B.TECH FOOD TECHNOLOGY

18BTFT305

THERMODYNAMICS

Instruction Hours/week: L:3 T:0 P:0

Marks: Internal:40 External:60 Total:100

End Semester Exam:3 Hours

Course Objectives

- State the fundamentals and calculations involved in zeroth law of thermodynamics.
- Discuss the applications of first law of thermodynamics.
- Illustrate the knowledge on second law of thermodynamics and entropy
- Describe thermodynamic properties of pure substances, its phase change processes and to study the working principle of steam boilers.
- Expqalin the working principle of carnot, vapor compression, vapor absorption and air refrigeration systems.

Course Outcomes

- 1. Understand the laws, concepts and principles of thermodynamics.
- 2. Apply first law of thermodynamics to closed and open systems.
- 3. Solve problems related to cycles and cyclic devices using second law of thermodynamics.
- 4. Calculate the thermodynamic properties of pure substances and phase change processes
- 5. Discuss the classification, working and accessories of steam boilers
- 6. Understand the working of carnot, vapour compression, vapor absorption and air refrigeration systems.

UNIT I - BASIC CONCEPTS AND FIRST LAW

Thermodynamics, Terminologies, systems – classification – properties and state of a system. Thermodynamic process, cycle and equilibrium. Zeroth law of thermodynamics. Law of conservation of energy. Heat – specific heat – thermal capacity and water equivalent. Mechanical equivalent of heat, work – power - universal gas constant. Internal energy, enthalpy and molar specific heat of a gas. First law of thermodynamics – Limitations of first law of thermodynamics

UNIT II - APPLICATION OF FIRST LAW OF THERMODYNAMICS TO NON-FLOW AND FLOW PROCESSES

Work done during a non-flow process - Work done for constant volume, constant pressure, constant temperature, adiabatic and polytropic process. Application of first law of thermodynamics to a steady flow system - boiler, condenser, evaporator, nozzle, turbine, rotary and reciprocating compressor.

2018-2019

Semester-III 3H-3C

UNIT III - SECOND LAW OF THERMODYNAMICS

Kelvin planck and Clausius statements. Heat engine, heat pump and refrigeration. Relation between heat and entropy – Importance and units of entropy – Clausius inequality - available and unavailable heat energy.

UNIT IV - STEAM PROPERTIES AND BOILERS

Formation of steam at a constant pressure – Temperature vs total heat during steam formation. Wet, dry saturated and super heated steam – Dryness fraction of wet steam – Enthalpy and specific volume of steam – uses of steam tables. Boilers: Classification of steam boilers, Vertical and Cross tube Cradley boiler, Cochran, Lancashire, Locomotive and Babcock-Wilcox boilers. Boiler mountings and accessories.

UNIT V - REFRIGERATION SYSTEMS AND COMPONENTS

Principles of refrigeration, choice of refrigerants, components of refrigeration cycle. Types of refrigeration: Carnot refrigeration, vapor compression cycle, air refrigeration cycle, absorption refrigeration cycle.

SUGGESTED READINGS

- Narayanan, K.V. (2013). A Text book of chemical engineering thermodynamics. 2nd Edition. PHI Learning Private Limited.
- Rajput, R.K. (2009). Engineering Thermodynamics. 3rd Edition. Laxmi Publication. New Delhi.
- Nag, P.K. (2017). Engineering Thermodynamics. 6th Edition. McGraw Hill Education (India) Private Limited.



KARPAGAM ACADEMY OF HIGHER EDUCATION DEPARTMENT OF FOOD TECHNOLOGY,FOE B.TECH – FOOD TECHNOLOGY

18BTFT305 THERMODYNAMICS

STAFF NAME : Mr. V. Arun Joshy

CLASS: II Year B.Tech - FOOD TECHNOLOGY

SEMESTER: III

S.NO	DESCRIPTION OF PORTIONS TO BE COVERED	HOURS	Suggested Readings used for Teaching	TEACHING AIDS	
	UNIT- I DIMENSIONS AND UNIT				
1	Thermodynamics, Terminologies, systems – classification – properties and state of a system	1	S[1] pg no. 1-2	РРТ	
2	Thermodynamic process, cycle and equilibrium	1	S[1] pg no. 3-5	PPT	
3	Zeroth law of thermodynamics	1	S[1] pg no. 11-12	PPT	
4	Law of conservation of energy,	1	S[1] pg no. 145-		
5	Heat – specific heat – thermal capacity and water equivalent	1	S[2] pg no. 140	PPT	
6	Mechanical equivalent of heat, work – power- universal gas constant	1	S[2] pg no. 141- 142	РРТ	
7	Internal energy, enthalpy and molar specific heat of a gas.	1	S[2] pg no. 138- 139	PPT	
8	First law of thermodynamics – Limitations of first law of thermodynamics	1	S[1] pg no. 24-25	PPT	
10	Tutorial: Problem Solving and Quiz of definitions	1			
11	Tutorial: Class test	1			
TOTAL HOURS FOR UNIT - I			Theory hours: 8 Tutorial hour:2 Total hours: 10		
UNIT -II APPLICATION OF FIRST LAW OF THERMODYNAMICS TO NON-FLOW AND FLOW PROCESSES					
12	Work done during a non-flow process	1	S[1] pg no. 40	РРТ	
13	Work done for constant volume, constant pressure, constant temperature	2	S[1] pg no. 41-43	PPT	

14	Adiabatic and polytropic process	1	S[1] pg no. 48	PPT
15	Steady flow system	1	S[1] pg no. 49-51	РРТ
16	Application of first law of thermodynamics to a steady flow system - boiler, condenser, evaporator, nozzle, turbine, rotary and	3	S[2] pg no. 155- 161	PPT
17	Tutorial: Oral Quiz on definitions	1		
18	Tutorial: Class test on Unit I and II	1		
	TOTAL HOURS FOR UNIT - II	Theory hours: 8 Tutorial hour: 2 Total hours: 10		
	UNIT-III SECOND LAW OF TH	ERMODY	YNAMICS	
19	Kelvin planck and Clausius statement	2	S[1] pg no. 108	PPT
20	Heat engine	1	S[1] pg no. 105	PPT
21	Heat pump and refrigeration	1	S[1] pg no.	PPT
22	Relation between heat and entropy	1	S[1] pg no. 90	PPT
23	Importance and units of entropy	1	S[1] pg no. 93	РРТ
24	Clausius inequality - available and unavailable heat energy.	2	S[1] pg no. 108- 109	BB
25	Tutorial: Problems solving and doubt clarifications	2		
TOTAL HOURS FOR UNIT - III		Theory hours: 8 Tutorial hour: 2 Total hours: 10		
	UNIT- IV ENERGY BA	ALANCE		
26	Formation of steam at a constant pressure – Temperature vs total heat during steam formation.	1	S[2] pg no. 361- 363	РРТ
27	Wet, dry saturated and super heated steam-	1	S[2] pg no. 364-	РРТ
28	Dryness fraction of wet steam	1	S[2] pg no. 366- 367	РРТ
29	Enthalpy and specific volume of steam – uses of steam tables	2	S[2] pg no. 368- 369	РРТ
30	Boilers: Classification of steam boilers, Vertical and Cross tube Cradley boiler, Cochran, Lancashire, Locomotive and Babcock-Wilcox boilers.	2	S[2] pg no. 681	BB
31	Boiler mountings and accessories	1	S[2] pg no. 683	PPT

32	Tutorial: Problems discussion and revision	1		
33	Tutorial: Class Test	1		
TOTAL HOURS FOR UNIT-IV			Theory hours: 8 Tutorial hour: 2 Total hours: 10	
UNIT- V REFRIGERATION SYSTEMS AND COMPONENTS				
34	Principles of refrigeration	2	S[2] pg no. 713	РРТ
35	choice of refrigerants	1	S[2] pg no. 714	РРТ
36	components of refrigeration cycle	1	S[2] pg no. 715	PPT
37	Types of refrigeration: Carnot refrigeration, vapor compression cycle, air refrigeration cycle, absorption refrigeration cycle.	5	S[2] pg no. 716- 719	PPT
38	Tutorial: Problem solving - discussion	1		
39	Tutorial: Class Test	1		
TOTAL HOURS FOR UNIT-V		Theory hours: 9 Tutorial hour: 2 Total hours: 12		
TOTAL HOURS		52		

Suggested Readings

1	Narayanan K.V.(2013) A Text book of chemical engineering thermodynamics. 2nd Edition.PHI Learning Private Limited.
2	R.k.Rajput (2009).Engering thermodynamics 3rd Edition.Laxmi publication New delhi.
3	Nag P.K. (2017). Engineering Thermodynamics, 6th Edition, McGraw Hill Education

Signature of the faculty Signature of the HOD (i/c)

Signature of the Dean (FOE)

UNIT 1 BASIC CONCEPTS AND FIRST LAW

Thermodynamics, Terminologies, systems – classification – properties and state of a system. Thermodynamic process, cycle and equilibrium. Zeroth law of thermodynamics. Law of conservation of energy. Heat – specific heat – thermal capacity and water equivalent. Mechanical equivalent of heat, work – power - universal gas constant. Internal energy, enthalpy and molar specific heat of a gas. First law of thermodynamics – Limitations of first law of thermodynamics

THERMODYNAMICS

Thermodynamics may be defined as follows:

Thermodynamics is an axiomatic science which deals with the relations among heat, work and properties of system which are in equilibrium. It describes state and changes in state of physical systems.

Or

Thermodynamics is the science of the regularities governing processes of energy conversion.

Or

Thermodynamics is the science that deals with the interaction between energy and material systems.

Thermodynamics, basically entails four laws or axioms known as Zeroth, First, Second andThird law of thermodynamics.

- The **First law** throws light on concept of internal energy.
- The **Zeroth law** deals with thermal equilibrium and establishes a concept of temperature.
- The **Second law** indicates the limit of converting heat into work and introduces theprinciple of increase of entropy.

• The **Third law** defines the absolute zero of entropy.

These laws are based on experimental observations and have no mathematical proof. Like all physical laws, these laws are based on logical reasoning.

TERMINOLOGIES

System. In thermodynamics, a substance or group of substances in which we have special interest iscalled a system. It is that part of the universe which is set apart for our special consideration. It may be a reaction vessel, a distillation column, or a heat engine.

Process. The changes taking place within the system is referred to as a process. Thus, hydrocarbon fuel and oxygen in a combustion chamber constitute the system and the combustion of fuel to form water and carbon dioxide constitutes a process.

Surroundings. The part of the universe outside the system and separated from the system byboundaries is called surroundings. The boundaries may be either physical or imaginary; they may berigid or movable. For practical reasons, the surroundings are usually restricted to that portion of the universe which is in the immediate vicinity of the system and

are affected by changes occurring in the system. For example, when the steam condensing in a shell-and-tube heat exchanger is treated as the system, the cooling water to which the latent heat of vaporisation is transferred may be treated as the surroundings.

Homogeneous and Heterogeneous Systems

Homogeneous system. This system is also called a phase. Here the properties are the samethroughout or the properties vary smoothly without showing any surface of discontinuity. Liquid water in a beaker and a column of dust-free air above the earth's surface are examples of homogeneous system.

Heterogeneous system. This is a system which consists of two or more distinct homogeneous regions or phases. There is a sudden change in properties at the phase boundaries. A liquid mixture of benzene and water forms a heterogeneous system made up of two immiscible liquid phases. Water and water vapour taken in a closed container is another example of a heterogeneous system. Systems consisting of only gases and vapours are always homogeneous. With liquids, two phases are common, and with solids any number of different phases are possible.

CLOSED AND OPEN SYSTEMS

Closed system and open system. Systems that can exchange energy with the surroundings butwhich cannot transfer matter across the boundaries are known as closed systems. Open systems, on the other hand, can exchange both energy and matter with their environment. In a multiphase system, each phase is open since material is free to enter and leave each phase, although the system as a whole may be closed to the flow of matter. A batch reactor is a closed system while a tubular flow reactor is an open system. Cyclical processes, like power and refrigeration cycles are closed systems when considered as a whole, whereas each component of the cycle such as compressor, pump, and heat exchanger is open.

Isolated system. This is a system, which is totally unaffected by the changes in its environment. Neither energy nor matter can cross the boundaries of an isolated system. A closed system is thermally isolated, when the enclosing walls are impervious to the flow of heat; it is mechanically isolated, when enclosed by rigid walls, and is completely isolated, when neither material nor energy in any form can be added to it or removed from it. A perfectly isolated system is an ideal concept that cannot be attained in practice. The system and surroundings considered together constitute an isolated system. Thus, the universe can be treated as an isolated system.

TYPES OF SYSTEMS

Here are some more important terms which are found frequently in the subject area of thermodynamics and various types of system.

Change of state of system

When one or more properties of the system like pressure, temperature, volume changes, the state of system changes.

Path of change of state

The succession of states through which the system undergoes change to reach the final state is called as the path of change of state of the system.

Homogeneous system

The system that has single or uniform phase such as like solid or liquid or gaseous is called as homogeneous system.

Heterogeneous system

The system that has more than one phase i.e. the combination of solid, liquid and gaseous state is called as heterogeneous system.

STATE OF THE SYSTEM

The present status of the system described in terms of properties such as pressure, temperature, and volume is called the state of system.

PROPERTIES OF THE SYSTEM

The characteristics by which the physical condition of the system is described are called as properties of system. Some examples of these characteristics are: temperature, pressure, volume etc and are called as properties of system. The system properties are of two types: extensive and intensive properties.

EXTENSIVE PROPERTIES OF SYSTEM

The properties of the system that depend on the mass or quantity of the system are called extensive properties. Some examples of extensive properties are: mass, volume, enthalpy, internal energy, entropy etc.

INTENSIVE PROPERTIES OF THE SYSTEM

These properties do not depend on the quantity of matter of the system. Some of the examples of intensive properties are: freezing point temperature, boiling point, temperature of the system, density, specific volume etc.

THERMODYNAMICS PROCESS

When the system changes from one thermodynamic state to the final thermodynamic state due to change in pressure, temperature, volume etc, the system is said to have undergone thermodynamic process. The various types of thermodynamic processes are: isothermal process, adiabatic process, isochoric process, isobaric process and reversible process.

CYCLIC PROCESS

When the system undergoes a number of changes in states and returns back to the initial state, the system is said to have undergone cyclic process.

ISOTHERMAL PROCESS

The process during which the temperature of the system remains constant is called as isothermal process.

ADIABATIC PROCESS

The process during which the heat content of the system remains constant i.e. no flow of heat takes place across the boundaries of system, the process is called as adiabatic process.

ISOCHORIC PROCESS

In this process the volume of system remains constant.

Isobaric process

The process during which the pressure of the system remains constant, is called as

isobaric process. Deemed to be University

Reversible process

When the system undergoes changes infinitesimally slowly the changes can be reversed back, such a process is called as reversible process. During reversible process the system remains in equilibrium during the change of state of the system.

CYCLE

Any process or series of processes whose end states are identical is termed a **cycle**. Theprocesses through which the system has passed can be shown on a state diagram, but a complete section of the path requires in addition a statement of the heat and work crossing the boundary of the system. The below figure shows such a cycle in which a system commencing at condition '1' changes in pressure and volume through a path 123 and returns to its initial condition '1'.





The distinction between steady state and the equilibrium state must be clear at the outset. A system, which is interacting with the surroundings, is said to have attained a *steady-state condition* when the properties at a specified location in the system do not vary with time. Consider the walls of a furnace, the inside surface of which is exposed to hot combustion gases and the outside surface to the atmospheric air. Heat transfer occurs from the inside of the furnace to the outside and the temperature at a specified location in the wall varies with time. When the wall has attained steady state with respect to heat transfer, the temperature at any given point remains constant and does not vary with time. However, the temperatures at different points in the wall would be different. It is obvious that asystem in the steady state exchanges mass, heat, or work with the surroundings, even when exhibiting time invariance for the properties.

Equilibrium State

A system is said to be in a state of equilibrium if the properties are uniform throughout andthey do not vary with time. By properties we mean the properties on a macroscopic scale and

do not exclude the probability of individual molecules having different values for the properties. A system is in *thermal equilibrium*, when no heat exchange occurs between various points within the system and the temperature is uniform throughout. In a system which is in *mechanicalequilibrium*, the pressure is uniform. Even under the conditions of uniform temperature and pressure, transfer of mass may occur between the various phases constituting the system, or chemical reaction may occur between the various components present in the system. In a system, which is in a state of *thermodynamic equilibrium*, in addition to the absence of heat and work exchange, there would be no mass transfer between the phases, no diffusion of mass within the phase, and no chemical reaction between the constituents. A state of equilibrium implies, therefore, a state at rest. Since all such changes are caused by driving forces of some kind, the state of equilibrium may also be treated as the one in which all forces are in exact balance. The state of equilibrium will be retained by the system after any small, but short mechanical disturbance in the external conditions.

Phase Rule

The concept of equilibrium is important in thermodynamics, because, properties have any real meaning only in the equilibrium state. The state of an equilibrium system consisting of a pure fluid is uniquely determined by specifying any two intensive variables, as observed earlier. Thus, when we say that CO2 gas is contained in a vessel at a pressure of 2 bar and temperature of 300 K, the intensive state of the system is completely determined. The number of independent variables necessary to define the state of equilibrium uniquely is known as the number of degrees offreedom. This number will be different for different equilibrium states.

For example, for water and water vapour in thermodynamic equilibrium, only one independent variable needs to be specified to define the state uniquely. The number of degrees of freedom in this case is just one. That is, when we say that this system is at a pressure of one standard atmosphere, the temperature gets automatically specified as 373 K, the normal boiling point of water. Thus, the specification of pressure determines the temperature and all other intensive thermodynamic properties of the system. In fact, there exists a definite relationship between the number of degrees of freedom (F), the number of distinct chemical species constituting the system (C) and the number of phases present at equilibrium (p). This is given by the Gibbs phase rule,

$$F = C - p + 2$$

Zeroth Law

Let a body A be brought in thermal contact with another body B. Heat flows from one to the other and eventually thermal equilibrium is established between A and B. If another body C is also in thermal equilibrium with B, then it is experimentally observed that A and C are also in thermal equilibrium. This observation although appears as frivolous, cannot be explained using known scientific principles. Hence, it has come to be accepted as a law of nature. It is known as the zeroth law ofthermodynamics, as it precedes the first and second laws in the logical hierarchy of thermodynamic principles. It may be stated thus: If body A is in thermal equilibrium with B and B is in thermal equilibrium with C, then C is also in thermal equilibrium with A.

LAW OF CONSERVATION OF ENERGY

In the early part of nineteenth century the scientists developed the concept of energy andhypothesis that it can be neither created nor destroyed; this came to be known as the *law of theconservation of energy*. The first law of thermodynamics is merely one statement of this general law/principle with particular reference to heat energy and mechanical energy *i.e.*, work.

HEAT

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Heat Transfer Direction

Heat is energy transferred from one system to another solely by reason of a temperature difference between the systems. Heat exists only as it crosses the boundary of a system and the direction of heat transfer is from higher temperature to lower temperature.

For thermodynamics sign convention, heat transferred to a system is positive; Heat transferred from a system is negative.

The heat needed to raise a object's temperature from T_1 to T_2 is:

$$\mathbf{Q} = \mathbf{c}_{\mathrm{p}} \mathbf{m} \left(\mathbf{T}_2 - \mathbf{T}_1 \right)$$

where

Unit of heat is the amount of heat required to cause a unit rise in temperature of a unit mass of water at atmospheric pressure.

- Btu: Raise the temperature of 1 lb of water 1 °F
- Cal: Raise the temperature of 1 gram of water 1 °C

J is the unit for heat in the S.I. unit system. The relation between Cal and J is

1 Cal = 4.184 J

Notation used in this book for heat transfer:

- Q : total heat transfer
 - Q: the rate of heat transfer (the amount of heat transferred per unit time)
- δQ : the differential amounts of heat
- q: heat transfer per unit mass

Modes of Heat Transfer

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Conduction: Heat transferred between two bodies in direct contact.

Fourier's law:

$$\dot{Q}_{cond} = -k_t A \frac{dT}{dx}$$

If a bar of length L was put between a hot object $T_{\rm H}$ and a cold object $T_{\rm L}$, the heat transfer rate is:

$$\dot{Q}_{cond} = k_t A \frac{(T_H - T_L)}{L}$$

where

 k_t = Thermal conductivity of the bar

A = The area normal to the direction of heat transfer

Convection: Heat transfer between a solid surface and an adjacent gas or liquid. It is the combination of conduction and flow motion. Heat transferred from a solid surface to a liquid adjacent is conduction. And then heat is brought away by the flow motion.

Newton's law of cooling:

$$\dot{Q}_{conv} = hA(T_s - T_f)$$

where

h = Convection heat transfer coefficient

 T_s = Temperature of the solid surface

 $T_f =$ Temperature of the fluid

The atmospheric air motion is a case of convection. In winter, heat conducted from deep ground to the surface by conduction. The motion of air brings the heat from the ground surface to the high air.



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Double Pane Window



Definition of Work

Radiation: The energy emitted by matter in the form of electromagnetic waves as a result of the changes in the electronic configurations of the atoms or molecules.

Stefan - Boltzmann law:

$$\dot{Q}_{rad} = s\sigma AT_s^4$$

where

 σ = Stefan - Boltzmann constant ϵ = emissivity T_s = Surface temperature of the object

Solar energy applications mainly use radiation energy from the Sun.

The three modes of heat transfer always exist simultaneously. For example, the heat transfer associated with double pane windows are:

- Conduction: Hotter (cooler) air outside each pane causes conduction through solid glass.
- Convection: Air between the panes carries heat from hotter pane to cooler pane.
- Radiation: Sunlight radiation passes through glass to be absorbed on other side.

Please view heat transfer books for details of modes of heat transfer.

Work

Work is the energy transfer associated with a force acting through a distance.

 $W = F \cdot L = FLsin(\alpha)$

Dot product means the distance along the force's direction. For example, if a car runs at a flat road, its weight does zero work because the weight and the moving distance have a 90° angle.

Like heat, Work is an energy interaction between a system and its surroundings and associated with a process.

In thermodynamics sign convection, work transferred out of a system is positive with respect to that system. Work transferred in is negative.

Units of work is the same as the units of heat.

Notation:

- W : total work
- δW : differential amount of work
- w: work per unit mass
- \dot{W} : Power, the work per unit time

Expansion and Compression Work

A system without electrical, magnetic, gravitational motion and surface tension effects is called a simple compressible system. Only two properties are needed to determine a state of a simple compressible system.

Considering the gas enclosed in a piston-cylinder device with a cross-sectional area of the piston A.

Initial State:

- Pressure P₁
- Volume V₁

Finial State:

- Pressure P₂
 - Volume V₂

Then a work between initial and final states is: Pressure P, Volume V. Let the piston moving ds in a quasi-equilibrium manner. The differential work done during this process is:

$$\delta W = F ds = P A ds = P dV$$

The total work done during the whole process (from state (P_1, V_1) to state (P_2, V_2)) is:

This quasi-equilibrium expansion process can be shown on a P-V diagram. The differential area dA is equal to P dV. So the area under the process curve on a P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.



Expansion and Compression Work

Energy



Chemical Energy Transfers to Kinetic Energy in Rocket

Kinetic Energy and Gravitational

Potential Energy

Energy is the capacity for doing work. It may exist in a variety of forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear. It may be transferred from one type of energy to another. For example,

- Heating water by gas: Chemical energy ---> thermal energy
- Heating water by electricity: electric energy ---> thermal energy
- Running nuclear power plant: Nuclear energy ---> electric energy
- Flying rocket: Chemical energy ---> thermal Energy ---> Kinetic Energy

Forms of Energy

Kinetic Energy (KE): The energy that a system possesses as a result of its motion.

$$KE = mv^2/2$$

where

m = mass of the system

v = velocity of the system

If an object of mass m changes velocity from v_1 to v_2 , thus the change of its kinetic energy is:

 $\Delta KE = 1/2 (v_2^2 - v_1^2)$

Potential Energy (PE): The energy that a system possesses as a result of its elevation in a gravitational field or change of configurations.

Gravitational potential energy (elevation in a gravitational field):

PE = mgz

where

m = mass of the system

z = height relative to a reference frame

Moving an object from location A to B, its gravitational potential energy change is:

 $\Delta PE = mg(Z_B - Z_A)$



final start $\Delta KE = 1/2kL_2^2 - 1/2kL_1^2$







Molecules Random Movement

Elastic potential energy (change of configurations):

$$PE = 1/2 \ kx^2$$

where

k = spring constantx = change in spring length

If a spring elongates from L_1 to L_2 , the elastic potential energy stored in the spring is :

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$$\Delta PE = 1/2 \text{ k } L_2^2 \text{-} 1/2 \text{ k } L_1^2$$

Internal energy (U): The energy associated with the random, disordered motion of molecules. It is the sum of the kinetic and potential energies of all molecules.

- Experience has shown that for most substances with no phase change involved, internal energy strongly depends on temperature. Its dependence on pressure and volume is relatively small.
- It is not possible to calculate the absolute value of the internal energy of a body. Only internal energy change of a system can be determined.
- Internal energy is a property.

Total Energy (E): The sum of all forms of energy exist in a system. The total energy of a system that consists of kinetic, potential, and internal energies is expressed as:

$$E = U + KE + PE = U + mv^2/2 + mgz$$

The change in the total energy of a system is:

 $\Delta E = \Delta U + \Delta KE + \Delta PE$

Enthalpy (H)

Enthalpy is a thermodynamics property of a substance and is defined as the sum of its internal energy and the product of its pressure and volume.

H = U + PV

Specific Heat (c)

Experiment shows that the temperature rise of liquid water due to heat transfer to the water is given by



P

 P_2

P

P₄=P₂

V₁=V₂ Isochoric Process

٧2

Isobaric Process

v

$$\mathbf{Q} = \mathbf{m} \mathbf{c} (\mathbf{T}_2 - \mathbf{T}_1)$$

where

Q = heat transfer to the water

m = mass of water

 $T_2 - T_1 =$ temperature rise of the water

In general, the value of specific heat c depends on the substance in the system, the change of state involved, and the particular state of the system at the time of transferring heat. Specific heat of solids and liquids is only a function of temperature but specific heat of gaseous substances is a function of temperature and process.

Specific Heat at Constant Volume (c_v)

Specific heat at constant volume is the change of specific internal energy with respect to temperature when the volume is held constant (Isochoric process).

$$v_v = \left(\frac{\partial u}{\partial T}\right)_v$$

For constant volume process:

$$(\Delta u)_v = \int_{T_1}^{T_2} c_{vdT}$$

Specific Heat at Constant Pressure (c_P)

Specific heat at constant pressure is the change of specific enthalpy with respect to temperature when the pressure is held constant (Isobaric process).



For constant pressure process

$$(\Delta h)_{P} = \int_{T_{1}}^{T_{2}} c_{PdT}$$

Power. It is defined as the time rate of doing work. Its unit in the SI system is J/s, commonly designated as W (watts). In engineering calculations, power is sometimes expressed as horsepower (hp). Hence, 1 hp = 745.7 W.

FIRST LAW OF THERMODYNAMICS FOR CYCLIC PROCESS

Consider a static system undergoing a cycle of changes. Work is done on the system by forces actingfrom the surroundings, or vice versa, and heat is transferred between the system and the surroundingsduring the process. Then, according to the first law of thermodynamics, the algebraic summation of all work effects exactly equals the summation of all heat effects.

Let Q denote the heat added to the system and W the work done by the system (Q is negative when heat is rejected by the system and W is negative when work is done on the system) and if both are measured in consistent units,

SW = SQ

If the units chosen for heat and work are different, the above equation can be written

as

SW = JSO

J is the mechanical equivalent of heat if the work is mechanical, and electrical equivalent of heat if the work is electrical.

LIMITATIONS OF THE FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics deals with energy changes involved in a process. But, it alone cannot answer many questions related to transformation of energy. The first law specifies only this: ifenergy is produced during a process, it must be compensated with a loss of an exactly equal quantity, so that the total energy before and after the process are the same. It helps us to determine the energy changes involved in a process, but it cannot tell us whether a proposed change would actually occur or not. If it occurs, what is the direction of the change and what are the conditions of equilibrium under which the system undergoes no further change? The major limitation of the first law of thermodynamics is, therefore, its inability to deal with the direction of the process and the extent of change. Also, according to the first law, all forms of energy are quantitatively equivalent and they are just additive terms in an energy balance. It fails to recognise the qualitative differences between various forms of energy. This difference is apparent when we attempt to convert heat into work by means of a heat engine.

Direction of Change

We have seen that the first law of thermodynamics deals with the amount of energy in different formsthat are involved in various spontaneous processes, but it is not concerned with the 'direction of change'. For example, when water on the top of a mountain runs to the bottom as a stream or as a waterfall, the initial potential energy of water is converted to the kinetic energy and the first law of thermodynamics is satisfied, because, the total energy remains unchanged. It would equally be satisfied in the reverse process in which the water flows upwards spontaneously. The first law doesn't suggest the impossibility of water flowing upwards spontaneously. However, such an occurrence is contrary to our experience. Now, let us consider another example. When two bodies at different temperatures are brought into contact, heat energy flows from the body at high temperature to that at low temperature spontaneously.

Heat energy will never flow from a lower temperature level to a higher temperature level without applying external work. According to the first law, the energy gained by the cold body should beequal to the energy lost by the hot body. Again, there is nothing in the first law that predicts that the transfer of heat must always be from the hot to the cold body.

The first law would be satisfied equally well if the transfer of energy took place in the reverse direction, but such a transfer never happens in nature. Similarly, we never observe a mixture of gases made up of two or more components spontaneously separating into its constituents. Though such a process is against our experience, it would not be inconsistent with the first law of thermodynamics as long as no net change in the total energy is involved. Thus, it is clear that apart from the first law, but complementary to it, there should be some principle to deal with the spontaneous processes and their direction.

The inadequacy of the first law of thermodynamics to explain our general experience withspontaneous processes or tendency to change led to the development of the second law of thermodynamics, which deals with the direction of change. With the help of the tools provided by the second law, we can find answers to many problems that are not answered by the first law. For a chemical reaction occurring from a given initial state of reactants to a given final state of products, the first law can be utilised to estimate the heat of reactants to a the effect of temperature and pressure on it. But, will the reaction proceed spontaneously? What is the equilibrium point at which no further change occurs? How is the equilibrium affected by the operating conditions? What is the maximum work available from a process? What is the minimum work required to carry out a process? What is the maximum efficiency with which a process could be carried out? Such questions are answered by the second law of thermodynamics, usually in combination with the first law.

Qualitative Difference between Heat and Work

Another limitation of the first law of thermodynamics is that it does not take into account the difference in quality between heat and work. When we treat heat and work as additive terms in an energy balance, we are in fact ignoring the intrinsic difference between them. It is true that, in the application of the first law this difference is not going to affect our calculations. However when we consider converting heat energy to other forms of energy, the qualitative difference between heat and work would be obvious. It is possible to convert one form of work to another (such as electrical to mechanical) with almost 100 per cent efficiency, provided, the irreversibilities in the apparatus are eliminated. But the efficiency of converting energy transferred to a system as heat into any of the forms of work is limited to very low values. This leads us to the conclusion that heat is a less versatile or more degraded form of energy compared to the other forms of energy or work can be termed energy of a higher quality than heat. During the conversion of heat into work, a portion of the energy becomes *unavailable*, that is, not capable of being transformed into useful form.

The difference between the quality of heat and other forms of energy are accounted for in the secondlaw of thermodynamics. When we say that heat flows always from a higher to a lower temperature we are assigning a characteristic quality as well as quantity to heat, the quality being represented by temperature. We know that the efficiency of a thermal power plant increases as the temperature of the steam in the boiler increases. In the transformation of heat to work, the increase in the efficiency that results from the increase in the temperature of the source clearly establishes the connection between the temperature and the quality of heat.



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APPLICATION OF FIRST LAW OF THERMODYNAMICS TO NON-FLOW AND FLOW PROCESSES

Work done during a non-flow process - Work done for constant volume, constant pressure, constant temperature, adiabatic and polytropic process. Application of first law of thermodynamics to a steady flow system - boiler, condenser, evaporator, nozzle, turbine, rotary and reciprocating compressor.

Some Applications of the Laws of Thermodynamics

Engineers would be able to devise methods for improving the efficiency of a process by proper application of laws of thermodynamics. This chapter deals with the thermodynamic analysis of some typical industrial processes using the first and the second laws of thermodynamics. The first section deals with the general energy balance equations and their application to some important fluid flow problems. Refrigeration and liquefaction processes are discussed next, with emphasis on the thermodynamic cycles rather than on the equipment used. In the last sections, the thermodynamic analysis of various power cycles that are commonly used in steam-power plants, internal combustion engines and gas turbines are discussed.

FLOW PROCESSES

Thermodynamics can be used to find solutions to many fluid flow problems. Some of the basic equations in fluid mechanics are developed using the first and second laws of thermodynamics. However, questions that are related to the mechanism of flow, such as the loss of heat due to friction are not within the scope of thermodynamics. In order to facilitate the application of thermodynamic principles to flow process, we assume that the flow is unidirectional and the fluid properties do not change in the direction perpendicular to the direction of flow. By the latter idealisation, we mean that the properties at any point in the flow system are average values applicable for the entire crosssection. **Continuity Equation**

For a control volume (see Fig. 5.1), the law of conservation of mass may be written as:

Rate of accumulation of mass + Net rate of mass out within the control volume + by the flowing streams = 0

Mathematically, the above relation can be represented as

$$\frac{dm}{dt} + \Delta(\rho u A) = 0$$

where r is the average fluid density, A is the fluid cross-sectional area and u is the average fluid velocity is known as the continuity equation. For steady-state flow process, there is no accumulation of mass within the control volume, and the equation reduces to



Fig. 5.1 Energy balance for a control volume.

Denoting the conditions at the entrance to the control volume by subscript 1 and the conditions at the exit by subscript 2, Eq. (5.2) may be re-written as $r_1u_1A_1 = r_2u_2A_2$

Energy Equation

[THERMODYNAMICS]

The law of conservation of energy for a control volume is given by where and are the rate at which heat is supplied to the fluid and the rate at which shaft work is done by the fluid respectively.

Rate of accumulation of energy is dUt/dt, where Ut is the total internal energy within the control volume. The total energy of the fluid stream is the sum of its kinetic energy (*KE*), potential energy (*PE*), and internal energy (*IE*). The law of conservation of energy can now be expressed as

$$\frac{dU^{t}}{dt} + \Delta(KE) + \Delta(PE) + \Delta(IE) = \dot{Q} - \dot{W}$$

In Eq. (5.3), the symbol Δ represents the difference between exit and entrance streams.

$$\Delta (KE) + \Delta (PE) + \Delta (IE) = \Delta \left[\dot{m} \left(\frac{u^2}{2} + gZ + U \right) \right]$$

where is the mass flow rate and Z is the height above a reference plane. The work rate is made up of two parts—the shaft work and the flow-work, the latter being the product of the pressure and the volume of the fluid. The flow work is equal to and it is the net work done by the fluid in pushing it into and out of the control volume.

$$\dot{W} = \dot{W}_{\rm S} + \Delta[\dot{m}(PV)] \tag{5.5}$$

Substituting Eqs. (5.4) and (5.5) in Eq. (5.3) and noting that H = U + PV, the energy equation becomes

$$\frac{dU^{t}}{dt} + \Delta \left[\dot{m} \left(\frac{u^{2}}{2} + gZ + H \right) \right] = \dot{Q} - \dot{W}_{S}$$
(5.6)

For steady-state flow process, there is no accumulation of energy within the control volume, and Eq. (5.6) reduces to

$$\Delta \left[\dot{m} \left(\frac{u^2}{2} + gZ + H \right) \right] = \dot{Q} - \dot{W}_S \tag{5.7}$$

For flow systems where the kinetic and potential energy changes are negligible, Eq. (5.7) can be further simplified to

$$\Delta \left[\dot{m} \left(\frac{u^2}{2} + gZ + H \right) \right] = \dot{Q} - \dot{W}_S \tag{5.7}$$

For flow systems where the kinetic and potential energy changes are negligible, Eq. (5.7) can be further simplified to

$$\Delta \dot{m}H = \dot{Q} - \dot{W}_{\rm s} \tag{5.8}$$

If the fluid enters and leaves the control volume in a single stream, the mass rate of flow remains the same at the entrance and exit. Then Eq. (5.7) becomes

$$\Delta\left(\frac{u^2}{2} + gZ + H\right) = Q - W_S$$
(5.9)

This equation is known as the total energy balance. For the case, where changes in kinetic and potential energies are negligible, Eq. (5.9) becomes

 $\mathsf{D}H = Q - W_S \tag{5.10}$

In both Eqs. (5.9) and (5.10), $Q = (\dot{Q}/\dot{m})$ and $W_s = (\dot{W}_s/\dot{m})$.

The 'total energy balance' considers only the input and output from the system. For fluid mechanics calculations, it is customary to express this equation in the form of mechanical energy balance. The mechanical energy balance takes irreversible effects, such as, fluid friction also into account. Equation (5.9) may be put in the following form:

$$\frac{\Delta t t^2}{2} + g \Delta Z + \Delta H = Q - W_g \qquad (5.11)$$

From the definition of enthalpy of a fluid [see Eq. (2.9)], we get

 $dH = dU + PdV + VdP \tag{5.12}$

Using the first law of thermodynamics [see Eq. (2.5)],

 $dU = dQ - dW \tag{5.13}$

For a reversible process, the work done by the fluid is

dW = P dV

Substituting this into Eq. (5.13) and combining the resulting equation with Eq. (5.12), we get dH = dQ + V dP (5.14)

Integrate Eq. (5.14) between the entrance and exit of the control volume. Then,

$$\Delta H = Q + \int_{P_1}^{P_2} V \, dP \tag{5.15}$$

Using this relation, Eq. (5.11) can be modified to the following form:

$$-W_{S} = \frac{\Delta u^{2}}{2} + g\Delta Z + \int_{P_{1}}^{P_{2}} V \, dP \tag{5.16}$$

If the changes in kinetic and potential energies are negligible, the shaft work is given by

$$W_{S} = -\int_{P_{1}}^{P_{2}} V \, dP \tag{5.17}$$

The above equations are developed assuming reversible processes. On including the work lost due to the irreversibilities, Eq. (5.16) takes the following form:

The above equations are developed assuming reversible processes. On including the work lost due to the irreversibilities, Eq. (5.16) takes the following form:

$$\frac{\Delta u^2}{2} + g\Delta Z + \int_{P_1}^{P_2} V \, dP + W_S + F = 0 \tag{5.18}$$

Here, F represents the lost work due to friction or mechanical energy dissipated to heat due to irreversibilities in the system. Equation (5.18) is known as the *mechanical energy balance*.

Bernoulli's equation. Bernoulli's equation is a special form of the mechanical energy balance applicable only to non-viscous incompressible fluids, which do not exchange shaft work with the surroundings. For non-viscous fluids, F = 0. The integral in Eq. (5.18) can be evaluated if the functional relationship between pressure and volume is known. For incompressible fluids, volume is independent of pressure, and hence

$$\int_{P_1}^{P_2} V \, dP = V \Delta P = \frac{\Delta P}{\rho} \tag{5.19}$$

where r is the density of the fluid. Since no shaft work is exchanged, $W_S = 0$. Using these simplifications, Eq. (5.18) can be written as

$$\frac{\Delta u^2}{2} + g\Delta Z + \frac{\Delta P}{\rho} = 0 \tag{5.20}$$

$$\frac{u^2}{2} + gZ + \frac{P}{\rho} = \text{constant}$$
(5.21)

Equation (5.21) is known as Bernoulli's equation.



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Second Law, Entropy and Availability

Inside of this Chapter...

Second law of thermodynamics – Kelvin's and Clausius statement Reversibility and irreversibility – Carnot cycle – Concept of Entropy – Entropy of ideal gas – Carnot theorem – availability

2.1 Limitations of first law of thermodynamics

i) According to first law of thermodynamics heat and work are mutually convertible during any cycle of a closed system. But this law does not specify the possible conditions under which the heat is converted into work. The law also does not specify the direction of heat and work.

ii) According to first law of thermodynamics it is impossible to transfer heat from lower temperature to higher temperature.

iii) It does not give any information regarding change of state or whether the process is possible or not.

2.2 Energy Reservoir

Source:- It is the thermal energy reservoir from which the heat Q_1 is transferred to the system operating in a heat engine cycle is called source.

Sink:- It is the thermal energy reservoir to which the heat Q_2 is rejected from the system during a cycle is called sink.

22 2.3 Second law of thermodynamics

The second law of thermodynamics can be stated by the following two statements

(i) Kelvin - Planck Statement

It is impossible to construct a heat engine to produce net work in a complete cycle if it exchanges heat from a single reservoir at single fixed temperature.

In other words for a heat engine, it is impossible to convert entire heat energy supplied to it into work. That is some heat energy must be lost to its surroundings as shown in figure 2.1

Therefore efficiency of the engine is not equal to 100%. It is always less than 100%





The efficiency of the heat engine

Heat supplied

$$\eta = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

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or

$$\eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

Perpetual motion machine of second kind (PMM2)

For an engine

If $Q_2 = 0$ then $\eta = 100$ (ie) it violates Kelvin - planck statement. Such an engine is called perpetual motion machine of Second Kind (PMM2) and it is not possible.

(ii) Clausius Statement

It is impossible to transfer heat from low temperature reservoir to high temperature reservoir without the aid of any external device.

Heat cannot flow from lower temperature body to higher temperature body. To achieve this heat transfer from low temperature body to high temperature body, some work must be done. Heat pump is used for this purpose.

Refrigerator and heat Pump

Refrigerator is a device which operates in a cycle maintaining the temperature lower that that of its surrounding as shown in figure (2.2).



Figure 2.2: Refrigerator

ENGINEERING THERMODYNAMICS

The cold reservoir is the refrigerated space and the hot reservoir is atmosphere. The performance parameter is measured by coefficient of performance. (COP)

 $COP of refrigeration = \frac{\text{Net Refrigeration effect}}{\text{Work Input}}$

$$[COP]_{ref} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$$

Heat pump is a device which operating in a cycle, maintains a body at temperature higher than that of its surrounding as shown in figure 2.3.





The net work (W_{net}) is the difference between compressor work and expansion device work.

COP of the Heat pump = $\frac{\text{Heat supplied}}{\text{net work}}$

$$\frac{\text{COP}_{\text{H.P}}}{\text{W}} = \frac{Q_1}{W}$$

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SECOND LAW, ENTROPY AND AVAILABILITY

or .

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

Perpetual motion machine of second kind (PMM2)

n =

For an engine

If $Q_2 = 0$ then $\eta = 100$ (ie) it violates Kelvin - planck statement. Such an engine is called perpetual motion machine of Second Kind (PMM2) and it is not possible.

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Figure 2.2: Refrigerator

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SECOND LAW, ENTROPY AND AVAILABILITY

2.7

A reversible process is one which is performed in such a way that at the conclusion of process, both system and surroundings may be restored to their initial state, without producing any changes in rest of the universe as shown in figure 2.5.

The assumptions made for reversible process

- 1. The reversible process has to be a quasi-equilibrium process
- 2. No friction is involved in the process
- 3. Heat transfer occurs due to an infinitesimal temperature difference only
- 4. Unrestrained expansion does not occur.

The reversible process is purely an ideal process and it is an imaginary process which is used for theoritical calculations or ideal condition.

In the figure A and B are system, the process is carried out along the path A - B. In the reversible process, the system has to be taken from the state B to A by following the same path B - A. A reversible process should not leave any trace or relic to show that the process had ever occurred.

2.6 Irreversibility and and

The mixing of two substances and combustion also leads to irreversibility. All spontaneous process are irreversible.

2.7 Causes of Irreversibility

The irreversibility of a process may be due to the following reasons.

1. Lack of equilibrium during the process

- i) Heat transfer due to Lack of equilibrium
- ii) Lack of pressure equilibrium with the interior of the system or between system

iii) Free expansion



210 210 A will expand into B until the pressures in A and antiput of the gas in the chamber A will expand and expansion. punctured uncertained expansion. Energy of the gas in By using the reversed free expansion, the system can hold for the former by using the reversed free expansion. energy on unce. By using uncertained wacuum in B. It is observed that the reasonable reservoir source. By using uncertained wacuum in B. It is observed that the reasonable reservoir. This violation of high pressure in A and vacuum in a single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. 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This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and vacuum in the single reservoir. This violation of high pressure in A and In the passing the reversed free expansion, the system can be reversed free expansion, the system can be real by the passing the reversed free expansion. It is observed that the real energy of the gas in B can be reversed that the real energy of the gas in B can be reversed free expansion, the system can be reversed that the reverse expansion, the system can be reversed to the system can be reversed free expansion, the system can be reversed to the system can be law therefore free expansion is irreversible. 2.7.2 Irreversibility due to dissipative effects done without producing an even of the system. This work transformation occurs due to friction, viscosity, inelasticity, elevit the system. This work transformation occurs due to friction are known as discimulation of the system. The ineversibility of a provent increase in the Kinetic energy or Potential environment of the without producing an equivalent increase in the Kinetic energy of Potential environment of the second s (i) Friction and the work is said to be dissipated. the system. This work under the system of the system as dissipative efforts are known as dissipative efforts and magnetic i.e., hysteresis. the friction cannot be completely eliminated. The friction makes a process inteversible it is proved by second law. ncumered This is known to be the store the initial state of the gas. The interest of the gas is should restore the initial value by heat transfer O is initial value by heat t would cause the fly wheel to rotate, which is not possible. Therefore friction is ineverse the hot brakes were to cool off, it should give back its internal energy to the fly wheel the work transfer is equal to Zero. If the brake is applied there will be a heat transfer the hot brake wards and the brake is applied there will be a heat transfer to be a hea and it is stopped by applying the friction brake. The distance moved is negligible that Friction is always present in moving part and it is reduced by lubrication methods h 2 Inteversibility of a process may be due to the dissipative effects in which Consider a fly wheel and brake block. The fly wheel is rotating with a certainf Figure 2.8: Ineversibility due to dissipative effect like friction Flywheel • System boundary Brake block ENGINEERING THERMODY --SECOND LAW, ENTROPY AND AVAILABILITY wheel, is known as paddle wheel work or stirring work. (ii) Paddle - wheel work transfer a) Adiabatic work transfer internal energy and the temperature of the system goes down. The system restore its consider the same amount of work is delivered by the system at the expense of its molecular in which there is work output and the system exchanges heat with a single reservoir. It original state by heat transfer from source. These two process together constitute a cycle violates second law. Therefore the dissipation of stirring work into internal energy is ineversible. (iii) Transfer of electricity through a resistor The work transferred to a system in an insulated container by means of a paddle SESSION used to drive the motor. Figure 2.10: Irreversibility due to dissipation of electrical work into internal energy Insulation System The flow of electric current through a wire represents work transfer, the current i The work and heat transfer is negative. the heat transfer during any reversible process. reversible process. The area under the T - S diagram represents process irreversible unrestrained expansion cannot occur in a Heat transfer across a finite temperature difference makes a 4 Figure 2.9: Paddle work $Q_{1-2} = U_2 - U_1 + W_{1-2}$ Diathermic source b) Inteversibility due to dissipation of - Resistor (system) string work into internal energy Adiabatic System ¥ W 2.11




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2.15

216 2.10 Thermodynamic temperature Scale The COP of the refrigerator = Net Refrigeration effect TIP OF THE SEMON It is an independent of the property of thermodynamic substance. The ratio $\frac{Q_1}{Q_2}$ depends on the temperatures t_1, t_2 of the reservor. We know that dependent only on the absolute, temperatures of reservoirs, of any real engine. The thermal efficiency of a carnot engine is The carnot engine establishes the maximum possible efficiency $(\mathrm{COP}_{\mathrm{ref}})_{\mathrm{ref}} = \frac{T_2}{T_1 - T_2}$ $\left(\mathrm{COP}_{\mathrm{lip}}\right)_{\mathrm{rev}} = \frac{\mathrm{T_{l}}}{\mathrm{T_{l}} - \mathrm{T_{2}}}$ Wree = W. - W. $\begin{aligned} &\eta_{tev} = f(t_{1}, t_{2}) \\ &1 - \frac{Q_{2}}{Q_{1}} = f(t_{1}, t_{2}) \end{aligned}$ (or) $\frac{Q_1}{Q_2} = f(t_1, t_2)$ $=(T_1 - T_2) (S_1 - S_4)$ $= Q_1 - Q_2$ $\eta = 1 - \frac{Q_1}{Q_1}$ ENGINEERING THERMODY SECOND LAW, ENTROPY AND AVAILABILITY then we can write the function \$ (t) Kelvin proposed that similarly where T_t - is the triple point of water T-temperature of the particular Reservoir each engine is the same as the temperature selected The thermodynamic temperature scale may be defined by taking an arbitary form of Thermodynamic temperature = Celsius temperature +273.16° (S I units) Consider a series of reversible engines as shown in figure 2.14. The work done by $\phi(f) = T$ $\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$ $\frac{Q}{Q_{1}} = \frac{T}{T_{1}}$ Figure 2.14: Reversible heat engines $T=T_t \frac{Q}{Q_t}$ $T = 273.16 \frac{Q}{Q_1}$ Source 1 HE HE 2 Sink T ** * * 2.17



constant in all adiabatic friction less process as shown in figure 2.16 constant in all adiabatic friction lace and be decreased in entropy. The entropy remains define c tropy but the change in entropy can be easily defined. which increases with addition of heat and decreases with removal of heat. It is difficulta finite pressure gradient is known as mechanical irrevesibility. Mechanical irreversibility transformation. the entropy is an important thermodynamic property of a working substance 2.13 Concept of entropy reaction is known as chemical irreversibility. Chemical irreversibility Thermal irreversibility termal irreversibility 220 SESSION TIP OF THE è If the heat is supplied to the system, then dS will be increased in entropy and if the where T = absolute temperature For a reversible process change in entropy (dS) $\frac{dQ}{r}$ The irreversibility of process is due to a finite temperature gradient is known a The concept of entropy was introduced by clausius. The term 'entropy' mean The irreversibility of process is due to a finite concentration gradient or chemica dQ = the heat supplied or rejected by the substance This is known as inequality of clausius. For all cycles whether reverible or irreversible $\oint \frac{dQ}{T} \le 0$. SECOND LAW, ENTROPY AND AVAILABILITY which will increase the entropy by dS and T is the absolute temperature at this point. point on the curve. The small quantity (dQ) of heat is supplied to the working substance 2.14 Significance of entropy We know that 3) The increase in entropy is obtained from a given quantity of heat at a low 2) The change in entropy may be regarded as a measure of the rate of the availability For reversible and adiabatic process, Consider the process 1-2 is the reversible process of the substance. 'A' is the any Similarly the total change in entropy in the process 1-2. 1) The change in entropy represents the maximum amount of work obtainable per Therefore reversible and adiabatic process is an isentropic process or unavailability of heat for transformation into work. degree drop in temperature. temperature. Figure 2.16: Temperature-entropy diagram Temperature $d'S = \frac{dQ}{T}$ Entropy dS = dS = 0dQ = T d SS = constantsp 52 at the etu cit 1.30 2.21

process. According to the clausius statement we know that, for any process undergone by a system 2.15 Change in entropy for a irreversible process From equation (2), the above equation is written as $= -\int_{B_2}^{1} \frac{dQ}{T} + \int_{C_2}^{1} \frac{dQ}{T} < 0$ For the irreversible process A - C For a reversible process A and B The Process A and B are reversible process and the process C is an irreversible Figure 2.17: Entropy change in an irreversible process $\oint \frac{dQ}{T} = \int_{A_1}^{2} \frac{dQ}{T} + \int_{C_2}^{1} \frac{dQ}{T} < 0$ $\int_{A1}^{2} \frac{dQ}{T} = - \int_{B_{2}}^{2} \frac{dQ}{T}$ $\int_{R} \frac{dQ}{T} = \int_{A_{1}}^{2} \frac{dQ}{T} + \int_{B_{2}}^{1} \frac{dQ}{T} = 0$ ds ≥ dQ $\frac{dQ}{T} \le dS$...(3) ...(1) ...(2) We know that the entropy is a property. The entropy changes for the paths B and C would be the same. Therefore, Session an isolated system undergoing a real process must increase. Since the path is reversible According to equation (4), Therefore, we can write Therefore for any irreversible process the change in entropy dS $> \frac{dQ}{T}$ For reversible process $dS = \frac{dQ_{rev}}{T}$ Entropy production is positive for a real process. The entropy of $\int_{B_2} dS = \int_{C_2}^{1} dS$ $\int_{B_2} \frac{dQ}{T} = \int_{B_2} dS$ $\int_{B_2} \frac{dQ}{T} > \int_{C_2} \frac{dQ}{T}$ $\int_{C_2}^{1} dS > \int_{C_2}^{1} \frac{dQ}{T}$ $S_2 - S_1 \ge \int \frac{dQ}{T}$ $\int_{1}^{2} dS \ge \int_{1}^{2} \frac{dQ}{T}$ $dS \ge \frac{dQ}{T}$...(4) ...(5)



...(5)

2.27



If a process is irreversible The of THE Session The of THE that $\Delta S = 0$ only the change datum for entropy is if no	$S_2 - S_1 = mC_v (\gamma - n) \ln \left(\frac{V_2}{V_1} \right)$	$S_2 - S_1 = mC_v \frac{n-\gamma}{n} \ln \left(\frac{p_2}{p_1}\right)$	$S_{2} - S_{1} = m C_{v} \left(\frac{n-\gamma}{n-1}\right) ln \frac{T_{2}}{T_{1}}$ The change in entropy of polytropic process	$= m C_{v} \ln T_{y} \left(1 - \frac{n-y}{n-1} + 1 \right)$ $= m C_{v} \ln T_{y} \left(\frac{n-y}{n-1} \right)$	= $mC_{1} \ln T_{2} \left[1 - \frac{y-1}{p-1} \right]$ = $mC_{2} \ln T_{2} \left[1 - \frac{y-1}{p-1} \right]$	$= mC_{1} \ln \left(\frac{T_{1}}{T_{1}}\right) - \frac{m(C_{1} - C_{1})}{n-1}$ $= mC_{1} \ln \left(\frac{T_{1}}{T_{1}}\right) - \frac{m(C_{1} - C_{1})}{n-1}$	$\frac{2.30}{m(C_{1}-C_{1})}\ln\left(\frac{T_{1}}{T_{1}}\right) + mC_{1}^{-1}$
but adiabatic it is not generally true ^{e in} entropy is of interest, the arbitary ^{consequence.}			s is also expressed as	Entropy	Temperature	$\ln\left(\frac{T_1}{T_1}\right) = \min T_2 \left[\frac{C_V - \frac{U_P - C_1}{n-1}}{n-1} \right]$	$\ln\left(\frac{T_{L}}{T_{T}}\right)$

SECOND LAW, ENTROPY AND AVAILABILITY

2.31

2.18 Carnot theorem

The corollary of second law which compromised the Carnot theorem.

Corollary of Carnot theorem:

It states that "No heat engine operating in a cycle between two constant temperature heat reservoir can be more efficient than a reversible engine operating between the same reservoir" as shown in figure 2.24.



 $E_A =$ is the heat engine

Let

 $E_{\rm B} = \mbox{ is the reversible heat engine we have to prove that $\eta_{\rm B} > \eta_{\rm A}$}$ But let us assume that this is not true and $\eta_{\rm A} > \eta_{\rm B}$ then the rates of working of an engine will be

 $Q_{1A} = \dot{Q}_{1B} = Q$ Since

 $\eta_A > \eta_B$

2.33



Figure 2.25: E_A and E_B together violet Kelvin-Planck statement

2.19 Absolute entropy

The third law of thermodynamics provides the basis for calculation of absolut entropies of substances. This law provides a reference point for the calculation of entropy By making measurements of heat capacities of different crystalline forms of substances and then calculating entropies at 0 Kelvin (at absolute zero temperature) they found the the entropy values were the same.

2.20 The Third law of thermodynamics

The entropy of all perfect crystalline solids is zero at absolute zero temperature.



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Available energy is the maximum part of thermal energy which can be converted in the useful work under ideal condition. The remaining part which cannot be converted into work is known as unavailable energy as shown in figure 2.25.

Availability

The maximum useful work (total work - pdV) obtained during a process in which the final condition of the system is the same as that of the surrounding is called availability of the system.

Availability is the composite property depending upon the state of both the system

and surrounding.





$$\sum_{k=0}^{2M} \sum_{\substack{k=0 \ k=0 \ k=0 \ k=0 \ k=0}}^{M} \left[(V_{i} - V_{i}) - T_{i} \left(S - S_{i}\right) + V_{i} - V_{i} - S_{i} + V_{i} + mgz_{i} \right) + P_{0} \left(V - V_{i}\right) - (S - S_{i}) + V_{i} + \frac{m_{i}C_{i}}{2} + mgz_{i} \right) + P_{0} \left(V - V_{i}\right) - (S - S_{i}) + V_{i} + P_{i} \left(V - V_{i}\right) - T_{i} \left(S - S_{i}\right) + V_{i} + P_{i} \left(V - V_{i}\right) - T_{i} \left(S - S_{i}\right) + (V_{i} + P_{i} V_{i} - T_{i} S_{i}) + (V_{i} - V_{i} - S_{i}) + (V_{i} - V_{i}) + T_{i} S_{i} + S_{i} + S_{i} + (V_{i} - V_{i}) + T_{i} S_{i} + S_{i} + (V_{i} - V_{i}) + T_{i} S_{i} + S_{i} + (V_{i} - V_{i}) + T_{i} S_{i} + S_{i} + S_{i} + (V_{i} - V_{i}) + T_{i} S_{i} + S_{i} + S_{i} + (V_{i} - V_{i}) + T_{i} S_{i} + (V_{i} - V_{i}) + T_{i} S_{i} + S_$$

SECOND LAW, ENTROPY AND AVAILABILITY

2.35

If the number of flows is more than one in and out of control volume is $involved_{int}$ maximum work done or availability is given by

$$W_{max} = \sum_{i} m_{i} \psi_{i} - \sum_{e} m_{e} \psi_{e}$$



Availability is a comporite property depending on the state of both the system and surroundings. Availability is the maximum work obtainable in a process, When the system $come_s t_0$ equilibrium with its surroundings.

Solved Problems

Heat Engine Problems

Example 1:

A reversible engine receives heat from a mixture of water vapour and liqui water under a pressure of 1.01 bar and rejects 7200 kJ of heat per hour to mixture of ice and liquid water under a pressure of 1.01 bar. Find the powe delivered by the engine.





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A **boiler** is a closed vessel in which fluid (generally water) is heated. The fluid does not necessarily boil. The heated or vaporized fluid exits the boiler for use in various processes or heating applications, including water heating, central heating, boiler-based power generation, cooking, and sanitation.

The pressure vessel of a boiler is usually made of steel (or alloy steel), or historically of wrought iron. Stainless steel, especially of the austenitic types, is not used in wetted parts of boilers due to corrosion and stress corrosion cracking.However, ferritic stainless steel is often used in superheater sections that will not be exposed to boiling water, and electricallyheated stainless steel shell boilers are allowed under the European "Pressure Equipment Directive" for production of steam for sterilizers and disinfectors.

In live steam models, copper or brass is often used because it is more easily fabricated in smaller size boilers. Historically, copper was often used for fireboxes (particularly for steam locomotives), because of its better formability and higher thermal conductivity; however, in more recent times, the high price of copper often makes this an uneconomic choice and cheaper substitutes (such as steel) are used instead.

For much of the Victorian "age of steam", the only material used for boilermaking was the highest grade of wrought iron, with assembly by riveting. This iron was often obtained from specialist ironworks, such as those in the Cleator Moor (UK) area, noted for the high quality of their rolled plate, which was especially suitable for use in critical applications such as high-pressure boilers. In the 20th century, design practice moved towards the use of steel, with welded construction, which is stronger and cheaper, and can be fabricated more quickly and with less labour. Wrought iron boilers corrode far more slowly than their modern-day steel counterparts, and are less susceptible to localized pitting and stress-corrosion. That makes the longevity of older wrought-iron boilers far superior to that of welded steel boilers.

Cast iron may be used for the heating vessel of domestic water heaters. Although such heaters are usually termed "boilers" in some countries, their purpose is usually to produce hot water, not steam, and so they run at low pressure and try to avoid boiling. The brittleness of cast iron makes it impractical for high-pressure steam boilers.

Boilers can be classified into the following configurations:

- *Pot boiler* or *Haycock boiler*/Haystack boiler: A primitive "kettle" where a fire heats a partially filled water container from below. 18th century Haycock boilers generally produced and stored large volumes of very low-pressure steam, often hardly above that of the atmosphere. These could burn wood or most often, coal. Efficiency was very low.Flued boiler with one or two large flues—an early type or forerunner of fire-tube boiler.
- Fire-tube boiler: Here, water partially fills a boiler barrel with a small volume left above to accommodate the steam (*steam space*). This is the type of boiler used in nearly all steam locomotives. The heat source is inside a furnace or *firebox* that has to be kept permanently surrounded by the water in order to maintain the temperature of the *heating surface* below the boiling point. The furnace can be situated at one end of a fire-tube which lengthens the path of the hot gases, thus augmenting the heating surface which can be further increased by making the gases reverse direction through a second parallel tube or a bundle of multiple tubes (two-pass or return flue boiler); alternatively the gases may

be taken along the sides and then beneath the boiler through flues (3-pass boiler). In case of a locomotive-type boiler, a boiler barrel extends from the firebox and the hot gases pass through a bundle of fire tubes inside the barrel which greatly increases the heating surface compared to a single tube and further improves heat transfer. Fire-tube boilers usually have a comparatively low rate of steam production, but high steam storage capacity. Fire-tube boilers mostly burn solid fuels, but are readily adaptable to those of the liquid or gas variety. Fire-tube boilers may also be referred to as "scotch-marine" or "marine" type boilers.

- Water-tube boiler: In this type, tubes filled with water are arranged inside a furnace in a number of possible configurations. Often the water tubes connect large drums, the lower ones containing water and the upper ones steam and water; in other cases, such as a mono-tube boiler, water is circulated by a pump through a succession of coils. This type generally gives high steam production rates, but less storage capacity than the above. Water tube boilers can be designed to exploit any heat source and are generally preferred in high-pressure applications since the high-pressure water/steam is contained within small diameter pipes which can withstand the pressure with a thinner wall. These boilers are commonly constructed in place, roughly square in shape, and can be multiple stories tall.
- Flash boiler: A flash boiler is a specialized type of water-tube boiler in which tubes are close together and water is pumped through them. A flash boiler differs from the type of mono-tube steam generator in which the tube is permanently filled with water. In a flash boiler, the tube is kept so hot that the water feed is quickly flashed into steam and superheated. Flash boilers had some use in automobiles in the 19th century and this use continued into the early 20th century.
- Fire-tube boiler with Water-tube firebox. Sometimes the two above types have been combined in the following manner: the firebox contains an assembly of water tubes, called thermic siphons. The gases then pass through a conventional firetube boiler. Water-tube fireboxes were installed in many Hungarian locomotives, but have met with little success in other countries.
- Sectional boiler. In a cast iron sectional boiler, sometimes called a "pork chop boiler" the water is contained inside cast iron sections. These sections are assembled on site to create the finished boiler.

Super Heated Steam Boiler

When water is boiled the result is saturated steam, also referred to as "wet steam." Saturated steam, while mostly consisting of water vapor, carries some unevaporated water in the form of droplets. Saturated steam is useful for many purposes, such as cooking, heating and sanitation, but is not desirable when steam is expected to convey energy to machinery, such as a ship's propulsion system or the "motion" of a steam locomotive. This is because unavoidable temperature and/or pressure loss that occurs as steam travels from the boiler to the machinery will cause some condensation, resulting in liquid water being carried into the machinery. The water entrained in the steam may damage turbine blades or in the case of a reciprocating steam engine, may cause serious mechanical damage due to hydrostatic lock.

Superheated steam boilers evaporate the water and then further heat the steam in a *superheater*, causing the discharged steam temperature to be substantially above the boiling temperature at the boiler's operating pressure. As the resulting "dry steam" is much hotter than needed to stay in the vaporous state it will not contain any significant unevaporated water. Also, higher steam pressure will be possible than with saturated steam, enabling the steam to carry more energy. Although superheating adds more energy to the steam in the form of heat there is no effect on pressure, which is determined by the rate at which steam is drawn from the boiler and the pressure settings of the safety valves. The fuel consumption required to generate superheated steam is greater than that required to generate an equivalent volume of saturated steam. However, the overall energy efficiency of the steam plant (the combination of boiler, superheater, piping and machinery) generally will be improved enough to more than offset the increased fuel consumption.

Superheater operation is similar to that of the coils on an air conditioning unit, although for a different purpose. The steam piping is directed through the flue gas path in the boiler furnace, an area in which the temperature is typically between 1,300 and 1,600 degrees Celsius (2,372 and 2,912 degrees Fahrenheit). Some superheaters are radiant type, which as the name suggests, they absorb heat by radiation. Others are convection type, absorbing heat from a fluid. Some are a combination of the two types. Through either method, the extreme heat in the flue gas path will also heat the superheater steam piping and the steam within.

The design of any superheated steam plant presents several engineering challenges due to the high working temperatures and pressures. One consideration is the introduction of feedwater to the boiler. The pump used to charge the boiler must be able to overcome the boiler's operating pressure, else water will not flow. As a superheated boiler is usually operated at high pressure, the corresponding feedwater pressure must be even higher, demanding a more robust pump design.

Boiler fittings and accessories

- Pressuretrols to control the steam pressure in the boiler. Boilers generally have 2 or 3 pressuretrols: a manual-reset pressuretrol, which functions as a safety by setting the upper limit of steam pressure, the operating pressuretrol, which controls when the boiler fires to maintain pressure, and for boilers equipped with a modulating burner, a modulating pressuretrol which controls the amount of fire.
- Safety valve: It is used to relieve pressure and prevent possible explosion of a boiler.
- Water level indicators: They show the operator the level of fluid in the boiler, also known as a sight glass, water gauge or water column.
- Bottom blowdown valves: They provide a means for removing solid particulates that condense and lie on the bottom of a boiler. As the name implies, this valve is usually located directly on the bottom of the boiler, and is occasionally opened to use the pressure in the boiler to push these particulates out.
- Continuous blowdown valve: This allows a small quantity of water to escape continuously. Its purpose is to prevent the water in the boiler becoming saturated with dissolved salts. Saturation would lead to foaming and cause water droplets to be carried over with the steam a condition known as priming. Blowdown is also often used to monitor the chemistry of the boiler water.
- Trycock: a type of valve that is often use to manually check a liquid level in a tank. Most commonly found on a water boiler.

- Flash tank: High-pressure blowdown enters this vessel where the steam can 'flash' safely and be used in a low-pressure system or be vented to atmosphere while the ambient pressure blowdown flows to drain.
- Automatic blowdown/continuous heat recovery system: This system allows the boiler to blowdown only when makeup water is flowing to the boiler, thereby transferring the maximum amount of heat possible from the blowdown to the makeup water. No flash tank is generally needed as the blowdown discharged is close to the temperature of the makeup water.
- Hand holes: They are steel plates installed in openings in "header" to allow for inspections & installation of tubes and inspection of internal surfaces.
- Steam drum internals, a series of screen, scrubber & cans (cyclone separators).
- Low-water cutoff: It is a mechanical means (usually a float switch) or an electrode with a safety switch that is used to turn off the burner or shut off fuel to the boiler to prevent it from running once the water goes below a certain point. If a boiler is "dry-fired" (burned without water in it) it can cause rupture or catastrophic failure.
- Surface blowdown line: It provides a means for removing foam or other lightweight noncondensible substances that tend to float on top of the water inside the boiler.
- Circulating pump: It is designed to circulate water back to the boiler after it has expelled some of its heat.
- Feedwater check valve or clack valve: A non-return stop valve in the feedwater line. This may be fitted to the side of the boiler, just below the water level, or to the top of the boiler.
- Top feed: In this design for feedwater injection, the water is fed to the top of the boiler. This can reduce boiler fatigue caused by thermal stress. By spraying the feedwater over a series of trays the water is quickly heated and this can reduce limescale.
- Desuperheater tubes or bundles: A series of tubes or bundles of tubes in the water drum or the steam drum designed to cool superheated steam, in order to supply auxiliary equipment that does not need, or may be damaged by, dry steam.
- Chemical injection line: A connection to add chemicals for controlling feedwater pH.

Steam accessories

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- Main steam stop valve:
- Steam traps:
- Main steam stop/check valve: It is used on multiple boiler installations.

Combustion accessories

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- Fuel oil system:fuel oil heaters
- Gas system:
- Coal system:

Other essential items

- Pressure gauges:
- Feed pumps:
- Fusible plug:
- Insulation and lagging;
- Inspectors test pressure gauge attachment:
- Name plate:
- Registration plate:

Draught

A fuel-heated boiler must provide air to oxidize its fuel. Early boilers provided this stream of air, or *draught*, through the natural action of convection in a chimney connected to the exhaust of the combustion chamber. Since the heated flue gas is less dense than the ambient air surrounding the boiler, the flue gas rises in the chimney, pulling denser, fresh air into the combustion chamber.

Most modern boilers depend on mechanical draught rather than natural draught. This is because natural draught is subject to outside air conditions and temperature of flue gases leaving the furnace, as well as the chimney height. All these factors make proper draught hard to attain and therefore make mechanical draught equipment much more reliable and economical.

Types of draught can also be divided into *induced draught*, where exhaust gases are pulled out of the boiler; *forced draught*, where fresh air is pushed into the boiler; and *balanced draught*, where both effects are employed. Natural draught through the use of a chimney is a type of induced draught; mechanical draught can be induced, forced or balanced.

There are two types of mechanical induced draught. The first is through use of a steam jet. The steam jet oriented in the direction of flue gas flow induces flue gases into the stack and allows for a greater flue gas velocity increasing the overall draught in the furnace. This method was common on steam driven locomotives which could not have tall chimneys. The second method is by simply using an induced draught fan (ID fan) which removes flue gases from the furnace and forces the exhaust gas up the stack. Almost all induced draught furnaces operate with a slightly negative pressure.

Mechanical forced draught is provided by means of a fan forcing air into the combustion chamber. Air is often passed through an air heater; which, as the name suggests, heats the air going into the furnace in order to increase the overall efficiency of the boiler. Dampers are used to control the quantity of air admitted to the furnace. Forced draught furnaces usually have a positive pressure.

Balanced draught is obtained through use of both induced and forced draught. This is more common with larger boilers where the flue gases have to travel a long distance through many boiler passes. The induced draught fan works in conjunction with the forced draught fan allowing the furnace pressure to be maintained slightly below atmospheric.

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3.1 Introduction

Steam is a vapour. It is used as the working substance in the operation of steam engines and steam turbines. As stated in chapter 2, a vapour is a partially evaporated liquid carrying in it particles of liquid and it can be liquefied by minor changes in temperature or pressure. Steam as a vapour would not obey the laws of perfect gases unless it is in a highly dried condition. Steam in such a dried state is known as *superheated steam* and it is assumed to behave like a perfect gas when highly superheated.

Although steam is considered as a perfect gas on account of it being a mixture of dry steam (gas) and moisture (water), it possesses properties like those of gases : namely, pressure, volume, temperature, internal energy, enthalpy and entropy. But the pressure, volume and temperature of steam as a vapour are not connected by any simple relationship such as is expressed by the characteristic equation for a perfect gas.

Properties of steam were first investigated experimentally by Regnault and subsequently investigated by Prof. Callender by carrying out extensive thermodynamic experiments by means of electrical calorimeters. Tables giving the properties of steam in each condition were compiled from study of the equations derived experimentally. These properties are also represented on charts. The quantities tabulated in steam tables are :

- Pressure,
- Temperature,
- Specific Volume,
 - Enthalpy, and
 - Entropy.

Pressure, temperature and volume can be given their actual absolute values; whereas, enthalpy and entropy are purely relative quantities. They are measured relatively from convenient datum condition and calculated per 1 kg of steam. For steam, datum point is arbitrarily fixed as the condition of the water at 0°C. Thus, the enthalpy, the internal energy and the entropy of water at 0°C are assumed to be zero. All their values measured above this temperature are considered positive and those measured below are taken as negative.

The general conservation of energy equation is applicable to steam in the same manner as it is applicable to gases. The properties of steam and the changes in the properties can be determined by using standard steam tables or steam charts.

3.2 Formation of Steam at Constant Pressure

Consider a cylinder fitted with frictionless piston which may be loaded to any desired pressure p bar as shown in fig. 3-1(a). Now, assume for convenience that there is one

kilogram of water initially at temperature 0°C in the cylinder under the piston and the piston exerts a constant pressure p bar. Let the area of the piston be one square metre and the volume of one kilogram of water be $v_W m^3$, the length of the cylinder occupied by water will be $v_W m$. Now, let heat be supplied to the water in the cylinder. The temperature of water will rise when sensible enthalpy be supplied. The rise in temperature will continue until the boiling point is reached, where it will remain constant. The temperature at which water boils depends upon the pressure on it. For any given pressure, there is one *definite* boiling point. The boiling point is called the saturation temperature (t_s) or the temperature of steam formation. Water boils at 99.63°C when the pressure on it is 1 bar, and at 184.09°C when the pressure on it is 11 bar (these values are taken from steam tables).





The water will expand slightly during the rise of temperature. The increase in volume of water causes the piston to move up slightly as shown in the fig. 3-1(b), thus, work is done in moving the piston against this pressure p. This work, however, is only a small portion of the heat added to water during the rise in temperature and may be neglected in general. Figure 3-1(a) represents the condition before the first stage commences and fig. 3-1(b) represents the condition at the end of the first stage. It will be noted that the piston is at slightly higher level at the end of operation.

The next stage, as shown in fig. 3-1(c), is the actual production of steam. If the heating of this one kilogram of water is continued after the boiling point is reached, it will be noticed that there is no further increase in temperature, as the pressure is maintained constant but steam begins to form and piston commences to ascend (rise) in the cylinder, rising higher and higher as more and more steam is formed. The heat absorbed is now utilised in converting water into steam and is known as *evaporation enthalpy* or *latent heat*. As long as there is some water left unevaporated in the cylinder, the steam formed will not be pure (dry) steam, but will have some water mixed with it. In fig. 3-1(c), part of water is evaporated and the cylinder has in it, mixture of water and steam (about half steam and half water). A mixture of steam and water is called *wet steam*.

If the heating of this wet steam is further continued and as soon as last particle of water in suspension in wet steam disappears (evapcrates), the steam produced is known as dry saturated steam.

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Figure 3-1(d) shows that the process of formation of steam is completed. The water is entirely evaporated and the volume of steam below the piston is $v_s m^3$ (v_s is the volume of one kilogram of dry saturated steam at a given pressure p). The piston will rise to accommodate this increased volume, and will occupy length v_s m of the cylinder. The work done on the piston during the change of volume of the steam from v_w to v_s

$$= \frac{10^3 p (v_s - v_w)}{10^3}$$
 kJ where p is the pressure in bar. ... (3.1a)

If p is in kPa, then the above expression is written as

Work done =
$$p(v_s - v_w)$$
 kJ ... (3.1b)

Finally, if further heat is added to one kilogram of dry steam in the cylinder at the constant pressure, the temperature of steam will rise and there will be further increase in volume of steam as shown in fig. 3-1(e). The steam produced is known as *superheated steam*.



Fig. 3-2. Formation of steam at constant pressure.

Figure 3-2 shows graphically that what happens when heat is added to one kilogram of water initially at 0°C. The heat added is plotted along the horizontal axis in kJ units while the corresponding temperatures are plotted along the vertical axis in centigrade units.

During the first stage of heating, the temperature of water will begin to rise until the water boils at a temperature known as saturation temperature which depends upon the pressure in the cylinder. After the boiling temperature is reached, steam begins to be formed during which time the temperature remains constant. Until the point is reached at which all water is converted into steam, the contents of mixture will be steam and water known as wet steam. When all the

water including those particles of water held in suspension will be evaporated, the steam is said to be dry and is known as *dry saturated steam*. As heating continues further, the temperature of steam begins to rise again and steam is now known as *superheated steam* and behaves more or less as a perfect gas.

3.2.1 Enthalpy : For reasons too long to explain here, the term heat content is not recommended for use in thermodynamics. The terms formerly known as "heat of water" (sensible heat), "heat of evaporation" (latent heat) and "total heat of steam" are now known as the "enthalpy of (saturated) water", "enthalpy of evaporation" and "enthalpy of saturated steam" respectively. Similarly, the term total heat of superheated steam is now known as "enthalpy of superheated steam". Enthalpy of evaporation is the difference between enthalpy of dry saturated steam and enthalpy of (saturated) water, i.e,

Enthalpy of evaporation = Enthalpy of dry saturated steam - Enthalpy of boiling water

3.2.2 Enthalpy of Water : The amount of heat absorbed by one kilogram of water in being heated from the freezing point (0°C) to the boiling point t_s , is known as the enthalpy of the saturated water (sensible heat of water) and is denoted by the symbol

h. It is customary to reckon the enthalpy of water from 0°C at which temperature the enthalpy of water is said to be zero. To raise the temperature of one kilogram of water from 0°C to 100°C requires $4.187 \times 100 = 418.7$ kJ; hence this number is the enthalpy of one kg of water at 100°C. If the temperature of water to begin with is say 20°C instead of 0°C, then number of heat units required to raise 1 kg of water at 20°C to water at 100°C is equal to 4.187 (100 - 20) = 334.96 kJ, where 4.187 kJ/kg K is the specific heat water.

If the specific heat of water were 4.187 kJ/kg K at all temperatures, then the enthalpy of water would be 4.187 ($t_s - 0$) kJ/kg. For engineering purpose, it is of sufficient accuracy to assume the value of specific heat of water (k) to be 4.187 kJ/kg K at low pressures in which case,

Enthalpy of (saturated) water, h at any temperature ts above 0'C is

$$h = 4.187 \times (t_s - 0) \text{ kJ/kg}$$

.. (3.2)

... (3.3)

The error in results calculated by this formula becomes larger as the temperature rises. The value of enthalpy of saturated water, *h* given in column 4 of the steam tables (given at the end of this book) should be used in preference to the results calculated from the above formula.

3.2.3 Enthalpy of Evaporation : The enthalpy of evaporation (or latent heat) is defined as the amount of heat required to convert one kilogram of water at a given temperature t_s and pressure p into steam at the same temperature and pressure. The value of enthalpy of evaporation varies with the pressure. It is usually expressed by the symbol L and its value at 1 bar is 2,258 kJ per kg. The value of enthalpy of evaporation, L of 1 kg of dry saturated steam can be directly obtained from the steam tables.

The value of enthalpy of evaporation of dry saturated steam is given in column 5 of the steam tables.

3.2.4 Enthalpy of Dry Saturated Steam : It is the sum of enthalpy of saturated water and enthalpy of evaporation and is defined as the quantity of heat required to raise the temperature of one kilogram of water from freezing point to the temperature of evaporation t_s (corresponding to given pressure p) and then convert it into dry saturated steam at that temperature and pressure. It is denoted by the symbol H_s . The enthalpy of one kg of dry saturated steam, H_s = enthalpy of (saturated) water + enthalpy of evaporation,

.e.,
$$H_s = h + L kJ/kg$$

The value of enthalpy (total heat), H_s of 1 kg of dry saturated steam can be directly obtained from the steam tables corresponding to given value of pressure or temperature. The value of enthalpy of dry saturated steam is given in column 6 of the steam tables.

Enthalpy of evaporation is the enthalpy difference between dry saturated steam and saturated water.

3.2.5 Wet Steam : The steam in the steam space of a boiler generally contains water mixed with it in the form of a mist (fine water particles). Such a steam is termed as wet steam. The quality of steam as regards its dryness is termed as dryness fraction. Dryness fraction is usually expressed by the symbol x or q. Dryness fraction is often spoken as the quality of wet steam.

If m_s = mass of dry steam contained in the steam considered, and

m = mass of water in suspension in the steam considered.

Then, dryness fraction, $x = \frac{m_s}{m_s + m}$

Thus, if drynes fraction of wet steam, x = 0.8, then one kg of wet steam contains 0.2 kg of moisture (water) in suspension and 0.8 kg of dry steam.

When the steam produced is not dry steam, but a mixture of steam and water as is often the case, the enthalpy of one kilogram of mixture of water and steam (wet steam) is less than enthalpy of the same quantity of pure or dry steam. To generate steam of dryness fraction 0.8, takes only 0.8 of the enthalpy of evaporation necessary for the formation of dry steam at the same temperature. Hence, enthalpy of evaporation of one kg of wet steam is the value of the enthalpy of evaporation given in steam tables for dry steam, at the required pressure, multiplied by its dryness fraction x.

i.e. Enthalpy of evaporation of 1 kg of wet steam = xL kJ/kg ... (3.5)

Enthalpy of wet steam is the amount of heat required to raise the temperature of one kilogramof water from freezing point (0°C) to the boiling point t_s (corresponding to given pressure, p) and then to convert the boiling water into wet steam,

i.e. Enthalpy of one kg of wet steam = enthalpy of saturated water + enthalpy of evaporation,

i.e.
$$H_{wet} = h + xL kJ/kg$$

3.2.6 Superheated Steam : If the steam remains in intimate contact with water during its formation, interchange of molecules between the water and steam will result. This interchange of molecules will continue as long as there is any water in the cylinder of fig. 3-1(d). This will not allow the steam to become dry.

If the water is entirely evaporated and further heat is then supplied, the first effect on the steam is to make it dry if it is not already dry. The temperature of steam will then begin to increase with a corresponding Increase in volume. Steam in this condition, heated out of contact with water, is said to be superheated. Superheating is assumed to take place at constant pressure. The amount of superheating is measured by the rise in temperature of the steam above its saturation temperature (t_s). Greater the amount of superheating, the more will the steam acquire the properties of a perfect gas.

In practice, steam is superheated after it has left the boiler by passing it through a nest of tubes known as *superheater*. The superheater is heated externally by the furnace gases of the boiler. The additional heat supplied to steam during the process of superheating is known as the heat of superheat.

Heat absorbed per kg of dry steam during superheating = $k_p(t_{sup} - t_s) \text{ kJ/kg...(3.7)}$ where t_{sup} = temperature of superheated steam,

 t_s = saturation temperature at the given pressure, and

 $k_{\rm p}$ = mean specific heat of superheated steam at constant pressure.

The temperature rise $(t_{sup} - t_s)$ is termed as *dgree of superheat*. It means the number of degrees of temperature by which steam at a given pressure is raised above the saturation temperature corresponding to that pressure. The condition of superheated steam is given either by its degree of superheat or by its temperature. The value of specific heat of superheated steam (k_p) varies with the pressure and degree of superheating. It increases with the increase of pressure and decreases with the increase of degree of superheating. The value of superheating. The value of specific heat at constant pressure of superheated steam (k_p) varies from 2 to 2.5 kJ/kg K.

... (3.4)

... (3.6)

The enthalpy (or total heat) of one kg of superheated steam may be defined as the number of heat units required to convert one kg of water at freezing temperature (0°C) into superheated steam at a given pressure and temperature, assuing that the heat is added at constant pressure, which is the case in practice. The enthalpy of 1 kg of superheated steam is, therefore, the sum of enthalpy of water, the enthalpy of evaporation, and the heat of superheat. It is denoted by symbol H_{sup} . Hence, enthalpy of one kg of superheated steam,

$$H_{sup} = h + L + k_p(t_{sup} - t_s) = H_s + k_p(t_{sup} - t_s) k_J/kg \qquad \dots (3.8)$$

3.2.7 Specific Volume of Steam : The volume of one kilogram of dry saturated steam at all pressures is given in column 3 of the steam tables. The value in cubic metre per kg of dry saturated steam (m³/kg) is known as the *specific volume of dry saturated steam* and its symbol is v_s .

Density of dry steam is the mass of one cubic metre of steam (kg/m³) and is the reciprocal of specific volume and, therefore, is equivalent to $1/v_s$ kg per cubic metre.

If the steam is wet, having a dryness fraction of x, one kg of wet steam will consist of x kg of dry (pure) steam and (1 - x) kg of water held in suspension.

Specific volume of wet steam, having a dryness fraction of x

= volume of dry steam + volume of water particles

 $= xv_s + (1 - x)v_w$

where, vs and vw denote the specific volume of steam and water respectively.

As the volume of water at low pressure is very small compared with the steam, the term $(1 - x)v_w$ will become still smaller and can be neglected.

Hence, the specific volume of wet steam, neglecting volume of water particles

= xv_s m³/kg, and density of wet steam = $1/xv_s$ kg/m³.

For some problems of thermodynamics, it is sufficiently accurate that, at a given pressure, the volume of superheated steam is proportional to its absolute temperature. This assumption is made on the ground that superheated steam behaves like a perfect gas. The approximate specific volume of *superheated steam* may be calculated from the expression,

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s}$$
 m³/kg

where T_{sup} is the absolute temperature of superheated steam, T_s is the absolute saturation temperature of steam and v_s is the specific volume of dry saturated steam.

3.3 Steam Tables

Reference is now made to the steam tables which give the properties of 1 kg of dry saturated steam. The information given in steam tables (given at the end of this book) has been obtained by performing experiments on dry saturated steam at various pressures and temperatures. In the steam tables, the initial temperature of water is taken as 0°C.

Absolute pressures given in column 1 of the steam tables are in bar. Before the steam tables can be used, it is necessary to convert boiler gauge pressure (shown by the steam pressure gauge fitted on the boiler) to absolute pressure. This is obtained by adding atmospheric (barometric) pressure to boiler gauge pressure. See solved problem no.5. The information contained in steam tables is as under :

... (3.9)

Absolute pressure of steam	p bar
Saturation temperature of steam (temperature of formation of steam)	ts C
Specific volume of dry saturated steam	vs m ³ /kg
Enthalpy of saturated water (reckoned above 0°C)	h kJ/kg
Enthalpy of evaporation of dry steam	L kJ/kg
Enthalpy of dry saturated steam (reckoned above 0°C)	Hs kJ/kg
Entropy of saturated water	Øw kJ/kg K
Entropy of dry saturated steam	Øs kJ/kg K

It is important to note that the data given in steam tables is for *dry saturated steam* only and therefore, the effect of dryness fraction (x) must be taken into account in the manner already explained. The enthalpy of wet steam and superheated steam can be calculated by using eqns. (3.6) and (3.8).

The properties of 1 kg of dry saturated steam at various absolute pressures are given in steam tables, at the end of this book.

Note : In this text, the pressures stated in bar, kPa and MPa will indicate absolute pressures. Gauge pressure will be indicated as gauge pressure or pressure gauge reading.

Problem-1 : Determine the dryness fraction of steam if 0.8 of water is in suspension with 45 kg of dry steam.

Mass of wet steam

= { mass of dry steam in certain mass of wet steam} + { mass of water in suspension in the same mass of wet steam}

= 45 + 0.8 = 45.8 kg.

Thus, in 45.8 kg of wet steam, the dry steam is 45 kg.

The dryness fraction of wet steam is the ratio of the mass of actual dry steam to the mass of wet steam containing it.

 \therefore Dryness fraction, x = 45/45.8 = 0.982

i.e. Steam is 98.2 per cent dry or 1.8 per cent wet.

Problem-2 : How much heat is needed to convert 1 kg of feed water at 20°C into dry saturated steam at 10 bar (1 MPa) ? Take specific heat of water as 4187 kJ/kg K.

From steam tables, at 10 bar, enthalpy of saturated water, h = 762.81 kJ/kg and enthalpy of evaporation, L = 2,015.3 kJ/kg.

Enthalpy of dry saturated steam at 10 bar (above 0°C), $H_s = h + L$

= 762.81 + 2,015.3 = 2,778.11 kJ/kg.

Enthalpy of 1 kg of feed water at 20°C above 0°C = $k(t_1 - 0)$

= 4.187 (20 - 0) = 83.74 kJ/kg.

.: Heat supplied to convert 1 kg of feed water at 20°C into dry saturated steam at 10 bar = enthalpy of dry saturated steam - enthalpy of feed water

 $= 2,778 \cdot 11 - 83 \cdot 74 = 2,694 \cdot 37 \text{ kJ/kg}.$

Problem-3 : How much heat is needed to convert 5 kg of water at 40°C into 90 per cent dry (or 10 per cent wet) steam at 5 bar (500 kPa) ? Take specific heat of water as 4.187 kJ/kg K.

From steam tables, at 5 bar, h = 640.23 kJ/kg and L = 2,108.5 kJ/kg.

Enthalpy of 1 kg of wet steam at 5 bar and 0.9 dry above 0°C,

 $H_{wei} = h + xL = 640.23 + 0.9 \times 2,108.5 = 2,537.88 \text{ kJ/kg}.$

Enthalpy of 1 kg of feed water at 40°C above 0°C

 $= k(t_1 - 0) = 4.187 (40 - 0) = 167.48 \text{ kJ/kg}.$

... Heat needed to convert 1 kg of feed water at 40°C into wet steam at 5 bar and

0.9 dry = Enthalpy of wet steam - Enthalpy of feed water

= 2,537.88 - 167.48 = 2,370.4 kJ/kg.

... Heat supplied to convert 5 kg of water at 40°C into steam at 5 bar and 0.9 dry

 $= 5 \times 2,370.4 = 11,852 \text{ kJ}.$

Problem-4 : How much heat is needed to convert 4 kg of water at 20°C into steam at 8 bar (800 kPa) and 200°C. Take k_p of superheated steam as 2.1 kJ/kg K and specific heat of water as 4.187 kJ/kg K.

From steam tables, at 8 bar, $t_s = 170.43$ °C, h = 721.11 kJ/kg and L = 2,048 kJ/kg. Since the temperature (200 °C) of given steam is more than saturation temperature, t_s (170.43 °C), the steam is superheated.

Degree of Superheat = $t_{sup} - t_s = 200 - 170.43 = 29.57$ °C.

Enthalpy of 1 kg of superheated steam (above 0°C),

 $H_{sup} = h + L + k_p (t_{sup} - t_s) = 721.11 + 2,048 + 2.1 (200 - 170.43)$ = 2.831.21 kJ/kg

Enthalpy of 1 kg of water above $0^{\circ}C = k(t_1 - 0) = 4.187(20 - 0) = 83.74 \text{ kJ/kg}$.

Heat needed to convert 1 kg of water at 20°C into superheated steam at 8 bar and 200°C = Enthalpy of superheated steam - Enthalpy of water

= 2,831.21 - 83.74 = 2,747.47 kJ/kg

... Heat needed to convert 4 kg of water into steam = 4 x 2,747.47 = 10,990 kJ.

Problem-5 : A boiler is supplied with feed water at a temperature of 44°C and converted into steam at a gauge pressure of 4493 bar and a temperature of 188°C. If 900 kg of steam is generated by the boiler in one hour, find the quantity of heat supplied per minute to feed water to produce steam assuming barometric pressure of 750 mm of Hg and k_p of superheated steam as 2.1 kJ/kg K.

Now, 760 mm of Hg = 1.01325 bar.

 $\therefore 750 \text{ mm of Hg} = \frac{1.01325 \times 750}{760} = 1.007 \text{ bar (barometric pressure)}$ Absolute pressure of steam = Boiler gauge pressure + Barometric pressure

= 4.493 + 1.007 = 5.5 bar.

Referring to steam tables, at 5.5 bar h = 655.93 kJ/kg, L = 2,097 kJ/kg and $t_s = 155.48$ °C. Since the temperature of given steam (188 °C) is more than the saturation . temperature (155.48 °C), the steam produced is superheated.

Enthalpy of 1 kg of feed water at 44°C above 0°C = $k(t_1 - 0)$

= 4.187 (44 - 0) = 184.23 kJ/kg.

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:. Enthalpy of (saturated) water = $h - k(t_1 - 0) = 655.93 - 184.23 = 471.7$ kJ/kg. Heat supplied/kg = $[h - k(t_1 - 0) + L + k_p(t_{sup} - t_s)]$

= 471.7 + 2.097 + 2.1 (188 - 155.48) = 2.636.99 kJ/kg

:. Heat supplied per min. = $\frac{900}{60}$ × 2,636.99 = 39,554.85 kJ/min.

Problem-6 : Find the volume of one kilogram of steam at a pressure of 15 bar (1.5 MPa) in each of the following cases :

(i) when steam is dry saturated,

(ii) when steam is wet having dryness fraction of 0.9, and

(iii) when steam is superheated, the degree of superheat being 40°C.

At 15 bar, $v_s = 0.13177 \text{ m}^3/\text{kg}$ and $t_s = 198.32^{\circ}\text{C}$ (from steam tables).

(i) When steam is dry saturated :

Specific volume (vs) of dry saturated steam at 15 bar is 0.13177 m3/kg.

(ii) When steam is wet, dryness fraction 0.9 :

Specific volume of wet steam of dryness fraction x, neglecting the volume of water $= xv_s \text{ m}^3/\text{kg}.$

.: Volume of wet steam at a pressure of 15 bar and 0.9 dry = xvs

 $= 0.9 \times 0.13177 = 0.1186 \text{ m}^3/\text{kg}$

(iii) When steam is superheated by 40°C :

Absolute temperature of saturated steam, $T_s = 198.32 + 273 = 471.32$ K Absolute temperature of superheated steam, $T_{sup} = 198.32 + 40 + 273 = 511.32$ K The specific volume of superheated steam is given by eqn. (3.9),

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0.13177 \times \frac{511.32}{471.32} = 0.1426 \text{ m}^3/\text{kg}.$$

Problem-7 : A closed vessel contains 1.2 m^3 of dry saturated steam at 14 bar (1.4 MPa). What is the temperature and mass of this steam ?

From steam tables, saturation temperature corresponding to 14 bar = $195 \cdot 7^{\circ}C$. Specific volume (v_s) at 14 bar = $0.14084 \text{ m}^3/\text{kg}$ (from steam tables).

 $\therefore \text{ Mass of steam} = \frac{\text{Volume of steam}}{\text{Specific volume of steam } (v_s)} = \frac{1.2}{0.14084} = 8.52 \text{ kg.}$

Problem-8 : Determine the condition of steam in each of the following cases :

(i) at a pressure of 10 bar and temperature 200°C,

(ii) at a pressure of 8 bar and volume 0.22 m3/kg, and

(iii) at a pressure of 12 bar, if 2,688 kJ/kg are required to produce it from water at 0°C.

(i) Saturation temperature (t_s) corresponding to pressure of 10 bar from steam tables is 179.91°C. Since the temperature of given steam is 200°C, the steam is superheated. Its degree of superheat, $t_{sup} - t_s = 200 - 179.91 = 20.09°C$.

(ii) Specific volume of dry saturated steam (v_s) at 8 bar is 0.2404 m³/kg. Since the volume of given steam (0.22 m³) is less than the specific volume of dry saturated steam, it is obvious that the steam with a volume of 0.22 m³/kg is wet.

:. Dryness fraction, x = 0.22/0.2404 = 0.915 i.e. 91.5% dry.

(iii) Enthalpy of dry saturated steam (H) at 12 bar from steam tables is 2,784.8 kJ/kg. Since the enthalpy of given steam(2,688 k l/kg) is less than the enthalpy of dry saturated steam, we conclude that the given steam is wet.

At 12 bar, h = 798.65 kJ/kg, L = 1,986.2 kJ/kg (from steam tables).

Using eqn. (3.6) for determining quality of steam, $H_{wet} = h + xL$

i.e. 2,688 = 798.65 + x 1,986.2

:. Dryness fraction of steam, $x = \frac{2,688 - 798.65}{1,986.2} = 0.9513$ i.e. 95.13% dry

Problem-9 : A boiler is supplying steam at a pressure of 9 bar and 90 percent dry. Find : (i) the mass of 5 m^3 of this steam, and (ii) the enthalpy per m^3 of this steam above 0°C.

(i) From steam tables, at 9 bar,

h = 742.83 kJ/kg, L = 2,031.1 kJ/kg, and $v_s = 0.215$ m³/kg. Mass of one m³ of wet steam $= \frac{1}{xv_s} = \frac{1}{0.9 \times 0.215} = 5.168$ kg

 \therefore Mass of 5 m³ of wet steam = 5 x 5.168 = 25.84 kg

(ii) Enthalpy of 1 kg of wet steam at a pressure of 9 bar and dryness fraction 0.9,

 $H_{wet} = h + xL = 742.83 + 0.9 \times 2,031.1 = 2,570.83 \text{ kJ/kg}$

:. Enthalpy of one m³ of wet steam = mass of steam \times (h + xL)

 $= 5.168 \times 2,570.83 = 13,286 \text{ kJ}.$

Problem-10 : Determine from steam tables the following :

(i) Enthalpy and volume of 1 kg of steam at 12.1 bar and dryness fraction 0.9, and

(ii) Enthalpy and volume of 1 kg of steam at 12.1 bar and 225°C.

Take the specific heat at constant pressure for superheated steam as 2.1 kJ/kg K.

By using steam tables and *interpolating* to find the values for a pressure of 12-1 bar, a table is constructed as shown below :

р bar	ts *C	h kJ/kg	L kJ/kg	H kJ/kg	v₅ m ³ /kg	
12.0	187-99	798-65	1986-2	2784-8	0.16333	from steam tables
12.2	188-74	801-98	1983-4	2785-4	0.16077	from steam tables
0.2	0.75	3.33	2.8	0.6	0.00256	for 0.2 bar
0.1	0.38	1.67	1.4	0.3	0.00128	for 0.1 bar
12.1	188-37	800-32	1984-8	2785-1	0.16205	by interpolating

(i) Enthalpy of 1 kg of steam at 12.1 bar and 0.9 dry,

 $H_{wet} = h + xL = 800.32 + 0.9 \times 1,984.8 = 2,463.52 \text{ kJ/kg}.$

Volume of 1 kg of steam at 12.1 bar and 0.9 dry

 $= x \times v_s = 0.9 \times 0.16205 = 0.14585 \text{ m}^3/\text{kg}$

(ii) Enthalpy of 1 kg of steam at 12.1 bar and 225°C,

 $H_{sup} = H + k_p(t_{sup} - t_s) = 2,785 \cdot 1 + 2 \cdot 1(225 - 188 \cdot 37) = 2,862 \cdot 02 \text{ kJ/kg}$ Using eqn. (3.9), volume of 1 kg of superheated steam at 12.1 bar and 225°C,

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0.16205 \times \frac{498}{461.37} = 0.1751 \text{ m}^3/\text{kg}.$$

Problem-11 : One kg of steam initially at 8 bar (800 kPa) and 0.7 dry, receives 410 kJ heat at constant pressure. Determine the enthalpy, condition, and density of steam at the end of constant pressure heat supply.

From steam tables, at 8 bar, h = 721.11 kJ/kg, L = 2,048 kJ/kg, $v_s = 0.2404$ m³/kg. Enthalpy initially, $H_1 = h_1 + x_1L_1 = 721.11 + 0.7 \times 2,048 = 2,154.71$ kJ/kg Enthalpy at the end of constant pressure process, $H_2 = 2,154.71 + 410 = 2,564.71$ kJ/kg Let the final condition of steam be x_2 . Then, $H_2 = h_2 + x_2L_2$

From which, $x_2 = \frac{H_2 - h_2}{L_2} = \frac{2,564 \cdot 71 - 721 \cdot 11}{2,048} = 0.9$ dry (final condition of steam)

Density of steam = $\frac{1}{x_2 v_s} = \frac{1}{0.9 \times 0.2404} = 4.62 \text{ kg/m}^3$.

Problem-12 : Two boilers A and B, are delivering steam in equal proportion to a common mains steam pipe, both at a pressure of 14 bar. Boiler A has a superheater and boiler B is without a superheater. The temperature of steam supplied by the boiler A is 300°C. The temperature of the resulting mixture of steam in the steam mains is 235°C. Assuming k_p for the superheated steam as 2.1 kJ/kg K, estimate the quality of steam supplied by the boiler by the boiler by the boiler by the boiler by the superheater, i.e., boiler B.

From steam tables, at 14 bar, L = 1,959.7 kJ/kg and $t_s = 195.07$ °C.

The wet steam from boiler B gains heat from the superheated steam produced by boiler A. As a result of which it (wet steam) becomes superheated. During the process of its mixing with superheated steam, first its moisture content is evaporated and then it is superheated. Let the dryness fraction of wet steam generated by boiler B be x.

Then, moisture in 1 kg of wet steam = (1 - x) kg. Heat required to evaporate this moisture and to make it dry = (1 - x)L kJ/kg.

Heat required to superheat this dry steam = $k_p(t_{sup2} - t_s)$ kJ/kg.

:. Heat gained by the wet steam of boiler $B = (1 - x)L + k_p(t_{sup2} - t_s) k_J/k_g$.

Heat lost by the superheated steam of boiler $A = k_p(t_{sup1} - t_{sup2})$

Heat gained by wet steam of boiler B = Heat lost by superheated steam of boiler A

i.e. $(1 - x) L + k_p(t_{sup2} - t_s) = k_p(t_{sup1} - t_{sup2})$

i.e. (1 - x) 1,959.7 + 2.1(235 - 195.07) = 2.1(300 - 235)

 $x = \frac{1,907.05}{1,959.7} = 0.9732$ i.e. 97.32 % dry (quality of steam supplied by boiler B)

Problem-13 : A boiler generates 1,400 kg of steam per hour at a pressure of 18 bar (1.8 MPa) and 0.95 dry. The steam after leaving the boiler stop valve, passes through a superheater where its temperature is raised to 305°C. If the feed water supplied to the

boiler is at 40°C, calculate : (a) the heat supplied to feed water per hour to produce wet steam, and (b) the percentage of the heat absorbed in the boiler and in the superheater. Take k_p of superheated steam as 2.3 kJ/kg K and specific heat of water as 4.187 kJ/kg K.

From steam tables, at 18 bar, H = 884.79 kJ/kg, L = 1,912.4 kJ/kg and $t_s = 207.15$ °C.

(a) Heat supplied to feed water to produce wet steam in the boiler per hour

 $= W_{s} [h - k(t_{1} - 0) + xL]$

 $= 1,400 [884.97 - (4.187 \times 40) + 0.95 \times 1,912.4] = 35,47,700 \text{ kJ/hr}.$

(b) The heat absorbed by superheater is utilized to remove the moisture content of wet steam and then to superheat the dry saturated steam from 207.15°C to 305°C.

Heat absorbed by the superheater per hour = $W_s [(1 - x)L + k_p(t_{sup} - t_s)]$

= 1,400 [(1 - 0.95) 1,912.4 + 2.3 (305 - 207.15)] = 4,48,950 kJ/hg.

Total heat absorbed per hour = 35,47,700 + 4,48,950 = 39,96,650 kJ/kg

Percentage of heat absorbed in boiler = $\frac{35,47,700}{39,96,650} \times 100 = 88.76$ %

Percentage of heat absorbed in superheater = $\frac{4,48,950}{39,96,650} \times 100 = 11.24 \%$

Problem-14: Wet steam of mass 2.5 kg and occupying a volume of 0.49 m³ at 7.5 bar has a total heat (enthalpy) increase of 1,500 kJ when superheated at constant pressure. Determine :

(i) Initial quality of steam,

(ii) Final quality (degree of superheat) of steam, and

(iii) Increase in volume of steam after superheating.

Assume kp for the superheated steam to be 2.1 kJ/kg K.

(i) From steam tables, at 7.5 bar,

 $h = 709.47 \text{ kJ/kg}, t_s = 167.78^{\circ}\text{C}, L = 2,057 \text{ kJ/kg}, v_s = 0.2556 \text{ m}^3/\text{kg}.$

Total volume of 2.5 kg of dry saturated steam = 2.5 x 0.2556 = 0.639 m³

As the volume of 2.5 kg of steam in data is given as 0.49 m³ at 7.5 bar (which is less than 0.639 m^3), the steam is wet.

.: Initial dryness fraction (quality) of steam = 0.49/0.639 = 0.767 i.e. 76.7 % dry.

(ii) 1,500 kJ of heat supplied (added) at constant pressure is utilized in evaporating the moisture content of wet steam and then superheating it. Let t_{sup} be the temperature of superheated steam. Then,

 $W_s [(1 - x)L + k_p(t_{sup} - t_s)] =$ Heat supplied to superheat 2.5 kg of wet steam

i.e. 2.5 $[(1 - 0.767) 2,057 + 2.1 (t_{sup} - 167.78)] = 1,500$

Solving the equation, tsup = 225.2°C.

 \therefore Degree of superheat = $t_{sup} - t_s = 225 \cdot 2 - 167 \cdot 78 = 57 \cdot 42^{\circ}C$ i.e. steam is superheated by 57 $\cdot 42^{\circ}C$.

(iii) Now, $T_s = 167.78 + 273 = 440.78$ K; and $T_{sup} = 225.2 + 273 = 498.2$ K

Let v_{sup} = Specific volume of superheated steam,

(specific volume of superheated steam is proportional to its absolute temperature) Then, volume of superheated steam is given by eqn. (3.9),

$$\therefore v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0.2556 \times \frac{498.2}{440.78} = 0.2891 \text{ m}^3/\text{kg}$$

... Total volume of 2.5 kg of superheated steam = 2.5 x0.2891

= 0.7228 m³ (final volume)

... Increase in volume of steam after superheating = 0.7228 - 0.49 = 0.2328 m³.

Problem-15 : Steam enters a steam engine at a pressure of 12 bar with 67°C of superheat and is exhausted at 0.15 bar and 0.94 dry. Calculate the drop in enthalpy from admission to exhaust, and volume of 1 kg of steam at admission and exhaust conditions. Take k_p of superheated steam as 2.1 kJ/kg K.

From steam tables, at 12 bar,

h = 798.65 kJ/kg, L = 1,986.2 kJ/kg, $t_s = 187.99$ °C and $v_s = 0.16333$ m³/kg. From stearn tables, at 0.15 bar,

h = 225.94 kJ/kg, L = 2,373.1 kJ/kg and $v_s = 10.022$ m³/kg.

Enthalpy of superheated steam at 12 bar (at admission),

 $H_{sup} = h + L + k_p \times degree of superheat$

= 798.65 + 1,986.2 + 2.1 (67) = 2,925.55 kJ/kg

Enthalpy of wet steam at 0.15 bar (at exhaust),

 $H_{wet} = h + xL = 225.94 + 0.94 \times 2,373.1 = 2,456.65 \text{ kJ/kg}.$

Hence, enthalpy difference (or drop) from admission to exhaust (during expansion)

 $= H_{sup} - H_{wet} = 2,925.55 - 2,456.65 = 468.9 \text{ kJ/kg}$

At 12 bar, $t_s = 187.99$ C, and $T_s = 187.99 + 273 = 460.99$ K,

 $t_{sup} = 187.99 + 67 = 254.99$ °C, and

 $T_{sup} = 254.99 + 273 = 527.99$ K.

Since, specific volume of steam is assumed to be proportional to its absolute temperature for approximate calculations. Using eqn. (3.9),

 $v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0.16333 \times \frac{527.99}{460.99} = 0.1871 \text{ m}^3/\text{kg} (at admission)$

Volume of wet steam (neglecting the volume of water) at 0.15 bar

 $= xv_s = 0.94 \times 10.022 = 9.421 \text{ m}^3/\text{kg}$ (at exhaust).

Problem-16 : A vessel having a capacity of $1 m^3$ contains steam at 10 bar and 0.92 dry. The steam is blown off from the vessel by opening the valve until the pressure drops to 5 bar. The valve is then closed and the vessel is cooled until the pressure is 4 bar. Assuming that the enthalpy per kg of steam in the vessel remains constant during the blowing off period, determine :

(a) the mass of steam blown off, (b) the dryness fraction of the steam in the vessel after cooling, and (c) the heat lost by the steam per kg during cooling.

From steam tables :

р bar	v₃ m³/kg	h kJ/kg	L kJ/kg
10	0.19444	762-81	2,015-3
5	0.3749	640-23	2,108-5
4	0.4625	604-74	2,133-8

(a) Before blowing-off, $p_1 = 10$ bar, v = 1 m³, $x_1 = 0.92$ and $v_{s1} = 0.19444$ m³.kg. Initial mass of steam in the vessel before blowing-off,

$$m_1 = \frac{1}{x_1 v_{s1}} = \frac{1}{0.92 \times 0.19444} = 5.642 \text{ kg}$$

After blowing of, $p_2 = 5$ bar, v = 1 m³ and $v_{s2} = 0.3749$ m³/kg. As given in the data,

Enthalpy before blowing off (at 10 bar) = Enthalpy after blowing off (at 5 bar)

i.e. $h_1 + x_1L_1 = h_2 + x_2L_2$

i.e. $762.81 + 0.92 \times 2,015.3 = 640.23 + x_2 \times 2,108.5$ $\therefore x_2 = 0.9373$ Final mass of steam in the vessel *after blowing-off*,

$$m_2 = \frac{1}{x_2 v_{s2}} = \frac{1}{0.9373 \times 0.3749} = 2.846 \text{ kg}$$

... Mass of steam blown off = $m_1 - m_2 = 5.642 - 2.846 = 2.796$ kg. (b) After cooling, $p_3 = 4$ bar, $v_{s3} = 0.4625$ m³/kg, and $m_3 = 2.846$ kg. Dryness fraction of steam in the vessel after cooling,

 $x_3 = \frac{1}{v_{s3} \times m_3} = \frac{1}{0.4625 \times 2.846} = 0.76$ or 76% dry

(c) Enthalpy before cooling, $H_2 = h_2 + x_2L_2$

= 640.23 + 0.9373 ×2,108.5 = 2,615.23 kJ/kg

Now, Enthalpy after cooling, $H_3 = h_3 + x_3 L_3$

= 604.74 + 0.76 × 2,133.8 = 2,226.43 kJ/kg

Enthalpy difference or heat lost per kg of steam during cooling,

 $H_2 - H_3 = 2,615 \cdot 23 - 2,226 \cdot 43 = 388 \cdot 8 \text{ kJ/kg}$

Problem-17 : Steam at a pressure of 6 bar (600 kPa) is passed into a tank containing water where it is condensed. Before the steam is introduced in the tank, the mass and temperature of water in the tank is 74 kg and 15°C respectively. The water equivalent of tank is one kg. Calculate the dryness fraction of steam as it enters the tank if 2.5 kg of steam is condensed in the tank and the resulting temperature of the mixture is 35°C. Assume no losses and specific heat of water as 4.187 kJ/kg K.

From steam tables, at 6 bar, h = 670.56 kJ/kg, and L = 2,086.3 kJ/kg.

Mass of steam condensed, $M_s = 2.5$; total mass of water, $M_w = 1 + 74 = 75$ kg. Assuming that all heat lost by steam is gained by water

i.e. Heat lost by steam = Heat gained by water

i.e. $M_s [h + xL - k \times t_2] = M_w \times k \times (t_2 - t_1)$

(where, t_2 = temp. of mixture, and t_1 = initial temp. of water)

i.e.
$$h + xL - k \times t_2 = \frac{M_w}{M_s} \times k \times (t_2 - t_1)$$

i.e. 670.56 + 2,086.3 $x - 4.187 \times 35 = \frac{75}{2.5} \times 4.187 \times (35 - 15)$

 $\therefore x = 0.95$ (dryness fraction of steam)

Problem-18 : Exhaust steam at a pressure of 0.5 bar and 0.8 dry enters a surface condenser. the water resulting from the condensation leaves the condenser at a temperature of 56°C. Assuming that all the heat lost by steam is taken up by the condensing water, find the heat removed from the steam per kg and also the mass of condensing water required per kg of steam, if the temperature rise of condensing water is 28°C. Take specific heat of water as 4.187 kJ/kg K.

From steam tables, at 0.5 bar, h = 340.49 kJ/kg and L = 2,305.4 kJ/kg.

Enthalpy of exhaust steam per kg as it enters the condenser

 $= h + xL = 340.49 + 0.8 \times 2,305.4 = 2,184.81 \text{ kJ/kg}$

Enthalpy of water formed by condensation of steam per kg

 $= 4.187 \times (56 - 0) = 234.47 \text{ kJ/kg}.$

... Heat removed by cooling or condensing water from 1 kg of exhaust steam in condenser or heat lost by 1 kg of exhaust steam = 2,184.81 - 234.47 = 1,950.34 kJ/kg

Each kg of condensing water removes (from data) 28 x 4.187 = 117.24 kJ

. Mass of condensing water required per kg of exhaust steam,

$$m_{\rm w} = \frac{1,950\cdot34}{117\cdot24} = 16\cdot63 \ \rm kg$$

Alternatively, assuming that all the heat lost by exhaust steam is gained by condensing water,

Heat lost by 1 kg of exhaust steam = Heat gained by m_W kg of condensing water

i.e. 1 $[(h + xL) - 56 \times 4.187] = m_w \times 28 \times 4.187$

i.e. 1 $[340.49 + (0.8 \times 2,305.4) - 234.47] = m_w \times 117.24$

 $\therefore m_w = \frac{1,950.34}{117.24} = 16.63 \text{ kg of water/kg of exhaust steam.}$

3.4 External Work Done during Evaporation

The enthalpy of evaporation (latent heat) absorbed by the steam during evaporation is utilized in two ways :

Firstly, in overcoming internal molecular resistance of water in changing its condition from water to steam and secondly, in overcoming the external resistance of the piston to its increasing volume during evaporation.

The first of these effects of enthalpy of evaporation (latent heat) is called *internal* work, because changes have been brought within the body itself, and the second is called *external work* because work has been done on the bodies external to itself. The first represents the energy stored in the steam and is known as *internal latent heat* and the second represents the energy which has passed out of the steam having been utilized

in doing work on the piston and is known as *external work of evaporation*. The value of enthalpy of evaporation (latent heat) = internal latent heat + external latent heat, can be directly obtained from the steam tables. In evaporating water to steam the volume increases from v_w to v_s (fig. 3-1) under a constant pressure p; external work is thus done and the energy for performing this work is obtained during the absorption of enthalpy of evaporation. This work is known as external work of evaporation.

External work done per kg of dry saturated steam

$$=\frac{10^{5} \times p \times (v_{s} - v_{w})}{10^{3}} \quad \text{kJ/kg} \qquad \dots (3.10)$$

where, p = absolute pressure of steam in bar, $v_s =$ volume of 1 kg of dry saturated steam in m³ at presure p, and $v_w =$ volume of 1 kg of water in m³.

It is sufficiently accurate to neglect the term v_w in eqn. (3.10) as at low pressure, the volume of h the steam it steam it forms.

The eqn. (3.10) may be written as

Work of evaporation of dry saturated steam =
$$\frac{10^5 p v_s}{10^3}$$
 kJ/kg ... (3.11)

If the steam is wet having a dryness fraction of x, the final volume of wet steam is xv, then

External work done per kg of wet steam =
$$\frac{10^5 p (xv_s)}{10^3}$$
 kJ/kg ... (3.12)

External work done per kg of superheated steam = $\frac{10^5 p v_{sup}}{10^3}$ kJ/kg

The above expressions for external work of evaporation give the portion of latent heat which has been transformed into mechanical work or represent the heat energy which has passed out of the steam. The remainder of the heat energy supplied remains as internal energy or energy stored in the steam and is known as *internal latent heat*. It is found by subtracting the external work of evaporation from the full latent heat.

i.e. Internal latent heat =
$$L - \frac{10^5 p v_s}{10^3}$$
 kJ/kg (for dry saturated steam) ... (3.13)

For wet steam having dryness fraction x,

Internal latent heat =
$$xL - \frac{10^5 p(xv_s)}{10^3}$$
 kJ/kg ...(3.14)

where p = absolute pressure in bar, v_s = volume of 1 kg of dry saturated steam in m^3 at pressure p, x = dryness fraction of steam, and L = enthalpy of evaporation in kJ/kg.

3.5 Internal Engery of steam

The internal energy of steam is the actual heat energy above the freezing point of water stored in the steam, and is the sum of internal latent enthalpy and sensible enthalpy reckoned from 0°C. It has already been shown that the latent enthalpy of steam consists of the internal latent enthalpy plus the external work of evaporation; hence the total

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enthalpy of steam consists of the sensible enthalpy, plus the internal latent enthalpy and the external work of evaporation. But the external work of evaporation is utilized in doing external work and represents the heat energy which has passed out of the steam. Hence, the internal energy of steam denoted by symbol *u* consists of two terms only, namely, the internal latent enthalpy and the sensible enthalpy.

Thus, internal energy is found by substracting external work of evaporation from the enthalpy of steam.

If the steam is dry saturated, Enthalpy, $H_s = h + L kJ/kg$, and

Internal energy,
$$u = H_s - \frac{10^5 p v_s}{10^3}$$
 kJ/kg ... (3.15)

If the steam is wet having dryness fraction x, Enthalpy, $H_{wet} = h + xL kJ/kg$, and

Internal energy,
$$u = H_{wet} - \frac{10^5 p (xv_s)}{10^3}$$
 kJ/kg ... (3.16)

If the steam is superheated to temperature t_{sup} and volume v_{sup} m³ per kg,

Enthalpy of superheated steam, $H_{sup} = H_s + k_p (t_{sup} - t_s) kJ/kg$, and

Internal energy,
$$u = H_{sup} - \frac{10^{9} p v_{sup}}{10^{3}}$$
 kJ/kg
= $H_{sup} - \frac{10^{5} p \left(v_{s} \frac{t_{sup} + 273}{t_{s} + 273} \right)}{10^{3}}$ kJ/kg

Problem-19 : Find the external work done during evaporation, internal latent enthalpy and internal energy per kg of steam at a pressure of 15 bar (1,500 kPa) when the steam is (i) 0.9 dry, and (ii) dry saturated.

(i) For wet steam (0.9 dry):

From steam tables, at 15 bar,

 $h = 844.89 \text{ kJ/kg}; L = 1,947.3 \text{ kJ/kg}; H_s = 2,792.2 \text{ kJ/kg}; v_s = 0.13177 \text{ m}^3/\text{kg}.$ Specific volume of wet steam neglecting the volume of water,

 $= xv_{s} = 0.9 \times 0.13177 \text{ m}^{3}/\text{kg}$

External work done during evaporation per kg of steam

$$= \frac{10^{5} p(x v_{s})}{1.000} = \frac{10^{5} \times 15(0.9 \times 0.13177)}{1.000} = 177.89 \text{ kJ/kg}.$$

Internal latent enthalpy

= enthalpy of evaporation - heat absorbed in doing work of formation of steam

$$= xL - \frac{10^{9} p(x v_{s})}{1,000} = (0.9 \times 1,947.3) - 177.89 = 1,574.68 \text{ kJ/kg}.$$

Enthalpy of wet steam, $H_{wet} = h + xL = 844.89 + 0.9 \times 1,947.3 = 2,597.46$ kJ/kg. Using eqn. (3.16), internal energy, u

= Enthalpy of 1 kg of wet steam-External work of evaporation

:
$$u = H_{wet} - \frac{10^9 p(x v_s)}{1,000} = 2,597.46 - 177.89 = 2,419.57 \text{ kJ/kg}$$

(ii) For dry saturated steam :

External work done during evaporation per kg of dry saturated steam

$$= \frac{10^{5} p \times v_{s}}{1,000} = \frac{10^{5} \times 15 \times 0.13177}{1,000} = 197.66 \text{ kJ/kg}$$

Internal latent enthalpy = $L - \frac{10^5 p \times v_s}{1,000} = 1,947.3 - 197.66 = 1,749.64 \text{ kJ/kg}$

Internal energy, $u = H_s - \frac{10^5 p \times v_s}{1,000} = 2,792 \cdot 2 - 197 \cdot 66 = 2,594 \cdot 54 \text{ kJ/kg}.$

Problem-20 : 0.025 m³ of steam at 3.5 bar and dryness fraction 0.8 is converted into dry saturated steam at 11 bar. By how much are the enthalpy and internal energy changed ?

From steam tables :

р bar	h kJ/kg	L kJ/kg	H kJ/kg	v₃ m³/kg
3.5	584-33	2,148-1	L. June	0.5243
11		i i i i i i i i i i i i i i i i i i i	2,781.7	0.17753

Volume of one kg of wet steam (at 3.5 bar and 0.8 dry) = xv_s = 0.8 × 0.5243 = 0.41944 m³/kg,

... Mass of 0.025 m³ of steam (at 3.5 bar and 0.8 dry) = 0.025/0.41944 = 0.0597 kg Enthalpy of one kg of wet steam (at 3.5 bar and 0.8 dry), $H_{wet} = h + xL$ = 584.33 + 0.8 × 2,148.1 = 2,302.81 kJ/kg.

... Enthalpy of 0.0597 kg of wet steam (at 3.5 bar and 0.8 dry), Hwet = 0.0597 × 2,302.81 = 137.48 kJ

Enthalpy of 0.0597 kg of dry saturated steam (at 11 bar), H_s = 0.0597 × 2,781.7 = 166.07 kJ

:. Change in Enthalpy = 166.07 - 137.48 = 28.59 kJUsing eqn. (3.16), initial internal energy of 0.025 m³ of steam at 3.5 bar and 0.8 dry,

$$u_1 = H_{wet} - \frac{10^5 pv}{10^3} = 137.48 - \frac{10^5 \times 3.5 \times 0.025}{10^3} = 128.73 \text{ kJ}$$

Using eqn. (3.15), final internal energy of dry saturated steam at 11 bar,

$$u_2 = H_s - \frac{10^5 pv}{10^3} = 166.07 - \frac{10^5 \times 11 \times (0.0579 \times 0.17753)}{10^3} = 154.41 \text{ kJ}$$

... Change in internal energy, u2 - u1 = 154.41 - 128.73 = 25.68 kJ

Problem-21 : The internal energy of 1 kg of steam at a pressure of 14 bar (1.4 MPa) is 2,420 kJ. Calculate the dryness fraction of this steam. Find the increase in internal energy if this steam is superheated at constant pressure to a temperature of 295°C. Take k_p of superheated steam as 2.3 kJ/kg K.
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From steam tables, at 14 bar,

 $h = 830.3 \text{ kJ/kg}, L = 1,959.7 \text{ kJ/kg}, v_s = 0.14084 \text{ m}^3/\text{kg}$ and $t_s = 195.07^{\circ}\text{C}$. Internal energy of 1 kg of wet steam,

1.000

 $u_1 = H_{wet} - External work done during evaporation$

$$= (h + xL) - \frac{10^5 p(xv_s)}{1,000}$$

i.e. 2,420 = $(830.3 + 1,959.7 x) - \frac{10^5 \times 14 (x \times 0.14084)}{1,000}$

i.e. 2,420 = (830.3 + 1,959.7x) - 197.18 x

$$\therefore x = \frac{2,420 - 830 \cdot 3}{1,959 \cdot 7 - 197 \cdot 18} = 0.9 \text{ (dryness fraction)}$$

Using eqn. (3.17), Internal engery of 1 kg of superheated steam,

$$u_{2} = \{h + L + k_{p} (t_{sup} - t_{s}) - \left\{ \frac{10^{5} p \left(v_{s} \times \frac{t_{sup} + 273}{t_{s} + 273} \right)}{1,000} \right\}$$
$$= \{830.3 + 1,959.7 + 2.3 (295 - 195.07)\} - \left\{ \frac{10^{5} \times 14 \times \left(0.14084 \times \frac{295 + 273}{195.07 + 273} \right)}{1,000} \right\}$$

= 3,020 - 239.2 = 2,780.8 kJ/kg

Increase in internal energy, u2 - u1 = 2,780.8 - 2,420 = 360.8 kJ/kg

Problem-22 : What fraction of enthalpy of 1 kg of steam at 10 bar and 0.9 dry represents the internal energy ? What is the change in internal energy when the pressure and temperature of this steam is raised to 13 bar and 250°C ? Take kp of superheated steam as 2.1 kJ/kg K.

For wet steam at 10 bar and 0.9 dry :

From steam tables, at 10 bar,

h = 762.81 kJ/kg, L = 2,015.3 kJ/kg and $v_s = 0.19444$ m³/kg.

Enthalpy of 1 kg of wet steam (at 10 bar and 0.9 dry), $H_{wet} = h + xL$ = 762.81 + 0.9 × 2,015.3 = 2,576.58 kJ/kg

External work done during evaporation = 10^{3}

$$= \frac{10^5 \times 10(0.9 \times 0.19444)}{10^3} = 175 \text{ kJ/kg}$$

Internal energy, u1 = Enthalpy - External work done during evaporation = 2,576.58 - 175 = 2,401.58 kJ/kg

 \therefore Required fraction of enthalpy = $\frac{2,401\cdot58}{2,576\cdot58} = 0.9324$

For superheated steam at 13 bar and 250°C :

At 13 bar (from steam tables), $v_s = 0.15125 \text{ m}^3/\text{kg}$, $H_s = 2,787.6 \text{ kJ/kg}$,

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 $t_s = 191.64$ °C or $T_s = 191.64 + 273 = 464.64$ K;

 $t_{sup} = 250^{\circ}C$, or $T_{sup} = 250 + 273 = 523$ K.

Enthalpy of 1 kg of superheated steam (at 13 bar and at 250°C),

 $H_{sup} = H_s + k_p (t_{sup} - t_s) = 2,787.6 + 2.1 (250 - 191.64) = 2,910.16 kJ/kg$ Using eqn. (3.9), volume of 1 kg of superheated steam,

$$v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0.15125 \times \frac{523}{464.64} = 0.1702 \text{ m}^3/\text{kg}$$

External work done during evaporation

$$= \frac{10^{3} \times p \times v_{sup}}{10^{3}} = \frac{10^{5} \times 13 \times 0.1702}{10^{3}} = 221.26 \text{ kJ/kg}$$

Internal energy, u₂ = Enthalpy - External work done during evaporation

= 2,910.16 - 221.26 = 2,688.9 kJ/kg

: Change in internal energy = $u_2 - u_1 = 2,688.9 - 2,401.58 = 287.32 \text{ kJ/kg}$.

Problem-23 : A certain quantity of steam in a closed vessel of fixed volume of 0.14 m³ exerts a pressure of 10 bar at 250°C. If the vessel is cooled so that the pressure falls to 3.6 bar, determine : (a) the final quality of steam, (b) the final temperature, (c) the change in internal energy, and (d) the heat transferred during the process. Take k_p for superheated steam as 2.1 kJ/kg K.

(a) From steam tables, at 10 bar,

$$t_s = 179.91$$
 C, $v_s = 0.19444$ m⁻/kg, $H_s = 2.778.1$ kJ/kg
Given steam is superheated with $t_{sup} = 250$ C, or $T_{sup} = 250 + 273$ K
nitial enthalpy of superheated steam,

$$H_1 = H_{sup} = H_s + k_p (t_{sup} - t_s) = 2,778 \cdot 1 + 2 \cdot 1 (250 - 179 \cdot 91)$$

= 2.925 \cdot 29 kJ/kg

$$v_1 = v_{sup} = v_s \times \frac{T_{sup}}{T_s} = 0.19444 \times \frac{250 + 273}{179.91 + 273} = 0.2246 \text{ m}^3/\text{kg}$$

 m_s = mass of steam = $\frac{\text{Volume of steam}}{\text{Sp. volume of steam}} = \frac{0.14}{0.2246} = 0.6233 \text{ kg.}$

Initial internal energy, $u_1 = m_s \left(H_1 - \frac{10^5 p_1 v_1}{10^3}\right)$

$$= 0.6233 (2,925.29 - \frac{10^5 \times 10 \times 0.2246}{10^3})$$

= 0.6233 (2,925.29 - 224.6) = 1,683.34 kJ

At 3.6 bar, $t_s = 139.87$ °C, $v_s = 0.5106$ m³/kg. h = 588.59 kJ/kg, L = 2145.1 kJ/kg. If steam is dry saturated at 3.6 bar, its volume

= $m_s \times \text{specific volume of dry saturated steam} = 0.6233 \times 0.5106 = 0.3183 \text{ m}^3$ But the volume of steam is equal to the volume of vessel, i.e. 0.14 m³. Therefore, steam is wet with dryness fraction, $x_2 = \frac{0.14}{0.3183} = 0.44$

Thus, finally steam is wet having dryness fraction of 0.44.

(b) As steam is wet at 3.6 bar, its temperature is equal to saturation temperature corresponding to this pressure, i.e. 139.87°C (from steam tables).

(c) Enthalpy at final state, $H_2 = h_2 + x_2L_2 = 588 \cdot 59 + 0.44 \times 2,145 \cdot 1 = 1,502 \cdot 43$ kJ/kg and $v_1 = v_2 = 0.2246$ m³/kg.

Final internal energy,
$$u_2 = m_s \left(H_2 - \frac{10^5 p_2 v_2}{10^3}\right)$$

= 0.6233 $\left(1,502.43 - \frac{10^5 \times 3.6 \times 0.2246}{10^3}\right)$ = 885.82 kJ

Change in internal energy = $u_2 - u_1 = 885.82 - 1,683.34 = -797.52$ kJ.

(d) As this is a constant volume process, the work done is zero and hence, heat transferred is equal to change in internal energy, i.e., -797.52 kJ.

3.6 Summary of Formulae

Following are the important formulae derived in this chapter : Enthalpy of 1 kg of wet steam, $H_{wet} = h + xL$ kJ Enthalpy of 1 kg of dry saturated steam, $H_s = h + L$ kJ Enthalpy of 1 kg of superheated steam, $H_{sup} = H_s + k_p (t_{sup} - t_s)$ kJ Volume of 1 kg of dry saturated steam = v_s m³

Volume of 1 kg of wet steam = xvs m³

Volume of 1 kg of superheated steam, $v_{sup} = v_s \times \frac{T_{sup}}{T_s} m^3$ eqn. (3.9)

External work done per kg of dry saturated steam = $\frac{10^5 pv_s}{10^3}$ kJ eqn. (3.11)

External work done per kg of wet steam = $\frac{10^5 p(xv_s)}{10^3}$ kJ eqn. (3.12)

External work done per kg of superheated steam = $\frac{10^5 pv_{sup}}{10^3}$ kJ

nternal latent enthalpy per kg of dry saturated steam = $L - \frac{10^9 pv_s}{10^3}$ kJ		eqn. (3·13)
	10	

Internal latent enthalpy per kg of wet steam =
$$xL - \frac{10^5 p (xv_s)}{10^3}$$
 kJ eqn. (3.14)

Internal energy of 1 kg of dry saturated steam =
$$H_s - \frac{10^5 pv_s}{10^3}$$
 kJ eqn. (3.15)

Internal energy of 1 kg of wet steam =
$$H_{wet} - \frac{10^5 p(xv_s)}{10^3}$$
 kJ eqn. (3-16)

Internal energy of 1 kg of superheated steam =
$$H_{sup} - \frac{10^5 p v_{sup}}{10^3}$$
 kJ eqn. (3.17)

Tutorial - 3

1. What are phases of a substance ? Explain the importance of vapour as a working medium in thermal engineering.

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2. Explain the following terms :

- (i) Saturated steam, (ii) Dry saturated steam, (iii) Wet steam, (iv) superheated steam, (v) Dryness fraction of steam, (vi) Specific volume of steam, and (vii) Saturated water.
- 3. Explain the term dryness fraction of stteam.

Determine the dryness fraction of steam if 0.6 kilogram of water is in suspension with 24 kilograms of dry steam.

- 4.(a) Explain the following terms as referred to steam :
 - (i) Enthalpy of water. (ii) Enthalpy of evaporation, (iii) Superheat, (iv) Specific volume, and (v) Enthalpy of dry saturated steam.
 - (b) Determine from steam tables the enthalpy of one kg of steam above 0°C :

(i) at a pressure of 10 bar and 0.9 dry, and

(ii) at a pressure of 15 bar and with 140°C of superheat.

Take specific heat at constant pressure of superheated steam as 2-1 kJ/kg K.

[(i) 2,576.58 kJ; (ii) 3,086.2 kJ]

- 5. (a) Differentiate between saturated steam and dry saturated steam.
 - (b) Estimate the amount of heat needed to convert 5 kg of water at 50°C into steam at a pressure of 9 bar and with 110°C of superheat. Take specific heat at constant pressure for superheated steam as 2.1 kJ/kg K and specific heat of water as 4-187 kJ/kg K.

[13,978 kJ]

- 6. (a) How much heat is needed to convert one kg of feed water at 20°C into dry saturated steam at a pressure of 9 bar ? Take specific heat of water as 4-187 kJ/kg K.
 - (b) How much heat is needed to convert 5 kg of water at 45°C into steam at pressure of 4 bar and 80 per cent dry. Take specific heat of water as 4-187 kJ/kg K.

[(a) 2,690 19 kJ; (b) 10,616 8 kJ]

- 7. What information can be found in steam tables ? What is the effect of increase in pressure on saturation temperature, enthalpy of saturated water, enthalpy of evaporation and enthalpy of dry saturated steam.
- 8. (a) What is meant by critical point ? What are critical parameters of H20 ?
 - (b) Find the heat required to produce 0.9 kg of steam at 7 bar and 240°C from water at 28°C. Take kp of superheated steam as 2.26 kJ/kg K and specific heat of water as 4.187 kJ/kg K.

[(b) 2,534.27 kJ]

9. Temperature of feed water entering a boiler is 50 °C and the pressure of steam in the boiler is 13 bar. How much heat will be required to produce one kilogram of steam if the steam produced is (a) 0.97 dry, (b) dry saturated, and (c) superheated with 40°C of superheat ? Take the specific heat at constant pressure for superheated steam as 2-1 kJ/kgK and specific heat of water as 4-187 kJ/kg K.

[(a) 2,519.1 kJ; (b) 2,578.28 kJ; (c) 2,662.25 kJ]

10. Distinguish clearly between the various qualities of steam.

Find the heat required to convert one kilogram of steam at 8 bar and 80 per cent dry into steam at 8 bar and 200°C. Assume kp for superheated steam as 2.1 kJ/kg K.

[471.74 kJ]

11. A boiler is supplied with feed water at 65°C and produces steam at 17 bar and 260°C. If 75% of the heat of the coal of calorific value of 29,300 kJ/kg is utilised in producing steam, calculate the mass of coal consumed in producing 5,000 kg of steam per hour. Take specific heat at constant pressure for superheated steam as 2.1 kJ/kg K.

[600-8 kg]

12. find the volume of one kilogram of steam at a pressure of 10 bar in each of the following cases : (i) when the steam is dry saturated, (ii) when the steam is wet, having a dryness fraction of 0.8 (neglecting the volume of water), and (iii) when the steam is superheated and temperature of steam is 240°C. Take specific heat at constant pressure for superheated steam as 2.1 kJ/kg K.

[(i) 0.19444 m³/kg; (ii) 0.15555 m³/kg; (iii) 0.2202 m³/kg]

13. Calculate the specific volume of superheated steam at 11 bar and 250°C, treating the superheated steam as a perfect gas. Take kp for superheated steam = 2.1 kJ/kg K.

[0.2031 m3/kg]

14. Find the volume of one kg of steam at a pressure of 9.8 bar (980 kPa) in each of the following cases : (i) when the steam is dry saturated,

[0.976]

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(ii) when the steam is wet, having a dryness fraction of 0.8, and

(iii) when the steam is superheated and the temperature of steam is 240°C.

Take specific heat at constant pressure of superheated steam as 2.1 kJ/kg K.

[(i) 0.1982 m³/kg; (ii) 0.15856 m³/kg; (iii) 0.22496 m³/kg]

15. Use the steam tables to find the following :

(a) Enthalpy and volume per kg of steam of dryness fraction 0.85 at a pressure of 8.5 bar.

- (b) Enthalpy and volume per kg of steam at 16 bar and at 230°C. Take specific heat at constant pressure for superheated steam as 2.1 kJ/kg K.
- (c) Dryness fraction of steam at 4.5 bar having enthalpy of 2,580 kJ/kg.
- (d) Density of 1 kg of steam at 7 bar, having a dryness fraction of 0.9.
- (e) Enthalpy of one cubic metre of steam at 9 bar and 0.9 dry.

[(a) 2,465-71 kJ/kg, 0.193 m³/kg; (b) 2,854 kJ/kg, 0.1312 m³/kg; (c) 0.923; (d) 4.071 kg/m³; (e) 13,280 kJ]

16. Determine the condition of steam in each of the following cases :

(a) at a pressure of 10 bar, if 2,640 kJ/kg are required to produce it from water at 0°C.

- (b) at a pressure of 8 bar and temperature 200°C, and
- (c) at a pressure of 12 bar and volume 0.144 m³/kg.

[(a) wet, dryness fraction 0.9313; (b) superheated by 29.57°C; (c) wet, dryness fraction 0.8816] 17. (a) What is meant by saturation temperature ? Differentiate between saturated water and dry saturated steam.

(b) Determine the condition of steam in each of the following cases :

(i) At a pressure of 10 bar (1 MPa) and temperature 200°C,

(ii) At a pressure of 8 bar and volume 0.22 m³/kg, and

(iii) At a pressure of 12 bar, if 2,688 kJ/kg are required to produce it from water at 0°C.

[(i) steam is superheated by 20.09°C; (ii) wet, 91.5% dry; (iii) wet, 95.15% dry] 18. Use the steam tables and find the following :

(i) Dryness fraction of steam at a pressure of 5 bar (500 kPa) having enthalpy of 2,500 kJ/kg.

(ii) Density of 1 kg of steam at a pressure of 6 bar, having a dryness fraction of 0.8.

(iii) Enthalpy and volume per kg of steam at a temperature of 250°C and at a pressure of 15 bar. Take kp of superheated steam as 2.1 kJ/kg K.

(iv) Enthalpy and volume per kg of steam at a pressure of 9 bar and 0.9 dry.

[(i) 0.882 dry; (ii) 3.96 kg/m³; (iii) 2,900.72 kJ/kg, 0.14626 m³/kg; (iv) 2,573.81 kJ/kg, 0.1935 m³/kg] 19. (a) A closed vessel contains 0.9 m³ of dry saturated steam at a pressure of 7.5 bar. How many kg of steam does the

vessel contain ?

- (b) A closed vesse! rontains 1.5 m³ of dry saturated steam at 12 bar. What is the temperature and mass of this steam ? [(a) 3.521 kg; (b) 187.99°C, 9.184 kg]
- 20. (a) A boiler supplies steam at a pressure of 11 bar and 0.8 dry. Find the mass of 0.5m³ of this steam and its enthalpy per cubic metre above 0°C.

(b) A closed drum of 0.15 m³ capacity contains 1.25 kg of wet steam at a pressure of 10 bar. Find the quality of steam. [(a) 3.52 kg, 16,770 kJ; (b) 0.617 dry]

21. Two boilers discharge equal amount of steam into the main steam pipe. The steam from one is at a pressure of 14 bar and temperature of 290°C and from the other at the same pressure and 92% dry. What is the resulting condition of the steam after mixing? Take k₀ of superheated steam as 2.1 kJ/kg K.

[superheated by 10.13°C]

22. A tank containing 180 kg of water of 16°C is to be heated to 66°C by blowing dry saturated steam at 2 bar into the tank. Find the mass of steam that should enter the tank to heat the water to the required temperature. Assume no losses. Take specific heat of water as 4-187 kJ/kg K.

[13.92 kg]

23. Dry saturated steam enters a surface condenser at a pressure of 1.1 bar and the condensate leaves at 85°C. The cooling water enters at 15°C and leaves at 60°C. Find the amount of cooling water required to condense 1 kg of steam. Assume that all the heat lost by steam is taken up by the cooling water. Take specific heat of water as 4.187 k J/kg K.

[12-31 kg]

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24. Exhaust steam at a pressure of 0.5 bar (50 kPa) and 0.8 dry enters a surface condenser. The water resulting from the condensation leaves the condenser at a temperature of 56°C. Assuming that all heat lost by steam is taken up by condensing water, find the mass of condensing water required per kg of steam, if the temperature rise of condensing water is 28°C. Take specific heat of water as 4.187 kJ/kg K.

[16-63 kg]

25. Steam is exhausted from a steam engine into a condenser at the rate of 5 kg/min. The pressure inside the condenser is 0.15 bar. The steam from the condenser leaves as water at 40°C. Cooling water is circulated through the condenser tubes at the rate of 115 kg/min. with a rise in temperature from inlet to outlet of 20°C. Calculate the dryness fraction of the steam entering the condenser. Take specific heat of water as 4.187 kJ/kg K.

[0.7954 dry]

26. (a) Explain the following terms as applied to steam :

(i) Internal latent heat, (ii) External work of evaporation, and (iii) Internal energy.

- (b) Find the external work of evaporation, internal latent heat and internal energy of one kg of steam at a pressure of 12 bar (1-2 MPa) :
 - (i) when the steam is dry saturated, and (ii) when the steam is 0.8 dry.
 - [(i) 196 kJ/ig, 1,790.2 kJ/kg, 2,588 kJ/kg; (ii) 156.8 kJ/kg, 1,432.16 kJ/kg, 2,230.81 kJ/kg]
- 27. Calculate the internal energy of 1 kg of steam at a pressure of 8 bar (800 kPa) : (a) when the steam is dry saturated, (b) when the steam is 0.8 dry, and (c) when the steam is superheated and temperature of steam is 270°C. Take specific heat of superheated steam at constant pressure as 2.2 kJ/kg K.

[(a) 2,576 79 kJ/kg; (b) 2,205 65 kJ/kg; (c) 2,752 56 kJ/kg]

28. Distinguish clearly between enthalpy and internal energy of steam.

1 kg of steam at 10 bar occupies a volume of 0.18 m³. Determine the condition of steam, and the enthalpy and internal energy of steam.

[0.9258 dry; 2,627.81 kJ; 2,447.81 kJ]

- 29. Use the steam tables to calculate the following :
 - (a) The internal energy of 1 kg of steam of dryness fraction 0.85, at a pressure of 6 bar.
 - (b) The internal energy of 1 kg of steam at 10 bar and temperature 200°C. Take kp of superheated steam as 2.1 kJ/kg K.
 - (c) Internal energy of 0.125 m³ of steam at 12 bar and dryness fraction 0.75.

[(a) 2,282.94 kJ; (b) 2,617.09 kJ; (c) 2,184.13 kJ]

30. The internal energy of 1 kg of steam at 10 bar is 2,400 kJ. Calculate the dryness fraction of this steam. Also find the increase in internal energy when the above steam is superheated at constant pressure to a temperature of 250°C. Take kp of superheated steam as 2.1 kJ/kg K.

[0-899 dry, 300-92 kJ/kg]

- 31. (a) Find the external work of evaporation and internal energy of 1 kg of steam at a temperature of 200°C and at a pressure of 10 bar (1 MPa). Take kp of superheated steam as 2·1 kJ/kg K.
 - (b) What fraction of enthalpy of 1 kg of steam at a temperature of 200°C and at a pressure of 10 bar represents the internal energy ?

[(a) 203 kJ/kg, 2,617.3 kJ/kg; (b) 0.929]

32. A certain quantity of steam in a closed vessel of fixed volume of 0.3 m³ exerts a pressure of 15 bar at 280°C. If the vessel is cooled so that the pressure falls to 10 bar, determine : (a) the final temperature , (b) the final quality of steam, (c) the change in internal energy, and (d) the heat transferred during the process. Take k_p for superheated steam = 2.1 kJ/kg K.

[(a) 179.91°C; (b) 0.7953 dry; (c) - 1,010 kJ; (d) - 1,010 kJ]