both S1 and S2 are correct	Both S1 and S2 are wrong	S1 is correct
Earth atmosphere is the mixture of	O ₂ &N ₂	CO ₂ &O ₂	He&O ₂	O ₂ ,N ₂ ,Ar,CO ₂	O ₂ ,N ₂ ,Ar,CO ₂
Dry air is the mixture of	O ₂ &N ₂	CO ₂ &O ₂	He&O ₂	O ₂ ,N ₂ ,Ar,CO ₂	O ₂ ,N ₂ ,Ar,CO ₂
Moist air is the mixture of	water and gas	air and oil vapour	dry air and water vapour	dry air and gas	dry air and water vapour
Mass of water present in 1 kg of dry air is known as	Humidity ratio	Degree of saturation	Saturated air	Absolute humidity	Humidity ratio
Mass of water vapour present in 1 m ³ of dry air is known as	Humidity ratio	Degree of saturation	Saturated air	Absolute humidity	Absolute humidity

UNIT - V PSYCHROMETRY

LECTURE NOTES

Psychrometry - Psychrometric charts - Property calculations of air vapour mixtures- Psychrometric Process-Adiabatic mixing - Evaporative cooling.

5.1 Introduction:

Air is a mixture of nitrogen, oxygen, and small amounts of some other gases. Air in the atmosphere normally contains some water vapour (or *moisture*) and is referred to as **atmospheric air**. By contrast, air that contains no water vapour is called **dry air**. It is often convenient to treat air as a mixture of water vapour and dry air since the composition of dry air remains relatively constant, but the amount of water vapour changes as a result of condensation and evaporation from oceans, lakes, rivers, showers, and even the human body. Although the amount of water vapour in the air is small, it plays a major role in human comfort. Therefore, it is an important consideration in air-conditioning applications. Also in the places where hygroscopic materials (eg. Paper, textiles) are handled.

5.2 Psychrometry:

It is the name given to the study of properties of air water vapour mixture.

The temperature of air in air-conditioning applications ranges from about -10 to about 50°C. In this range, dry air can be treated as an ideal gas with a constant c_p value of 1.005 kJ/kg K with negligible error.

It certainly would be very convenient to also treat the water vapour in the air as an ideal gas. At 50°C, the saturation pressure of water is 12.3 kPa. At pressures below this value, water vapour can be treated as an ideal gas with negligible error (under 0.2 percent), even when it is a saturated vapour. Therefore, water vapour in air behaves as if it existed alone and obeys the ideal-gas relation $P_v = RT$.

Then the atmospheric air can be treated as an ideal-gas mixture whose pressure is the sum of the partial pressure of dry air P_a and that of water vapour P_v :

$$P = P_a + P_v$$

The partial pressure of water vapour is usually referred to as the vapour pressure. It is the pressure water vapour would exert if it existed alone at the temperature and volume of atmospheric air.

5.3 Psychrometry Terminologies:**a) Specific Humidity, ω**

It is defined as the ratio of mass of water vapour present in the dry air in a given volume of atmospheric air.

$$\omega = \frac{m_v}{m_a} = 0.622 \frac{P_v}{P - P_v}, \quad \text{kg/kg of dry air}$$

b) Relative Humidity, ϕ

It is defined as the ratio of actual mass of water vapour in a given volume of atmospheric air to the saturated mass of water vapour in the same volume & temperature.

$$\phi = \frac{m_v}{m_s} = \frac{P_v}{P_{sat}}$$

$$\phi = \frac{\omega P}{(0.622 + \omega)P_g} \quad \text{and} \quad \omega = \frac{0.622\phi P_g}{P - \phi P_g}$$

The relative humidity ranges from 0 for dry air to 1 for saturated air. Note that the amount of moisture air can hold depends on its temperature. Therefore, the relative humidity of air changes with temperature even when its specific humidity remains constant.

c) Degree of Saturation, μ

It is defined as the ratio of specific humidity of the moist air to the specific humidity of the saturated air at the same temperature.

$$\mu = \frac{\omega}{\omega_{sat}} = \frac{P_v}{P_{sat}} \left(\frac{P - P_{sat}}{P - P_v} \right)$$

d) Dry Bulb Temperature, t_{db} (DBT):

It is the temperature recorded by the thermometer with a dry bulb.

e) Wet Bulb Temperature, t_{wb} (WBT):

It is the temperature recorded by the thermometer bulb covered with a cotton wick saturated with water.

f) Dew Point Temperature, t_{dp} (DPT):

The temperature at which the water vapour present in the saturated air starts condensing is called as dew point temperature. This is equal to the saturation temperature at the partial pressure of the water vapour, P_v .

h) Total enthalpy of moist air, h

It is the sum of the enthalpy of dry air and enthalpy of water vapour associated with the dry air.

$$h = c_p t_{db} + \omega h_g$$

5.4 partial pressure of water vapour, P_v

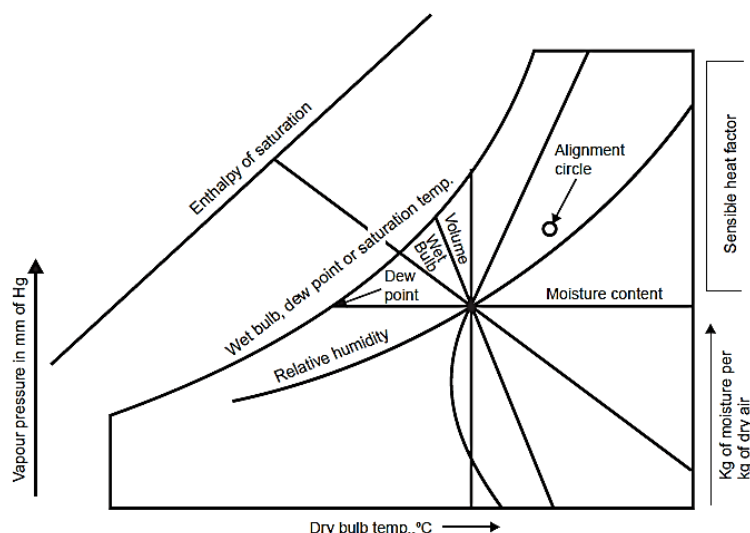
The partial pressure of water vapour is found using the relation,

$$P_v = P_{sat,w} - \frac{(P - P_{sat,w})(t_{db} - t_{wb})}{1527.4 - 1.3t_{wb}}$$

Where, $P_{sat,w}$ is the saturation pressure at wet bulb temperature (WBT).

5.5 Psychrometric Chart:

It is the graphical representation of interrelation of the psychrometric properties like specific humidity, relative humidity, DBT, WBT, DPT, specific volume, enthalpy. It is very useful in finding the missed out properties of a moist air.



5.6 Psychrometric Processes:

In order to condition air to the conditions of human comfort or of the optimum control of an industrial process required, certain processes are to be carried out on the outside air available. The processes affecting the psychrometric properties of air are called psychrometric processes. These processes involve mixing of air streams, heating, cooling, humidifying, dehumidifying, adiabatic saturation and mostly the combinations of these.

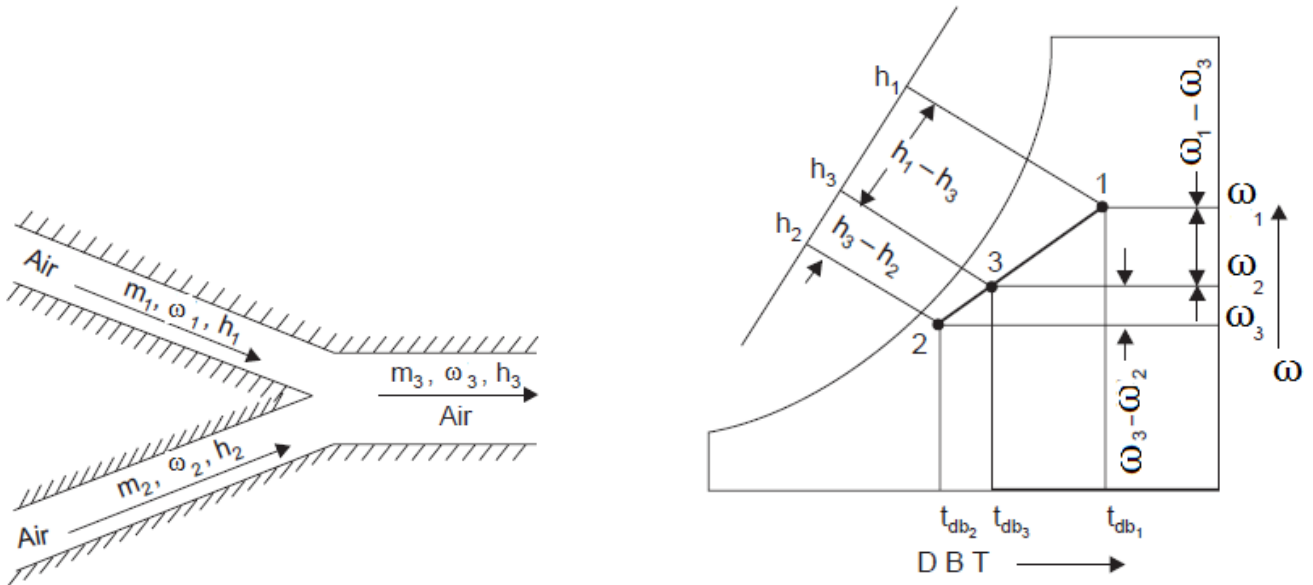
The important psychrometric processes are enumerated and explained in the following text:

1. Mixing of air streams
2. Sensible heating
3. Sensible cooling
4. Cooling and dehumidification
5. Cooling and humidification
6. Heating and dehumidification
7. Heating and humidification.

5.6.1. Mixing of Air streams:

Mixing of several air streams is the process which is very frequently used in air conditioning. This mixing normally takes place without the addition or rejection of either heat or moisture, i.e., adiabatically and at constant total moisture content. Thus we can write the following equation:

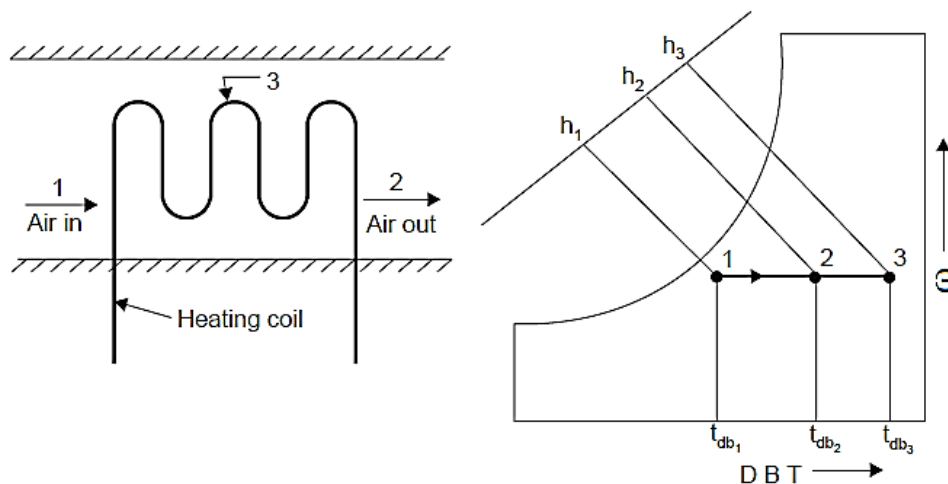
$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_3 - \omega_2}{\omega_1 - \omega_3} = \frac{h_3 - h_2}{h_1 - h_3}$$



5.6.2 Sensible Heating

When air passes over a dry surface which is at a temperature greater than its (air) dry bulb temperature, it undergoes sensible heating. Thus the heating can be achieved by passing the air over heating coil like electric resistance heating coils or steam coils. During such a process, the specific humidity remains constant but the dry bulb temperature rises and approaches that of the surface. The extent to which it approaches the mean effective surface temperature of the coil is conveniently expressed in terms of the equivalent by-pass factor.

The by-pass factor (BF) for the process is defined as the ratio of the difference between the mean surface temperature of the coil and leaving air temperature to the difference between the mean surface temperature and the entering air temperature.



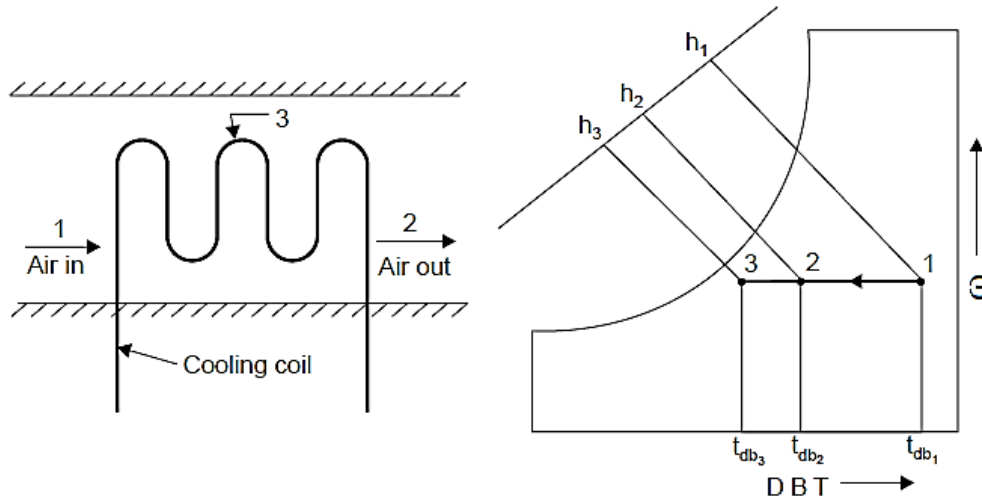
$$BF = \frac{t_{db3} - t_{db2}}{t_{db3} - t_{db1}}$$

The value of the by-pass factor is a function of coil design and velocity. The heat added to the air can be obtained directly from the entering and leaving enthalpies ($h_2 - h_1$) or it can be obtained from the humid specific heat multiplied by the temperature difference ($t_{db2} - t_{db1}$). In a complete air

conditioning system, the preheating and reheating of air are among the familiar examples of sensible heating.

5.6.3 Sensible Cooling

Air undergoes sensible cooling whenever it passes over a surface that is at a temperature less than the dry bulb temperature of the air but greater than the dew point temperature. Thus sensible cooling can be achieved by passing the air over cooling coil like evaporating coil of the refrigeration cycle or secondary brine coil. During the process, the specific humidity remains constant and dry bulb temperature decreases, approaching the mean effective surface temperature.

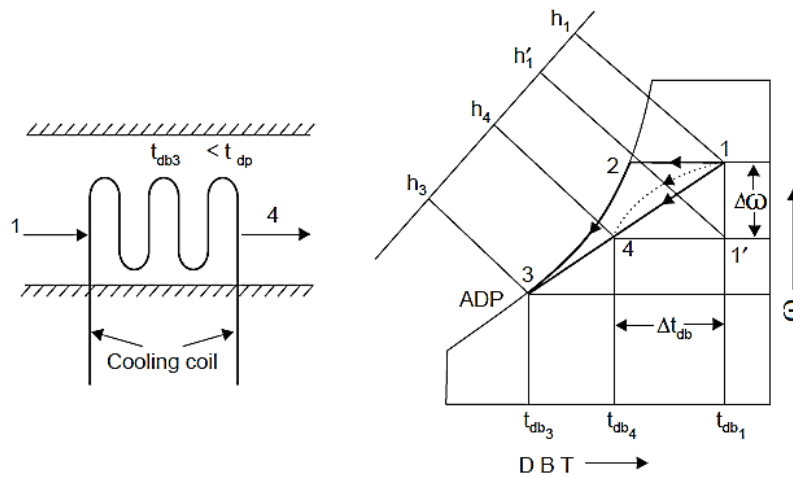


$$\text{By pass factor of cooling coil, } BF = \frac{t_{db2} - t_{db3}}{t_{db1} - t_{db3}}$$

The heat removed from air can be obtained from the enthalpy difference ($h_1 - h_2$) or from humid specific heat multiplied by the temperature difference ($t_{db1} - t_{db2}$).

5.6.4 Cooling and Dehumidification

Whenever air is made to pass over a surface or through a spray of water that is at a temperature less than the dew point temperature of the air, condensation of some of the water vapour in air will occur simultaneously with the sensible cooling process. Any air that comes into sufficient contact with the cooling surface will be reduced in temperature to the mean surface temperature along a path such as 1-2-3 in Fig, with condensation and therefore dehumidification occurring between points 2 and 3. The air that does not contact the surface will be finally cooled by mixing with the portion that did, and the final state point will somewhere on the straight line connecting points 1 and 3. The actual path of air during the path will not be straight line shown but will be something similarly to the curved dashed line 1-4.



For processes involving condensation, the effective surface temperature, e.g. t_{db3} in Fig. is called “apparatus dew point” (ADP). The final state point of air passing through a cooling and dehumidifying apparatus is in effect a mixture condition that results from mixing the fraction of the air, which is equal to the equivalent by-pass factor (BF) and is at initial state point and the remaining fraction which is equal to one minus by pass factor (1-BF) and is saturated at the apparatus dew point (ADP).

Total heat removed from the air during this process is given as

$$Q_t = h_1 - h_4 = (h_1 - h_1') + (h_1' - h_4)$$

$$Q_t = Q_L + Q_S$$

Where, Q_L is the latent heat removed ($h_1 - h_1'$) and Q_S is the sensible heat removed ($h_1' - h_4$)

The ratio of the sensible heat to the total heat removed during the process is known as sensible heat factor or sensible heat ratio (SHF),

$$SHF = \frac{Q_S}{Q_L + Q_S} = \frac{(h_1' - h_4)}{(h_1 - h_1') + (h_1' - h_4)}$$

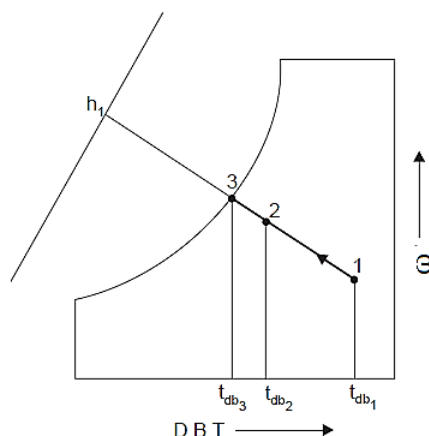
If the initial condition and SHF are known for the given process, then the process line can be drawn through the given initial condition at a slope given by SHF on the psychrometric chart. The capacity of the cooling coil in tonnes of refrigeration is given by,

$$Capacity \text{ in TR} = \frac{m_a (h_1 - h_4) \times 60}{14000}$$

where m_a = mass of air, kg/min and h = enthalpy in kJ/kg of air.

5.6.5 Cooling and Humidification

If unsaturated air is passed through a spray of continuously recirculated water, the specific humidity will increase while the dry bulb temperature decreases. This is the process of **adiabatic saturation or evaporative cooling**.



The concept of equivalent by pass can be applied to this process but another term is more used to describe the performance of a humidifying apparatus. It is the 'saturating' or 'humidifying efficiency' which is defined as the ratio of dry-bulb temperature decrease to the entering wet bulb depression usually expressed as percentage.

$$\% \eta_{sat} = \left(\frac{t_{db1} - t_{db2}}{t_{db1} - t_{db3}} \right) \times 100$$

As a fraction, it is equal to one minus the by-pass factor for the process. This adiabatic process, for all practical purposes, is line of constant enthalpy. The moisture added can be obtained from the increase in specific humidity.

5.6.6 Heating and Dehumidification

If air is passed over a solid absorbent surface or through a liquid absorbent spray simultaneous heating and dehumidification is accompanied. In either case the dehumidification results from adsorbent or absorbent having a lower water vapour pressure than air.

Moisture is condensed out of the air, and consequently the latent heat of condensation is liberated, causing sensible heating of air. If these were the only energies involved, the process would be the inverse of the adiabatic saturation process.

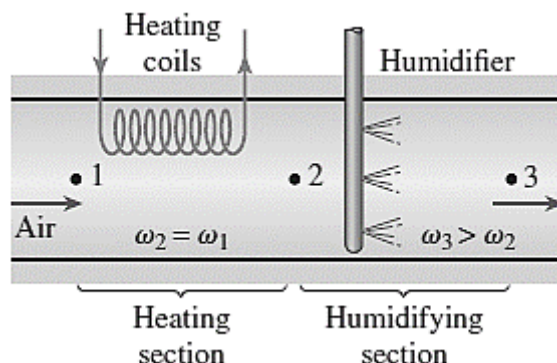
There is, however, an additional energy absorbed or liberated by the active material, termed the heat of adsorption or absorption. For the solid adsorbents used commercially, such as silica gel or activated alumina, and for the more common liquid absorbents, such as solutions of organic salts or inorganic compounds like ethylene, glycol, heat is involved and results in additional sensible heating.

5.6.7 Heating and Humidification

Problems associated with the low relative humidity resulting from simple heating can be eliminated by humidifying the heated air. This is accomplished by passing the air first through a heating section (process 1-2) and then through a humidifying section (process 2-3), as shown in Fig. The location of state 3 depends on how the humidification is accomplished.

If steam is introduced in the humidification section, this will result in humidification with additional heating ($T_3 > T_2$). If humidification is accomplished by spraying water into the airstream instead, part of the latent heat of vaporization comes from the air, which results in the cooling of the heated

airstream ($T_3 < T_2$). Air should be heated to a higher temperature in the heating section in this case to make up for the cooling effect during the humidification process.



(a) Applying the mass and energy balances on the heating section gives

Dry air mass balance: $\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a$

Water mass balance: $\dot{m}_{a_1} \omega_1 = \dot{m}_{a_2} \omega_2 \rightarrow \omega_1 = \omega_2$

Energy balance: $\dot{Q}_{in} + \dot{m}_a h_1 = \dot{m}_a h_2 \rightarrow \dot{Q}_{in} = \dot{m}_a (h_2 - h_1)$

(b) The mass balance for water in the humidifying section can be expressed as

$$\dot{m}_{a_2} \omega_2 + \dot{m}_w = \dot{m}_{a_3} \omega_3$$

or

$$\dot{m}_w = \dot{m}_a (\omega_3 - \omega_2)$$

TWO MARK QUESTIONS

1. Define dew point temperature.

ANS: It is the temperature at which water vapour present in air starts to condense on cooling of air.

2. Define Relative Humidity (RH).

ANS: It is defined as the ratio of partial pressure of water vapour (p_w) in a mixture to the saturation pressure (p_s) of pure water at the same temperature of mixture.

3. Define bypass factor (BPF) of a coil.

ANS: The ratio of the amount of air which does not contact the cooling coil (amount of bypassing air) to the amount of supply air is called BPF.

$$\text{BPF} = \frac{\text{Amount of air bypassing the coil}}{\text{Total amount of air passed}}$$

4. What are hygroscopic materials?

ANS: Nylon, Acrylic, Resin, ABS

5. Define Specific humidity.

ANS: It is defined as the ratio of the mass of water vapour (m_s) in a given volume to the mass of dry air in a given volume (m_a).

6. Differentiate between absolute and relative Humidity.

ANS: **Absolute humidity** is the mass of water vapour present in one kg of dry air.

Relative humidity is the ratio of the actual mass of water vapour present in one kg of dry air at the given temperature to the maximum mass of water vapour it can hold at the same temperature. Absolute humidity is expressed in terms of kg/kg of dry air. Relative humidity is expressed in terms of percentage.

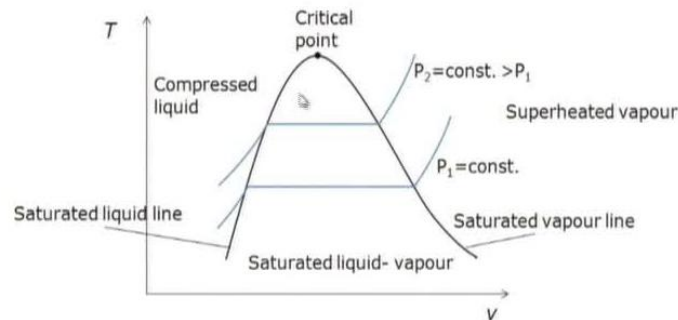
7. What is sensible heating?

ANS: The moisture content of air remains constant and its temperature increases as it flows over a heating coil.

8. Draw the phase equilibrium diagram for a pure substance on T-v coordinates.

ANS:

Properties of pure substances



9. Define degree of saturation.

ANS: It is the ratio of the actual specific humidity and the saturated specific humidity at the same temperature of the mixture.

$$\mu = \text{specific humidity of moist air} / \text{specific humidity of saturated air}$$

10. List down the psychrometric processes.

ANS:

- (i) Sensible heating and sensible cooling
- (ii) Cooling and dehumidification
- (iii) Heating and humidification
- (iv) Mixing of air streams
- (v) Chemical dehumidification
- (vi) Adiabatic evaporative cooling.

11. What is adiabatic evaporative cooling?

ANS: Evaporative cooling lowers the temperature of air through evaporation of water.

This evaporation process decreases temperature of air while increasing relative humidity.

12. Define psychrometry.

ANS: The science which deals with the study of behaviour of moist air (mixture of dry air and water vapour) is known as psychrometry

13. Define dry bulb temperature (DBT).

ANS: The temperature recorded by the thermometer with a dry bulb. The dry bulb thermometer cannot be affected by the moisture present in the air. It is the measure of sensible heat of the air.

14. What is humidification?

ANS: it is defined as the addition of water vapour into atmospheric air is called humidification

15. What is apparatus dew point?

ANS: The effective surface temperature of the cooling coil, and is known as apparatus dew-point (ADP) temperature.

16. What is a mole?

ANS: A mole is the amount of pure substance containing the same number of chemical units present the atoms.

17. Define wet bulb temperature.

ANS: It is the temperature recorded by a thermometer whose bulb is covered with cotton wick (wet) saturated with water. The wet bulb temperature may be the measure of enthalpy of air. WBT is the lowest temperature recorded by moistened bulb.

18. State the properties and major combination of atmospheric air.

ANS:

Nitrogen	78.08
Oxygen	20.95
Argon	0.93
Carbon Dioxide	0.039

and other gases are Neon, Helium, Krypton, Hydrogen, Xenon.

19. Define adiabatic mixing of air streams.

ANS: The process of mixing two or more stream of air without any heat transfer to the surrounding is known as adiabatic mixing. It is happened in air conditioning system.

20. What is sensible cooling?

ANS: The moisture content of air remains constant but its temperature decreases as it flows over a cooling coil.

PROBLEMS:

- The air at 28°C and 1 bar has a specific humidity of 0.016 kg/kg of dry air. Determine (a) partial pressure of water vapour, (b) relative humidity, (c) dew point temperature, (d) specific enthalpy.

Given:

$t_{db} = 28^\circ\text{C}$, $P = 1$ bar, $\omega = 0.016$ kg/kg of dry air

To Find:

$P_v = ?$, $\phi = ?$, $t_{dp} = ?$, $h = ?$

Solution:

We know that, specific humidity

$$\omega = \frac{m_v}{m_a} = 0.622 \frac{P_v}{P - P_v}, \quad \text{kg/kg of dry air}$$

$$0.016 = 0.622 \frac{P_v}{1 - P_v}$$

$$P_v = 2.507 \text{ kPa}$$

From property table, for $t_{db} = 28^\circ\text{C}$, $P_{sat} = 4.2469$ kPa

Relative humidity,

$$\phi = \frac{P_v}{P_{sat}} = \frac{2.507}{4.247} = 0.590 = 59.0 \%$$

From the property tables, for $P_v = 2.507$ kPa

$$t_{dp} = T_{sat} = 21.08^\circ\text{C}$$

Specific enthalpy of the given air is,

The specific enthalpy of vapour, h_g at $t_{db} = 28^\circ\text{C}$ from property tables is taken as 2555.6 kJ/kg

$$h = c_p t_{db} + \omega h_g = (1.005 \times 301) + (0.016 \times 2555.6)$$

$$h = 343.14 \text{ kJ/kg}$$

2. The atmospheric air at 25°C DBT and 12°C WBT is flowing at a rate of 100 m^3 per minute through a duct. The dry saturated steam at 100°C is injected into the air stream at a rate of 72 kg/hr. Calculate (i) specific humidity, (ii) DBT, (iii) WBT, (iv) Relative humidity & (v) Enthalpy of air leaving the duct.

Given Data:

DBT = 25°C , WBT = 12°C , $V = 100 \text{ m}^3/\text{min}$, saturation temperature $T_{sat} = 100^\circ\text{C}$, $\dot{m}_w = 72 \text{ kg/hr}$
 $\dot{m}_w = 1.2 \text{ kg/min}$

To Find:

$\omega_2 = ?$ DBT₂ = ? WBT₂ = ? $\phi_2 = ?$ & $h_2 = ?$

Solution:

From the psychrometric chart for $t_{db1} = 25^\circ\text{C}$ & $t_{wb1} = 12^\circ\text{C}$

$$\omega_1 = 3.5 \text{ g/kg of dry air} = 0.0035 \text{ kg/kg of dry air}$$

$$h_1 = 34 \text{ kJ/kg}$$

$$\text{specific volume, } v = 0.85 \text{ m}^3/\text{kg of dry air}$$

The mass flow rate of the atmospheric air is given as

$$\dot{m}_a = \frac{V}{v} = \frac{100}{0.85} = 117.65 \text{ kg/min}$$

(i) specific humidity of the air leaving the duct is given by mass balance

$$\dot{m}_a \omega_1 + \dot{m}_a \omega_2 = \dot{m}_w$$

$$\omega_2 = 0.014 \text{ kg/kg of dry air}$$

(ii) specific enthalpy of leaving air is given by energy balance

$$\dot{m}_a h_1 + \dot{m}_a h_2 = \dot{m}_w h_g$$

$$h_2 = 61.29 \text{ kJ/kg}$$

Where, $h_g = 2676 \text{ kJ/kg}$ is taken from property tables for $T_{sat} = 100^\circ\text{C}$

(iii) DBT, WBT, ϕ_2 of the leaving air is taken from the psychrometric chart for $\omega_2 = 14 \text{ g/kg}$ of dry air & $h_2 = 61.29 \text{ kJ/kg}$

$$t_{db2} = 25^\circ\text{C}$$

$$t_{wb2} = 21^\circ\text{C}$$

$$\phi_2 = 70\%$$

3. Atmospheric air at 1.0132 bar has a DBT of 32°C and a WBT of 26°C . Compute (i) The partial pressure of water vapour, (ii) Specific humidity, (iii) Dew point temperature, (iv) Relative humidity, (v) Degree of saturation, (vi) Density of air in mixture, (vii) Density of vapour in mixture, (viii) Enthalpy of mixture. Use thermodynamic table only.

Solution:

We know that the partial pressure of water vapour is given by the equation

$$P_v = P_{sat,w} - \frac{(P - P_{sat,w})(t_{db} - t_{wb})}{1527.4 - 1.3t_{wb}}$$

And from the property tables for $t_{wb} = 26^\circ\text{C}$, the saturation pressure

$$P_{sat,w} = 0.0317 \text{ bar}$$

$$P_v = 0.0317 - \frac{(1.0132 - 0.0317)(32 - 26)}{1527.4 - 1.3 \times 26}$$

$$P_v = 0.028 \text{ bar}$$

We know that, specific humidity

$$\omega = \frac{m_v}{m_a} = 0.622 \frac{P_v}{P - P_v}, \quad \text{kg/kg of dry air}$$

$$\omega = 0.622 \frac{0.028}{1.0132 - 0.028}$$

$$\omega = 0.018 \text{ kg/kg of dry air}$$

The dew point temperature is the temperature corresponding to the pressure, $P_v = 0.028 \text{ bar}$

From property tables, for $P_v = 0.028 \text{ bar} = 2.8 \text{ kPa}$

$$t_{dp} = 24.08^\circ\text{C}$$

From property table, for $t_{db} = 32^\circ\text{C}$, $P_{sat} = 4.2469 \text{ kPa}$

Relative humidity,

$$\phi = \frac{P_v}{P_{sat}} = \frac{2.8}{4.247} = 0.659 = 65.9\%$$

The degree of saturation,

$$\mu = \frac{\omega}{\omega_{sat}} = \frac{P_v}{P_{sat}} \left(\frac{P - P_{sat}}{P - P_v} \right) = \frac{2.8}{4.247} \left(\frac{101.32 - 4.247}{101.32 - 2.8} \right)$$

$$\mu = 0.649$$

The density of air is given as

$$\rho_a = \frac{1}{v} = \frac{P_a}{RT} = \frac{P - P_v}{R t_{db}} = \frac{101.32 - 2.8}{0.287 \times 305} = 1.125$$

The density of vapour is given as

$$\rho_v = \frac{1}{v_g}$$

The specific volume of vapour at $t_{db} = 32^\circ\text{C}$ is taken from property tables as $32.879 \text{ m}^3/\text{kg}$

$$\rho_v = \frac{1}{32.879} = 0.0304 \text{ kg/m}^3$$

Whereas the actual density of vapour at $\phi = 65.9\%$ is

$$\rho_v = 0.659 \times 0.0304 = 0.02 \text{ kg/m}^3$$

The specific enthalpy of vapour, h_g at $t_{db} = 32^\circ \text{C}$ from property tables is taken as 2555.6 kJ/kg

$$h = c_p t_{db} + \omega h_g = (1.005 \times 305) + (0.018 \times 2555.6)$$

$$h = 352.52 \text{ kJ/kg}$$

4. In a laboratory test, a sling psychrometric recorded dry bulb and wet bulb temperatures as 303 K and 298 K respectively. Calculate (i) Vapour pressure (ii) relative humidity (iii) specific humidity (iv) degree of saturation (v) dew point temperature (vi) enthalpy of mixture.

Solution:

We know that the partial pressure of water vapour is given by the equation

$$P_v = P_{sat,w} - \frac{(P - P_{sat,w})(t_{db} - t_{wb})}{1527.4 - 1.3t_{wb}}$$

And from the property tables for $t_{wb} = 25^\circ \text{C}$, the saturation pressure

$$P_{sat,w} = 0.0317 \text{ bar}$$

$$P_v = 0.0317 - \frac{(1.0132 - 0.0317)(30 - 25)}{1527.4 - 1.3 \times 25}$$

$$P_v = 0.028 \text{ bar}$$

We know that, specific humidity

$$\omega = \frac{m_v}{m_a} = 0.622 \frac{P_v}{P - P_v}, \quad \text{kg/kg of dry air}$$

$$\omega = 0.622 \frac{0.028}{1.0132 - 0.028}$$

$$\omega = 0.018 \text{ kg/kg of dry air}$$

The dew point temperature is the temperature corresponding to the pressure, $P_v = 0.028 \text{ bar}$

From property tables, for $P_v = 0.028 \text{ bar} = 2.8 \text{ kPa}$

$$t_{dp} = 24.08^\circ \text{C}$$

From property table, for $t_{db} = 30^\circ \text{C}$, $P_{sat} = 4.2469 \text{ kPa}$

Relative humidity,

$$\phi = \frac{P_v}{P_{sat}} = \frac{2.8}{4.247} = 0.659 = 65.9\%$$

The degree of saturation,

$$\mu = \frac{\omega}{\omega_{sat}} = \frac{P_v}{P_{sat}} \left(\frac{P - P_{sat}}{P - P_v} \right) = \frac{2.8}{4.247} \left(\frac{101.32 - 4.247}{101.32 - 2.8} \right)$$

$$\mu = 0.649$$

The specific enthalpy of vapour, h_g at $t_{db} = 30^\circ \text{C}$ from property tables is taken as 2555.6 kJ/kg

$$h = c_p t_{db} + \omega h_g = (1.005 \times 305) + (0.018 \times 2555.6)$$

$$h = 352.52 \text{ kJ/kg}$$

5. Consider a room that contains air at 1 atm, 35°C and 40% RH. Using psychrometric chart, determine (i) specific humidity, (ii) enthalpy, (iii) wet bulb temperature, (iv) dew point temperature & (v) specific volume of air.

Solution:

For $t_{db} = 35^\circ \text{C}$, $\phi = 40\%$ from the Psychrometric chart

$$\text{specific humidity, } \omega = 14 \text{ g/kg of dry air} = 0.014 \text{ kg/kg of dry air}$$

$$\text{specific enthalpy, } h = 72 \text{ kJ/kg}$$

$$\text{wet bulb temperature, } t_{wb} = 24^\circ \text{C}$$

$$\text{Dew point temperature, } t_{dp} = 19^\circ \text{C}$$

$$\text{specific volume of air, } v = 0.89 \text{ m}^3/\text{kg}$$

6. Air at 40°C DBT and 60% RH is cooled to 25°C DBT. It is achieved by cooling and dehumidification. Air flow rate is $40 \text{ m}^3/\text{min}$. Using psychrometric chart calculate, (i) dew point temperature, (ii) mass of water drained out per hour, (iii) capacity of cooling coil. If the apparatus dew point temperature is 20°C find the bypass factor of the coil.

Solution:

From the psychrometric chart for $t_{db1} = 40^\circ \text{C}$ & $\phi_1 = 60\%$

$$\text{specific humidity, } \omega_1 = 28.5 \text{ g/kg of dry air} = 0.0285 \text{ kg/kg of dry air}$$

$$\text{specific enthalpy, } h_1 = 114 \text{ kJ/kg}$$

$$\text{specific volume of air, } v = 0.93 \text{ m}^3/\text{kg}$$

For $t_{db2} = 25^\circ \text{C}$ & $t_{adp} = 20^\circ \text{C}$

$$\text{specific humidity, } \omega_2 = 18 \text{ g/kg of dry air} = 0.018 \text{ kg/kg of dry air}$$

$$\text{specific enthalpy, } h_2 = 72 \text{ kJ/kg}$$

(i) Dew Point Temperature

$$\text{Dew point temperature, } t_{dp} = 24^\circ \text{C}$$

(ii) mass of water drained out per hour,

The mass flow rate of the atmospheric air is given as

$$\dot{m}_a = \frac{V}{v} = \frac{40}{0.93} = 43 \text{ kg/min}$$

From mass balance

$$\dot{m}_a \omega_1 = \dot{m}_a \omega_2 + \dot{m}_w$$

$$\dot{m}_w = 0.452 \text{ kg/min}$$

(iii) capacity of cooling coil

$$\text{Capacity in TR} = \frac{\dot{m}_a (h_1 - h_2) \times 60}{14000} = \frac{43 (114 - 72) \times 60}{14000} = 7.74 \text{ TR}$$

(iv) By Pass factor

$$BF = \frac{t_{adp} - t_{db2}}{t_{adp} - t_{db1}} = \frac{20 - 25}{20 - 40} = 0.25$$

7. The pressure of air entering and leaving the adiabatic saturator is 1 bar. The air enters at 30°C and leaves as saturated air at 20°C. Calculate the specific humidity, relative humidity of air vapour mixture entering.

Solution:

From the property tables,

For $t_{db1} = 30^\circ\text{C}$

$$P_{sat,1} = 4.247 \text{ kPa}$$

$$h_{g1} = 2555.6 \text{ kJ/kg}$$

For $t_{db2} = 20^\circ\text{C}$

$$P_{sat,2} = 2.339 \text{ kPa}$$

$$h_{f2} = 83.913 \text{ kJ/kg}$$

$$h_{fg2} = 2453.5 \text{ kJ/kg}$$

Since the air leaving the adiabatic saturator is completely saturated ($\phi_2 = 100\%$),

$$P_{v2} = P_{sat,2} = 2.339 \text{ kPa}$$

Thus the specific humidity of air leaving the saturator is

$$\omega_2 = 0.622 \frac{P_{v2}}{P - P_{v2}}, \quad \text{kg/kg of dry air}$$

$$\omega_2 = 0.015, \quad \text{kg/kg of dry air}$$

The specific humidity of air entering the saturator is found by performing energy balance

$$h_1 = \omega_1 h_{f2} + \omega_2 h_{fg2}$$

$$c_p(t_{db2} - t_{db1}) + \omega_1 h_{g1} = \omega_1 h_{f2} + \omega_2 h_{fg2}$$

$$\omega_1 = \frac{c_p(t_{db1} - t_{db2}) + \omega_2 h_{fg2}}{(h_{g1} - h_{f2})}$$

$$\omega_1 = 0.0109 \text{ kg/kg of dry air}$$

The vapour pressure at the entry can be found from

$$\omega_1 = 0.622 \frac{P_{v1}}{P - P_{v1}}, \quad \text{kg/kg of dry air}$$

$$P_{v1} = 1.72 \text{ kPa}$$

The relative humidity of the air leaving the system,

$$\phi = \frac{P_{v1}}{P_{sat,1}} = \frac{1.72}{4.247} = 0.405 = 40.5\%$$

8. 142 m³/min moist air at 5°C with a specific humidity of 0.002 kg/kg of dry air is mixed adiabatically with 425 m³/min of moist air stream at 24°C and 50% RH. If the pressure is constant throughout at 1 bar. Determine a) The humidity ratio, b) Temperature of mixed stream.

Solution:

From Psychrometric chart,

For $t_{db1} = 5^\circ\text{C}$ & $\omega_1 = 0.002 \text{ kg/kg of dry air}$

$$h_1 = 10 \text{ kJ/kg}$$

$$v_1 = 0.79 \text{ m}^3/\text{kg}$$

For $t_{db2} = 24^\circ\text{C}$ & $\phi_2 = 50\%$

$$h_2 = 48 \text{ kJ/kg}$$

$$\omega_2 = 0.0095 \text{ kg/kg of dry air}$$

$$v_2 = 0.855 \text{ m}^3/\text{kg}$$

The mass flow rate of the entering air (1) is given as

$$\dot{m}_{a1} = \frac{V_1}{v_1} = \frac{142}{0.79} = 179.75 \text{ kg/min}$$

The mass flow rate of the entering air (2) is given as

$$\dot{m}_{a2} = \frac{V_2}{v_2} = \frac{425}{0.855} = 497.1 \text{ kg/min}$$

Total mass flow rate leaving the duct is

$$\dot{m}_{a3} = \dot{m}_{a1} + \dot{m}_{a2} = 179.75 + 497.1 = 676.85 \text{ kg/min}$$

The specific humidity of leaving air can be found by performing mass balance

$$\begin{aligned} \dot{m}_{a1}\omega_1 + \dot{m}_{a2}\omega_2 &= \dot{m}_{a3}\omega_3 \\ \omega_3 &= 0.0075 \text{ kg/kg of dry air} \end{aligned}$$

The enthalpy of the leaving air can be found by performing energy balance

$$\begin{aligned} \dot{m}_{a1}h_1 + \dot{m}_{a2}h_2 &= \dot{m}_{a3}h_3 \\ h_3 &= 37.9 \text{ kJ/kg} \end{aligned}$$

From the psychrometric chart, for $\omega_3 = 7.5 \approx 8 \text{ g/kg of dry air}$ & $h_3 = 38 \text{ kJ/kg}$

$$t_{db3} = 19^\circ\text{C}$$

9. Air at 20°C , 40% R.H is mixed adiabatically with air at 40°C , 40% R.H in the ratio of 1 kg of the former with 2 kg of the latter (on dry basis). Find the final condition of air.

From Psychrometric chart,

For $t_{db1} = 20^\circ\text{C}$ & $\phi_1 = 40\%$

$$\begin{aligned} \omega_1 &= 0.006 \text{ kg/kg of dry air} \\ h_1 &= 38 \text{ kJ/kg} \end{aligned}$$

For $t_{db2} = 40^\circ\text{C}$ & $\phi_2 = 40\%$

$$\begin{aligned} h_2 &= 88 \text{ kJ/kg} \\ \omega_2 &= 0.0195 \text{ kg/kg of dry air} \end{aligned}$$

Total mass flow rate leaving the duct is

$$m_{a3} = m_{a1} + m_{a2} = 1 + 2 = 3 \text{ kg}$$

The specific humidity of leaving air can be found by performing mass balance

$$\begin{aligned} m_{a1}\omega_1 + m_{a2}\omega_2 &= m_{a3}\omega_3 \\ \omega_3 &= 0.015 \text{ kg/kg of dry air} \end{aligned}$$

The enthalpy of the leaving air can be found by performing energy balance

$$\begin{aligned} mh_1 + m_{a2}h_2 &= m_{a3}h_3 \\ h_3 &= 71.33 \text{ kJ/kg} \end{aligned}$$

From the psychrometric chart, for $\omega_3 = 15 \text{ g/kg of dry air}$ & $h_3 = 71.33 \text{ kJ/kg}$

$$t_{db3} = 31.5^\circ\text{C}$$

10. 25 kg of air at 25°C DBT and 61% RH is mixed with 5 kg of air at 5°C DBT and 30% RH. Calculate the condition of the mixed air.

From Psychrometric chart,

For $t_{db1} = 25^\circ\text{C}$ & $\phi_1 = 61\%$

$$\omega_1 = 0.012 \text{ kg/kg of dry air}$$

$$h_1 = 56 \text{ kJ/kg}$$

For $t_{db2} = 5^\circ\text{C}$ & $\phi_2 = 30\%$

$$h_2 = 9 \text{ kJ/kg}$$

$$\omega_2 = 0.002 \text{ kg/kg of dry air}$$

Total mass flow rate leaving the duct is

$$m_{a3} = m_{a1} + m_{a2} = 25 + 5 = 30 \text{ kg}$$

The specific humidity of leaving air can be found by performing mass balance

$$m_{a1}\omega_1 + m_{a2}\omega_2 = m_{a3}\omega_3$$

$$\omega_3 = 0.0103 \text{ kg/kg of dry air}$$

The enthalpy of the leaving air can be found by performing energy balance

$$m h_1 + m_{a2} h_2 = m_{a3} h_3$$

$$h_3 = 48.2 \text{ kJ/kg}$$

From the psychrometric chart, for $\omega_3 = 10 \text{ g/kg of dry air}$ & $h_3 = 48.2 \text{ kJ/kg}$

$$t_{db3} = 22^\circ\text{C}$$

MULTIPLE CHOISE QUESTIONS

Questions	opt1	opt2	opt3	opt4	answer
It is the temperature of air recorded by a thermometer when the moisture present in it begins to condense	Dew point temperature	Dew point depression	Dry bulb temperature	Wet bulb temperature	Dew point temperature
Refrigeration is used to control	Humidity	Air velocity	Temperature	None of these	Temperature
Air conditioning is used to control	Humidity	Air velocity	Temperature	a,b,c	a,b,c
During sensible heating of air, the specific humidity	Increases	Decreases	Remains constant	Less than zero	Remains constant
During sensible cooling of air, the dry bulb temperature is	Increases	Decreases	Remains constant	Less than zero	Decreases
The process generally used in winter air conditioning to warm and humidify the air is called	Humidification	Dehumidification	Cooling & dehumidification	Heating and humidification	Heating and humidification
The horizontal line in the psychrometric chart indicates	Specific humidity	Absolute humidity	wet bulb depression	dew point depression	Specific humidity
The inefficiency of the cooling coil is expressed by	By pass factor	By pass rider	RPF	PRF	By pass factor
The cause for sweating is	More moisture present in the air	Less moisture present in the air	More pressure of air	Less pressure of air	More moisture present in the air
The term (CPa+WCps) is called	Humid specific heat	Humidity	Absolute humidity	Absolute density	Humid specific heat
Humidity is the indication of _____ present in the air	Moisture	Density	Temperature	Pressure	Moisture
Humidification is the process of _____ moisture	increasing	decreasing	maintaining	Removing	increasing
Dehumidification is the process of _____ moisture	increasing	decreasing	maintaining	Removing	decreasing

During a cooling process the specific humidity remains constant is known as	Sensible cooling	Sensible heating	Dew point temperature	Wet bulb temperature	Sensible cooling
During a heating process the specific humidity remains constant is known as	Sensible cooling	Sensible heating	Dew point temperature	Wet bulb temperature	Sensible heating
The relative humidity of air is defined as the ratio of	Mass of water vapour in a given volume to the total mass of the mixture of air and water vapour	Mass of water vapour in a given volume to the mass of water vapour, if air is saturated at the same temperature	Mass of water vapour in a given volume to the mass of air	Mass of water vapour in a given volume to the mass of air at superheated temp	Mass of water vapour in a given volume to the mass of water vapour, if air is saturated at the same temperature
during sensible cooling of air, the wet bulb temperature	Increases	Decreases	Zero	None of these	Decreases
The minimum temperature at which the moist air can be condensed is known as	Wet bulb temperature	Dry bulb temperature	Dew point temperature	Wet bulb depression	Dew point temperature
The by pass factor of a cooling coil decreases with	Decreases in fin spacing and increase in number of rows	Increase in fin spacing and increase in number of rows	Increase in fin spacing and decrease in number of rows	Increase in fin spacing and decrease in number of column	Decreases in fin spacing and increase in number of rows
The process generally used in winter air conditioning to warm and humidify the air is called	Humidification	Dehumidification	Heating and humidification	Cooling and dehumidification	Heating and humidification
In winter air conditioning, the air is	Cooled and dehumidified	Cooled and humidified	Heated and humidified	Heated and dehumidified	Heated and humidified
For summer air conditioning, the relative humidity should not be less than	0.4	0.6	0.75	0.9	0.6
For winter air conditioning, the relative humidity should not be more than	0.4	0.6	0.75	0.9	0.4
The human comfort temperature is	25°C	28°C	30°C	32°C	25°C
A fasting, weak or sick man will have _____ metabolic heat production	Less	More	Constant	None of these	Less

The degree of warmth or cold felt by a human body depends mainly on,	Dry bulb temperature	Relative humidity	Air velocity	All of these	Air velocity
When the specific humidity remains constant during a heat process then it is known as	Sensible heating	Sensible cooling	Humidification	Dehumidification	Dehumidification
.Psychrometry is the study of	air	water	water vapour	air and water vapour	air and water vapour
When the temperature of air recorded by a thermometer, when it is not affected by the moisture present in air is known as	Dry air	Moist air	Dry bulb temperature	Wet bulb temperature	Dry bulb temperature
It is the temperature of air recorded by a thermometer, when its bulb is surrounded by a wet cloth exposed to the air is known as	Dry air	Moist air	Dry bulb temperature	Wet bulb temperature	Wet bulb temperature
The difference between dry bulb temperature and wet bulb temperature at any point is known as	Wet bulb depression		Dry bulb temperature	Wet bulb temperature	Dew point depression