ENGINEERING THERMODYNAMICS

2nd Year B. Tech I- sem, Mechanical Engineering

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COURSE OBJECTIVES

UNIT - 1	CO1:To understand the concepts of energy transformation, conversion of heat into work.
UNIT - 2	CO2:To acquire knowledge about the fundamentals of thermodynamic laws, the concept of entropy, and principles
UNIT - 3	CO3: To understand how the change of state results in a process.
UNIT - 4	CO4: To understand the various gas laws, psychrometric properties and chart.
UNIT - 5	CO5: To learn the importance of thermodynamic cycles, and the derivation of efficiency.

UNIT 1

BASICS OF THERMODYNAMICS

CO1: **To understand the concepts of energy transformation, conversion of heat into work.**

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UNIT – I (SYLLABUS)

Introduction - System - Types of Systems

- System - Types of Systems - Control Volume - Macroscopic and Microscopic viewpoints
- Thermodynamic Equilibrium- State, Property, Process, Cycle
- Reversibility – Quasi static Process, Irreversible Process,

First law of Thermodynamics

- PMM I - Joule’s Experiment
- First law applied to a Process
- Steady Flow Energy Equation.

COURSE OUTLINE

UNIT -1

LECTURE	LECTURE TOPIC	KEY ELEMENTS	Learning objectives (2 to 3 objectives)
1	Basic Concepts – Types of systems	Definition of system.	Understanding of basics of systems (B2)
2	Macroscopic and Microscopic viewpoints	Study or view points	• Statistical thermodynamics (B2)
3	**Thermodynamic Equilibrium- State, Property, Process, Cycle**	**Intensive properties**	**Understanding of properties, process and cycle (B2)**
4	**Reversibility – Quasi static Process, Irreversible Process, Causes of Irreversibility**	**Reversible process and irreversible processes**	**Understanding of reversibility (B2)**
5	Work and Heat, Point and Path functions	Differences between heat and work	Knowledge on heat and work (B4)
6	**Zeroth Law of Thermodynamics – Principles of Thermometry**	**Principle of zeroth law**	**Measurement of temperature (B1)**
7	**PMM I - Joule's Experiment – First law of Thermodynamics**	**Conversion of Heat and work**	**Efficiency calculation (B4)**
8	**Steady Flow Energy Equation.**	**Continuity system**	**Knowledge of Nozzle, turbine, boiler etc (B2)**

LECTURE 1

Introduction - Types of systems

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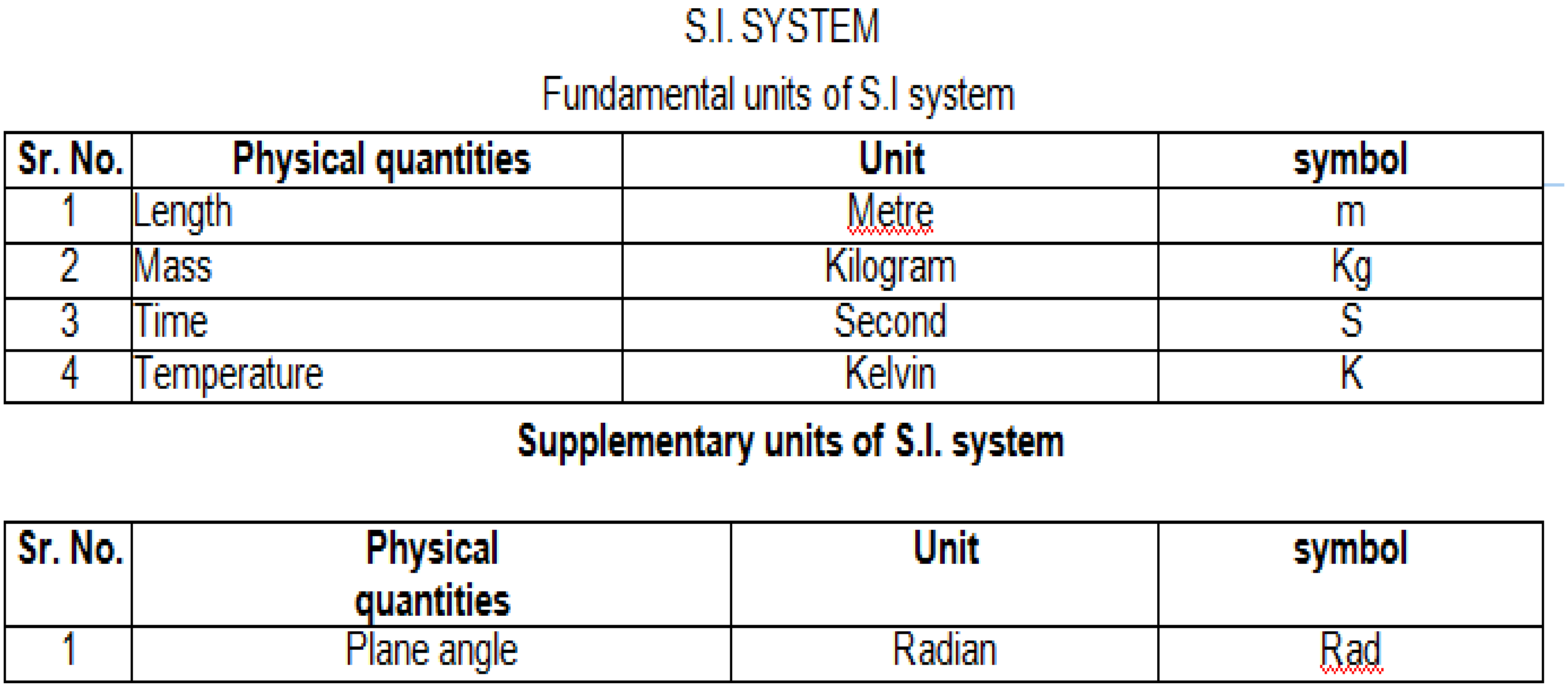
INTRODUCTION: UNITS



S.I. SYSTEM

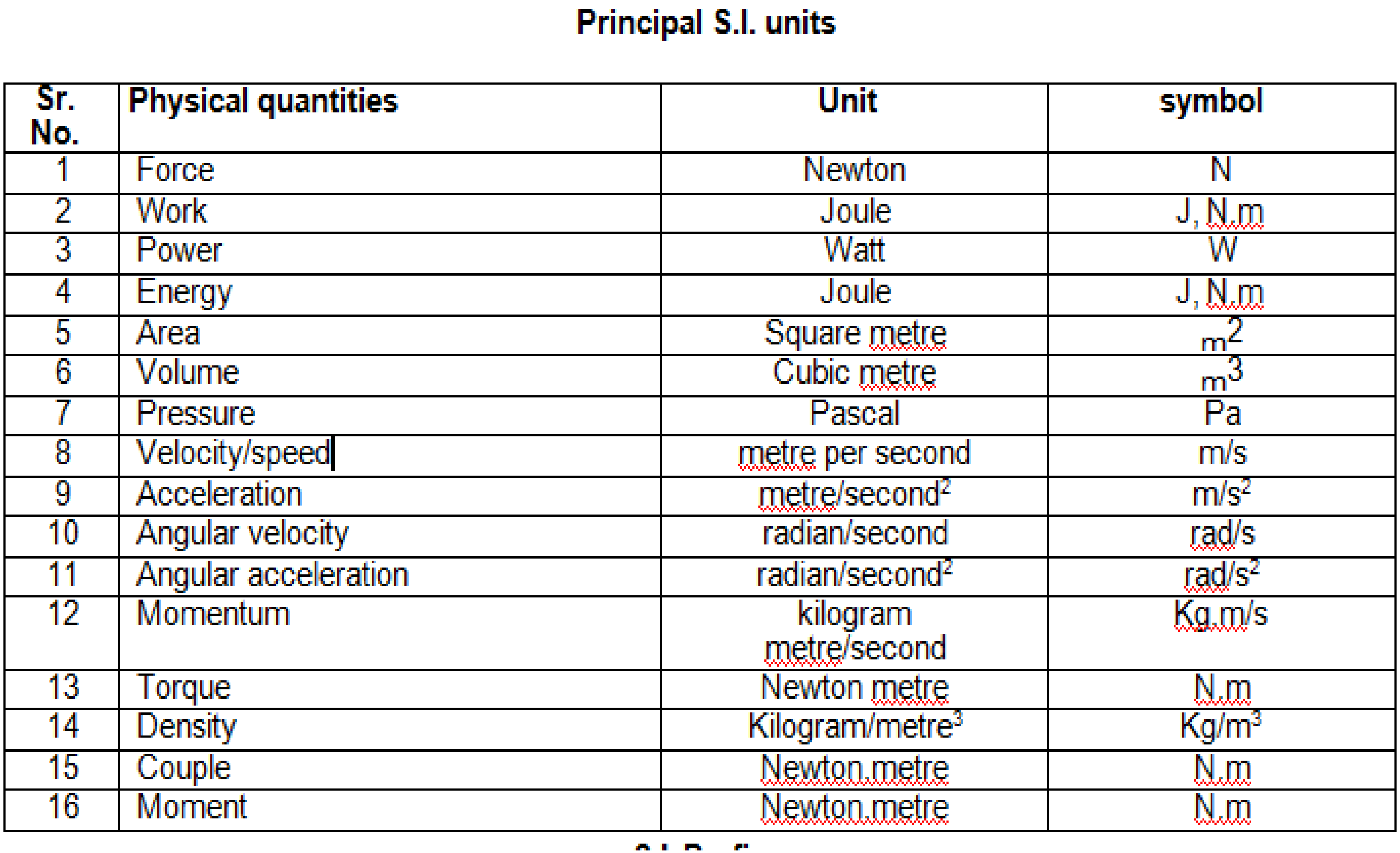
Fundamental units of S.I system

Sr. No.	Physical quantities	Unit	symbol
1	Length	Metre	m
2	Mass	Kilogram	Kg
3	Time	Second	S
4	Temperature	Kelvin	K

Supplementary units of S.I. system

Sr. No.	Physical quantities	Unit	symbol
1	Plane angle	Radian	Rad

INTRODUCTION: UNITS



Principal S.I. units

Sr. No.	Physical quantities	Unit	symbol
1	Force	Newton	N
2	Work	Joule	J, N.m
3	Power	Watt	W
4	Energy	Joule	J, N.m
5	Area	Square metre	m^2
6	Volume	Cubic metre	m^3
7	Pressure	Pascal	Pa
8	Velocity/speed	metre per second	m/s
9	Acceleration	metre/second^2	m/s^2
10	Angular velocity	radian/second	rad/s
11	Angular acceleration	radian/second^2	rad/s^2
12	Momentum	kilogram metre/second	Kg.m/s
13	Torque	Newton metre	N.m
14	Density	Kilogram/metre^3	Kg/m^3
15	Couple	Newton.metre	N.m
16	Moment	Newton.metre	N.m

INTRODUCTION:

- Thermodynamics is the branch of science that deals with the relationships between heat and other forms of energy.
- It describes how thermal energy is converted to and from other forms of energy and how it affects matter.
- Temperature is "a measure of the average kinetic energy of the particles in a sample of matter, expressed in terms of units or degrees.

BASIC CONCEPTS

- Temperature is "a measure of the average kinetic energy of the particles in a sample of matter, expressed in terms of units or degrees.
- Heat is a form of energy which is transferred by virtue of temperature difference.
- Energy of a body is its capacity to do work.

BASIC CONCEPTS

- Work is said to be done by a force when a body moves in the direction of force.

  Work done = Force * Displacement

- Specific heat is the amount of heat required to increase the temperature of a certain mass of a substance by unit degree.
- The fundamental concepts of heat capacity and latent heat, which were necessary for the development of thermodynamics.

SYSTEM

System:

- A thermodynamic system is defined as a quantity of matter or a region in space which is selected for the study.

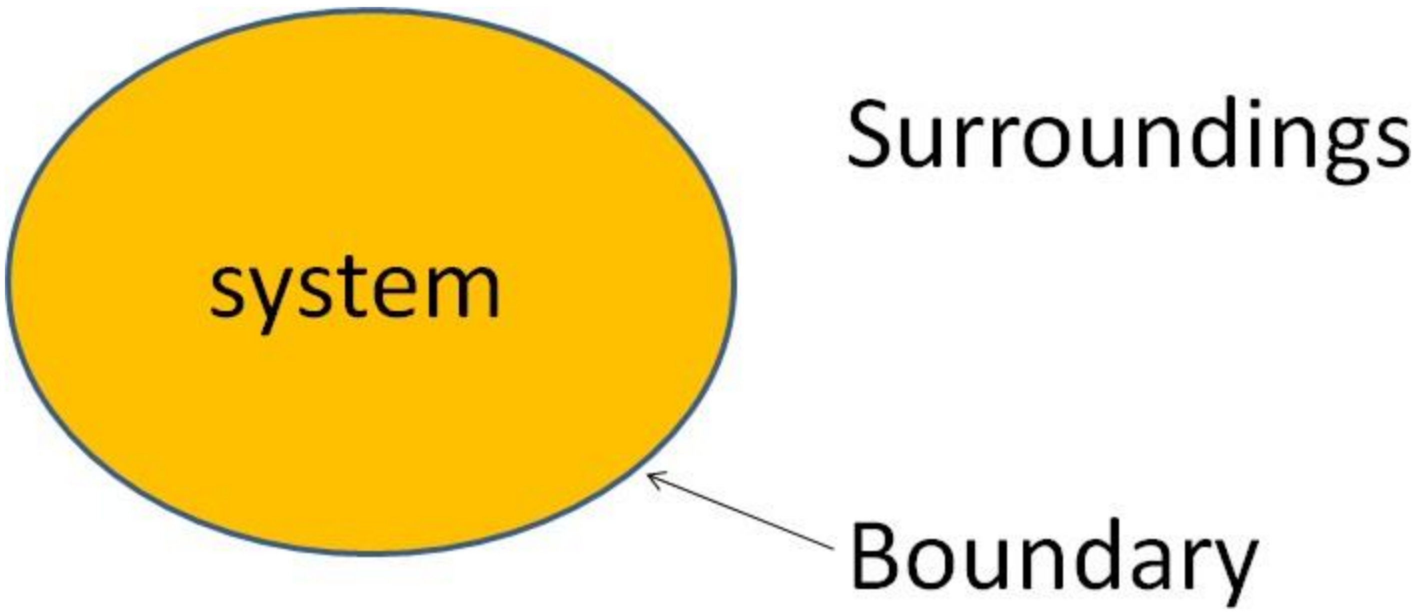
Surroundings:

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

Boundary:

- The real or imaginary surfaces which separates the system and surroundings is called boundary. The real or imaginary surfaces which separates the system and surroundings is called boundary.

SYSTEM



TYPES OF THERMODYNAMIC SYSTEM

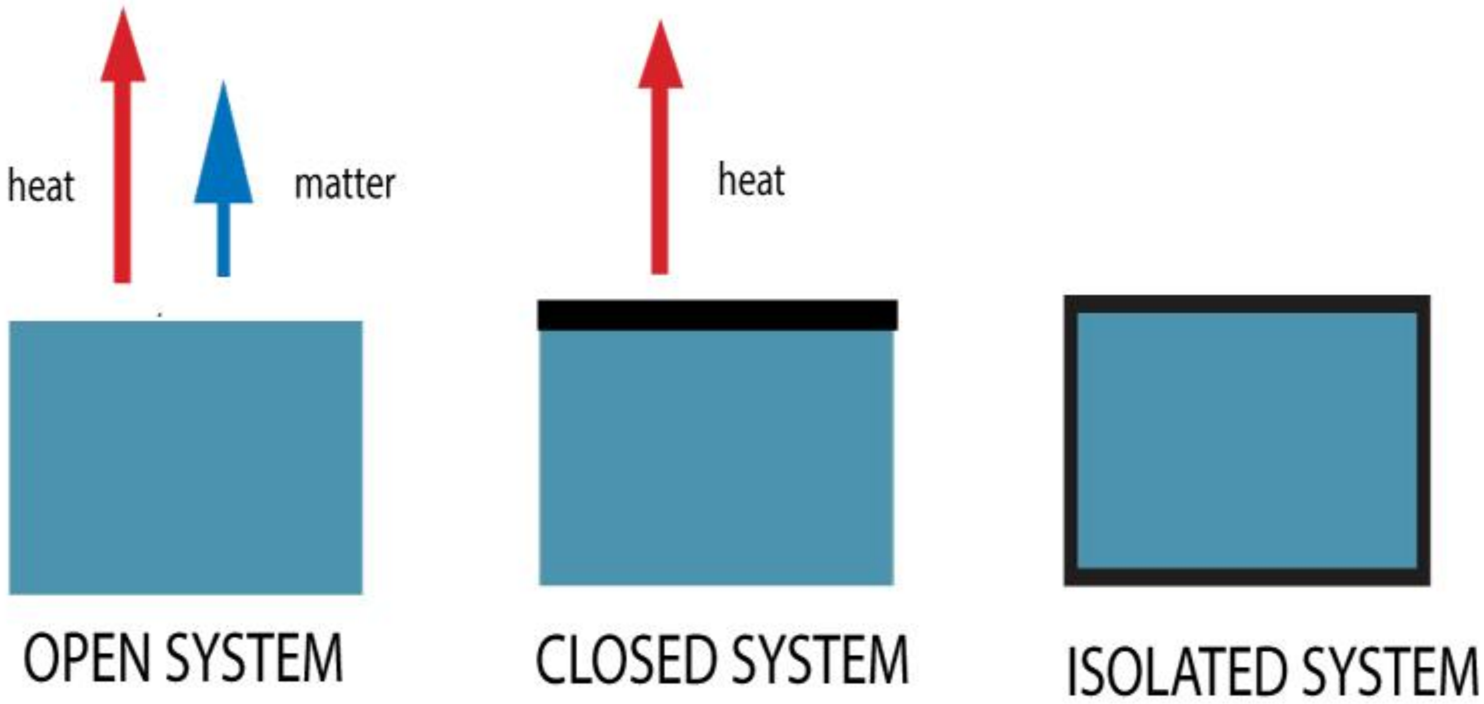
- On the basis of mass and energy transfer the thermodynamic system is divided into three types.

➢Closed system

➢Open system

➢Isolated system

TYPES OF THERMODYNAMIC SYSTEM



TYPES OF THERMODYNAMIC SYSTEM

- **Closed system**: A system in which the transfer of energy but not mass can takes place across the boundary is called closed system. The mass inside the closed system remains constant.
- **Open system:** A system in which the transfer of both mass and energy takes place is called an open system. This system is also known as control volume.
- **Isolated system:** A system in which the transfer of mass and energy cannot takes place is called an isolated system.

MICROSCOPIC VIEW OR STUDY:

- The approach considers that the system is made up of a very large number of discrete particles known as molecules.
- These molecules have different velocities are energies. The values of these energies are constantly changing with time.
- This approach to thermodynamics, which is concerned directly with the structure of the matter, is known as statistical thermodynamics.

MICROSCOPIC VIEW OR STUDY:

- The behavior of the system is found by using statistical methods, as the number of molecules is very large.
- So advanced statistical and mathematical methods are needed to explain the changes in the system.
- The properties like velocity, momentum, impulse, kinetic energy and instruments cannot easily measure force of impact etc. that describe the molecule.

MACROSCOPIC VIEW OR STUDY:

- In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level.
- In other words this approach to thermodynamics is concerned with gross or overall behavior. This is known as classical thermodynamics.
- The analysis of macroscopic system requires simple mathematical formula.

MACROSCOPIC VIEW OR STUDY:

- The value of the properties of the system are their average values. For examples consider a sample of gas in a closed container.
- The pressure of the gas is the average value of the pressure exerted by millions of individual molecules.
- In order to describe a system only a few properties are needed.

HEAT AND WORK

Similarities :

- *Both are path functions and inexact differentials.*
- Both are boundary phenomenon *i.e., both are recognized at the boundaries of the system* as they cross them.
- Both are associated with a process, not a state. Unlike properties, work or heat has no meaning at a state.

HEAT AND WORK

Dissimilarities :

- ✓In heat transfer temperature difference is required.
- ✓In a stable system there cannot be work transfer, however, there is no restriction for the transfer of heat.
- ✓The sole effect external to the system could be reduced to rise of a weight but in the case of a heat transfer other effects are also observed.

THERMODYNAMIC EQUILIBRIUM

- A thermodynamic system is said to exist in a state of thermodynamic equilibrium when no change in any macroscopic property is registered if the system is isolated from its surroundings.
- An isolated system always reaches in the course of time a state of thermodynamic equilibrium and can never depart from it spontaneously.

THERMODYNAMIC EQUILIBRIUM

Mechanical equilibrium:

- The criteria for Mechanical equilibrium are the equality of pressures.

Chemical equilibrium:

- The criteria for Chemical equilibrium are the equality of chemical potentials.

Thermal equilibrium:

- The criterion for Thermal equilibrium is the equality of temperatures.

STATE AND PROPERTY

State:

- The thermodynamic state of a system is defined by specifying values of a set of measurable properties sufficient to determine all other properties.
- For fluid systems, typical properties are pressure, volume and temperature.

Property:

- Properties may be extensive or intensive.

TYPES OF PROPERTIES

Intensive properties:

- The properties which are independent of the mass of the system.
- For example: Temperature, pressure and density are the intensive properties.

Extensive properties:

The properties which depend on the size or extent of the system are called extensive properties.

- For example: Total mass, total volume and total momentum.

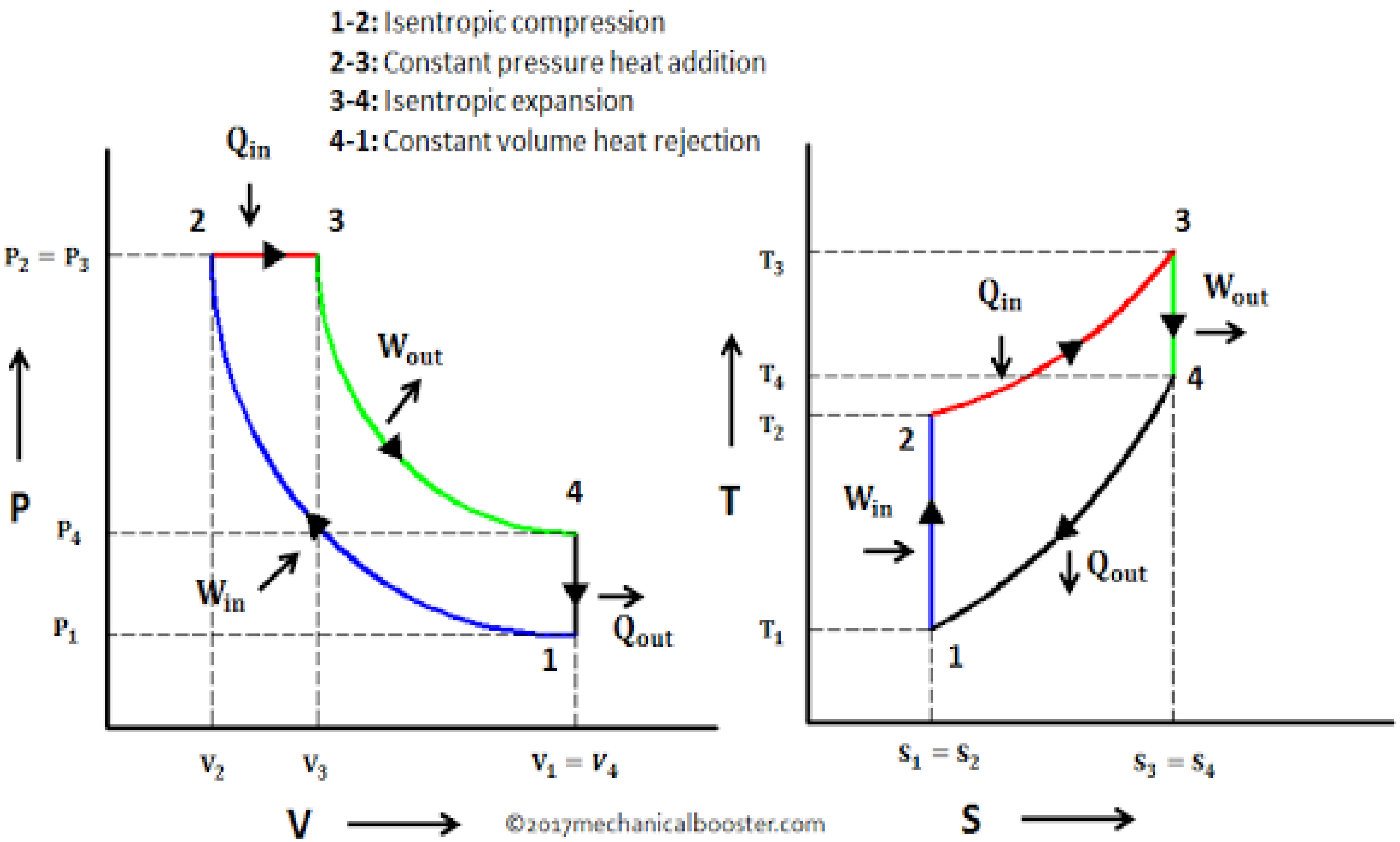
THERMODYNAMIC PROCESS

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

THERMODYNAMIC CYCLE

- Thermodynamic cycle refers to any closed system that undergoes various changes due to temperature, pressure, and volume, however, its final and initial state are equal.
- In the process of going through this cycle, the system may perform work on its surroundings, thereby acting as a heat engine

THERMODYNAMIC CYCLE



1-2: Isentropic compression

2-3: Constant pressure heat addition

3-4: Isentropic expansion

4-1: Constant volume heat rejection

P-V and T-S Diagram of Diesel Cycle

REVERSIBLE PROCESSES

- A thermodynamic process (state i → state f) is said to be reversible if the process can be turned back such that both the system and the surroundings return to their original states, with no other change anywhere else in the universe.
- As we know, in reality, no such processes as reversible processes can exist, thus, the reversible processes can easily be defined as idealizations or models of real processes, on which the limits of the system or device are to be defined. They help us in incurring the maximum efficiency a system can provide in ideal working conditions and thus the target design that can be set.

REVERSIBLE PROCESSES

- They help us in incurring the maximum efficiency a system can provide in ideal working conditions and thus the target design that can be set.

Examples of Reversible Process

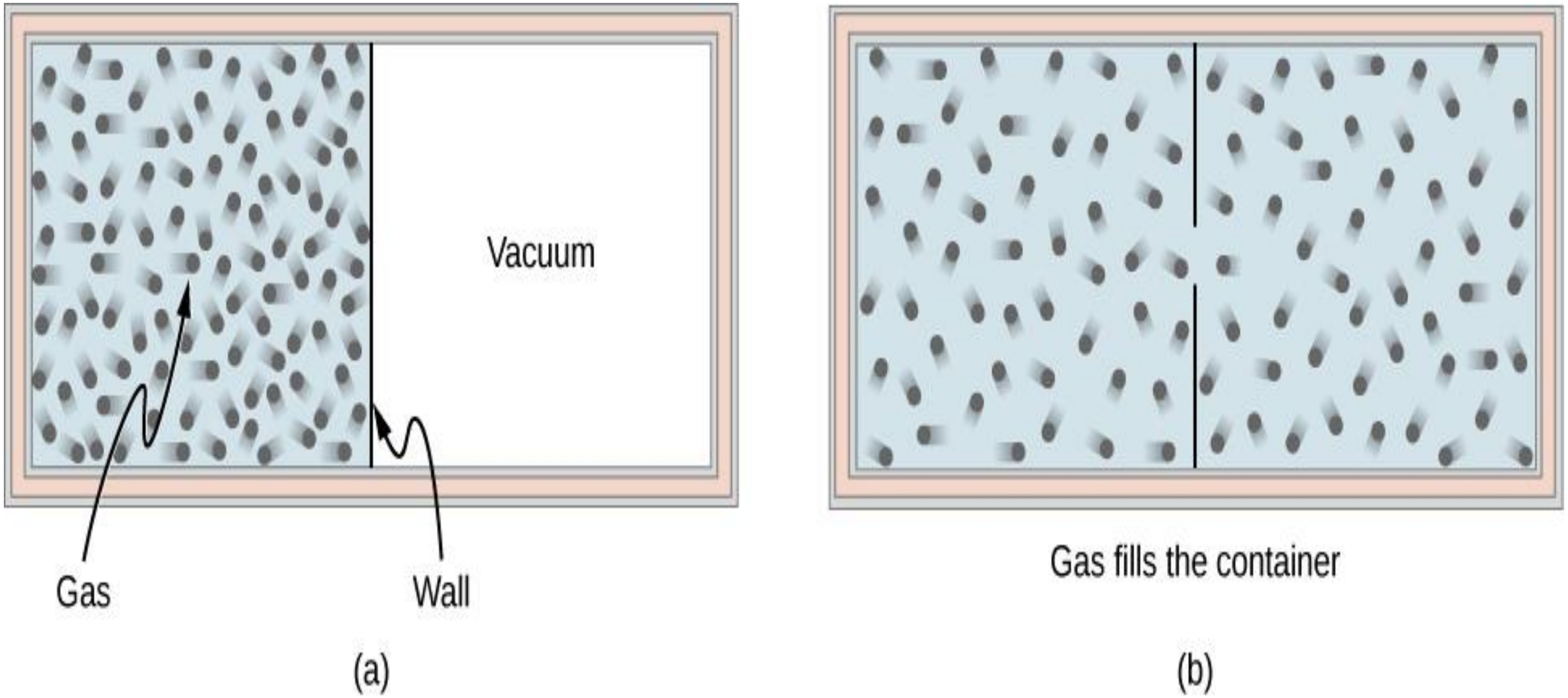
✓slow adiabatic compression or expansion of gases.

✓slow isothermal compression or expansion of gases

IRREVERSIBLE PROCESS

- An irreversible process can be defined as a process in which the system and the surroundings do not return to their original condition once the process is initiated.
- Taking an example of an automobile engine, that has travelled a distance with the aid of fuel equal to an amount ‘x’. During the process, the fuel burns to provide energy to the engine, converting itself into smoke and heat energy.

IRREVERSIBLE PROCESS



Irreversible Process

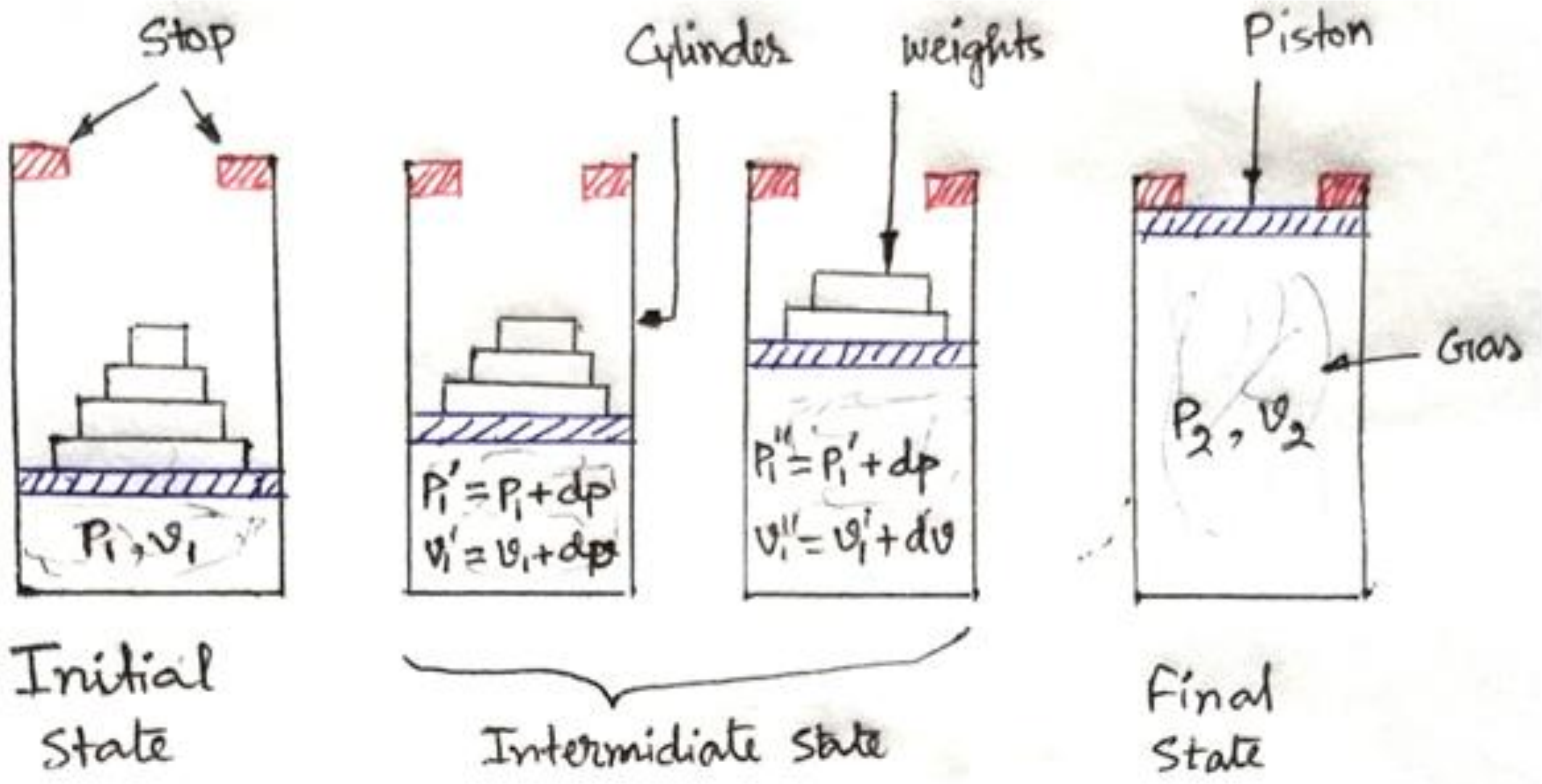
IRREVERSIBLE PROCESS

- We cannot retrieve the energy lost by the fuel and cannot get back the original form. There are many factors due to which the irreversibility of a process occurs, namely: The friction that converts the energy of the fuel to heat energy.
- Mixing of two different substances which cannot be separated as the process of intermixing is again spontaneous in nature, the reverse of which is not feasible.

EXAMPLES OF IRREVERSIBLE PROCESSES

- Relative motion with friction
- Throttling
- Heat transfer
- Diffusion
- Electricity flow through a resistance

QUASI-STATIC PROCESS

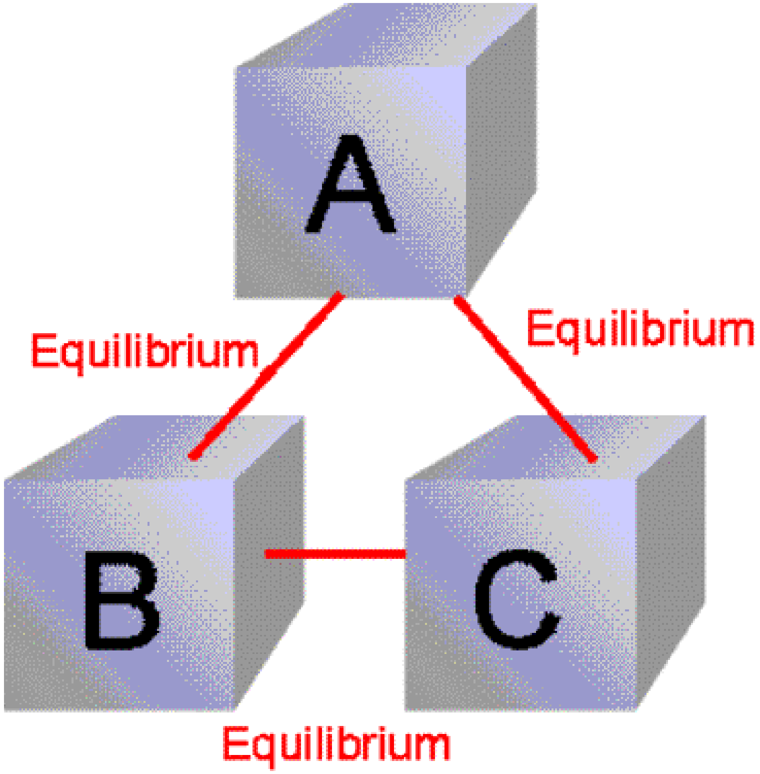


QUASI-STATIC PROCESS

- ✓When the process is carried out in such a way that at every instant, the system deviation from the thermodynamic equilibrium is infinitesimal, then the process is known as quasi-static or quasi-equilibrium process and each state in the process may be considered as an equilibrium state.
- ✓In simple words, we can say that if system is going under a thermodynamic process through succession of thermodynamic states and each state is equilibrium state then the process will be termed as quasi static process.

ZEROTH LAW OF THERMODYNAMICS

The Zeroth Law



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ZEROTH LAW OF THERMODYNAMICS

- If objects ‘A’ and ‘C’ are in thermal equilibrium with ‘B’, then object ‘A’ is in thermal equilibrium with object ‘C’. Practically this means all three objects are at the same temperature and it forms the basis for comparison of temperatures.
- If a=b; b=c then a=c

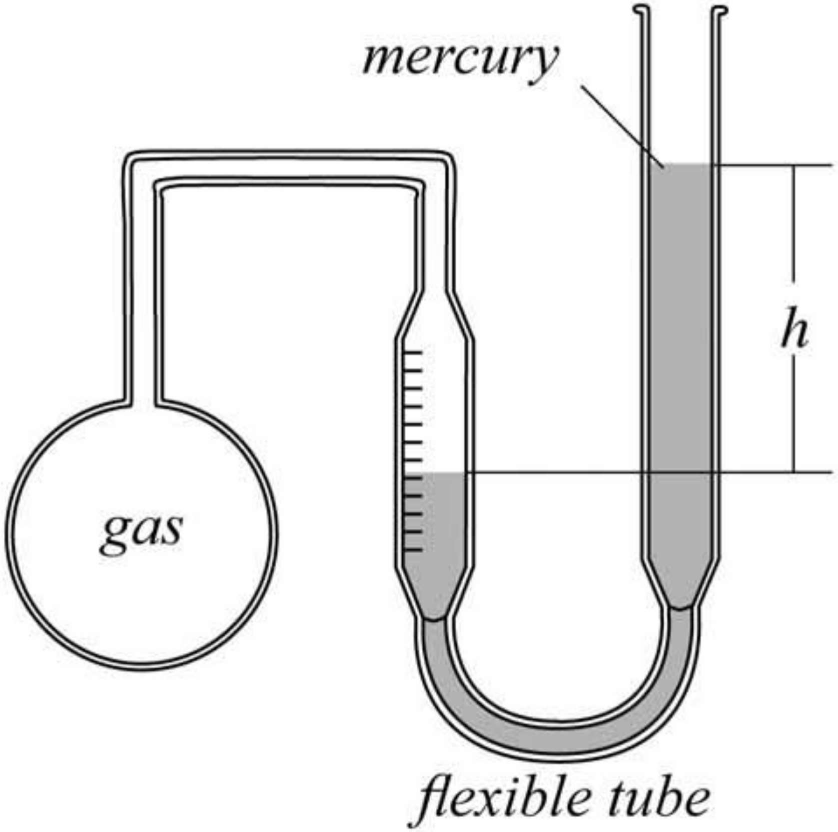
PRINCIPLES OF THERMOMETRY

- Thermometry is the science and practice of temperature measurement.
- Any measurable change in a thermometric probe (e.g. the dilatation of a liquid in a capillary tube, variation of electrical resistance of a conductor, of refractive index of a transparent material, and so on) can be used to mark temperature levels, that should later be calibrated against an internationally agreed unit if the measure is to be related to other thermodynamic variables.

PRINCIPLES OF THERMOMETRY

- Thermometry is sometimes split in metrological studies in two subfields: contact thermometry and noncontact thermometry.
- As there can never be complete thermal uniformity at large, thermometry is always associated to a heat transfer problem with some space-time coordinates of measurement, given rise to time-series plots and temperature maps.

CONSTANT VOLUME GAS THERMOMETER



CONSTANT VOLUME GAS THERMOMETER

- Thermometers are working examples of the zeroth law of thermodynamics.
- The significance of constant volume gas thermometers is that they are used to calibrate other th
- A constant volume gas thermometer is composed of a bulb filled with a fixed amount of a dilute gas that is attached to a mercury manometer.

CONSTANT VOLUME GAS THERMOMETER

- A manometer is a device used to measure pressure.
- The mercury manometer has a column partially filled with mercury that is connected to a flexible tube that has another partially filled column of mercury, called a reservoir, attached to the other end.
- The height of the mercury in the first column is set to a reference point or pressure P that it must stay at, while the mercury in the reservoir is allowed to move up and down in relation to a scale or ruler.

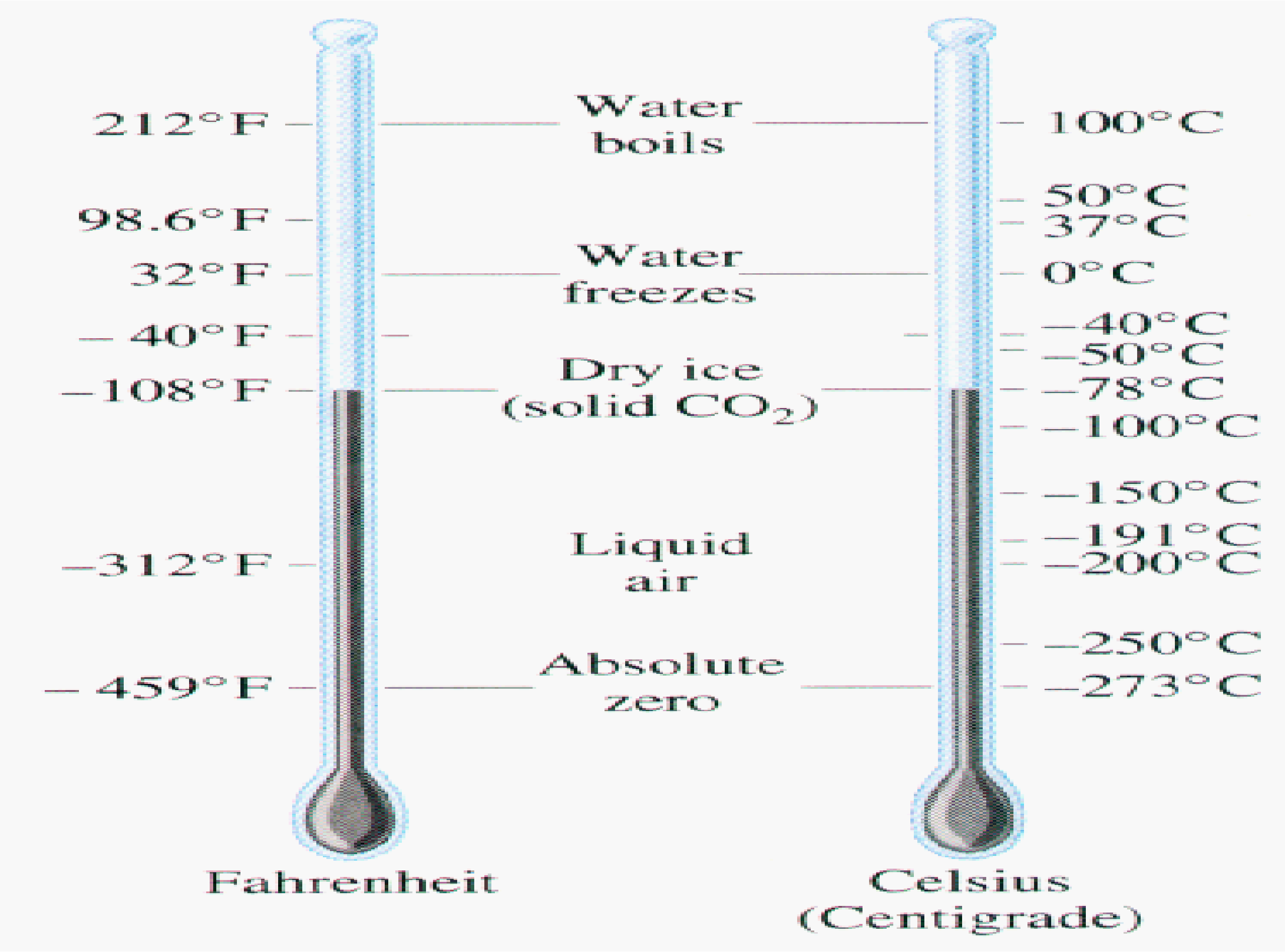
CONSTANT VOLUME GAS THERMOMETER

- the constant volume gas thermometer uses values from the triple point of water to calibrate other thermometers.
- To recall, 273.16 K (Kelvin) is the temperature where water exists in an equilibrium state as a gas, liquid, and solid.
- $T = 273.16\ K\ (P/P_{tp})$
- For low pressure and high temperatures, where real gases behave like ideal gases, equation 1 becomes:
- $T = 273.16\ K \lim P/P_{tp}$ as $P_{tp} \rightarrow 0$

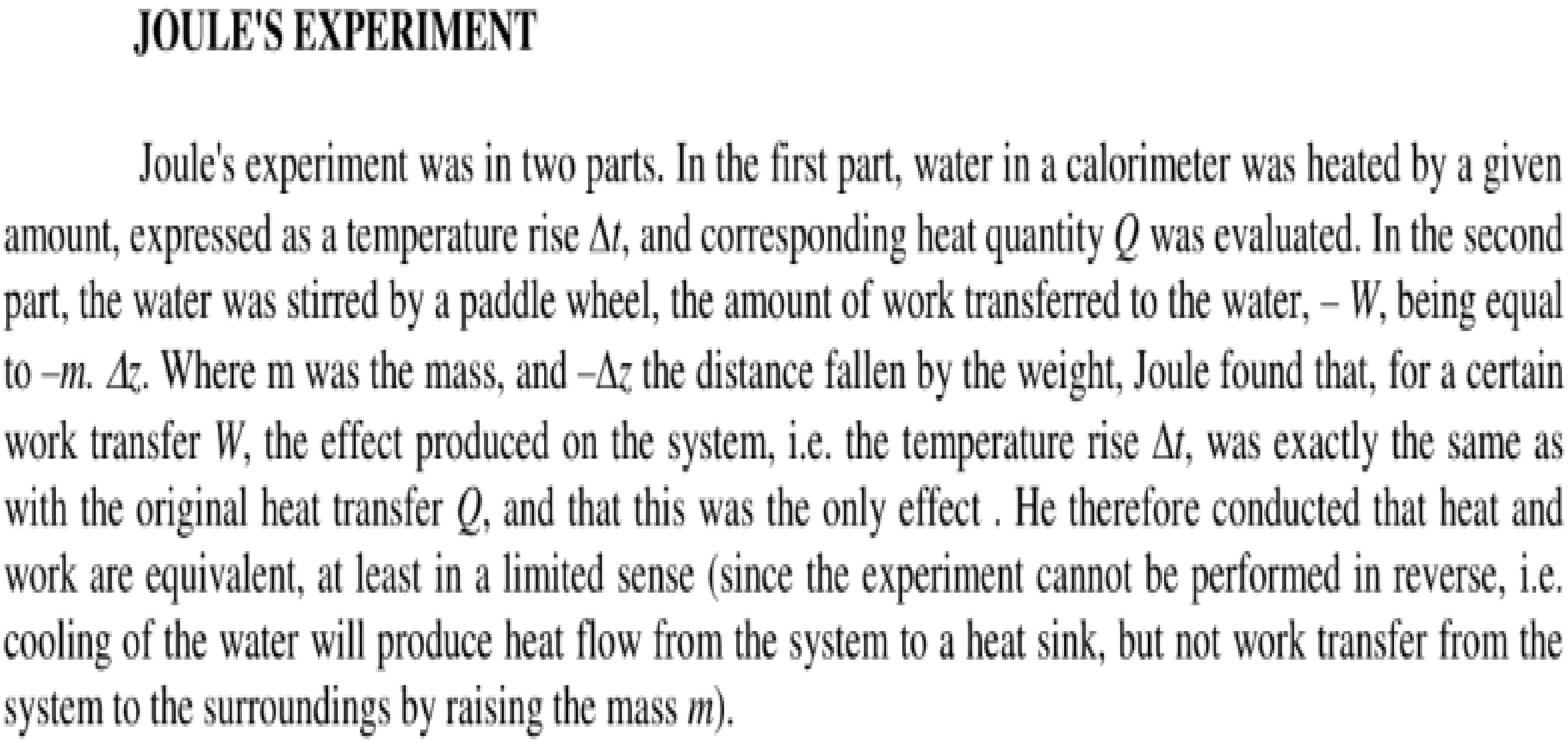
SCALES OF TEMPERATURE

- There are three temperature scales in use today, Fahrenheit, Celsius and Kelvin.
- Fahrenheit temperature scale is a scale based on 32 for the freezing point of water and 212 for the boiling point of water, the interval between the two being divided into 180 parts.
- The conversion formula for a temperature that is expressed on the Celsius (C) scale to its Fahrenheit (F) representation is: $F = 9/5C + 32$.

SCALES OF TEMPERATURE



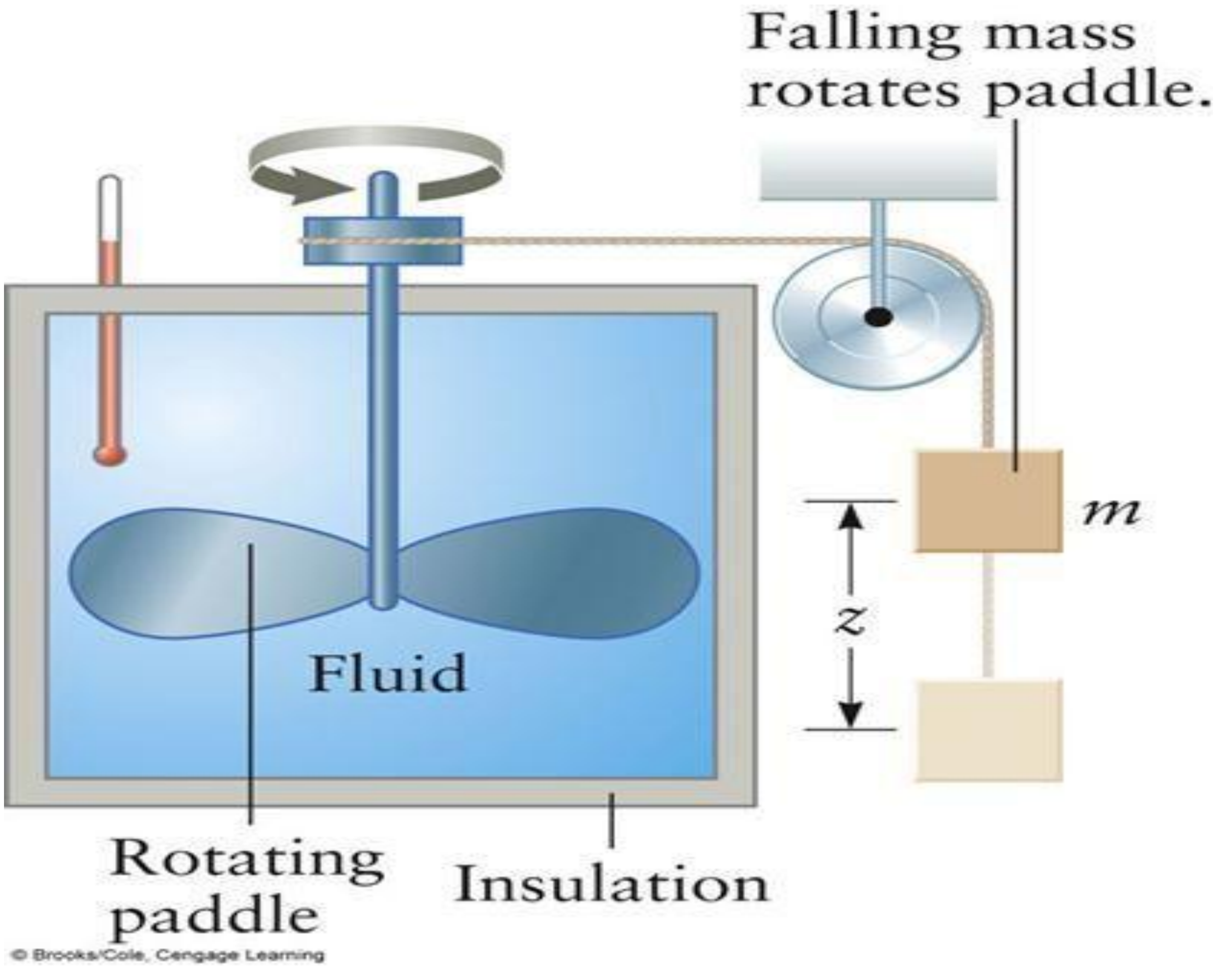
JOULES EXPERIMENT



JOULE'S EXPERIMENT

Joule's experiment was in two parts. In the first part, water in a calorimeter was heated by a given amount, expressed as a temperature rise Δt, and corresponding heat quantity Q was evaluated. In the second part, the water was stirred by a paddle wheel, the amount of work transferred to the water, $-W$, being equal to $-m.\ \Delta z$. Where m was the mass, and $-\Delta z$ the distance fallen by the weight, Joule found that, for a certain work transfer W, the effect produced on the system, i.e. the temperature rise Δt, was exactly the same as with the original heat transfer Q, and that this was the only effect . He therefore conducted that heat and work are equivalent, at least in a limited sense (since the experiment cannot be performed in reverse, i.e. cooling of the water will produce heat flow from the system to a heat sink, but not work transfer from the system to the surroundings by raising the mass m).

JOULES EXPERIMENT



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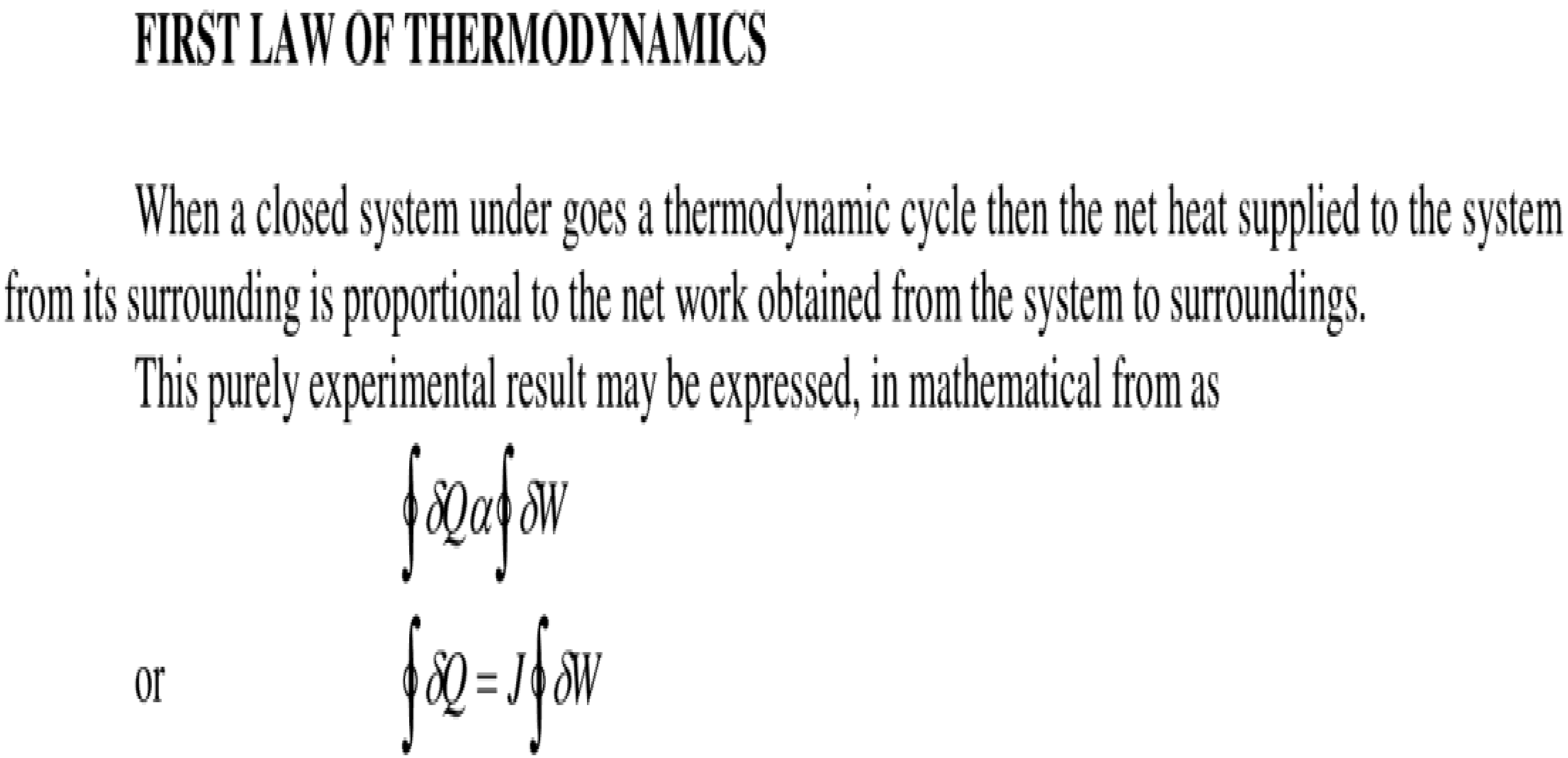
FIRST LAW OF THERMODYNAMICS



FIRST LAW OF THERMODYNAMICS

When a closed system under goes a thermodynamic cycle then the net heat supplied to the system from its surrounding is proportional to the net work obtained from the system to surroundings.

This purely experimental result may be expressed, in mathematical from as

$$\oint \delta Q \alpha \oint \delta W$$

or

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

FIRST LAW OF THERMODYNAMICS

where, *J* is a constant of proportionality and is known as Mechanical Equivalent of Heat, because this equation titled Joule's law, sets a relation between units used for measurement of work and heat.

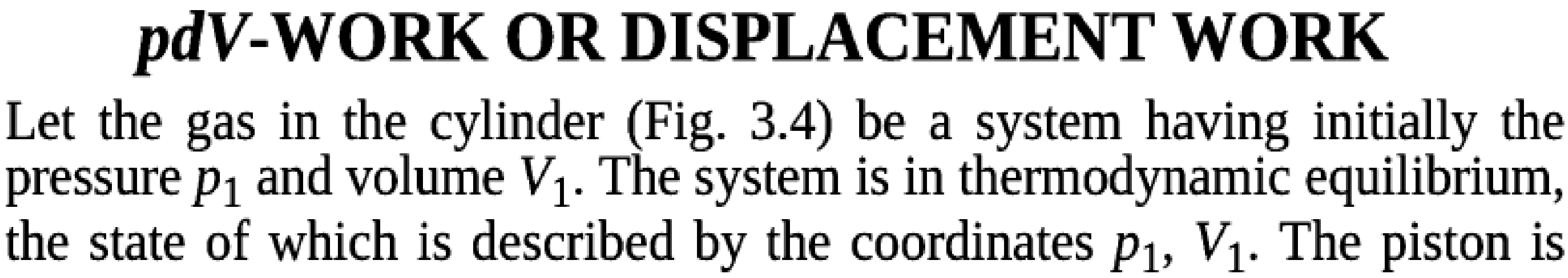
In the SI system of units, both heat and work are measured in Joule (*J*),and therefore, *J* is a pure constant having numerical value of unity.

$$\therefore \oint \delta Q = \oint \delta W \qquad (3.1)$$

Equation (3.1) may be written more conveniently as

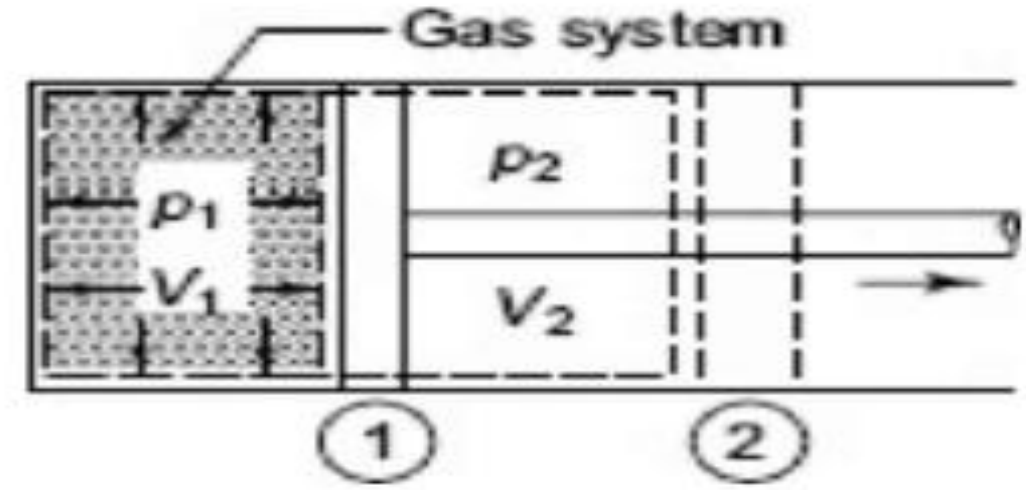
$$\oint (\delta Q - \delta W) \neq 0$$

PDV WORK



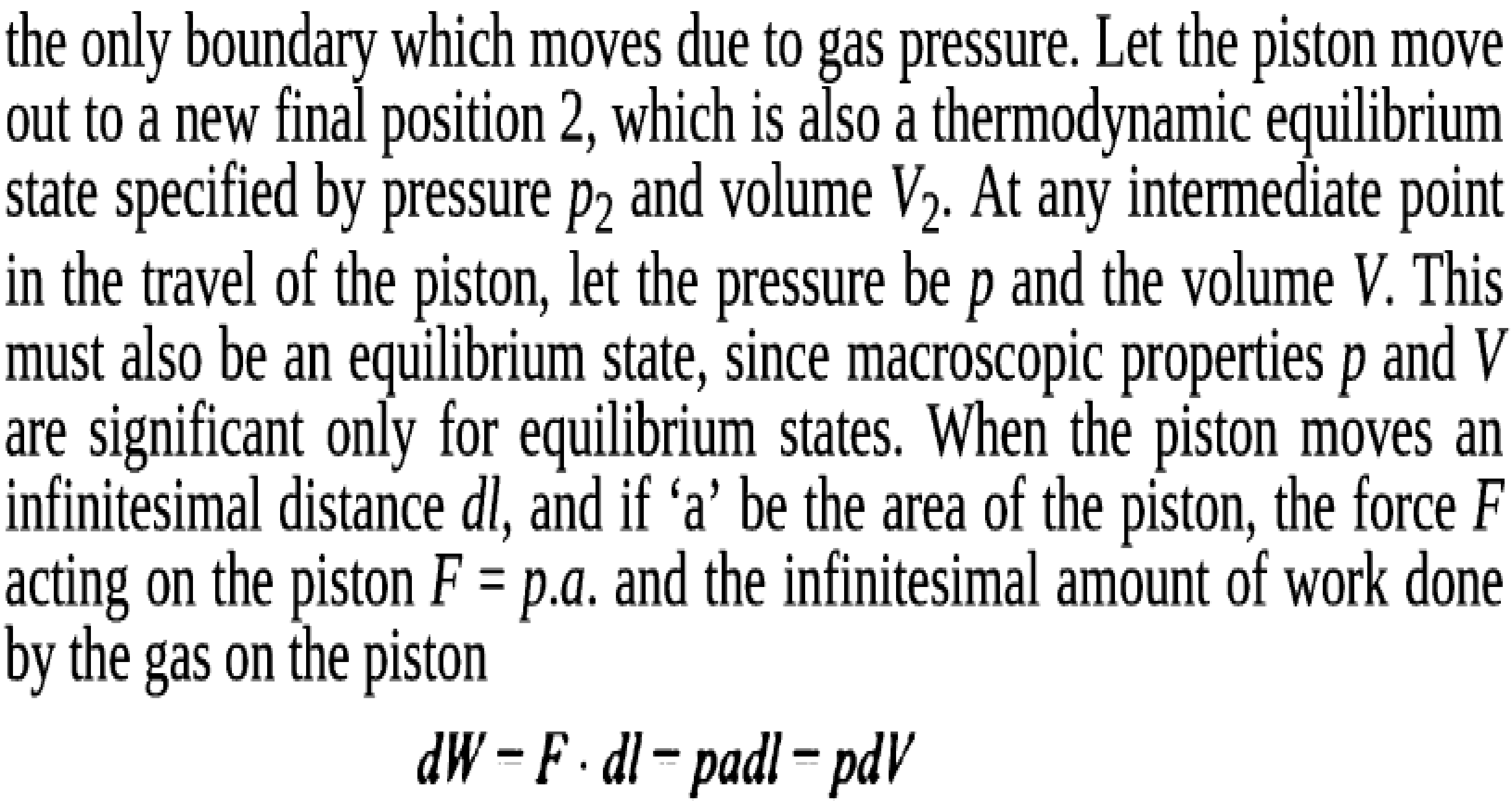
pdV-WORK OR DISPLACEMENT WORK

Let the gas in the cylinder (Fig. 3.4) be a system having initially the pressure p_1 and volume V_1. The system is in thermodynamic equilibrium, the state of which is described by the coordinates p_1, V_1. The piston is



pdV work

PDV WORK



the only boundary which moves due to gas pressure. Let the piston move out to a new final position 2, which is also a thermodynamic equilibrium state specified by pressure p_2 and volume V_2. At any intermediate point in the travel of the piston, let the pressure be p and the volume V. This must also be an equilibrium state, since macroscopic properties p and V are significant only for equilibrium states. When the piston moves an infinitesimal distance dl, and if 'a' be the area of the piston, the force F acting on the piston $F = p.a$. and the infinitesimal amount of work done by the gas on the piston

$$dW = F \cdot dl = padl = pdV$$

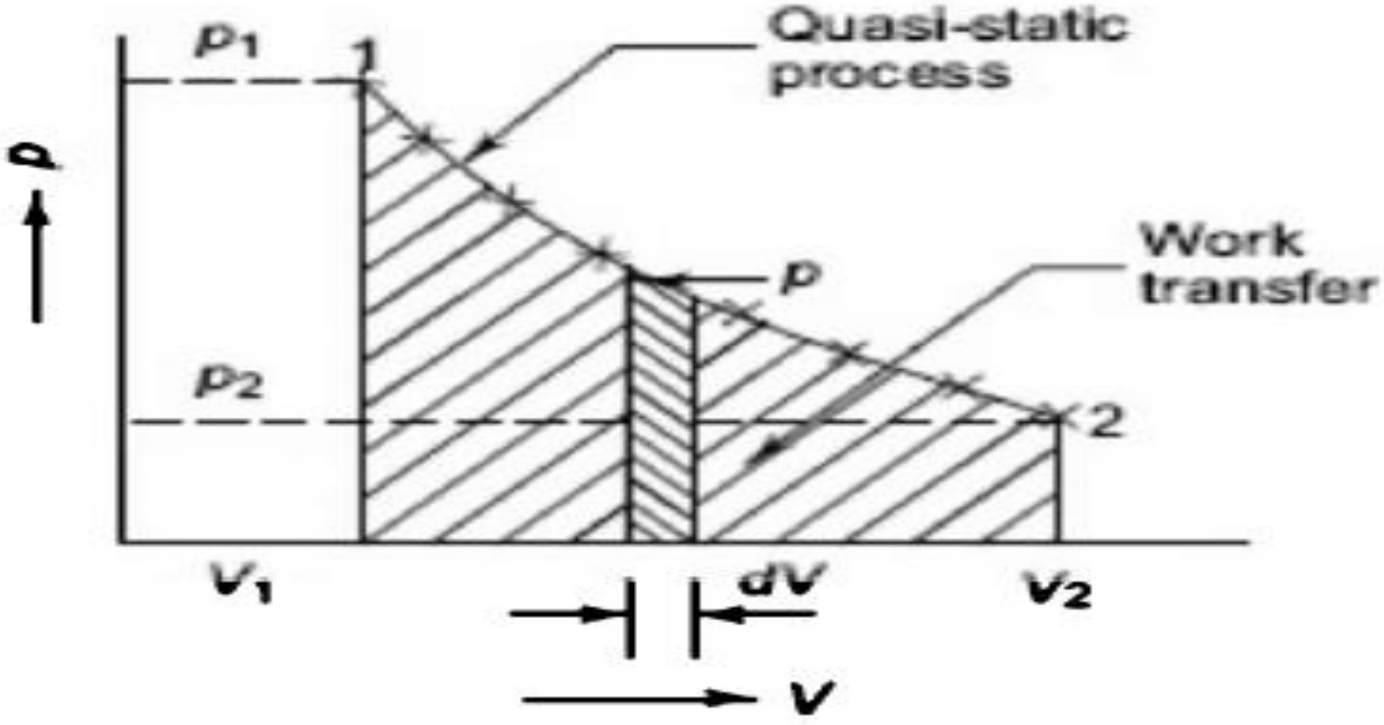
where $dV = adl$ = infinitesimal displacement volume. The differential sign in $đW$ with the line drawn at the top of it will be explained later.

When the piston moves out from position 1 to position 2 with the volume changing from V_1 to V_2, the amount of work W done by the system will be

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

The magnitude of the work done is given by the area under the path 1–2, as shown in Fig. 3.5. Since p is at all times a thermodynamic coordinate, all the states passed through by the system as the volume changes from V_1 to V_2 must be equilibrium states, and the path 1–2 *must be quasi-static*. The piston moves infinitely slowly so that every state passed through is an equilibrium state. *The integration $\int pdV$ can be performed only on a quasi-static path.*

PDV WORK



Quasi-static pdV work

SHAFT WORK

2. Shaft work When a shaft, taken as the system (Fig. 3.14a), is rotated by a motor, there is work transfer into the system. This is because the shaft can rotate a pulley which can raise a weight. If T is the torque applied to the shaft and $d\theta$ is the angular displacement of the shaft, the shaft work is

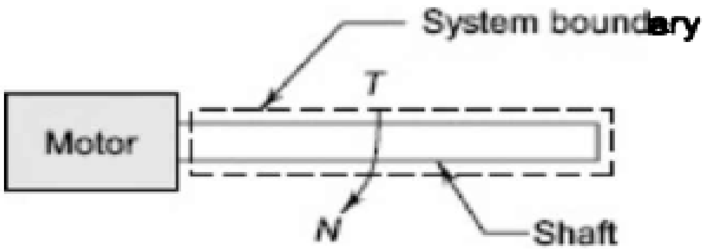


Fig. 3.14(A) *Shaft work*

$$W - \int_1^2 T d\theta \qquad (3.14\,a)$$

and the shaft power is

$$W \quad \int_1^2 T \frac{d\theta}{d\tau} \quad T\omega \qquad (3.15\,b)$$

where ω is the angular velocity and T is considered a constant in this

FLOW WORK

Flow work The flow work, significant only in a flow process or an open system, represents the energy transferred across the system boundary as a result of the energy imparted to the fluid by a pump, blower or compressor to make the fluid flow across the control volume. Flow work is analogous to displacement work. Let *p* be the fluid pressure in the plane of the imaginary piston, which acts in a direction normal to it (Fig. 3.16). The work done on this imaginary piston by the external pressure as the piston moves forward is given by

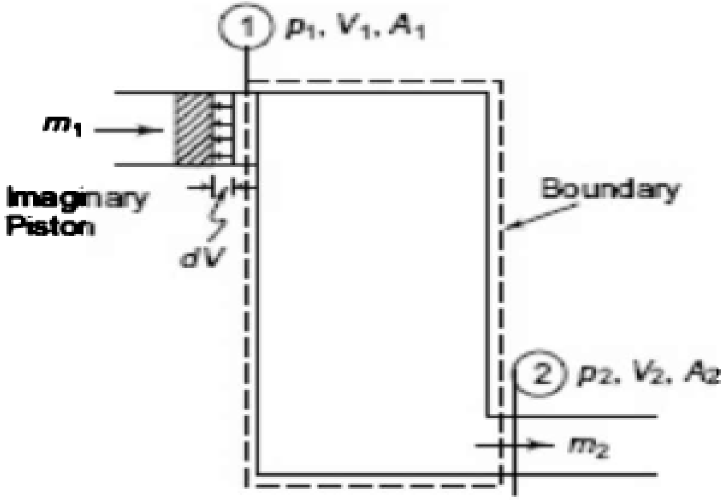


Fig. 3.16 *Flow work*

$$đW_{\text{flow}} = p\,dV, \tag{3.16}$$

FIRST LAW OF THERMODYNAMICS

- The work input to the paddle wheel is measured by the fall of weight, while the corresponding temperature rise of liquid in the insulated container is measured by the thermometer.

  by heat transfer. The experiments show :

  (*i*) *A definite quantity of work is always required to* accomplish the same temperature rise obtained with a unit amount of heat.

  (*ii*) *Regardless of*

  whether the temperature of liquid is raised by work transfer or heat transfer, the liquid can be returned by heat transfer in opposite direction to the identical state from which it started.

JOULES EXPERIMENT

shows the experiment for checking first law of thermodynamics.

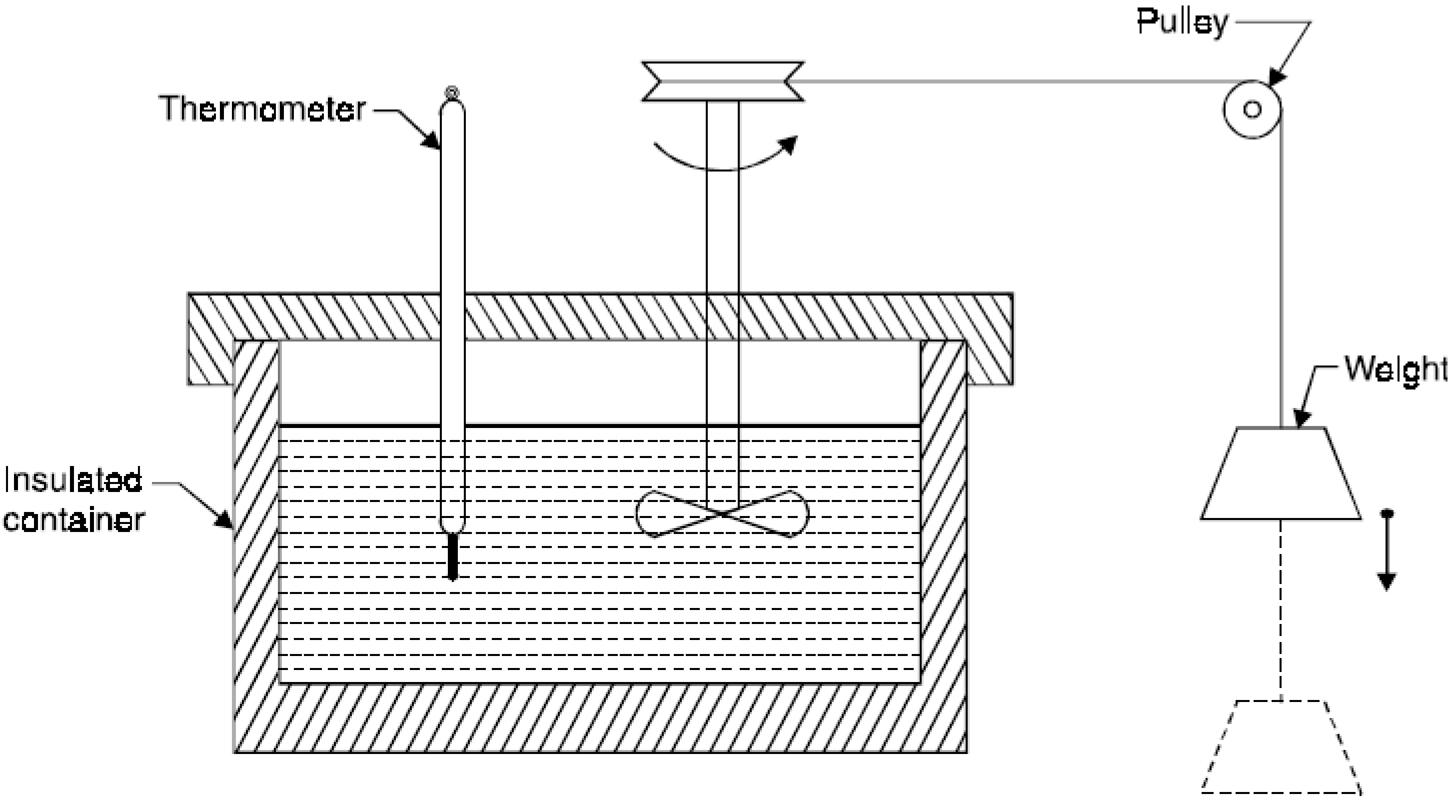


Fig. 4.1. Heat and work.

FIRST LAW OF THERMODYNAMICS

- It can be stated as an invariable experience that whenever a physical system passes through a complete cycle the algebraic sum of the work transfers during the cycle *dW bears a definite ratio to the algebraic sum of the heat transfers during the cycle, dQ .*
- *This may be expressed by the equation,*

  $dW = JdQ$

- where *J is the proportionality constant and is known as Mechanical Equivalent of heat.*
- In S.I. units its value is unity, *i.e., 1 Nm/J.*

APPLICATION OF FIRST LAW TO A PROCESS

- When a process is executed by a system, the *change in stored energy of the system is numerically equal to the net heat interactions minus the net work interaction during the process.*
- $\therefore E2 - E1 = Q - W$
- $\therefore \Delta E = Q - W$ [or $Q = \Delta E + W$]
- Or $d(Q - W)\ 12 = \Delta E = E2 - E1$
- Where E represents the *total internal energy.*

APPLICATION OF FIRST LAW TO A PROCESS

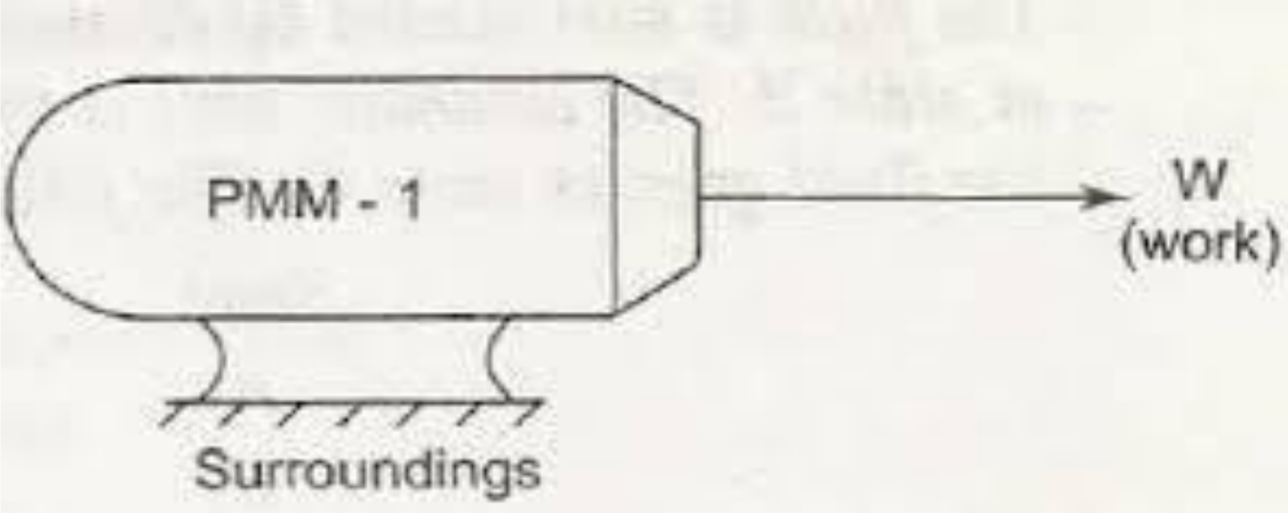
- If the electric, magnetic and chemical energies are *absent* and changes in potential and kinetic energy for a *closed system* are neglected, the above equation can be written as $d(Q - W)$ 12 $= \Delta U = U2 - U1$
- $\therefore Q - W = \Delta U = U2 - U1$
- Generally, when heat is added to a system its temperature rises and external work is performed due to increase in volume of the system.

APPLICATION OF FIRST LAW TO A PROCESS

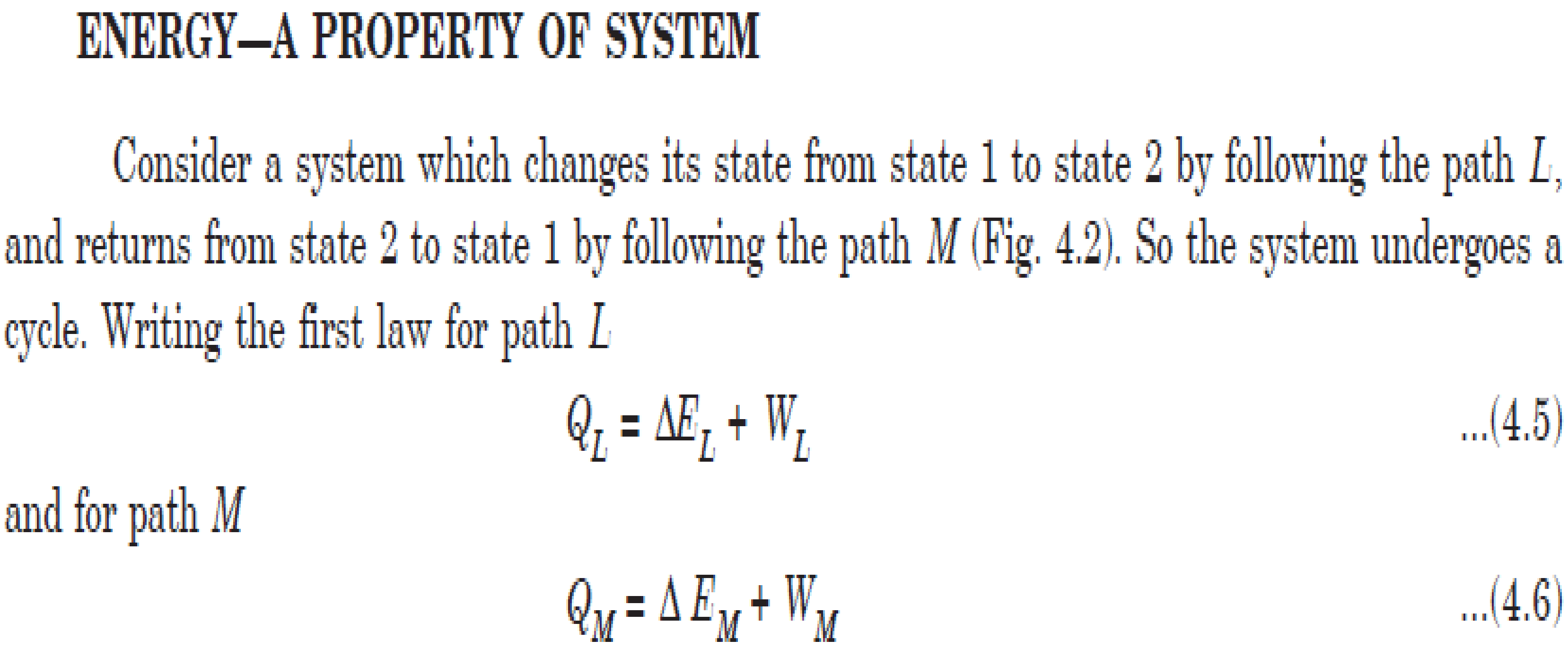
- *The rise in temperature is an indication of increase of internal energy*.
- Heat *added* to the system will be considered as *positive* and the heat *removed* or *rejected*, from the system, as *negative.*
- *Thus energy is conserved in the operation.*
- *The first law of thermodynamics is a particular formulation of the law of conservation of energy.*

PMM 1

- *There can be no machine which would continuously supply mechanical work without some form of energy disappearing simultaneously.*
- Such a *fictitious machine is called a perpetual motion machine of the first kind, or in* brief, PMM 1. A PMM 1 is thus *impossible.*



INTERNAL ENERGY—A PROPERTY OF SYSTEM



ENERGY—A PROPERTY OF SYSTEM

Consider a system which changes its state from state 1 to state 2 by following the path *L*, and returns from state 2 to state 1 by following the path *M* (Fig. 4.2). So the system undergoes a cycle. Writing the first law for path *L*

$$Q_L = \Delta E_L + W_L \qquad ...(4.5)$$

and for path *M*

$$Q_M = \Delta E_M + W_M \qquad ...(4.6)$$

INTERNAL ENERGY—A PROPERTY OF SYSTEM

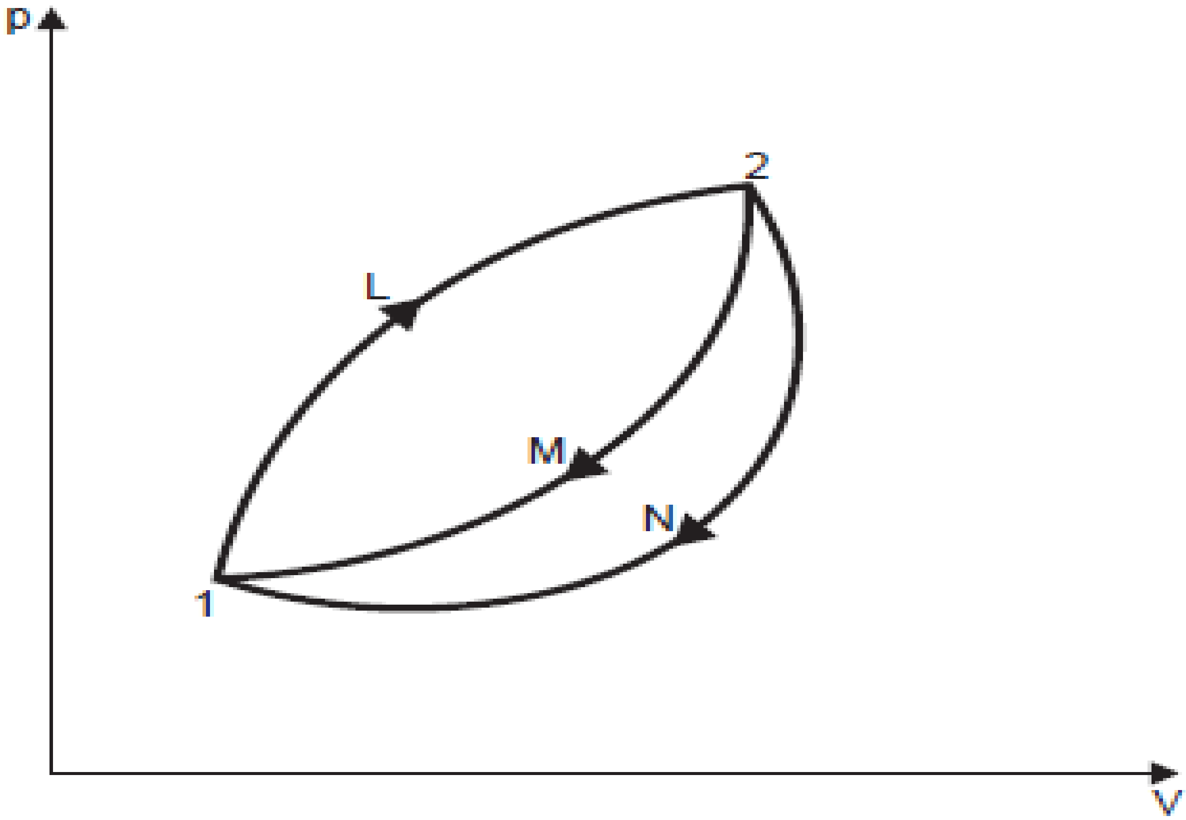


Fig. 4.2. Energy—a property of system.

INTERNAL ENERGY—A PROPERTY OF SYSTEM

The processes L and M together constitute a cycle, for which

$$\oint dW = \oint dQ$$

$$W_L + W_M = Q_L + Q_M$$

or $$Q_L - W_L = W_M - Q_M \qquad \text{...(4.7)}$$

From equations (4.5), (4.6) and (4.7), it yields

$$\Delta E_L = -\Delta E_M \qquad \text{...(4.8)}$$

Similarly, had the system returned from state 2 to state 1 by following the path N instead of path M

$$\Delta E_L = -\Delta E_N \qquad \text{...(4.9)}$$

From equations (4.8) and (4.9),

$$\Delta E_M = \Delta E_N \qquad \text{...(4.10)}$$

INTERNAL ENERGY—A PROPERTY OF SYSTEM

Thus, it is seen that the *change in energy between two states of a system is the same, whatever path the system may follow in undergoing that change of state.* If some arbitrary value of energy is assigned to state 2, the value of energy at state 1 is fixed independent of the path the system follows. Therefore, *energy has a definite value for every state of the system.* Hence, it is *a point function and a property of the system.*

STEADY FLOW ENERGY EQUATION (S.F.E.E.)

APPLICATION OF FIRST LAW TO STEADY FLOW PROCESS:

- ❖ In many practical problems, the rate at which the fluid flows through a machine or piece of apparatus is constant. This type of flow is called steady flow.

<u>Assumptions :</u>

- ❖The following assumptions are made in the system analysis :

STEADY FLOW ENERGY EQUATION (S.F.E.E.)

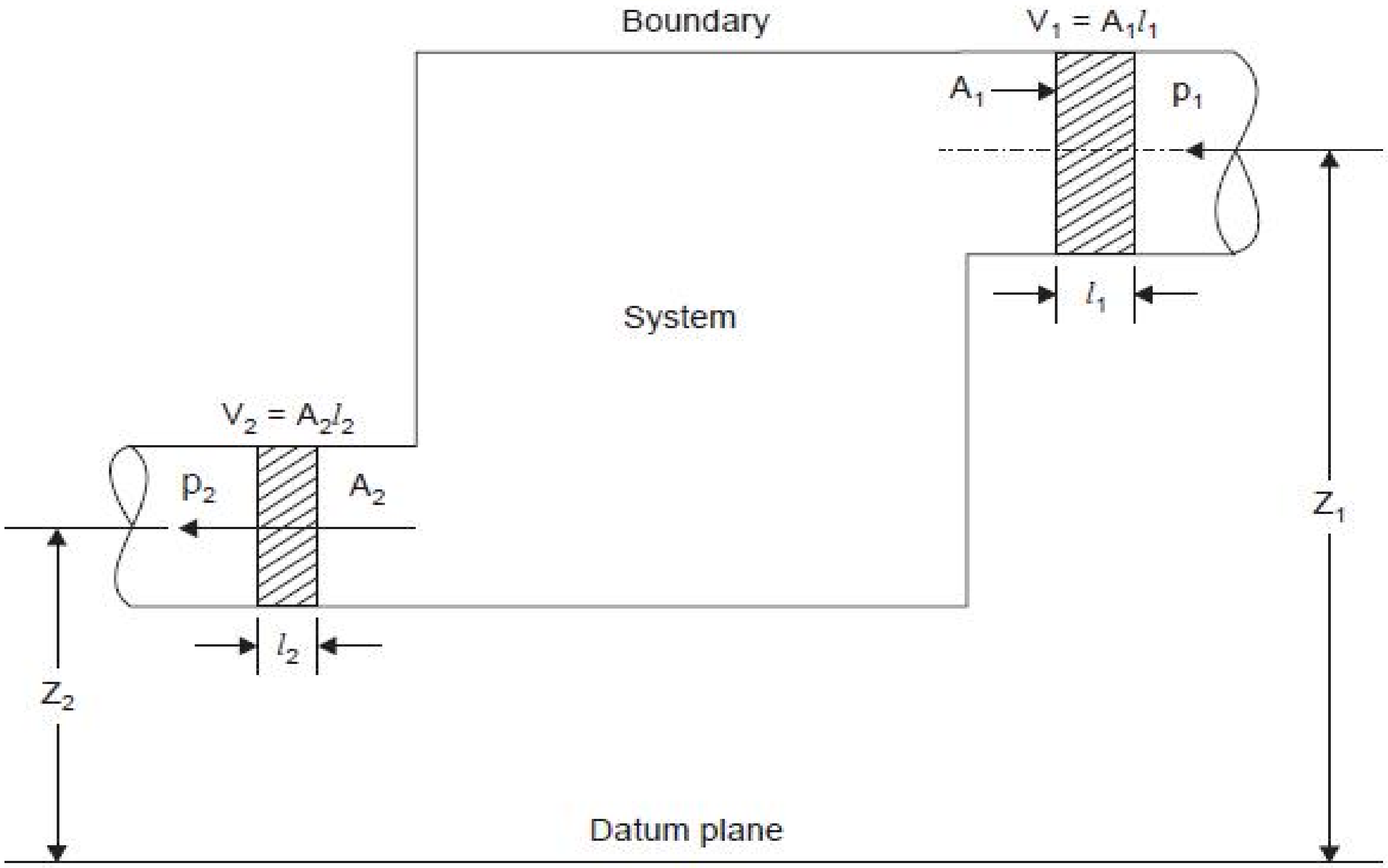
(i) The mass flow through the system remains constant.

(ii) Fluid is uniform in composition.

(iii) The only interaction between the system and surroundings are work and heat.

(iv) The state of fluid at any point remains constant with time.

(v) In the analysis only potential, kinetic and flow energies are considered



Boundary
$V_1 = A_1 l_1$
A_1
p_1
l_1
System
$V_2 = A_2 l_2$
p_2
A_2
l_2
Z_2
Z_1
Datum plane

Fig. 4.30

STEADY FLOW ENERGY EQUATION (S.F.E.E.)

The steady flow equation can be expressed as follows :

$$u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1 + Q = u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2 + W \qquad \text{...(4.45)}$$

$$(u_1 + p_1 v_1) + \frac{C_1^2}{2} + Z_1 g + Q = (u_2 + p_2 v_2) + \frac{C_2^2}{2} + Z_2 g + W$$

$$h_1 + \frac{C_1^2}{2} + Z_1 g + Q = h_2 + \frac{C_2^2}{2} + Z_2 g + W \qquad [\because \; h = u + pv]$$

If Z_1 and Z_2 are neglected, we get

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W \qquad \text{...[4.45 } (a)\text{]}$$

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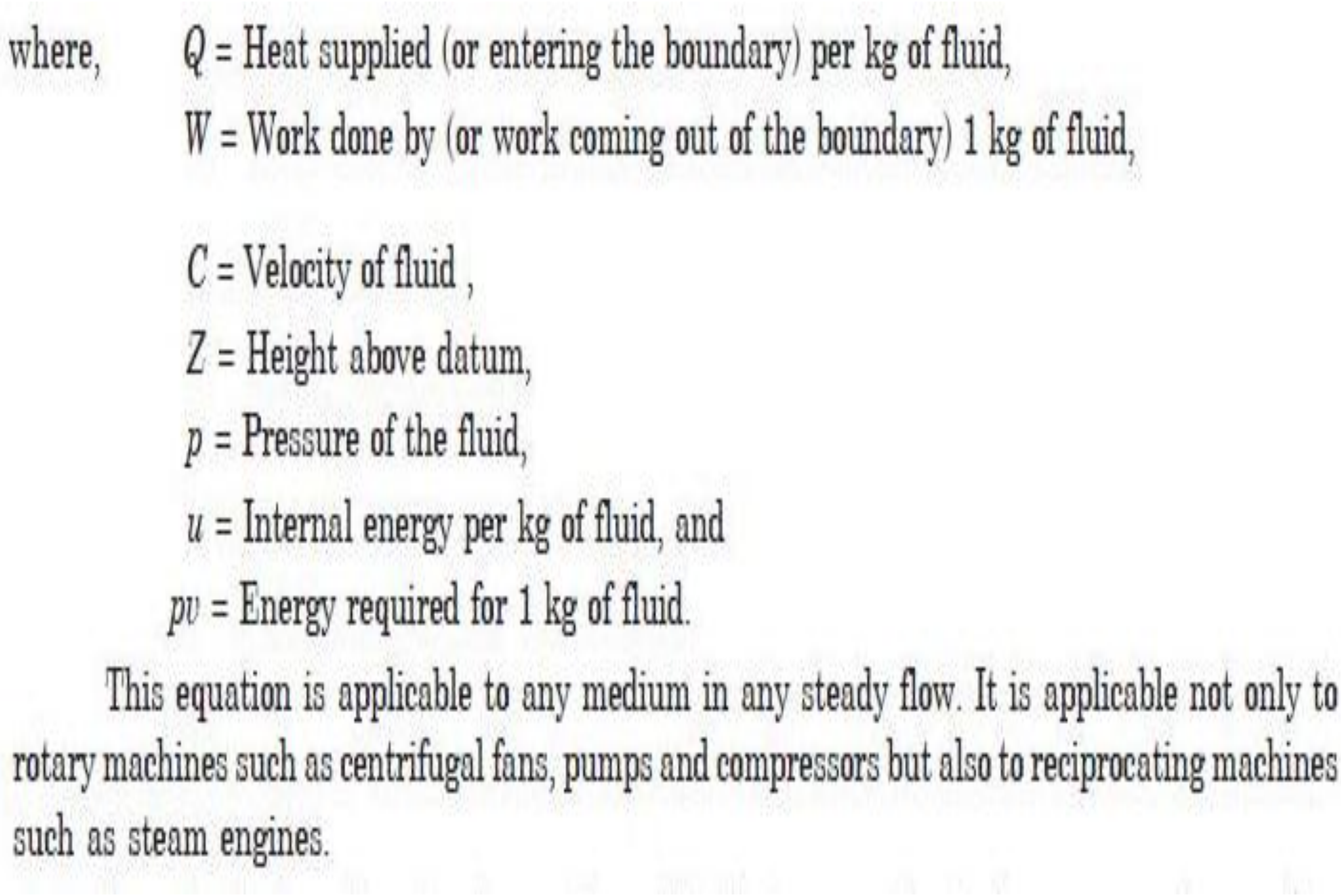
$$u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1 + Q = u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2 + W \qquad \text{...(4.45)}$$

$$(u_1 + p_1 v_1) + \frac{C_1^2}{2} + Z_1 g + Q = (u_2 + p_2 v_2) + \frac{C_2^2}{2} + Z_2 g + W$$

$$h_1 + \frac{C_1^2}{2} + Z_1 g + Q = h_2 + \frac{C_2^2}{2} + Z_2 g + W \qquad [\because \quad h = u + pv]$$

If Z_1 and Z_2 are neglected, we get

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W \qquad \text{...[4.45 }(a)\text{]}$$



where, Q = Heat supplied (or entering the boundary) per kg of fluid,

W = Work done by (or work coming out of the boundary) 1 kg of fluid,

C = Velocity of fluid ,

Z = Height above datum,

p = Pressure of the fluid,

u = Internal energy per kg of fluid, and

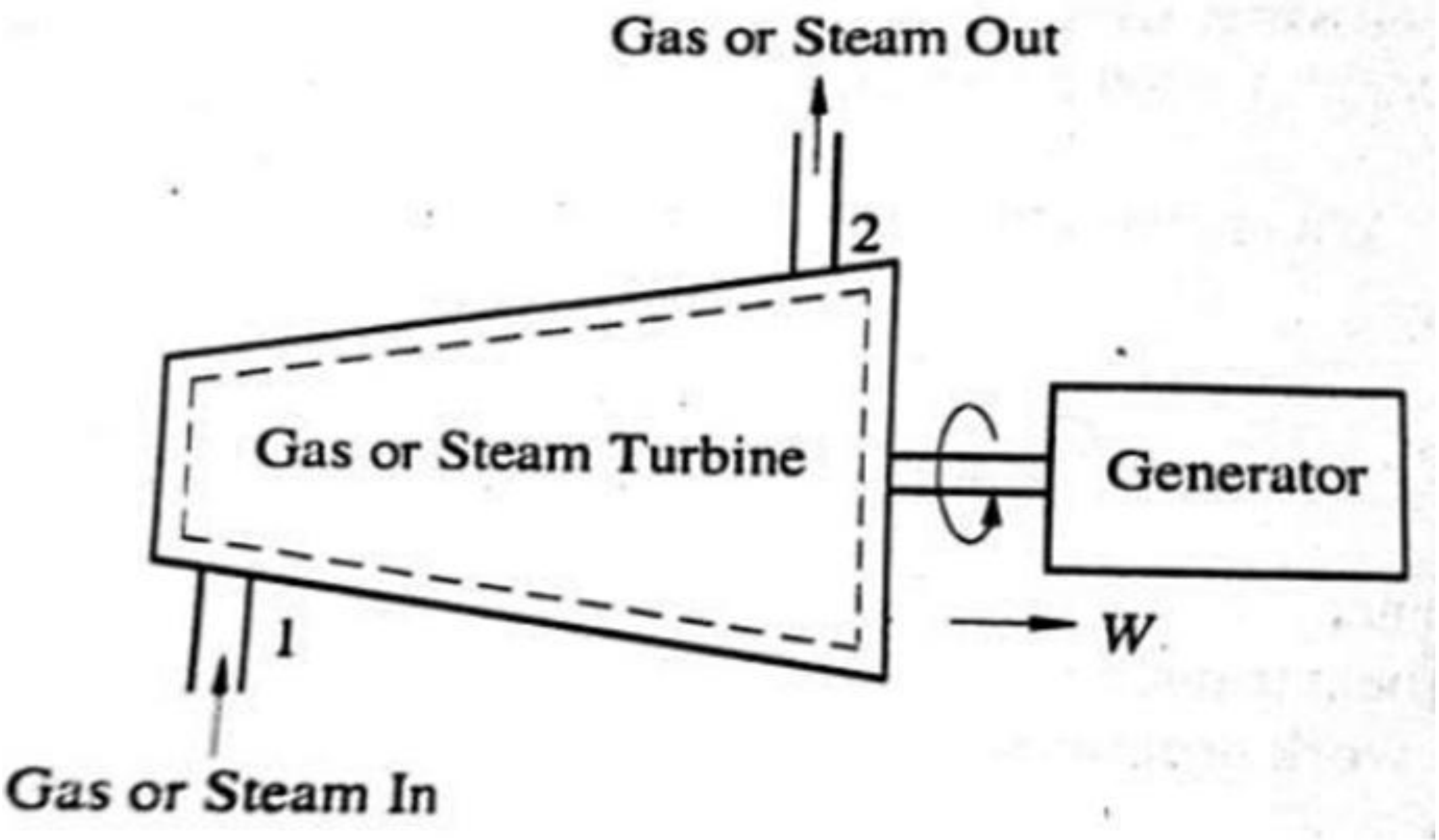
pv = Energy required for 1 kg of fluid.

This equation is applicable to any medium in any steady flow. It is applicable not only to rotary machines such as centrifugal fans, pumps and compressors but also to reciprocating machines such as steam engines.

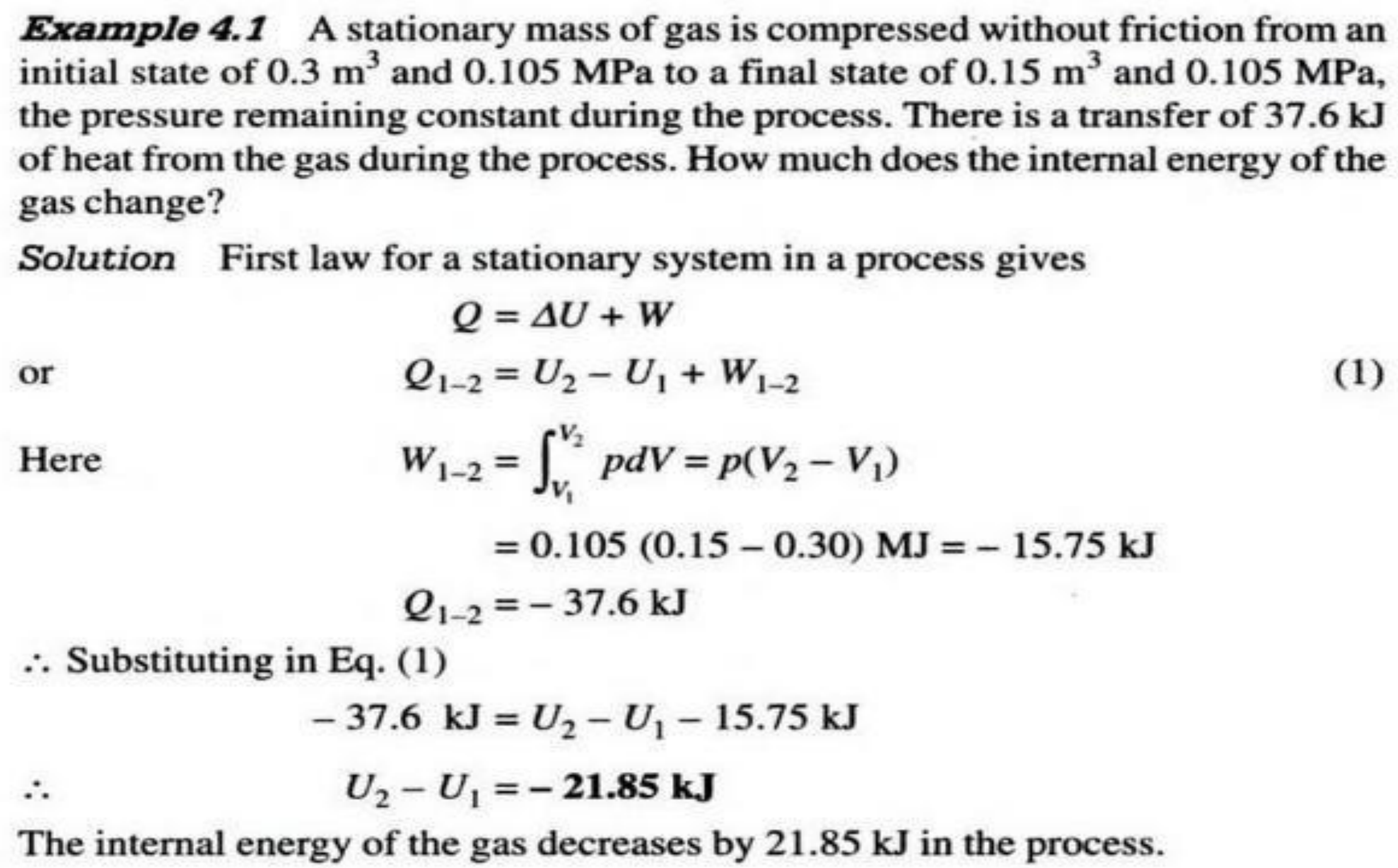
TURBINE

- A turbine is a rotary steady state steady flow machine whose purpose is the production of shaft power at the expense of the pressure of the working fluid.
- Two general classes of turbines are steam and gas turbines depending on the working substance used.
- Usually, changes in potential energy are negligible, as is the inlet kinetic energy.
- Normally, the process in the turbine is adiabatic and the work output reduces to decrease in enthalpy from the inlet to exit states.

TURBINE


Gas or Steam Out
2
Gas or Steam Turbine
Generator
1
W
Gas or Steam In

SOLVED PROBLEMS



Example 4.1 A stationary mass of gas is compressed without friction from an initial state of 0.3 m^3 and 0.105 MPa to a final state of 0.15 m^3 and 0.105 MPa, the pressure remaining constant during the process. There is a transfer of 37.6 kJ of heat from the gas during the process. How much does the internal energy of the gas change?

Solution First law for a stationary system in a process gives

$$Q = \Delta U + W$$

or $$Q_{1-2} = U_2 - U_1 + W_{1-2} \qquad (1)$$

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

$$= 0.105\ (0.15 - 0.30)\ \text{MJ} = -\ 15.75\ \text{kJ}$$

$$Q_{1-2} = -\ 37.6\ \text{kJ}$$

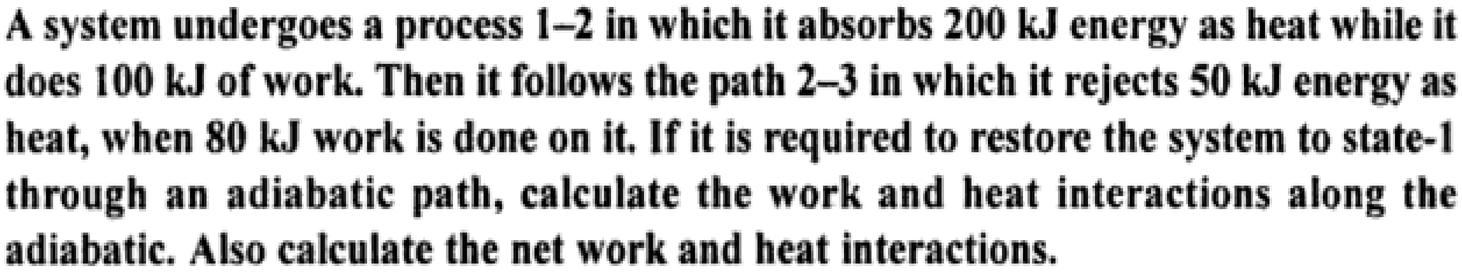
∴ Substituting in Eq. (1)

$$-\ 37.6\ \ \text{kJ} = U_2 - U_1 - 15.75\ \text{kJ}$$

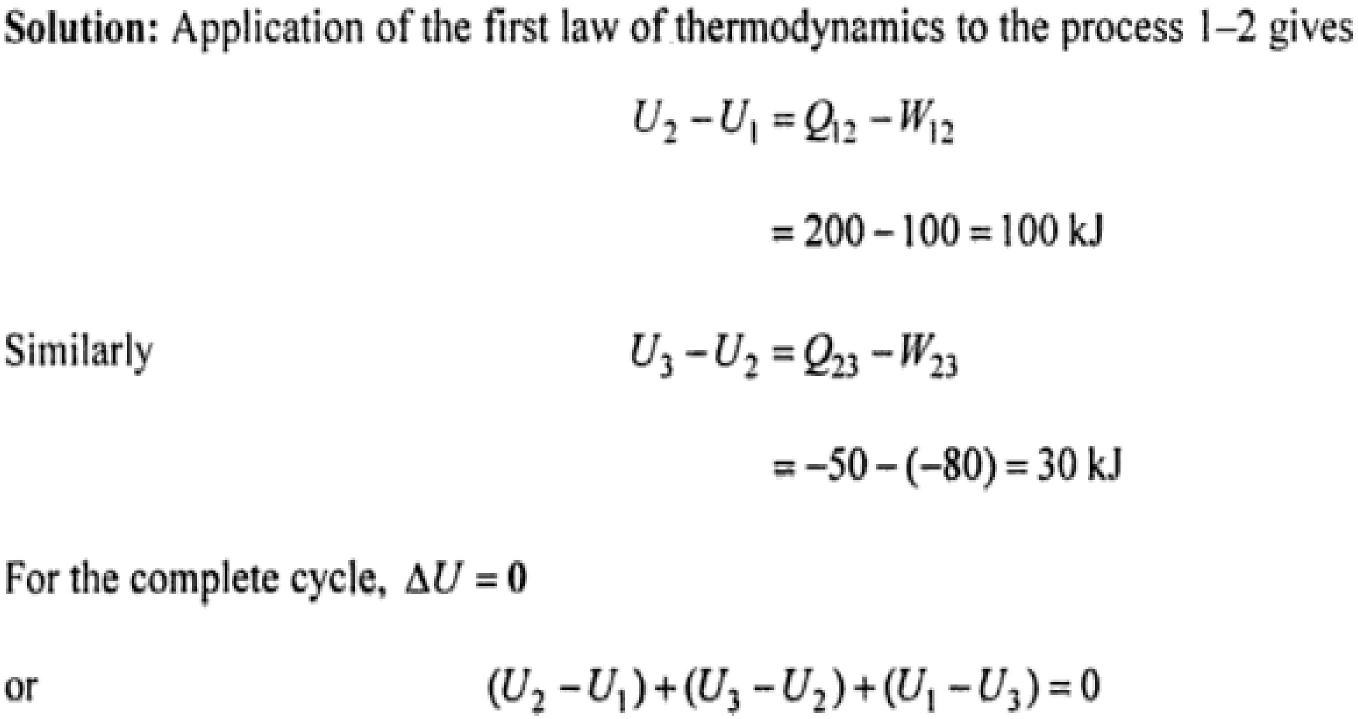
∴ $$U_2 - U_1 = \mathbf{-\ 21.85\ kJ}$$

The internal energy of the gas decreases by 21.85 kJ in the process.

SOLVED PROBLEMS



A system undergoes a process 1–2 in which it absorbs 200 kJ energy as heat while it does 100 kJ of work. Then it follows the path 2–3 in which it rejects 50 kJ energy as heat, when 80 kJ work is done on it. If it is required to restore the system to state-1 through an adiabatic path, calculate the work and heat interactions along the adiabatic. Also calculate the net work and heat interactions.



Solution: Application of the first law of thermodynamics to the process 1–2 gives

$$U_2 - U_1 = Q_{12} - W_{12}$$

$$= 200 - 100 = 100 \text{ kJ}$$

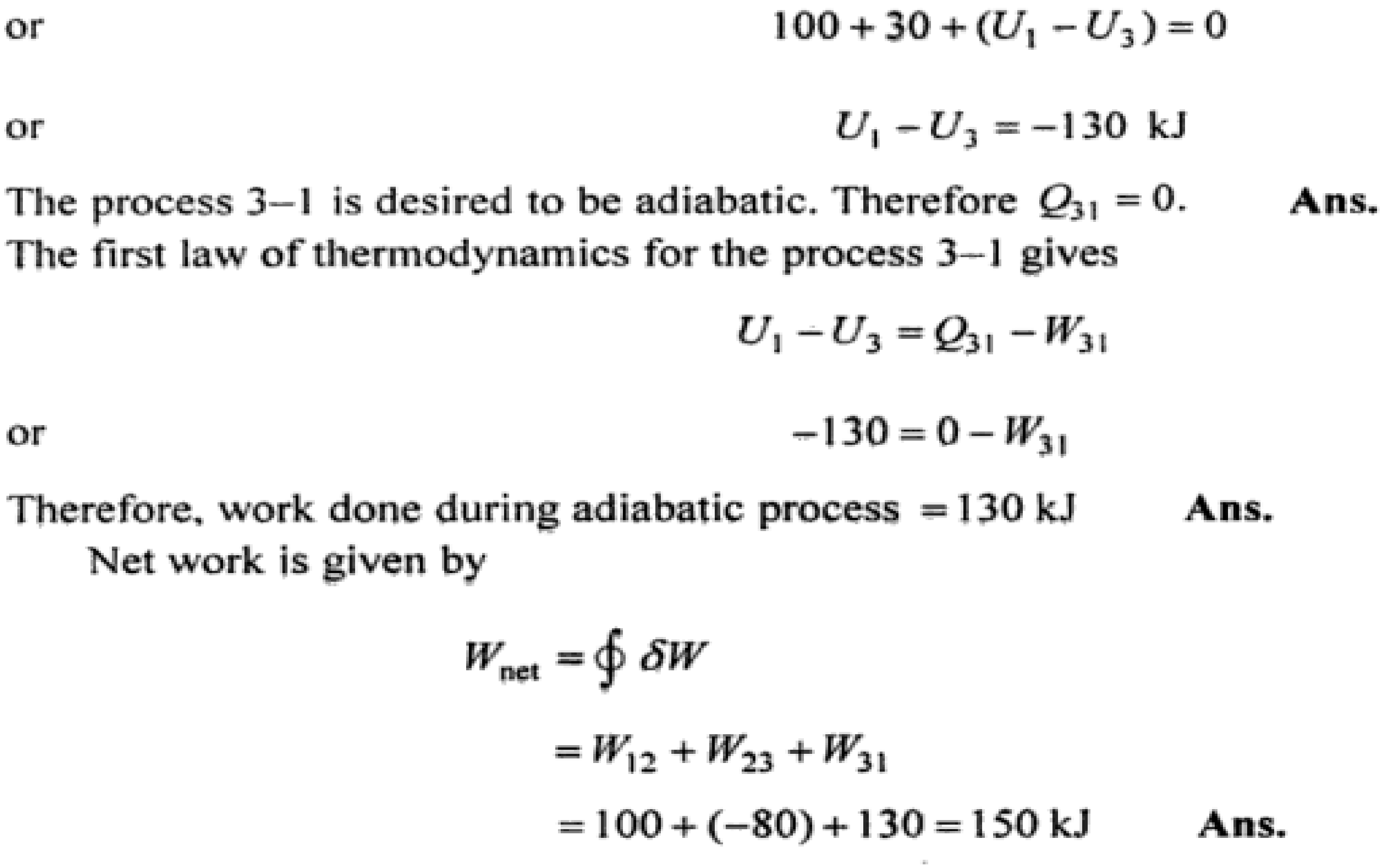
Similarly $$U_3 - U_2 = Q_{23} - W_{23}$$

$$= -50 - (-80) = 30 \text{ kJ}$$

For the complete cycle, $\Delta U = 0$

or $$(U_2 - U_1) + (U_3 - U_2) + (U_1 - U_3) = 0$$

SOLVED PROBLEMS



or $$100 + 30 + (U_1 - U_3) = 0$$

or $$U_1 - U_3 = -130 \text{ kJ}$$

The process 3–1 is desired to be adiabatic. Therefore $Q_{31} = 0$. **Ans.**
The first law of thermodynamics for the process 3–1 gives

$$U_1 - U_3 = Q_{31} - W_{31}$$

or $$-130 = 0 - W_{31}$$

Therefore, work done during adiabatic process $= 130$ kJ **Ans.**

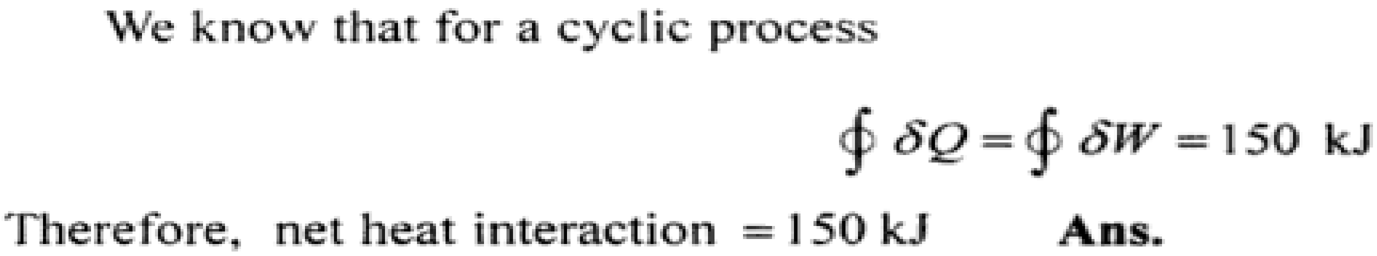
Net work is given by

$$W_{\text{net}} = \oint \delta W$$

$$= W_{12} + W_{23} + W_{31}$$

$$= 100 + (-80) + 130 = 150 \text{ kJ}$$ **Ans.**

SOLVED PROBLEMS



We know that for a cyclic process

$$\oint \delta Q = \oint \delta W = 150 \text{ kJ}$$

Therefore, net heat interaction $= 150$ kJ **Ans.**

SOLVED PROBLEMS

Example 4.2 When a system is taken from state *a* to state *b*, in Fig. 4.10 along path *acb*, 84 kJ of heat flow into the system, and the system does 32 kJ of work. (a) How much will the heat that flows into the system along path *adb* be, if the work done is 10.5 kJ? (b) When the system is returned from *b* to *a* along the curved path, the work done on the system is 21 kJ. Does the system absorb or liberate heat, and how much of the heat is absorbed or liberated? (c) If $U_a = 0$ and $U_d = 42$ kJ, find the heat absorbed in the processes *ad* and *db*.

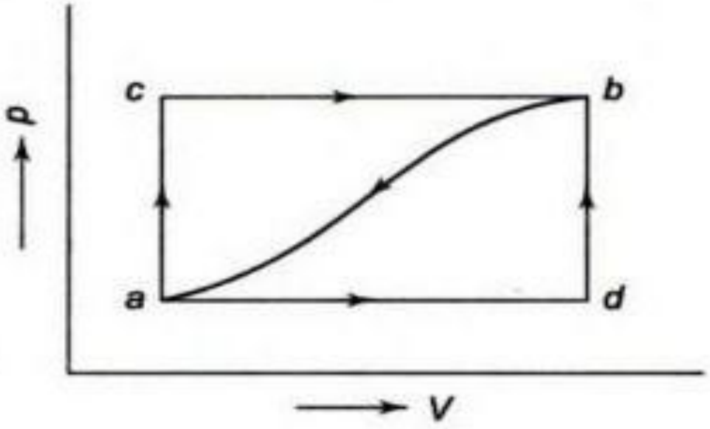


Fig. 4.10

Solution

$$Q_{acb} = 84 \text{ kJ}$$
$$W_{acb} = 32 \text{ kJ}$$

We have

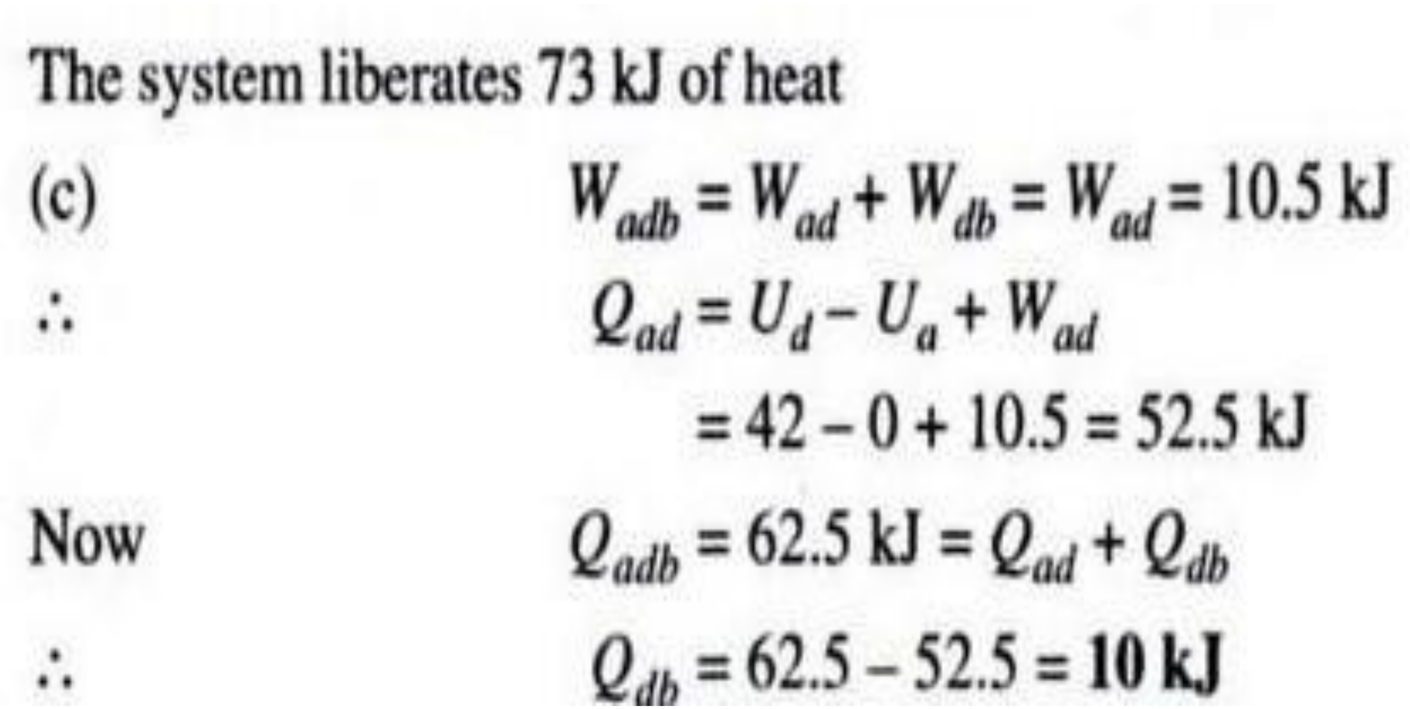
$$Q_{acb} = U_b - U_a + W_{acb}$$

$\therefore$
$$U_b - U_a = 84 - 32 = \mathbf{52\ kJ}$$

(a)
$$Q_{adb} = U_b - U_a + W_{adb}$$
$$= 52 + 10.5 = \mathbf{62.5\ kJ}$$

(b)
$$Q_{b-a} = U_a - U_b + W_{b-a}$$
$$= -52 - 21 = \mathbf{-73\ kJ}$$

SOLVED PROBLEMS



The system liberates 73 kJ of heat

(c) $$W_{adb} = W_{ad} + W_{db} = W_{ad} = 10.5 \text{ kJ}$$

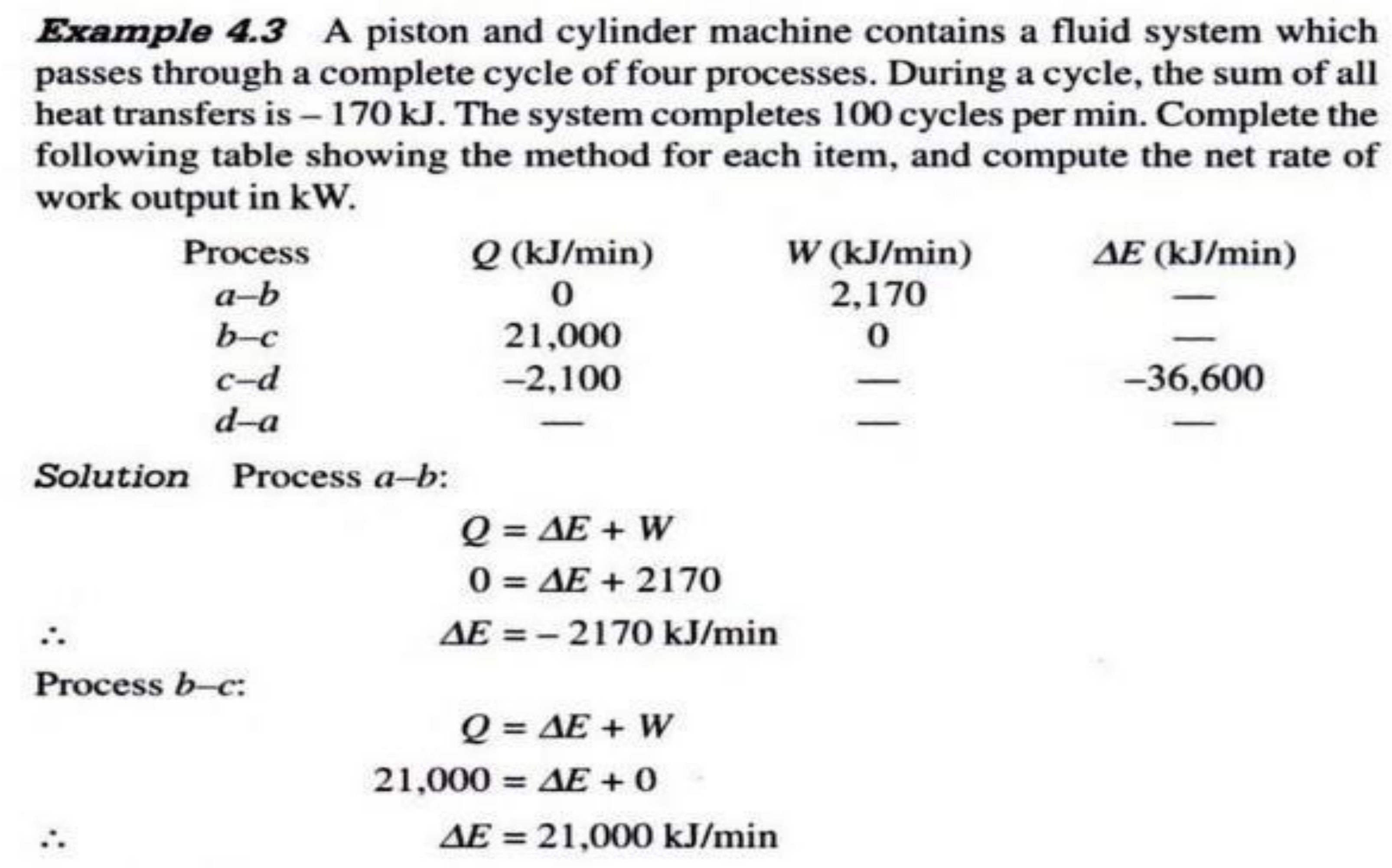
$\therefore$ $$Q_{ad} = U_d - U_a + W_{ad}$$

$$= 42 - 0 + 10.5 = 52.5 \text{ kJ}$$

Now $$Q_{adb} = 62.5 \text{ kJ} = Q_{ad} + Q_{db}$$

$\therefore$ $$Q_{db} = 62.5 - 52.5 = 10 \text{ kJ}$$

SOLVED PROBLEMS



Example 4.3 A piston and cylinder machine contains a fluid system which passes through a complete cycle of four processes. During a cycle, the sum of all heat transfers is – 170 kJ. The system completes 100 cycles per min. Complete the following table showing the method for each item, and compute the net rate of work output in kW.

Process	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a–b	0	2,170	—
b–c	21,000	0	—
c–d	–2,100	—	–36,600
d–a	—	—	—

Solution Process a–b:

$$Q = \Delta E + W$$

$$0 = \Delta E + 2170$$

$$\therefore \quad \Delta E = -\,2170 \text{ kJ/min}$$

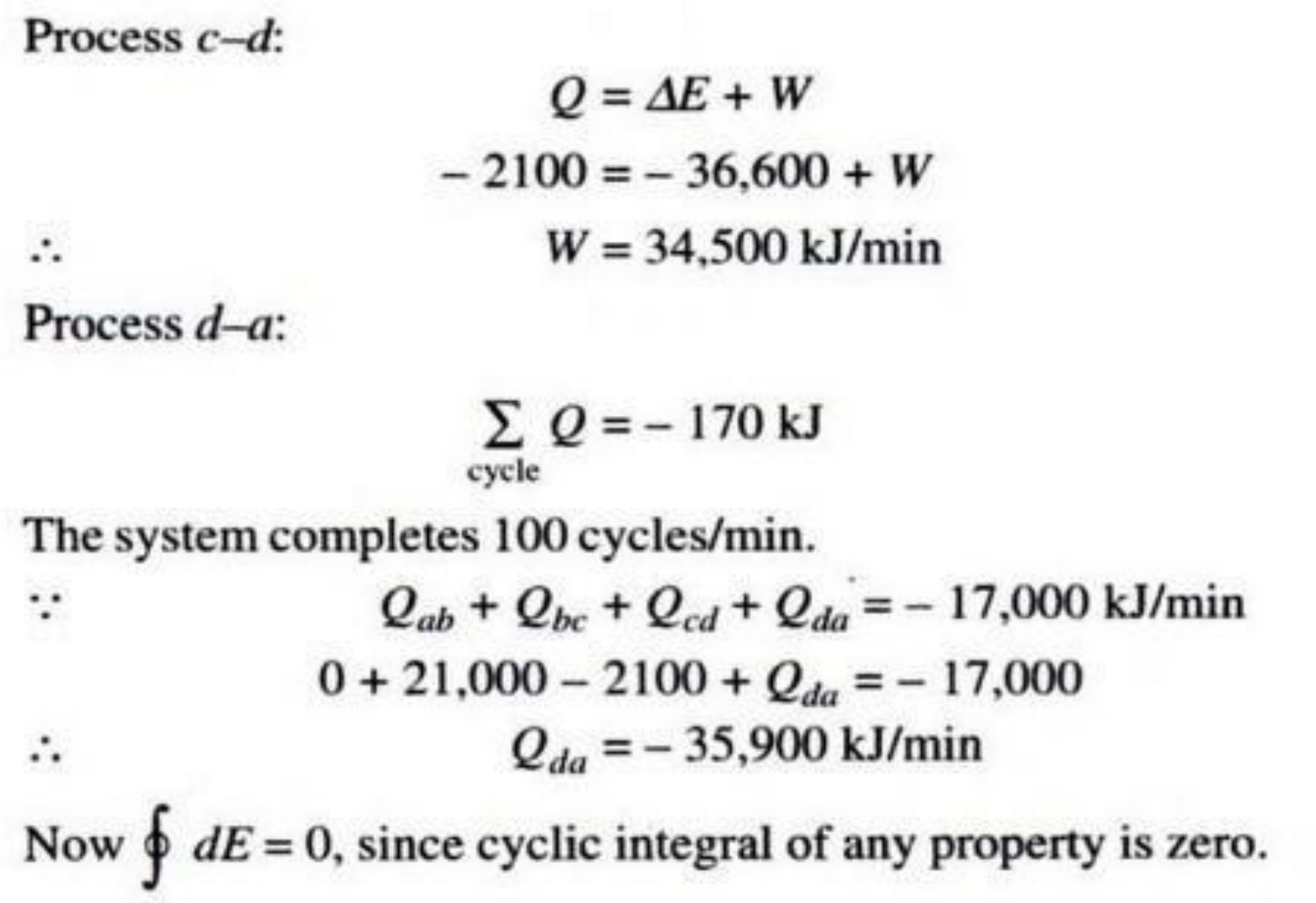
Process b–c:

$$Q = \Delta E + W$$

$$21{,}000 = \Delta E + 0$$

$$\therefore \quad \Delta E = 21{,}000 \text{ kJ/min}$$

SOLVED PROBLEMS



Process *c–d*:

$$Q = \Delta E + W$$

$$-2100 = -36{,}600 + W$$

$$\therefore \quad W = 34{,}500 \text{ kJ/min}$$

Process *d–a*:

$$\sum_{\text{cycle}} Q = -170 \text{ kJ}$$

The system completes 100 cycles/min.

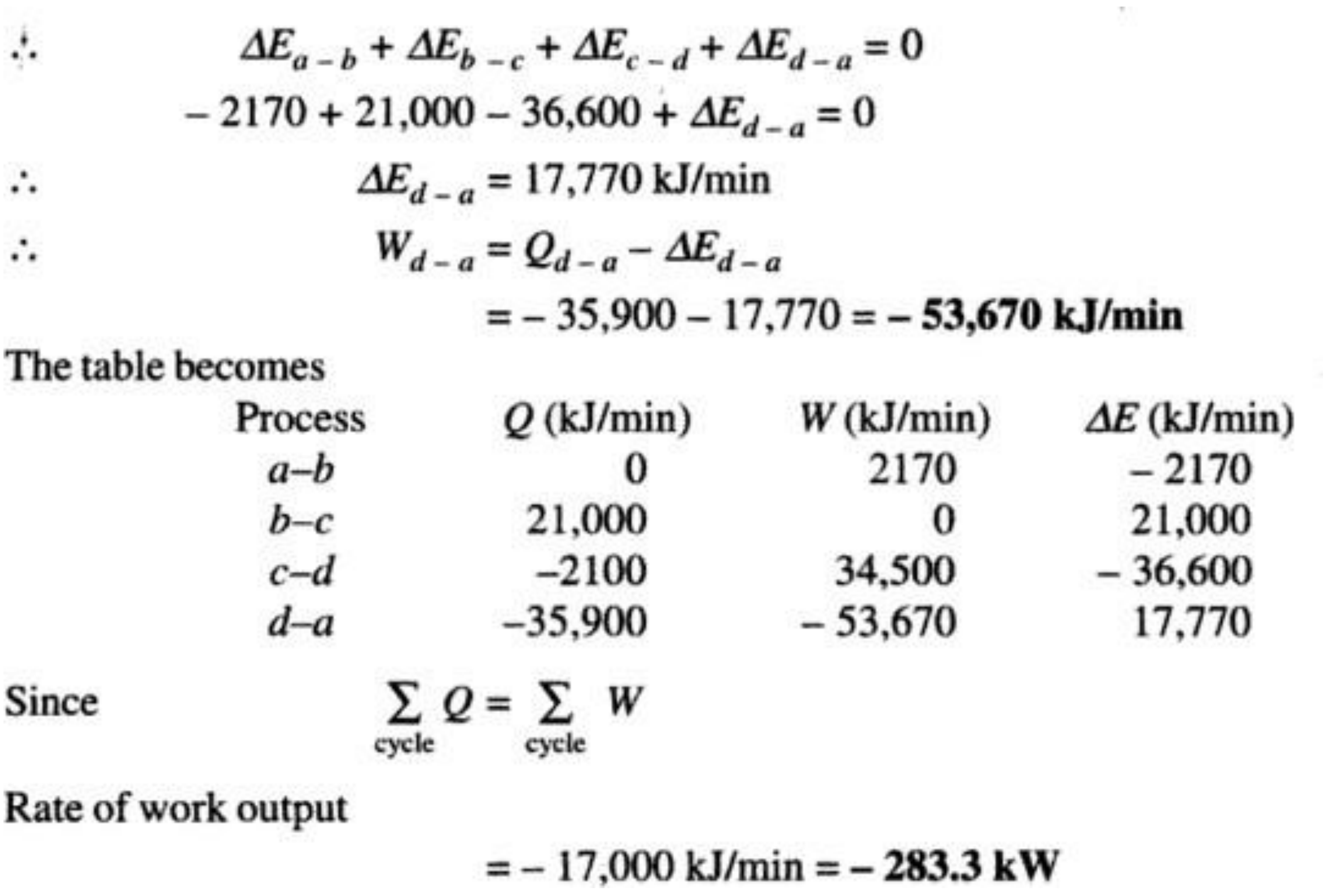
$$\because \quad Q_{ab} + Q_{bc} + Q_{cd} + Q_{da} = -17{,}000 \text{ kJ/min}$$

$$0 + 21{,}000 - 2100 + Q_{da} = -17{,}000$$

$$\therefore \quad Q_{da} = -35{,}900 \text{ kJ/min}$$

Now $\oint dE = 0$, since cyclic integral of any property is zero.

SOLVED PROBLEMS



$$\therefore \quad \Delta E_{a-b} + \Delta E_{b-c} + \Delta E_{c-d} + \Delta E_{d-a} = 0$$

$$-2170 + 21{,}000 - 36{,}600 + \Delta E_{d-a} = 0$$

$$\therefore \quad \Delta E_{d-a} = 17{,}770 \text{ kJ/min}$$

$$\therefore \quad W_{d-a} = Q_{d-a} - \Delta E_{d-a}$$

$$= -35{,}900 - 17{,}770 = \mathbf{-53{,}670\ kJ/min}$$

The table becomes

Process	Q (kJ/min)	W (kJ/min)	ΔE (kJ/min)
a–b	0	2170	– 2170
b–c	21,000	0	21,000
c–d	–2100	34,500	– 36,600
d–a	–35,900	– 53,670	17,770

Since $\sum_{\text{cycle}} Q = \sum_{\text{cycle}} W$

Rate of work output

$$= -17{,}000 \text{ kJ/min} = \mathbf{-283.3\ kW}$$

A system receives 0.7 kg/s of a fluid at a velocity of 40 m/s at an elevation of 25 m. At the exit, at an elevation of 50 m, the fluid leaves at a velocity of 10 m/s. The specific enthalpies of entering and leaving fluids are 2700 kJ/kg and 2900 kJ/kg respectively. If the work done by the system is 5 kW, determine the heat transformation.

Solution: Given: $\dot{m}_1 = \dot{m}_2 = \dot{m} = 0.7$ kg/s, $V_1 = 40$ m/s, $z_1 = 25$ m, $h_1 = 2700$ kJ/kg,

$$V_2 = 10 \text{ m/s}, z_2 = 50 \text{ m}, h_2 = 2900 \text{ kJ/kg}$$

Then

$$W_{12} = 5 \text{ kW} = 5 \text{ kJ/s}$$

Therefore,

$$w = \frac{W_{12}}{\dot{m}} = \frac{5}{0.7} = 7.143 \text{ kJ/kg}$$

We know that the steady state steady flow energy equation for $\dot{m}_1 = \dot{m}_2$ is:

$$q + h_1 + \frac{V_1^2}{2} + gz_1 = h_2 + \frac{V_2^2}{2} + gz_2 + w$$

Therefore,

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

$$= (2900 - 2700) + \left(\frac{10^2 - 40^2}{2}\right) \times 10^{-3} + (50 - 25) \times 9.81 \times 10^{-3} + 7.143$$

$$= 206.64 \text{ kJ/kg}$$

Total heat transferred $= 206.64 \times 0.7 = 144.65$ kW **Ans.**

INDUSTRIAL APPLICATIONS

- Automobile industries.
- Refrigeration industries
- Air craft applications
- Defense industries
- Thermal power plants
- Chemical industries
- Textile industries etc.

SELF LEARNING QUESTIONS

- What is meant by thermodynamic equilibrium? Explain with the help of examples.
- What is meant by SFEE and derive it and reduce it for the turbine.
- Write about constant volume gas Thermometer? Why it is preferred over a constant pressure gas Thermometer.
- Distinguish between macroscopic and microscopic point of view?

ASSIGNMENT EXERCISES

1. Discuss Quasi Static process, what are its characteristics?
2. Discuss First law of thermodynamics, explain Joule's experiment.
3. A blower handles 1kg/s of air at 200C and consuming a power of 15 kw. The inlet and outlet velocities of air are 100 m/s and 150 m/s respectively. Find the exit air temperature, assuming adiabatic conditions. Take C*p* of air as 1.005 kJ/kgk.
4. When a stationary mass of gas was compressed without friction at constant pressure, its initial state of 0.4m3 and 0.105MPa was found to change to final state of 0.20m3 and 0.105MPa. There was a transfer of 42.5kJ of heat from the gas during the process. Determine the change in internal energy of the gas?

THANK YOU

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ENGINEERING THERMODYNAMICS

2nd Year B. Tech I- sem, Mechanical Engineering

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COURSE OBJECTIVES

UNIT - 1	CO1:To understand the concepts of energy transformation, conversion of heat into work.
UNIT - 2	CO2:To acquire knowledge about the fundamentals of thermodynamic laws, the concept of entropy, and principles
UNIT - 3	CO3: To understand how the change of state results in a process.
UNIT - 4	CO4: To understand the various gas laws, psychrometric properties and chart.
UNIT - 5	CO5: To learn the importance of thermodynamic cycles, and the derivation of efficiency.

UNIT 2

BASICS OF THERMODYNAMICS

CO2:To acquire knowledge about the fundamentals of thermodynamic laws, the concept of entropy, and principles

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UNIT – II (SYLLABUS)

Introduction - System - Types of Systems

- Limitations of the First Law - Thermal Reservoir, Heat Engine, Heat pump
- Second Law of Thermodynamics, Kelvin-Planck and Clausius Statements
- PMM of Second kind, Carnot’s principle
- Clausius Inequality, Entropy
- Energy Equation, Availability and Irreversibility
- Thermodynamic Potentials, Gibbs and Helmholtz Functions
- Third Law of Thermodynamics.

COURSE OUTLINE

UNIT -1

LECTURE	LECTURE TOPIC	KEY ELEMENTS	Learning objectives (2 to 3 objectives)
1	**Limitations of the First Law - Thermal Reservoir**	**Definition of Energy reservoir**	**Understanding the draw backs (B2)**
2	Heat Engine, Heat pump, Parameters of performance	Performance parameters like efficiency	Understanding different types of efficiencies (B2)
3	**Second Law of Thermodynamics, Kelvin-Planck and Clausius Statements and their Equivalence**	**Temperature flow**	**Understanding Heat and work conversion (B2)**
4	Corollaries, PMM of Second kind	Possible engine and impossible engine	Understanding PMM II (B2)
5	**Carnot's principle, Carnot cycle and its specialties**	**Carnot's cycle**	**Performance evaluation of Carnot's cycle (B5)**
6	Clausius Inequality, Entropy, Principle of Entropy Increase – Energy Equation,	Entropy principle	Knowledge on entropy (B2)
7	**Availability and Irreversibility**	**Available and unavailable energies**	**Maximum possible work estimation (B4)**
8	Thermodynamic Potentials, Gibbs and Helmholtz Functions,	Gibbs function, Helmholtz functions	Heat and work calculations (B4)

LECTURE 2

Second law of thermodynamics - Entropy

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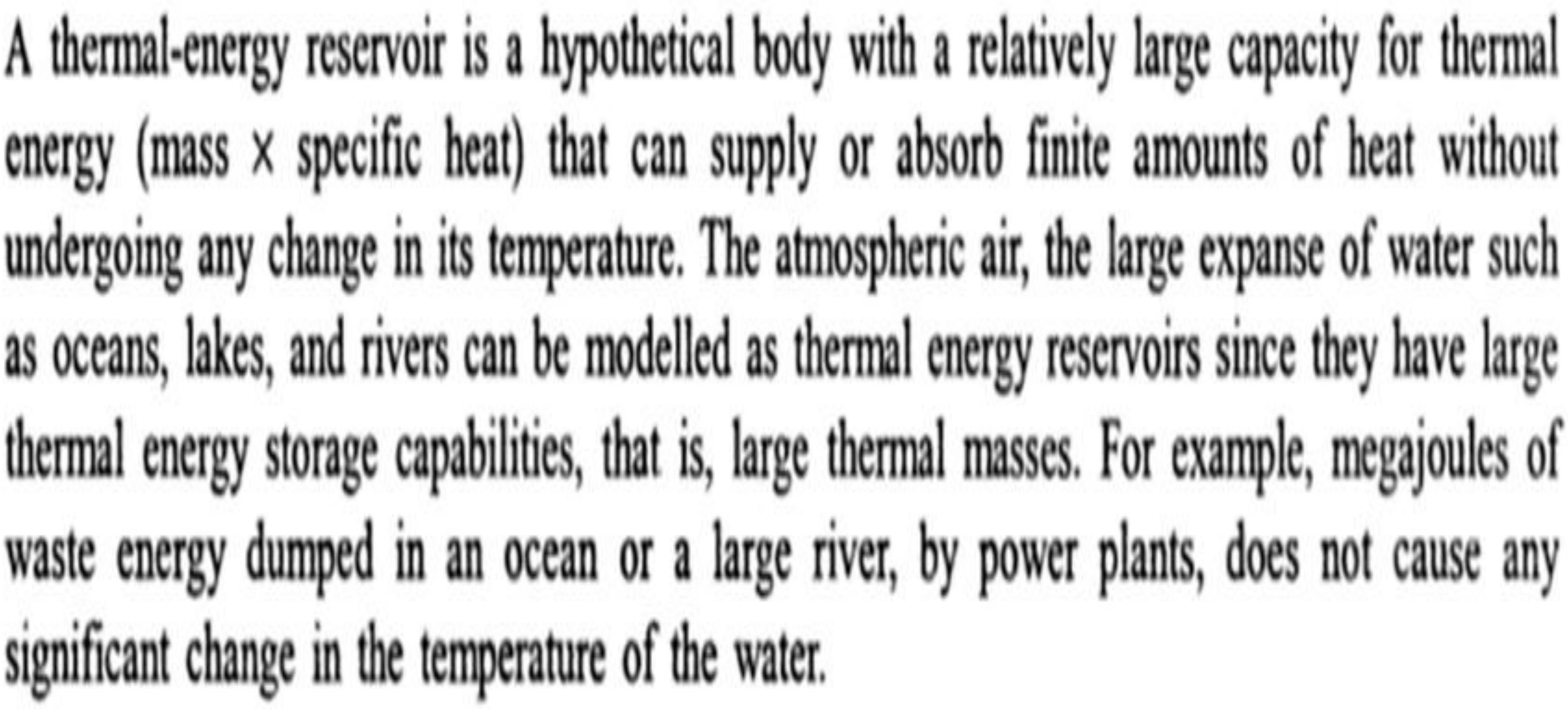
LIMITATIONS OF FIRST LAW OF THERMODYNAMICS

- First law does not provide any information regarding the direction processes will take whether it is a spontaneous or a non spontaneous process.
- The first law of thermodynamics merely indicates that in any process there is a transformation between the various forms of energy involved in the process but provides no information regarding the feasibility of such transformation.

LIMITATIONS OF FIRST LAW OF THERMODYNAMICS

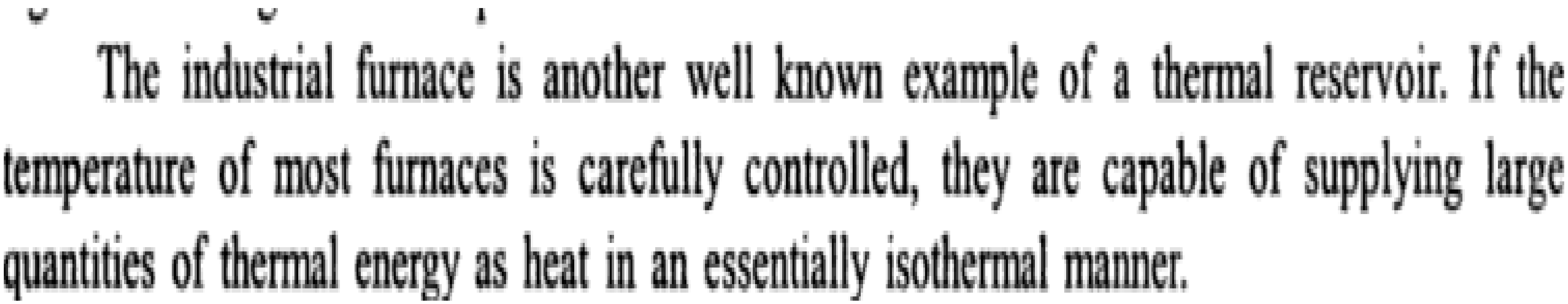
- First law of thermodynamics has not provided the information about the direction of the process.
- First law of thermodynamics has not provided the information that how much quantity of complete energy of the system will be converted in to the work energy.
- First law of thermodynamics has not provided any information about the conditions in which conversion of heat energy in work energy is possible.

THERMAL ENERGY RESERVOIR

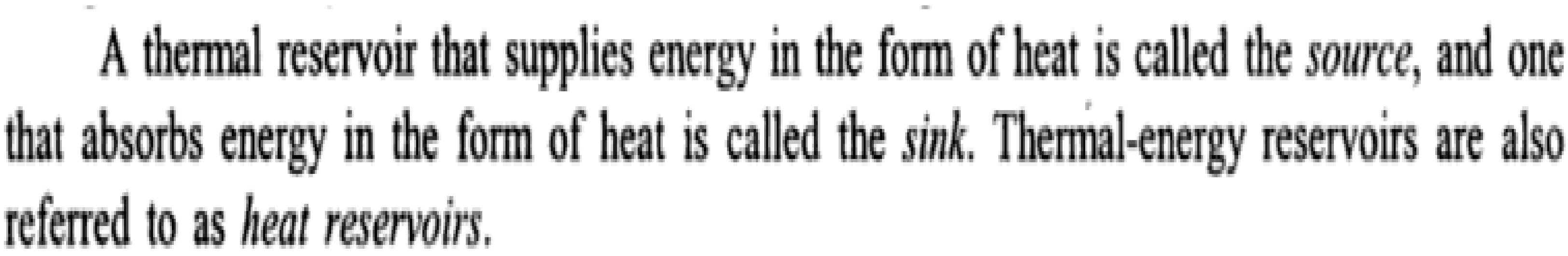


A thermal-energy reservoir is a hypothetical body with a relatively large capacity for thermal energy (mass × specific heat) that can supply or absorb finite amounts of heat without undergoing any change in its temperature. The atmospheric air, the large expanse of water such as oceans, lakes, and rivers can be modelled as thermal energy reservoirs since they have large thermal energy storage capabilities, that is, large thermal masses. For example, megajoules of waste energy dumped in an ocean or a large river, by power plants, does not cause any significant change in the temperature of the water.

THERMAL ENERGY RESERVOIR

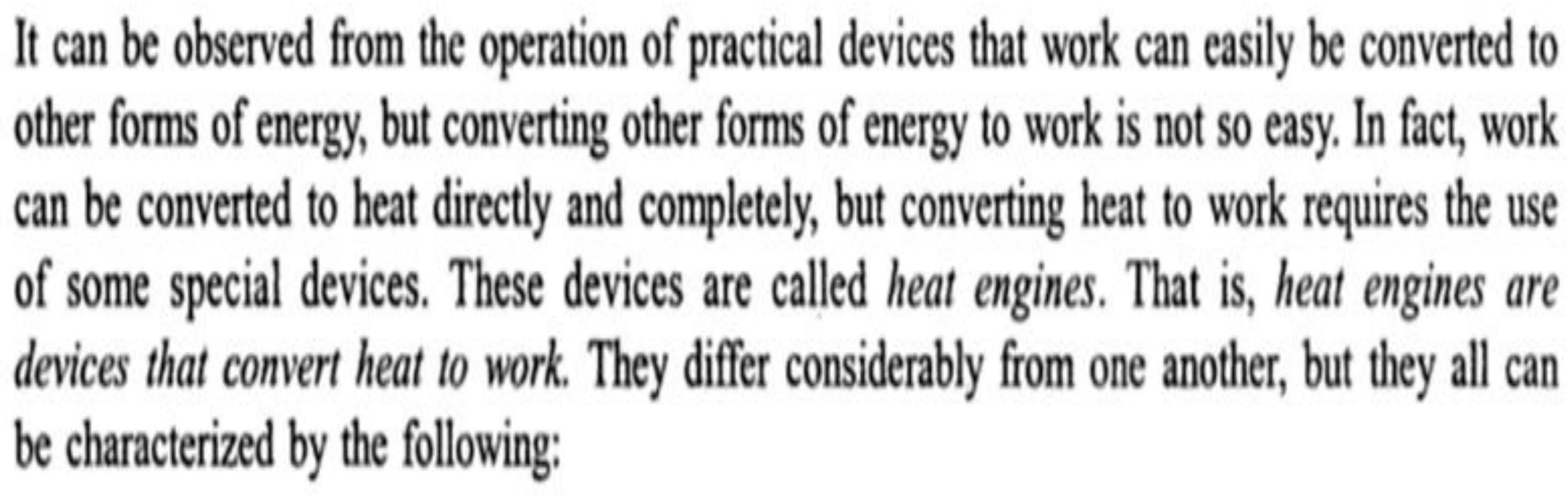


The industrial furnace is another well known example of a thermal reservoir. If the temperature of most furnaces is carefully controlled, they are capable of supplying large quantities of thermal energy as heat in an essentially isothermal manner.



A thermal reservoir that supplies energy in the form of heat is called the *source*, and one that absorbs energy in the form of heat is called the *sink*. Thermal-energy reservoirs are also referred to as *heat reservoirs*.

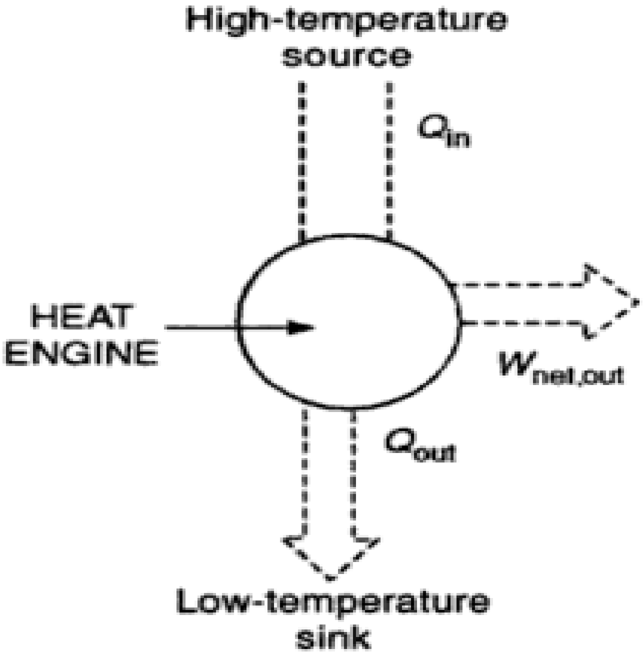
HEAT ENGINE



It can be observed from the operation of practical devices that work can easily be converted to other forms of energy, but converting other forms of energy to work is not so easy. In fact, work can be converted to heat directly and completely, but converting heat to work requires the use of some special devices. These devices are called *heat engines*. That is, *heat engines are devices that convert heat to work*. They differ considerably from one another, but they all can be characterized by the following:

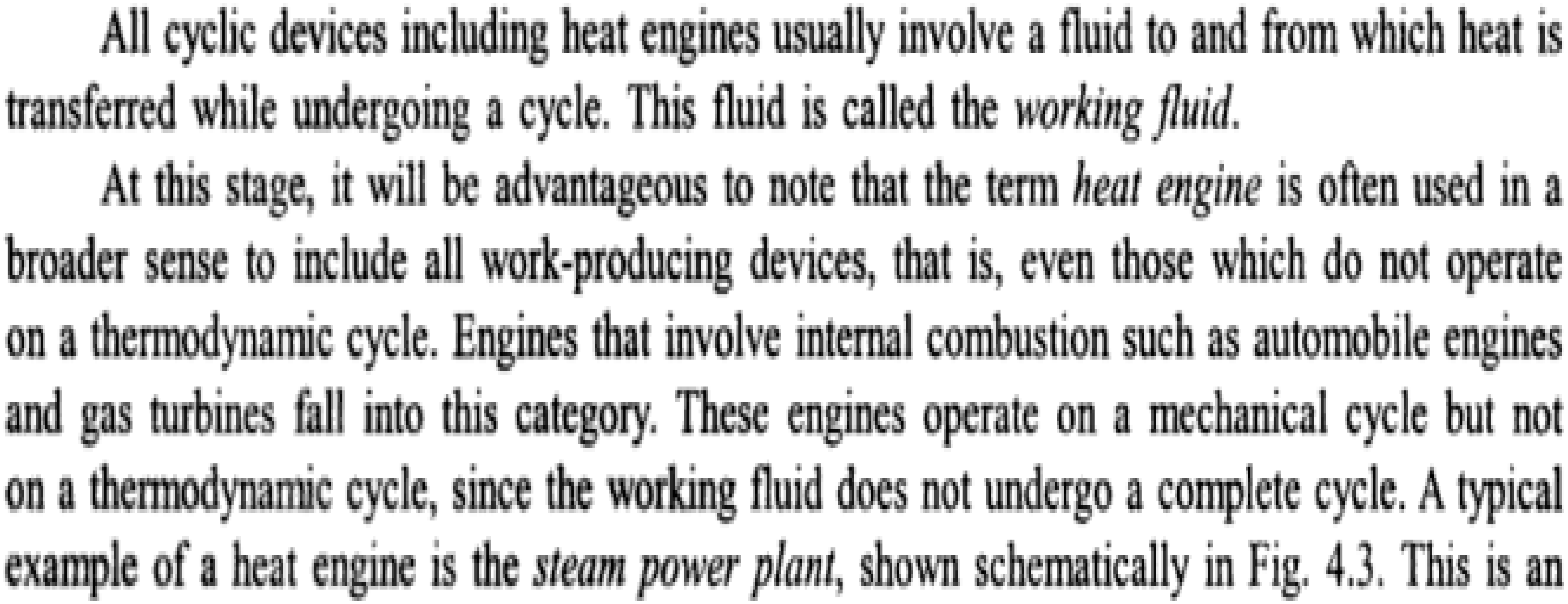
HEAT ENGINE

- Schematically, all heat engines can be represented as shown in Fig. 4.2.
- They receive heat from a source.
- They convert part of this heat to work.
- They reject the remaining heat to a sink.
- They operate on a cycle.



Schematic diagram of a heat engine.

HEAT ENGINE



All cyclic devices including heat engines usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the *working fluid*.

At this stage, it will be advantageous to note that the term *heat engine* is often used in a broader sense to include all work-producing devices, that is, even those which do not operate on a thermodynamic cycle. Engines that involve internal combustion such as automobile engines and gas turbines fall into this category. These engines operate on a mechanical cycle but not on a thermodynamic cycle, since the working fluid does not undergo a complete cycle. A typical example of a heat engine is the *steam power plant*, shown schematically in Fig. 4.3. This is an

HEAT ENGINE

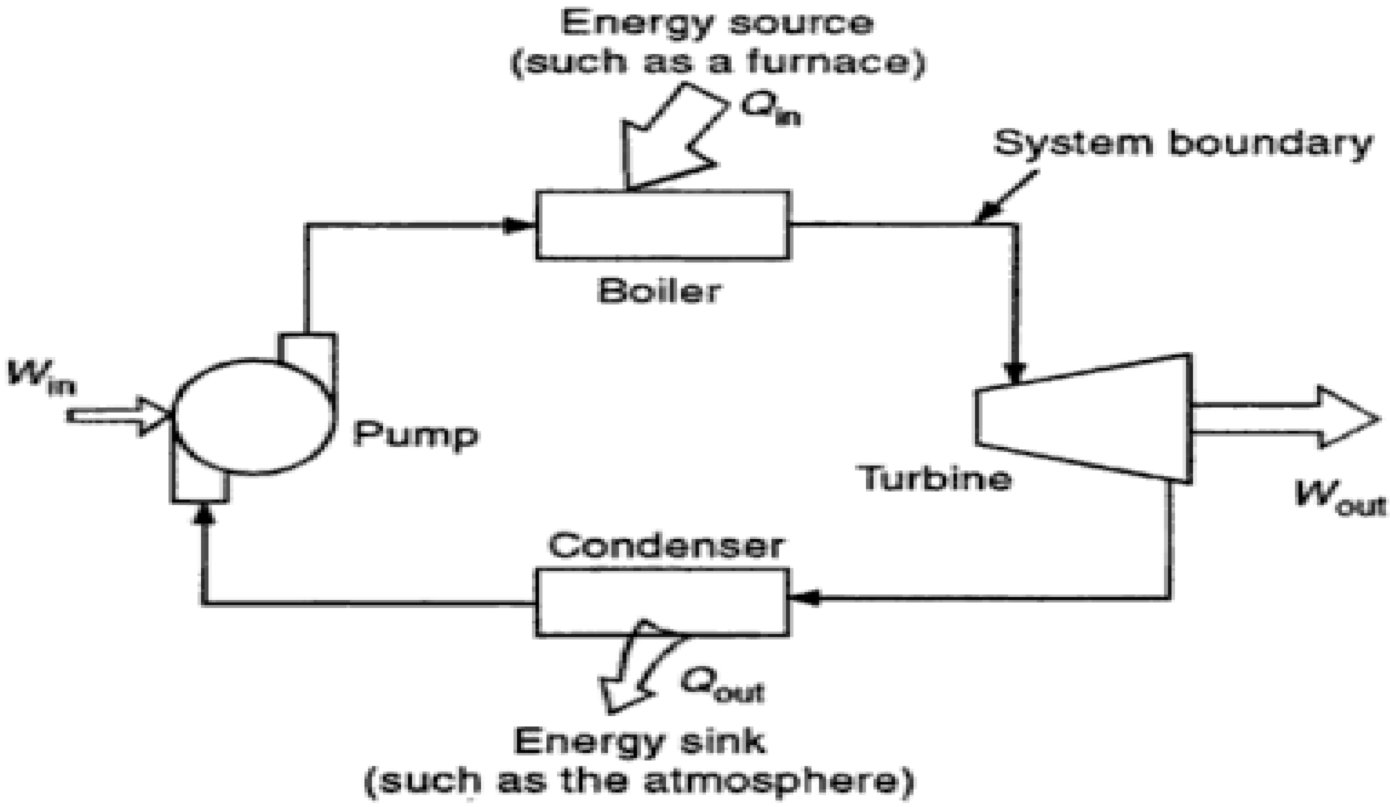
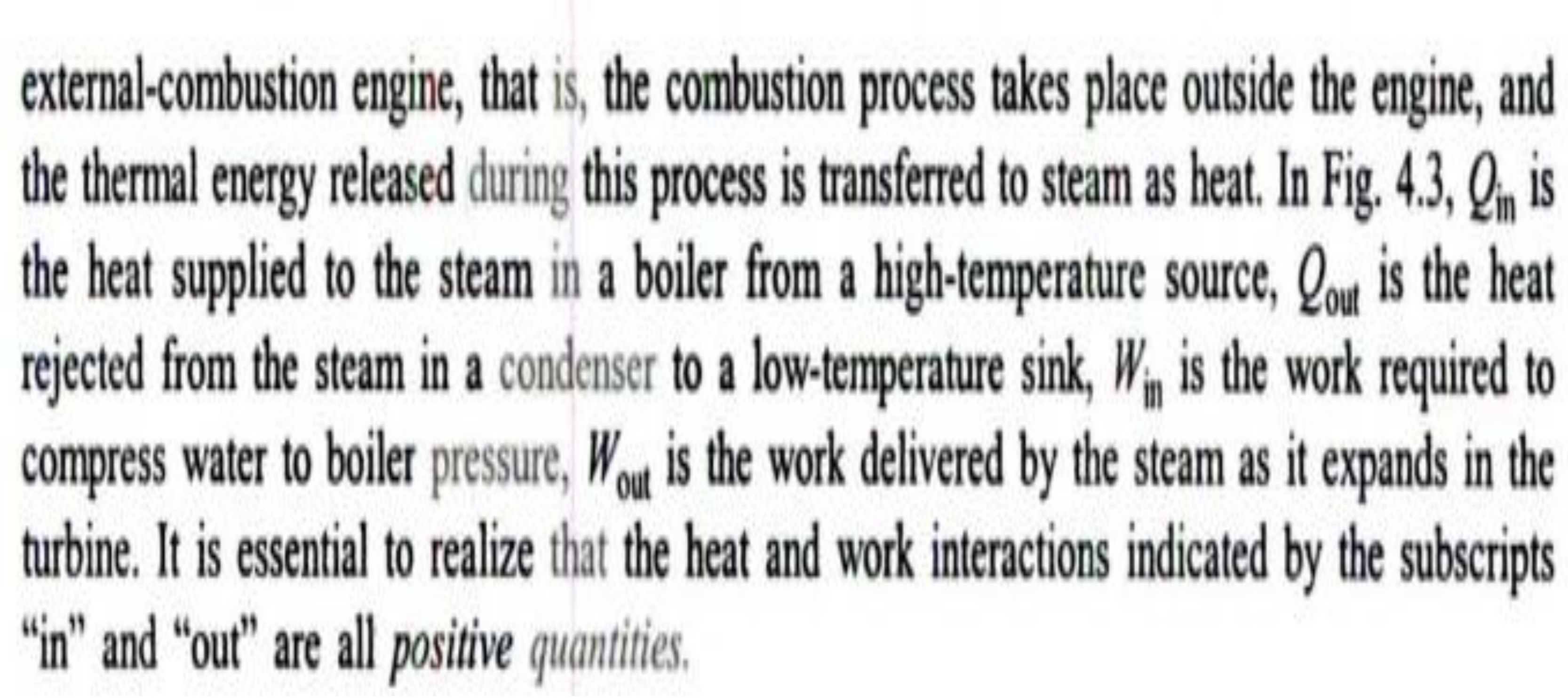


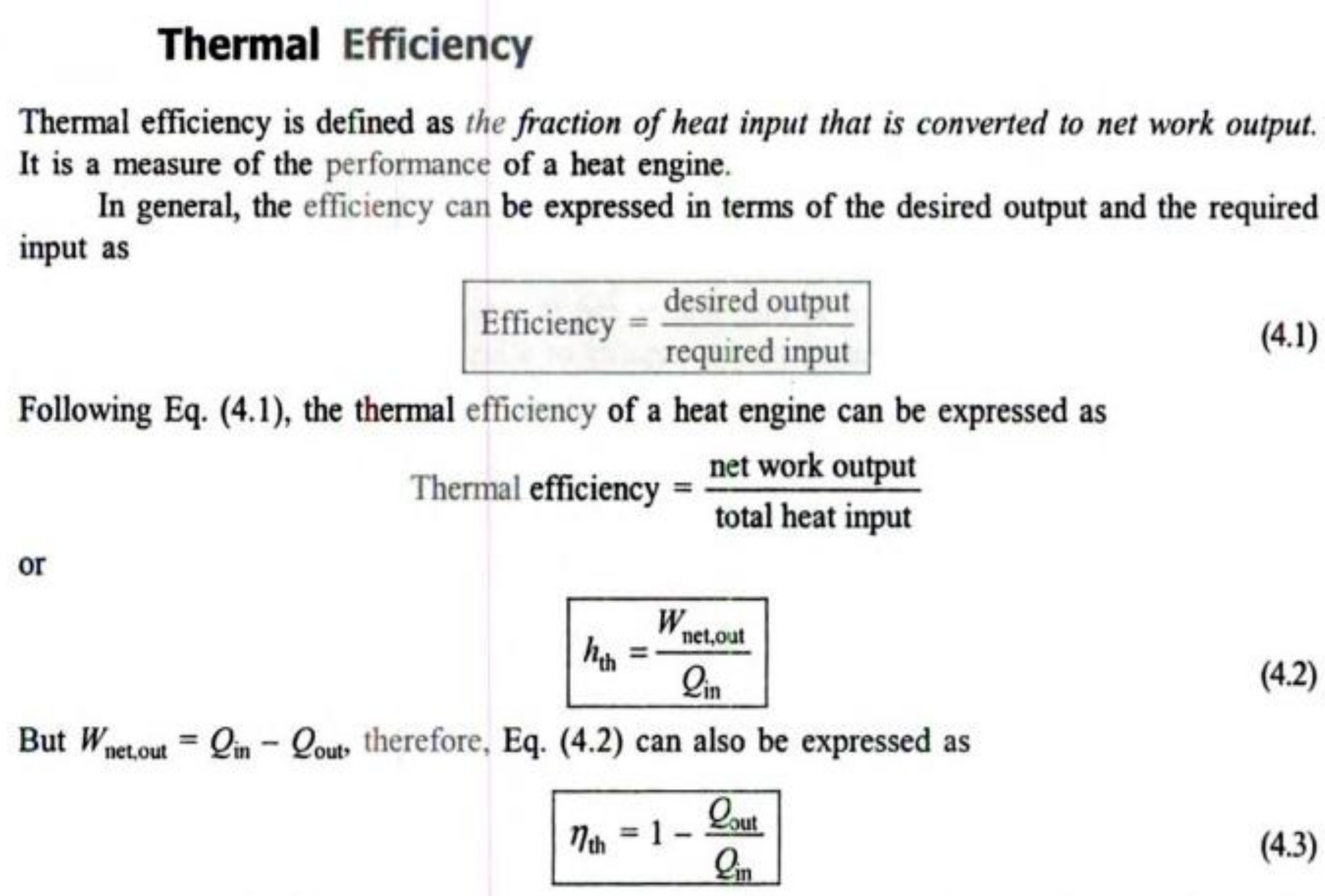
Figure 4.3 Schematic diagram of a steam power plant.

HEAT ENGINE



external-combustion engine, that is, the combustion process takes place outside the engine, and the thermal energy released during this process is transferred to steam as heat. In Fig. 4.3, Q_{in} is the heat supplied to the steam in a boiler from a high-temperature source, Q_{out} is the heat rejected from the steam in a condenser to a low-temperature sink, W_{in} is the work required to compress water to boiler pressure, W_{out} is the work delivered by the steam as it expands in the turbine. It is essential to realize that the heat and work interactions indicated by the subscripts "in" and "out" are all *positive quantities.*

PERFORMANCE PARAMETERS



Thermal Efficiency

Thermal efficiency is defined as *the fraction of heat input that is converted to net work output.* It is a measure of the performance of a heat engine.

In general, the efficiency can be expressed in terms of the desired output and the required input as

$$\boxed{\text{Efficiency} = \frac{\text{desired output}}{\text{required input}}} \tag{4.1}$$

Following Eq. (4.1), the thermal efficiency of a heat engine can be expressed as

$$\text{Thermal efficiency} = \frac{\text{net work output}}{\text{total heat input}}$$

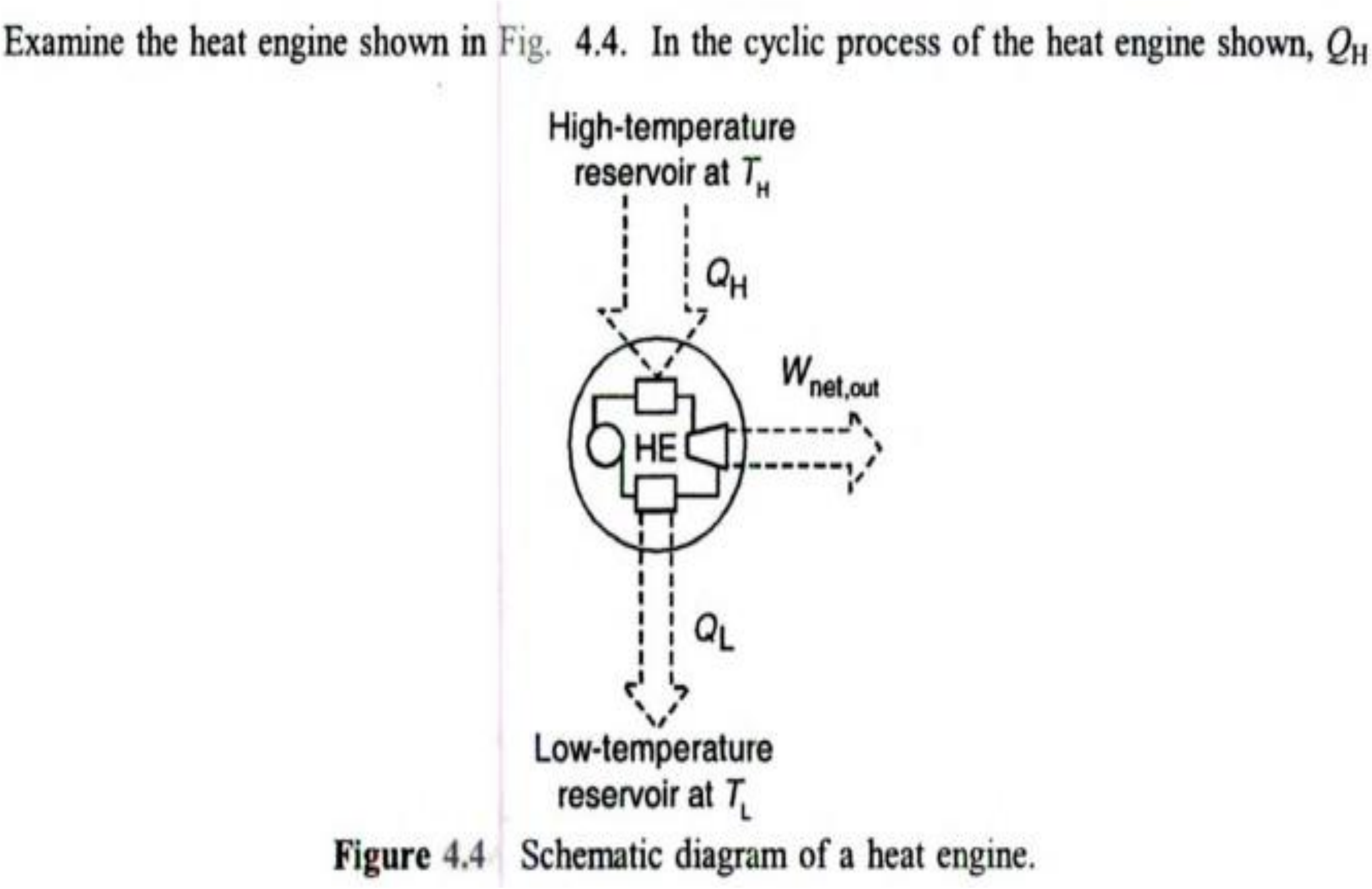
or

$$\boxed{h_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{\text{in}}}} \tag{4.2}$$

But $W_{\text{net,out}} = Q_{\text{in}} - Q_{\text{out}}$, therefore, Eq. (4.2) can also be expressed as

$$\boxed{\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}}} \tag{4.3}$$

PERFORMANCE PARAMETERS



Examine the heat engine shown in Fig. 4.4. In the cyclic process of the heat engine shown, Q_H

Figure 4.4 Schematic diagram of a heat engine.

PERFORMANCE PARAMETERS

is the magnitude of the heat transfer between the cyclic device and the high-temperature reservoir at temperature T_H, and Q_L is the magnitude of the heat transfer between the cyclic device and the low-temperature reservoir at temperature T_L. The net work output and the thermal efficiency relations for the heat engine can be expressed as

$$W_{\text{net,out}} = Q_H - Q_L \tag{4.4}$$

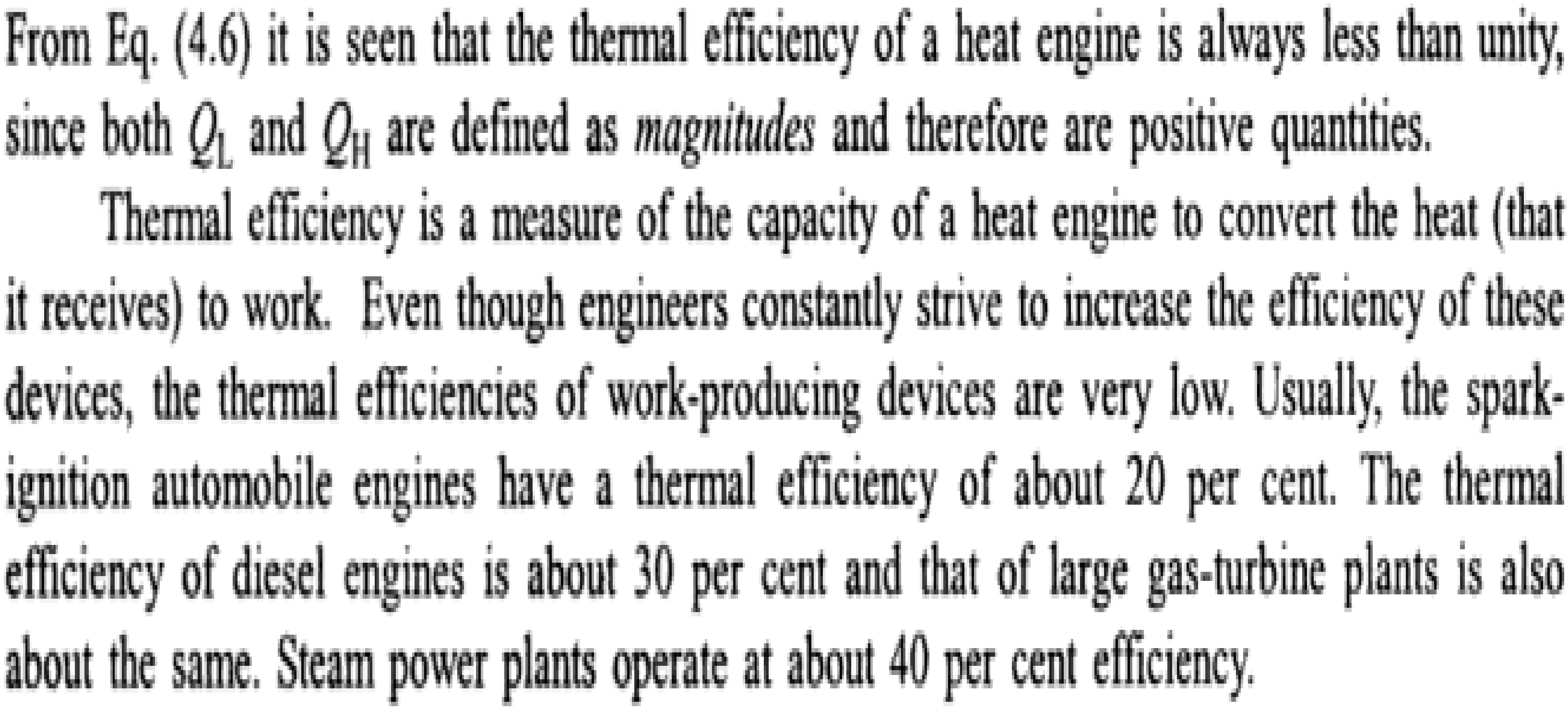
and

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_H} \tag{4.5}$$

or

$$\eta_{\text{th}} = 1 - \frac{Q_L}{Q_H} \tag{4.6}$$

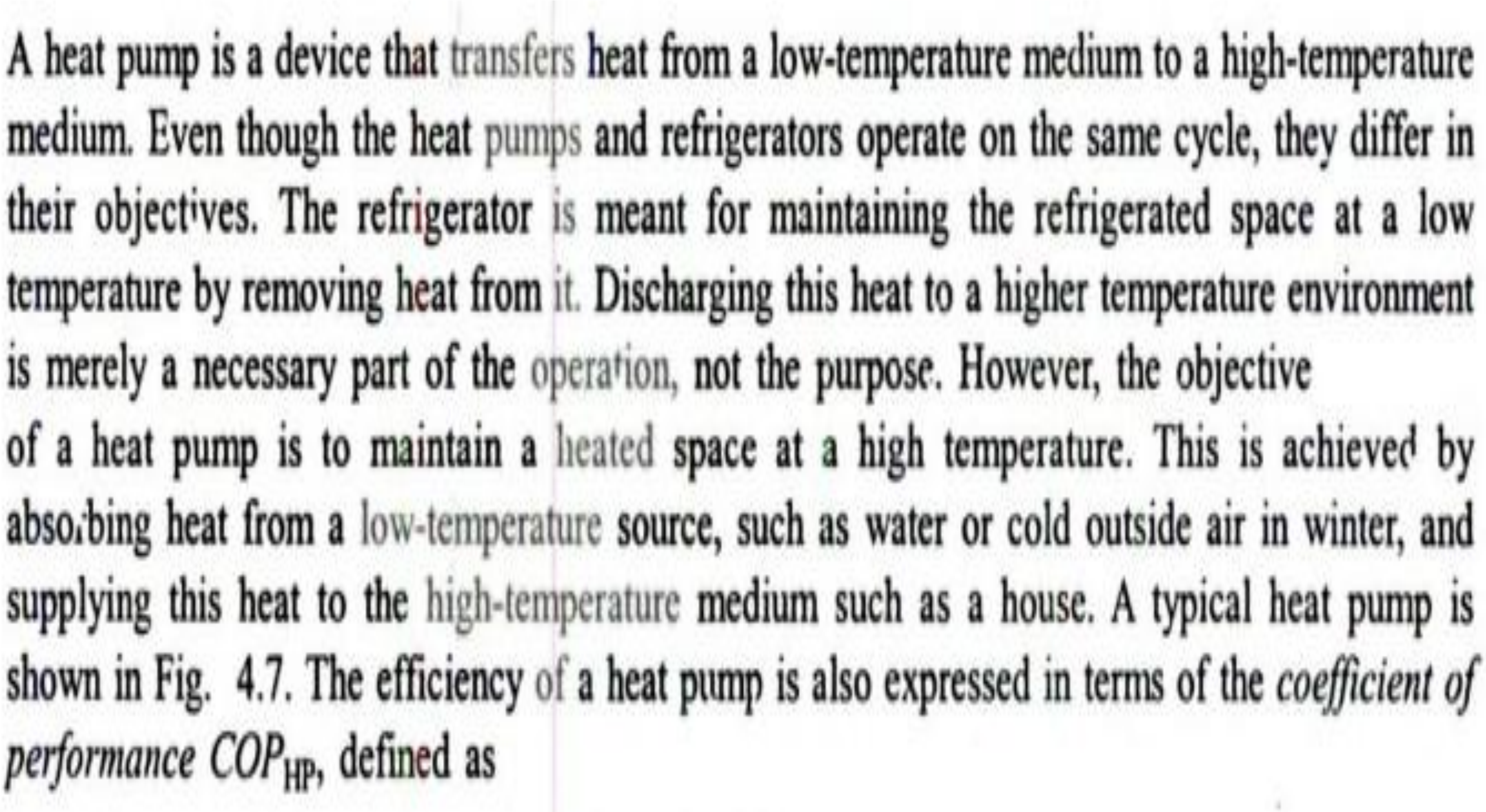
PERFORMANCE PARAMETERS



From Eq. (4.6) it is seen that the thermal efficiency of a heat engine is always less than unity, since both Q_L and Q_H are defined as *magnitudes* and therefore are positive quantities.

Thermal efficiency is a measure of the capacity of a heat engine to convert the heat (that it receives) to work. Even though engineers constantly strive to increase the efficiency of these devices, the thermal efficiencies of work-producing devices are very low. Usually, the spark-ignition automobile engines have a thermal efficiency of about 20 per cent. The thermal efficiency of diesel engines is about 30 per cent and that of large gas-turbine plants is also about the same. Steam power plants operate at about 40 per cent efficiency.

HEAT PUMP



A heat pump is a device that transfers heat from a low-temperature medium to a high-temperature medium. Even though the heat pumps and refrigerators operate on the same cycle, they differ in their objectives. The refrigerator is meant for maintaining the refrigerated space at a low temperature by removing heat from it. Discharging this heat to a higher temperature environment is merely a necessary part of the operation, not the purpose. However, the objective of a heat pump is to maintain a heated space at a high temperature. This is achieved by absorbing heat from a low-temperature source, such as water or cold outside air in winter, and supplying this heat to the high-temperature medium such as a house. A typical heat pump is shown in Fig. 4.7. The efficiency of a heat pump is also expressed in terms of the *coefficient of performance* COP_{HP}, defined as

HEAT PUMP

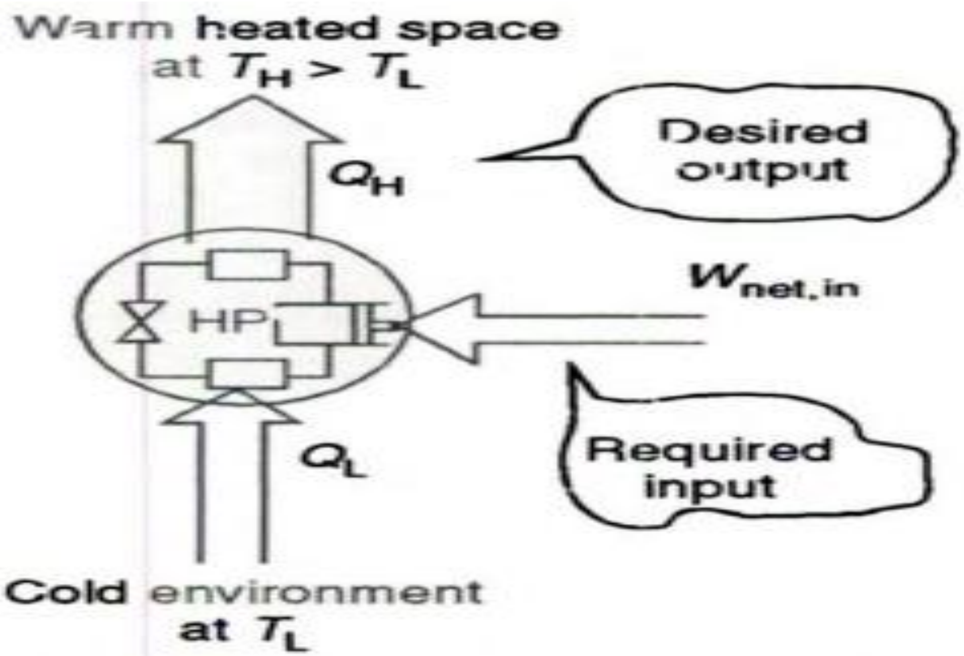
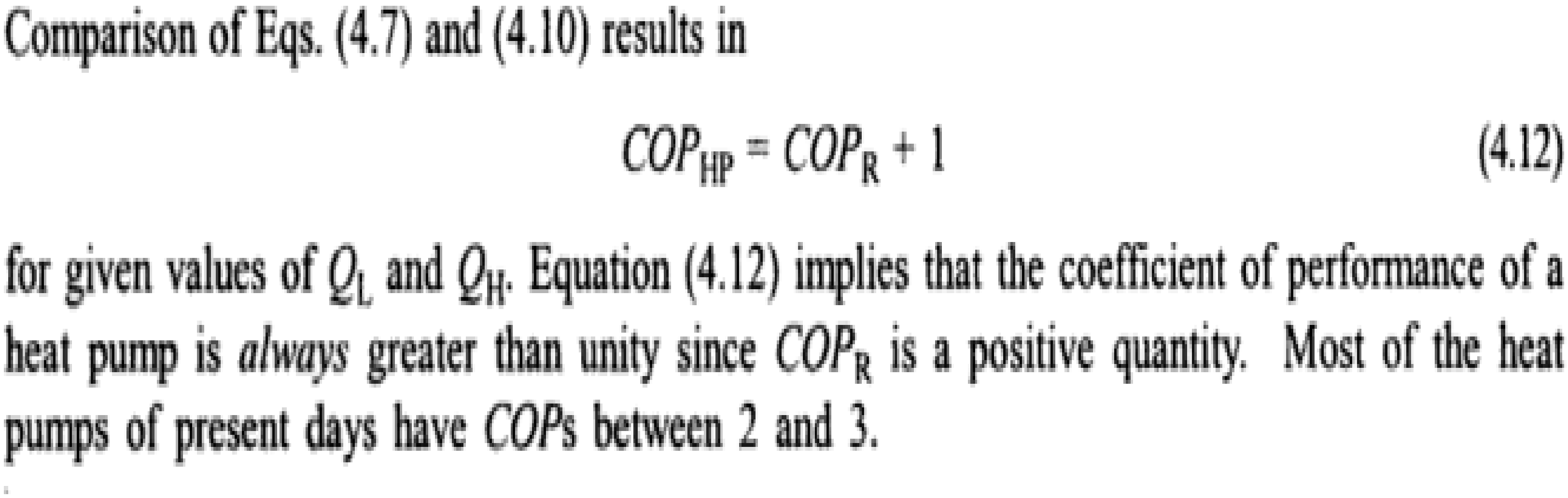


Figure 4.7 Schematic diagram of a heat pump.

$$\boxed{COP_{HP} = \frac{\text{net output}}{\text{net input}} = \frac{Q_H}{W_{net,in}}}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1-(Q_L/Q_H)}$$

HEAT PUMP

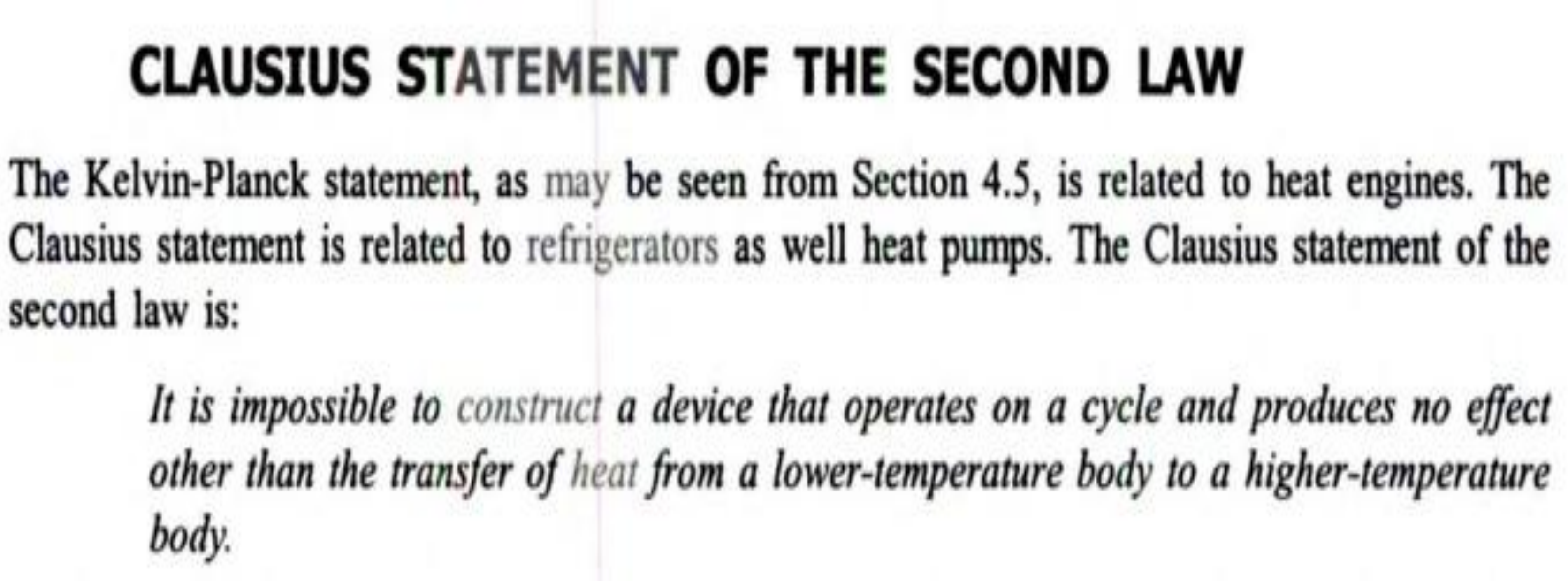


Comparison of Eqs. (4.7) and (4.10) results in

$$COP_{HP} = COP_R + 1 \tag{4.12}$$

for given values of Q_L and Q_H. Equation (4.12) implies that the coefficient of performance of a heat pump is *always* greater than unity since COP_R is a positive quantity. Most of the heat pumps of present days have *COP*s between 2 and 3.

SECOND LAW OF THERMODYNAMICS

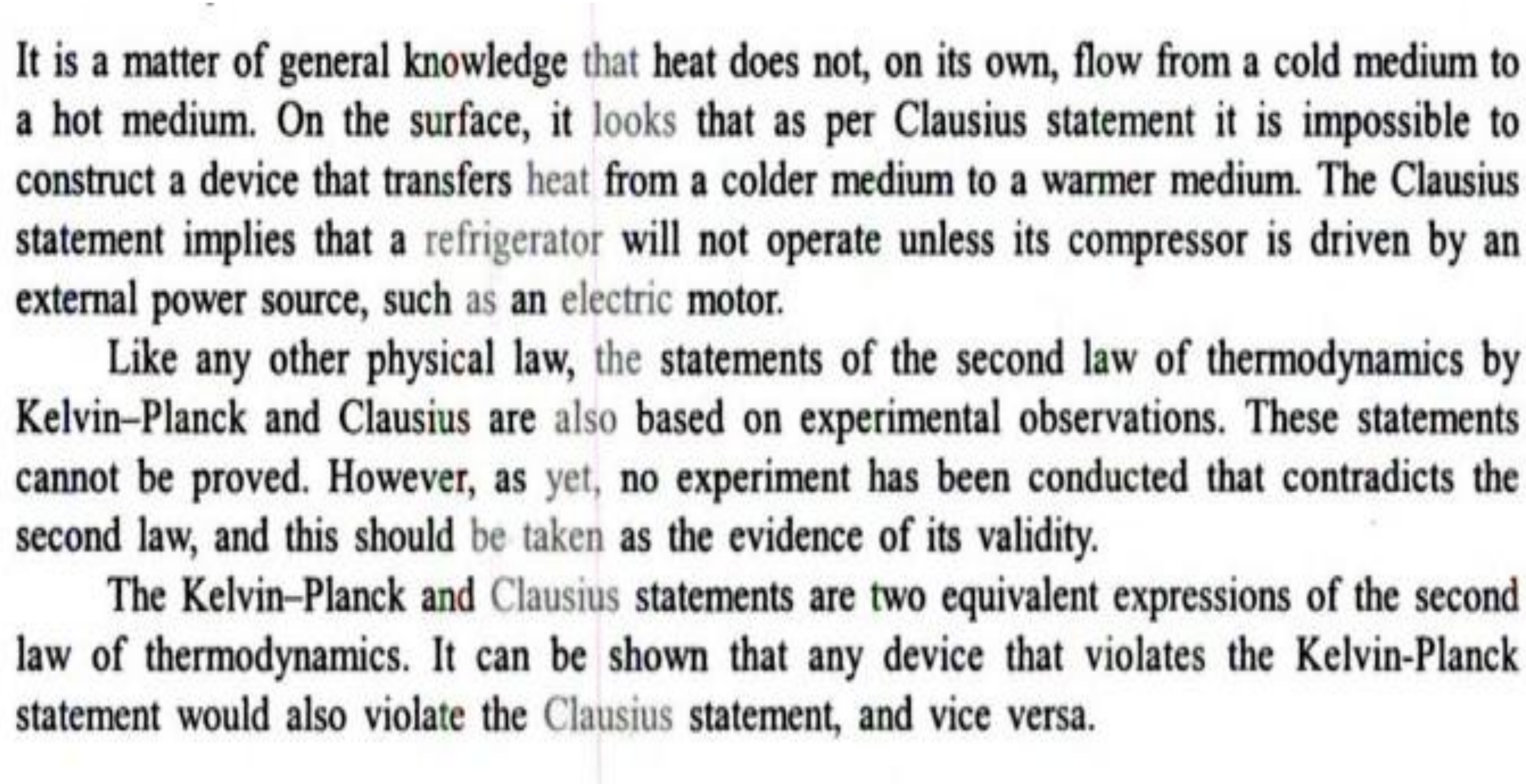


CLAUSIUS STATEMENT OF THE SECOND LAW

The Kelvin-Planck statement, as may be seen from Section 4.5, is related to heat engines. The Clausius statement is related to refrigerators as well heat pumps. The Clausius statement of the second law is:

> *It is impossible to construct a device that operates on a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.*

SECOND LAW OF THERMODYNAMICS

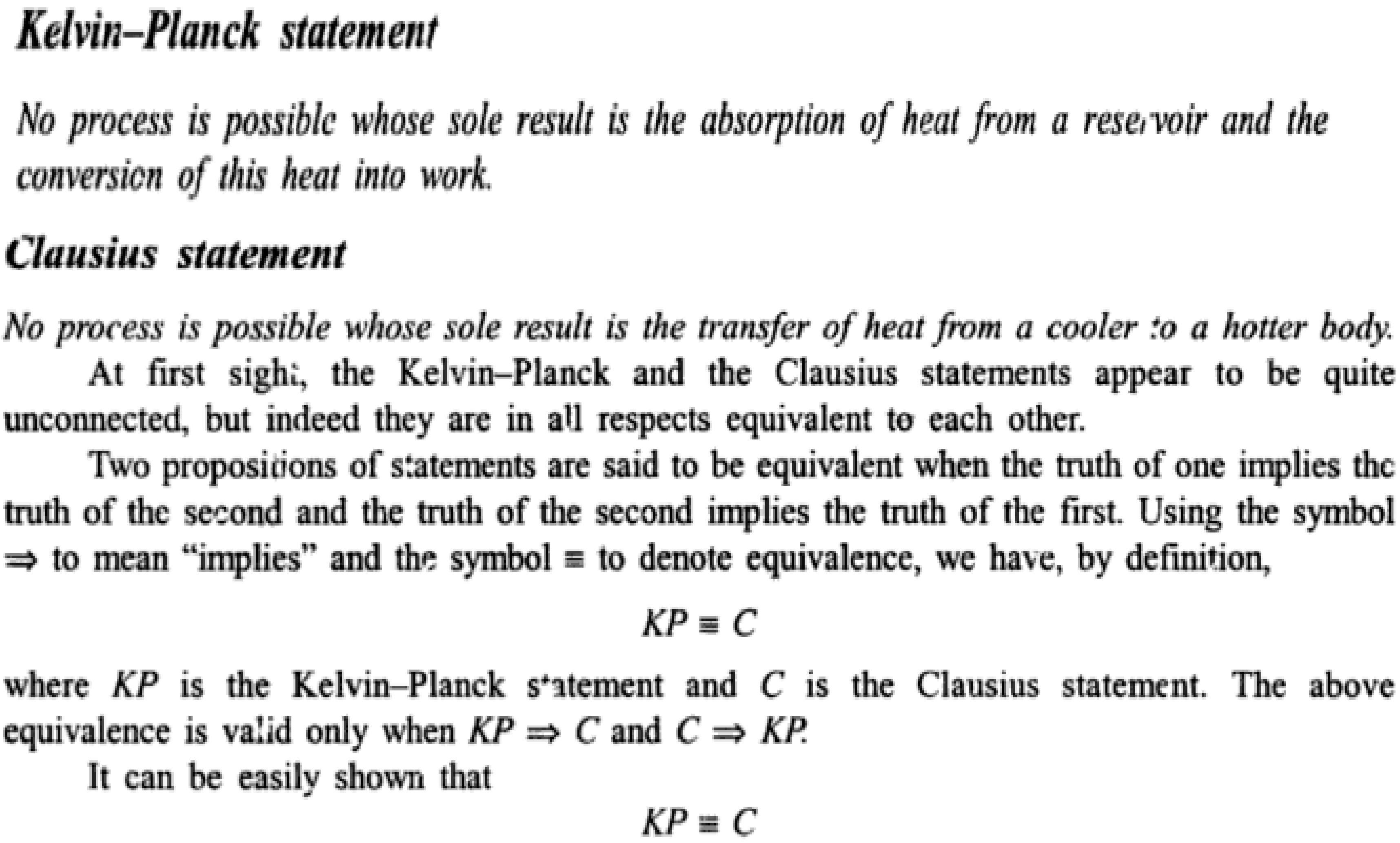


It is a matter of general knowledge that heat does not, on its own, flow from a cold medium to a hot medium. On the surface, it looks that as per Clausius statement it is impossible to construct a device that transfers heat from a colder medium to a warmer medium. The Clausius statement implies that a refrigerator will not operate unless its compressor is driven by an external power source, such as an electric motor.

Like any other physical law, the statements of the second law of thermodynamics by Kelvin–Planck and Clausius are also based on experimental observations. These statements cannot be proved. However, as yet, no experiment has been conducted that contradicts the second law, and this should be taken as the evidence of its validity.

The Kelvin–Planck and Clausius statements are two equivalent expressions of the second law of thermodynamics. It can be shown that any device that violates the Kelvin-Planck statement would also violate the Clausius statement, and vice versa.

EQUIVALENCE OF CLAUSIUS AND KELVIN PLANCK STATEMENTS



Kelvin–Planck statement

No process is possible whose sole result is the absorption of heat from a reservoir and the conversion of this heat into work.

Clausius statement

No process is possible whose sole result is the transfer of heat from a cooler to a hotter body.

At first sight, the Kelvin–Planck and the Clausius statements appear to be quite unconnected, but indeed they are in all respects equivalent to each other.

Two propositions of statements are said to be equivalent when the truth of one implies the truth of the second and the truth of the second implies the truth of the first. Using the symbol $\Rightarrow$ to mean "implies" and the symbol $\equiv$ to denote equivalence, we have, by definition,

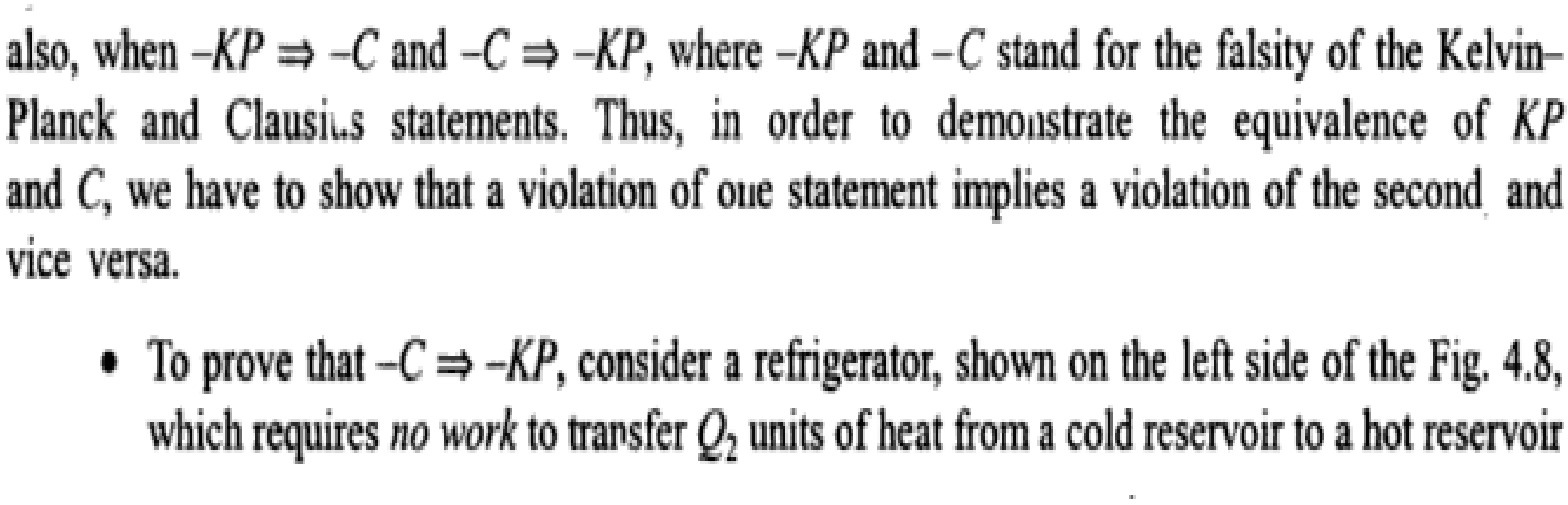
$$KP \equiv C$$

where KP is the Kelvin–Planck statement and C is the Clausius statement. The above equivalence is valid only when $KP \Rightarrow C$ and $C \Rightarrow KP$.

It can be easily shown that

$$KP \equiv C$$

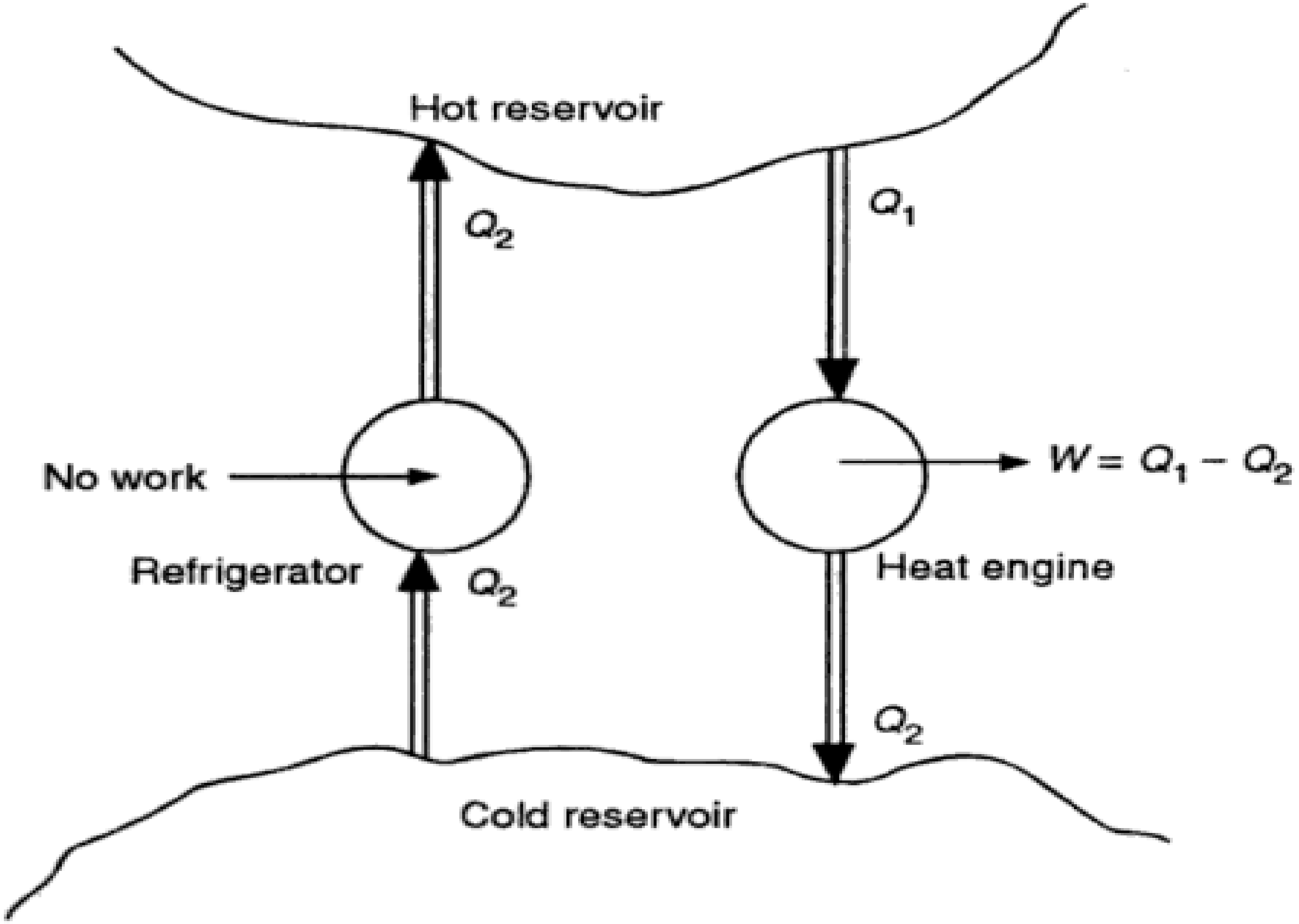
EQUIVALENCE OF CLAUSIUS AND KELVIN PLANCK STATEMENTS



also, when $-KP \Rightarrow -C$ and $-C \Rightarrow -KP$, where $-KP$ and $-C$ stand for the falsity of the Kelvin–Planck and Clausius statements. Thus, in order to demonstrate the equivalence of KP and C, we have to show that a violation of one statement implies a violation of the second and vice versa.

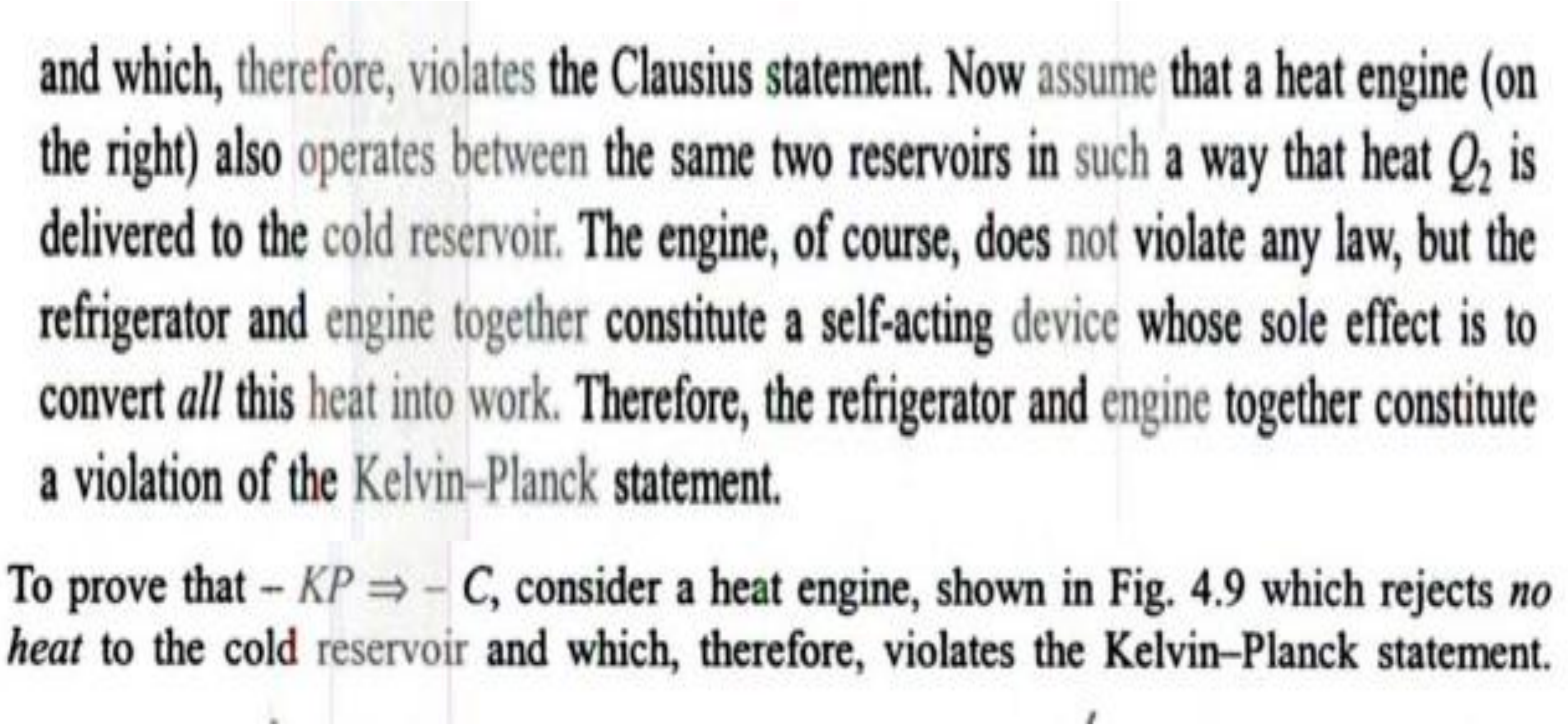
- To prove that $-C \Rightarrow -KP$, consider a refrigerator, shown on the left side of the Fig. 4.8, which requires *no work* to transfer Q_2 units of heat from a cold reservoir to a hot reservoir

EQUIVALENCE OF CLAUSIUS AND KELVIN PLANCK STATEMENTS



Proof that $-C \Rightarrow -KP$. The refrigerator on the left is a violation of C, the refrigerator and engine together constitute a violation of KP.

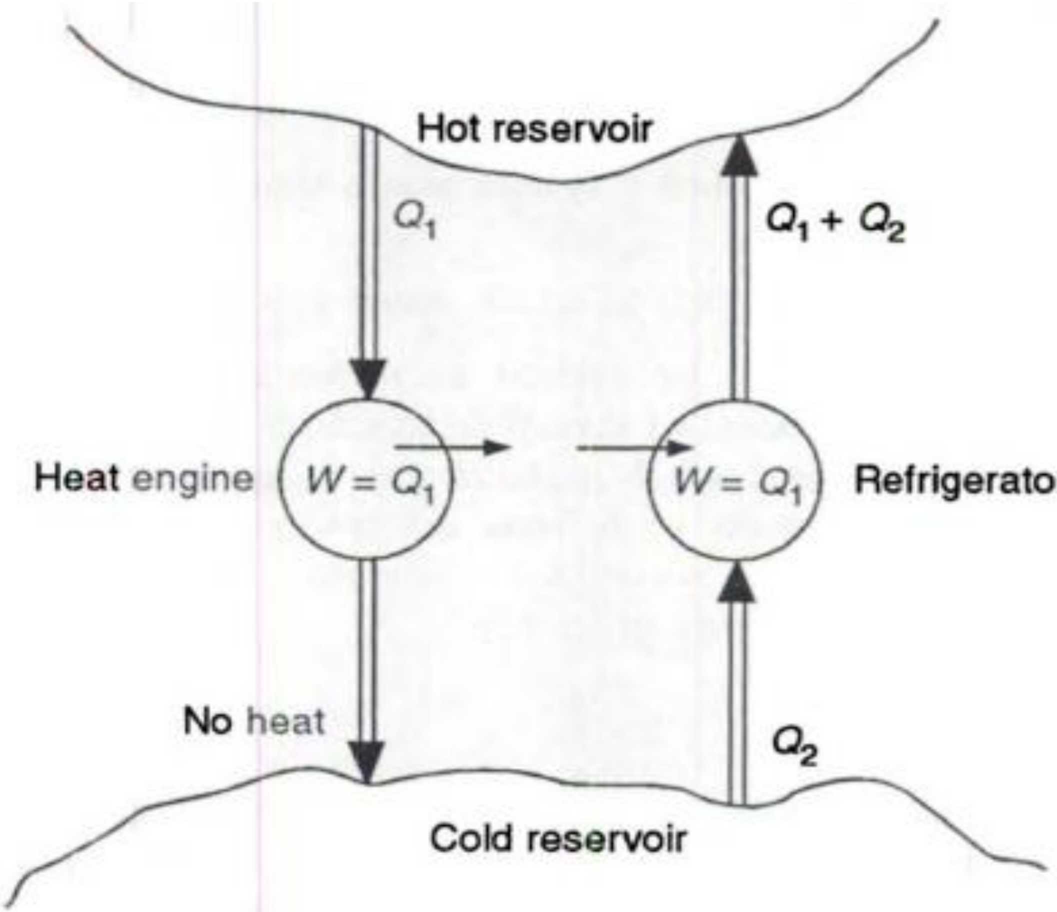
EQUIVALENCE OF CLAUSIUS AND KELVIN PLANCK STATEMENTS



and which, therefore, violates the Clausius statement. Now assume that a heat engine (on the right) also operates between the same two reservoirs in such a way that heat Q_2 is delivered to the cold reservoir. The engine, of course, does not violate any law, but the refrigerator and engine together constitute a self-acting device whose sole effect is to convert *all* this heat into work. Therefore, the refrigerator and engine together constitute a violation of the Kelvin–Planck statement.

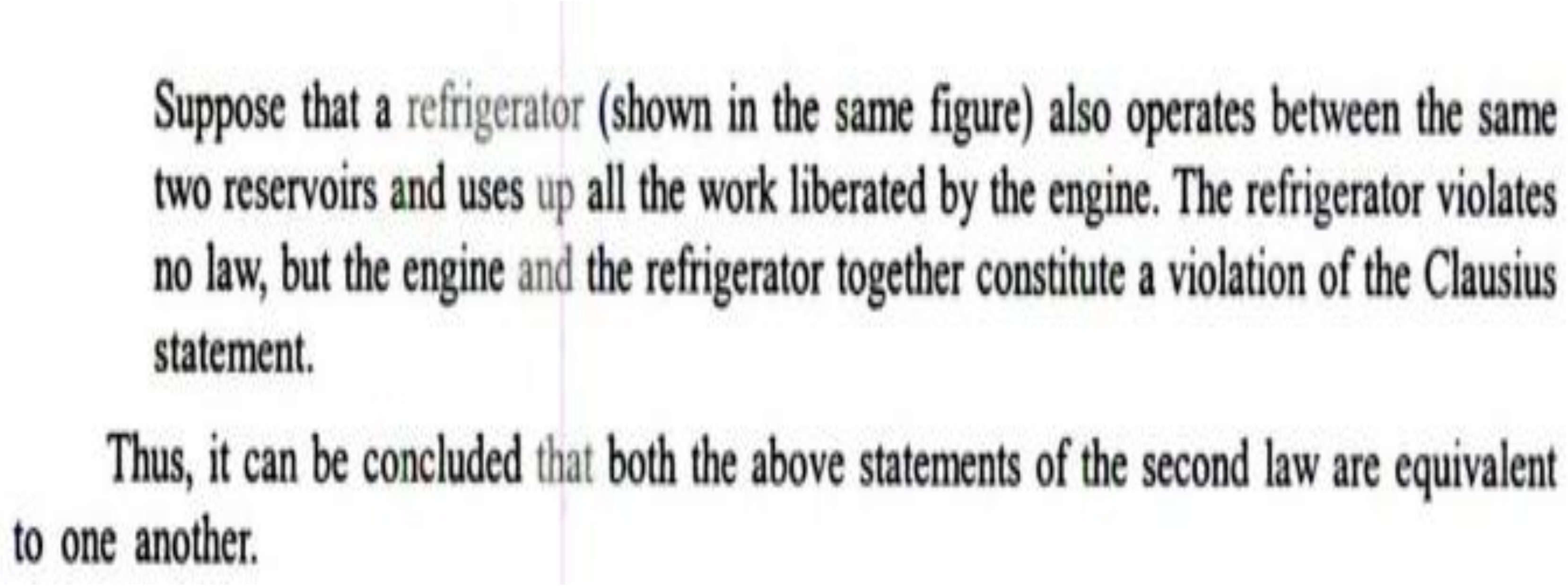
To prove that $-KP \Rightarrow -C$, consider a heat engine, shown in Fig. 4.9 which rejects *no heat* to the cold reservoir and which, therefore, violates the Kelvin–Planck statement.

EQUIVALENCE OF CLAUSIUS AND KELVIN PLANCK STATEMENTS



Proof that $-KP \Rightarrow -C$. The heat engine on the left is a violation of KP, the heat engine and refrigerator together constitute a violation of C.

EQUIVALENCE OF CLAUSIUS AND KELVIN PLANCK STATEMENTS



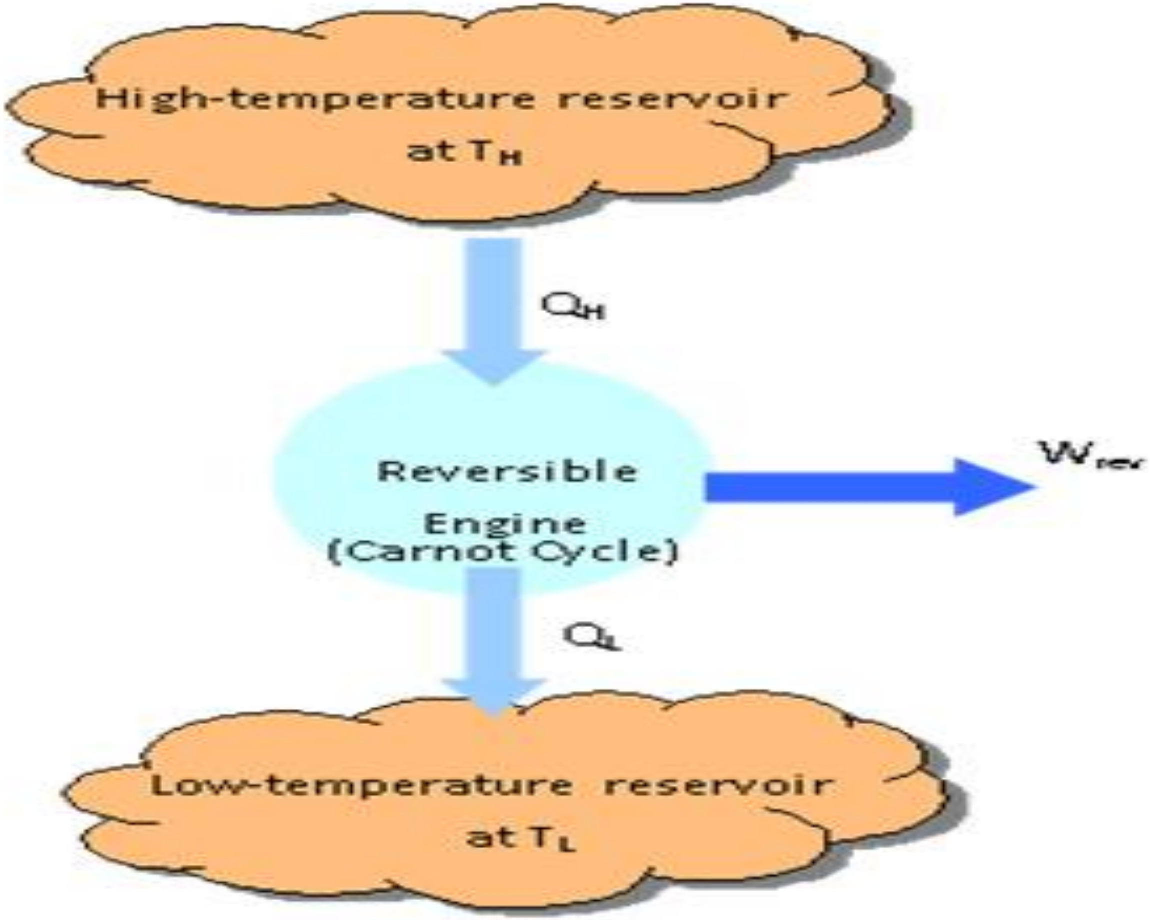
Suppose that a refrigerator (shown in the same figure) also operates between the same two reservoirs and uses up all the work liberated by the engine. The refrigerator violates no law, but the engine and the refrigerator together constitute a violation of the Clausius statement.

Thus, it can be concluded that both the above statements of the second law are equivalent to one another.

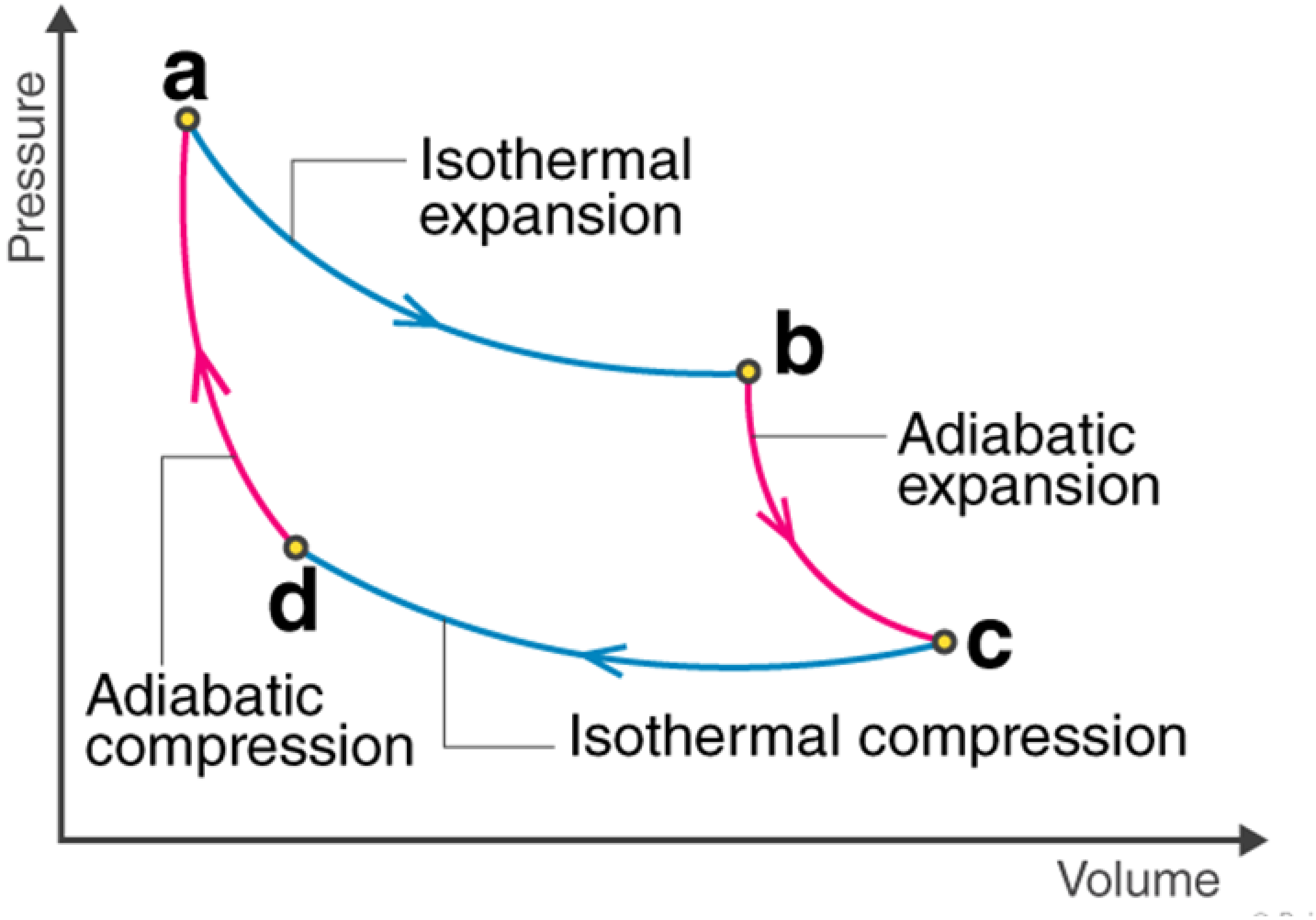
CARNOT CYCLE

- A Carnot cycle is defined as an ideal reversible closed thermodynamic cycle in which there are four successive operations involved and they are isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression.
- During these operations, the expansion and compression of substance can be done up to desired point and back to initial state.

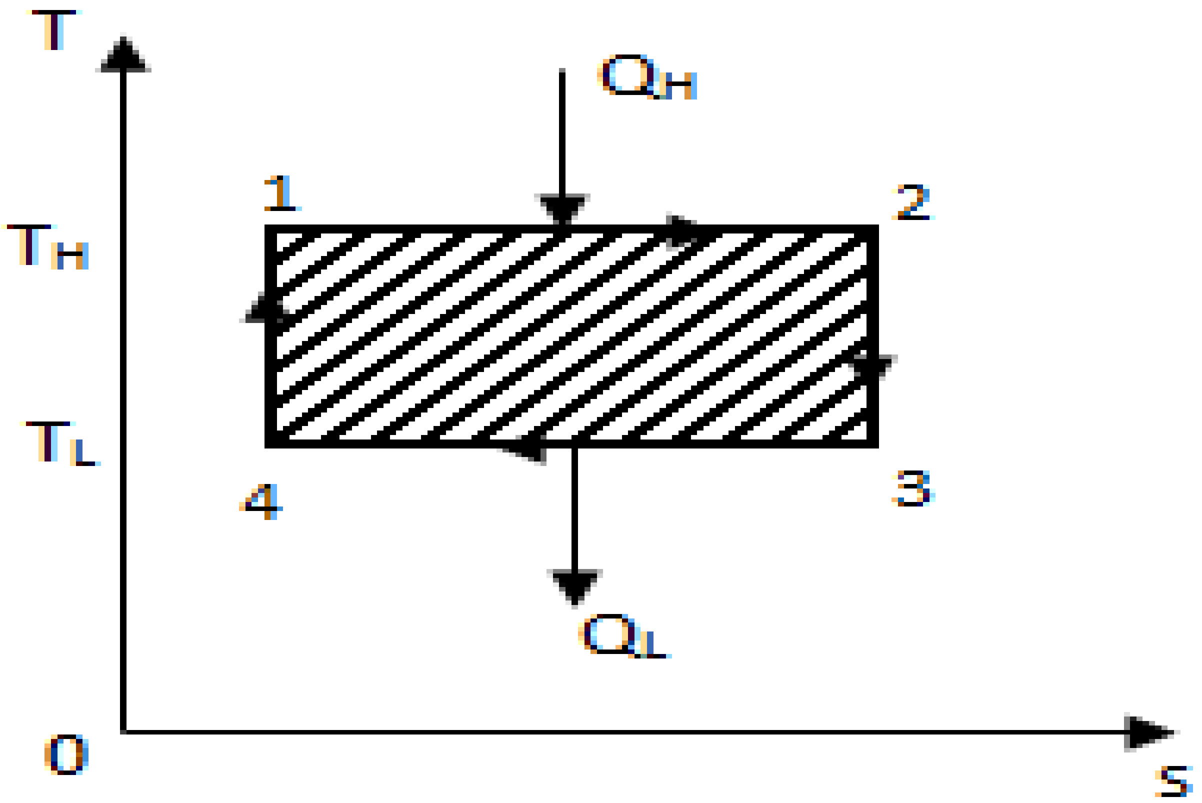
CARNOT CYCLE



CARNOT CYCLE



CARNOT CYCLE



CARNOT CYCLE

- Following are the four processes of Carnot cycle:
- In (a), the process is reversible isothermal gas expansion. In this process, the amount of heat absorbed by the ideal gas is q_{in} from the heat source which is at a temperature of T_h. The gas expands and does work on the surroundings.
- In (b), the process is reversible adiabatic gas expansion. Here, the system is thermally insulated and the gas continues to expand and work is done on the surroundings. Now the temperature is lower, T_l.

CARNOT CYCLE

- **Steps involved in a Carnot Cycle**
- For an ideal gas operating inside a Carnot cycle, the following are the steps involved:
- Process 1-2:
- Isothermal expansion: The gas is taken from P1, V1, T1 to P2, V2, T2. Heat Q1 is absorbed from the reservoir at temperature T1. Since the expansion is isothermal, the total change in internal energy is zero and the heat absorbed by the gas is equal to the work done by the gas on the environment, which is given as:
- $W1\rightarrow2=Q1=\mu\times R\times T1\times \mathrm{ln} v2v1$

CARNOT CYCLE

Process 2-3:

- Adiabatic expansion: The gas expands adiabatically from P_2, V_2, T_1 to P_3, V_3, T_2.
- **Here work done by the gas is given by:**
- $W2\rightarrow3=\mu R\gamma-1(T1-T2)$

Process 3 -4:

- Isothermal compression: The gas is compressed isothermally from the state (P_3, V_3, T_2) to (P_4, V_4, T_2).
- **Here, the work done on the gas by the environment is given by:**
- $W3\rightarrow4=\mu RT2lnv3v4$

CARNOT CYCLE

Step 4:

- Adiabatic compression: The gas is compressed adiabatically from the state (P_4, V_4, T_2) to (P_1, V_1, T_1).
- **Here, the work done on the gas by the environment is given by:**
- $W4 \rightarrow 1 = \mu R \gamma - 1 (T1 - T2)$

CARNOT CYCLE

- In (c), the process is reversible isothermal gas compression process. Here, the heat loss, q_{out} occurs when the surroundings do the work at temperature T_l.
- In (d), the process is reversible adiabatic gas compression. Again the system is thermally insulated. The temperature again rise back to T_h as the surrounding continue to do their work on the gas.

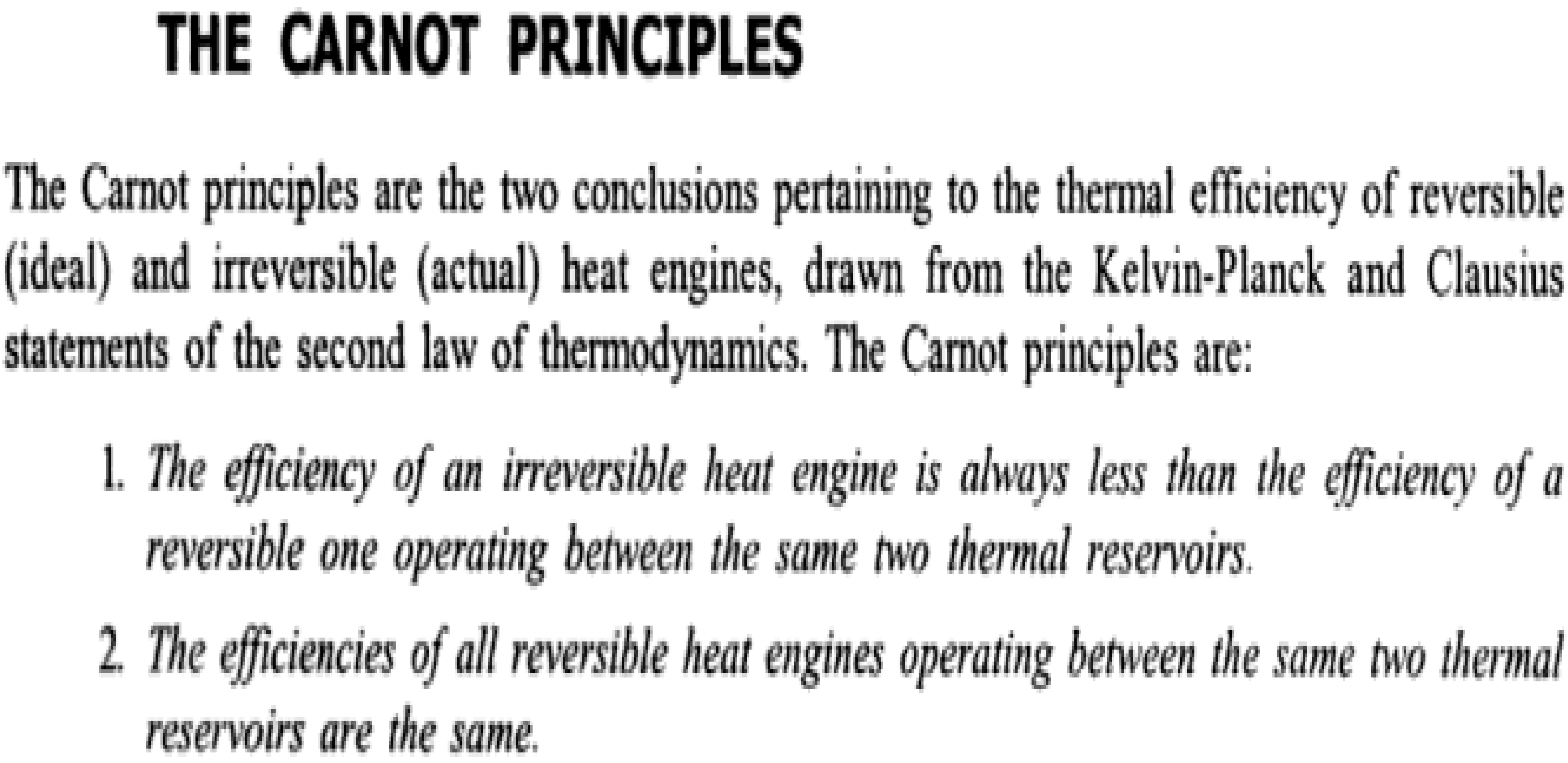
CARNOT CYCLE

- Netefficiency=WQ1=(Q1−Q2)/Q1

  =1−Q2/Q1

$$\eta_{th,c} = 1 + \frac{T_L \cdot \Delta S_{3\to 4}}{T_H \cdot \Delta S_{1\to 2}} = 1 - \frac{T_L}{T_H}$$

CARNOT PRINCIPLE



THE CARNOT PRINCIPLES

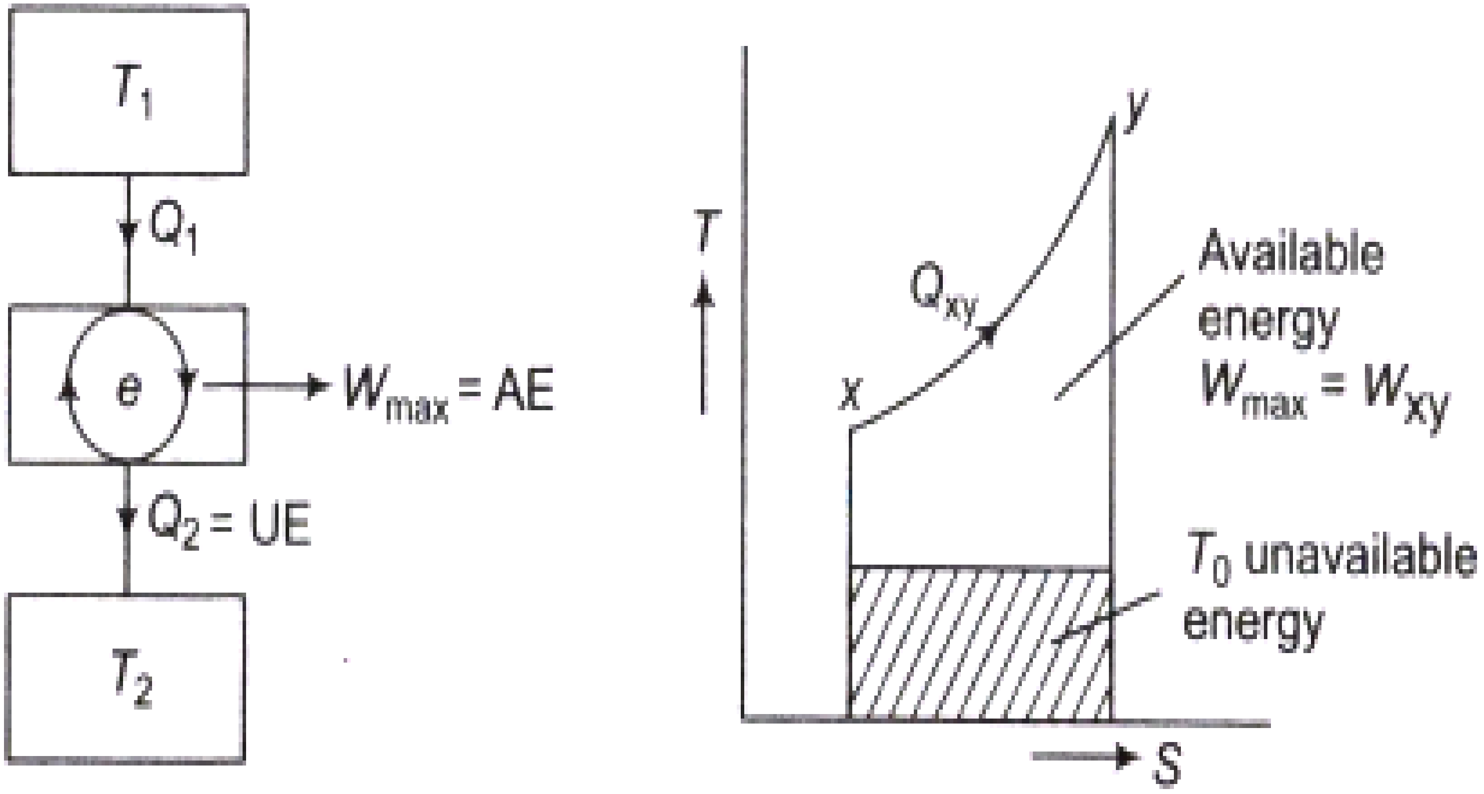
The Carnot principles are the two conclusions pertaining to the thermal efficiency of reversible (ideal) and irreversible (actual) heat engines, drawn from the Kelvin-Planck and Clausius statements of the second law of thermodynamics. The Carnot principles are:

1. *The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two thermal reservoirs.*
2. *The efficiencies of all reversible heat engines operating between the same two thermal reservoirs are the same.*

AVAILABILITY AND IRREVERSIBILITY

- **Availability:**
- When a system is subjected to a process from its original state to dead state the maximum amount of useful work that can be achieved under ideal conditions is known as available energy or availability of the system.

AVAILABILITY AND IRREVERSIBILITY

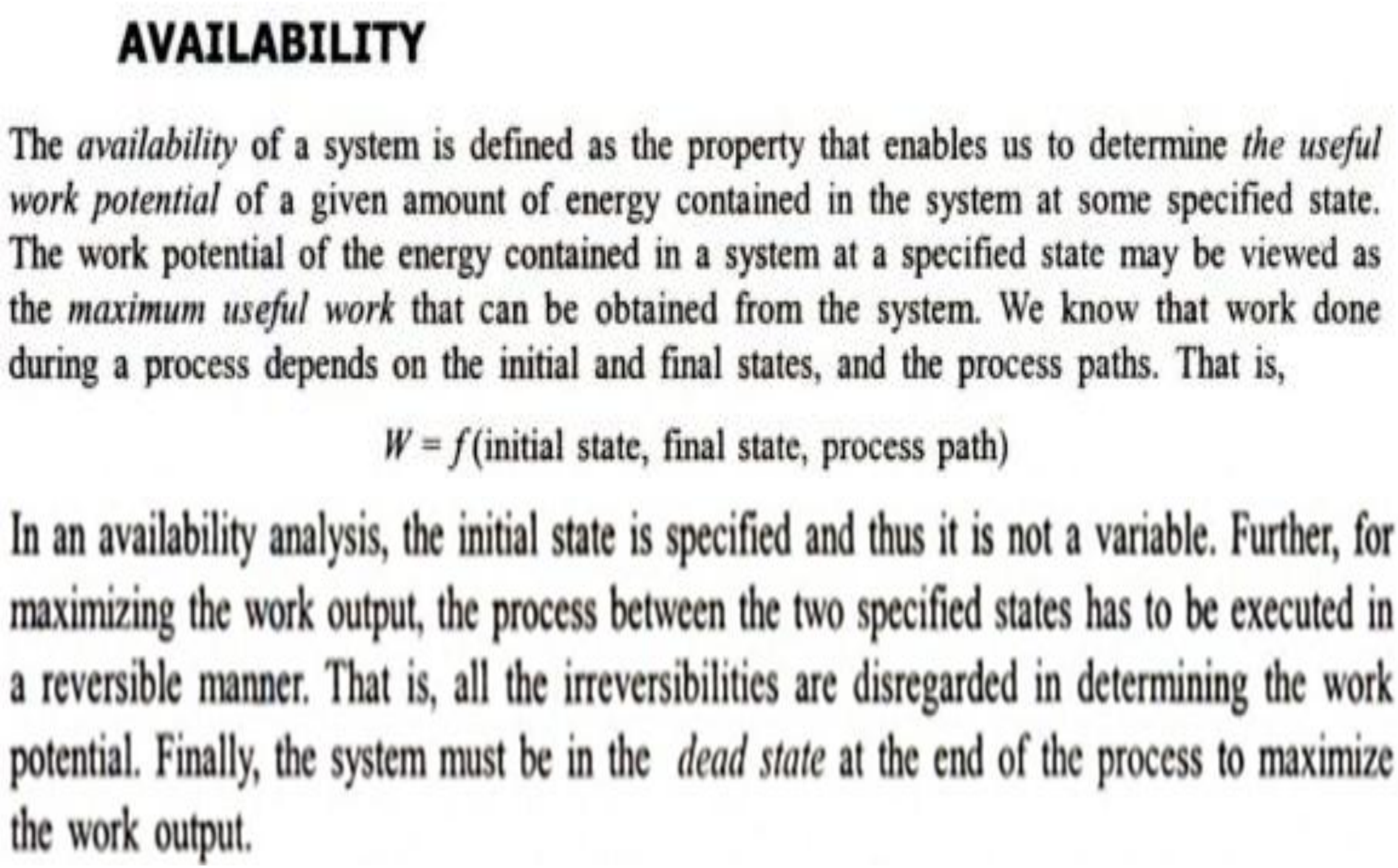


Availability and unavailability of energy

AVAILABILITY AND IRREVERSIBILITY

- $W_{max} = AE = Q_{xy} - T_0(S_y - S_x)$
- Unavailable Energy:
- $UE = T_0(S_y - S_x)$
- where, S_x and S_y are the entropy at x and y, respectively.
- The Available Energy (AE) is also known as exergy and the Unavailable Energy (UE) as energy.
- Availability = Maximum possible work- Irreversibility W useful= W rev- I

AVAILABILITY AND IRREVERSIBILITY



AVAILABILITY

The *availability* of a system is defined as the property that enables us to determine *the useful work potential* of a given amount of energy contained in the system at some specified state. The work potential of the energy contained in a system at a specified state may be viewed as the *maximum useful work* that can be obtained from the system. We know that work done during a process depends on the initial and final states, and the process paths. That is,

$$W = f(\text{initial state, final state, process path})$$

In an availability analysis, the initial state is specified and thus it is not a variable. Further, for maximizing the work output, the process between the two specified states has to be executed in a reversible manner. That is, all the irreversibilities are disregarded in determining the work potential. Finally, the system must be in the *dead state* at the end of the process to maximize the work output.

AVAILABILITY AND IRREVERSIBILITY

The actual work done by a system is always less than idealized reversible work and the difference between the two is called the irreversibility of the process.

$I = W_{\text{max}} - W$

$I = T_0(\Delta S_{\text{system}} + \Delta S_{\text{surrounding}})$

$I = T_0(\Delta S)_{\text{universal}}$

$T_0(\Delta S)_{\text{universal}}$ represent an increase in unavailable energy.

THERMODYNAMIC POTENTIALS, GIBBS AND HELMHOLTZ FUNCTIONS

- *Eight properties of a system, namely pressure (p), volume (v), temperature (T), internal energy (u), enthalpy (h), entropy (s), Helmholtz function (f) and Gibbs function (g) have been* introduced in the previous chapters. *h, f and g are sometimes referred to as thermodynamic* potentials.
- Both *f and g are useful when considering chemical reactions, and the former is of* fundamental importance in statistical thermodynamics.

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THERMODYNAMIC POTENTIALS, GIBBS AND HELMHOLTZ FUNCTIONS

- The first law applied to a closed system undergoing a reversible process states that

  $dQ = du + pdv$

According to second law,

$ds = dQ/T$

Combining these equations, we get

$Tds = du + pdv$

or $du = Tds - pdv$ ...(7.10)

The properties *h, f and g may also be put in terms of T, s, p and v as follows :*

$dh = du + pdv + vdp = Tds + vdp$

THERMODYNAMIC POTENTIALS, GIBBS AND HELMHOLTZ FUNCTIONS

- Helmholtz free energy function,

$$df = du - Tds - sdT\,.$$

$$= -pdv - sdT$$

$$F = U - TS$$

Helmholtz free energy in thermodynamics is a thermodynamic potential which is used to measure the work of a closed system with constant temperature and volume. It can be defined in the form of the following equation:

THERMODYNAMIC POTENTIALS, GIBBS AND HELMHOLTZ FUNCTIONS

- $F = U - TS$

  Where,
- F is the Helmholtz free energy in Joules
- U is the internal energy of the system in Joules
- T is the absolute temperature of the surroundings in Kelvin
- S is the entropy of the system in joules per Kelvin

- $dU=\delta Q+\delta W$ which is from first law of thermodynamics for closed system
- $dU=TdS-pdV$ ($\delta Q = TdS$ and $\delta W = pdV$)
- $dU=d(TS)-SdT-pdV$ (product rule ie; $d(TS) = TdS+SdT$)
- $d(U-TS)=-SdT-pdV$ $dF=-SdT-pdV$ (from $F=U-TS$)

<u>Application of Helmholtz free energy</u>

- In equation of state:
- Pure fluids with high accuracy (like industrial refrigerants) are represented using Helmholtz function as a sum of ideal gas and residual terms.

HELMHOLTZ AND GIBBS FUNCTIONS

The work done in a non-flow reversible system (per unit mass) is given by :

$$W = Q - (u_0 - u_1)$$

$$= T.ds - (u_0 - u_1)$$

$$= T(s_0 - s_1) - (u_0 - u_1)$$

i.e.,

$$W = (u_1 - Ts_1) - (u_0 - Ts_0) \quad ...(6.4)$$

The term $(u - Ts)$ is known as *Helmholtz function*. This gives maximum possible output when the heat Q is transferred at constant temperature and is the case with a very large source.

If work against atmosphere is equal to $p_0 (v_0 - v_1)$, then the maximum work available,

$$W_{max} = W - \text{work against atmosphere}$$

$$= W - p_0 (v_0 - v_1)$$

$$= (u_1 - Ts_1) - (u_0 - Ts_0) - p_0 (v_0 - v_1)$$

$$= (u_1 + p_0v_1 - Ts_1) - (u_0 + p_0v_0 - Ts_0)$$

$$= (h_1 - Ts_1) - (h_0 - Ts_0)$$

i.e.,

$$W_{max} = g_1 - g_0 \quad ...(6.5)$$

where $g = h - T.s$ is known as ***Gibb's function or free energy function.***

The maximum possible available work when system changes from 1 to 2 is given by

$$W_{max} = (g_1 - g_0) - (g_2 - g_0) = g_1 - g_2 \quad ...(6.6)$$

Similarly, for *steady flow system* the maximum work available is given by

$$W_{max} = (g_1 - g_2) + (\mathrm{KE}_1 - \mathrm{KE}_2) + (\mathrm{PE}_1 - \mathrm{PE}_2) \quad ...(6.7)$$

where K.E. and P.E. represent the kinetic and potential energies.

It may be noted that Gibb's function $g = (h - Ts)$ is a property of the system where availability function $a = (u + p_0 v - T_0 s)$ is a composite property of the system and surroundings.

Again,

$$a = u + p_0 v - T_0 s$$

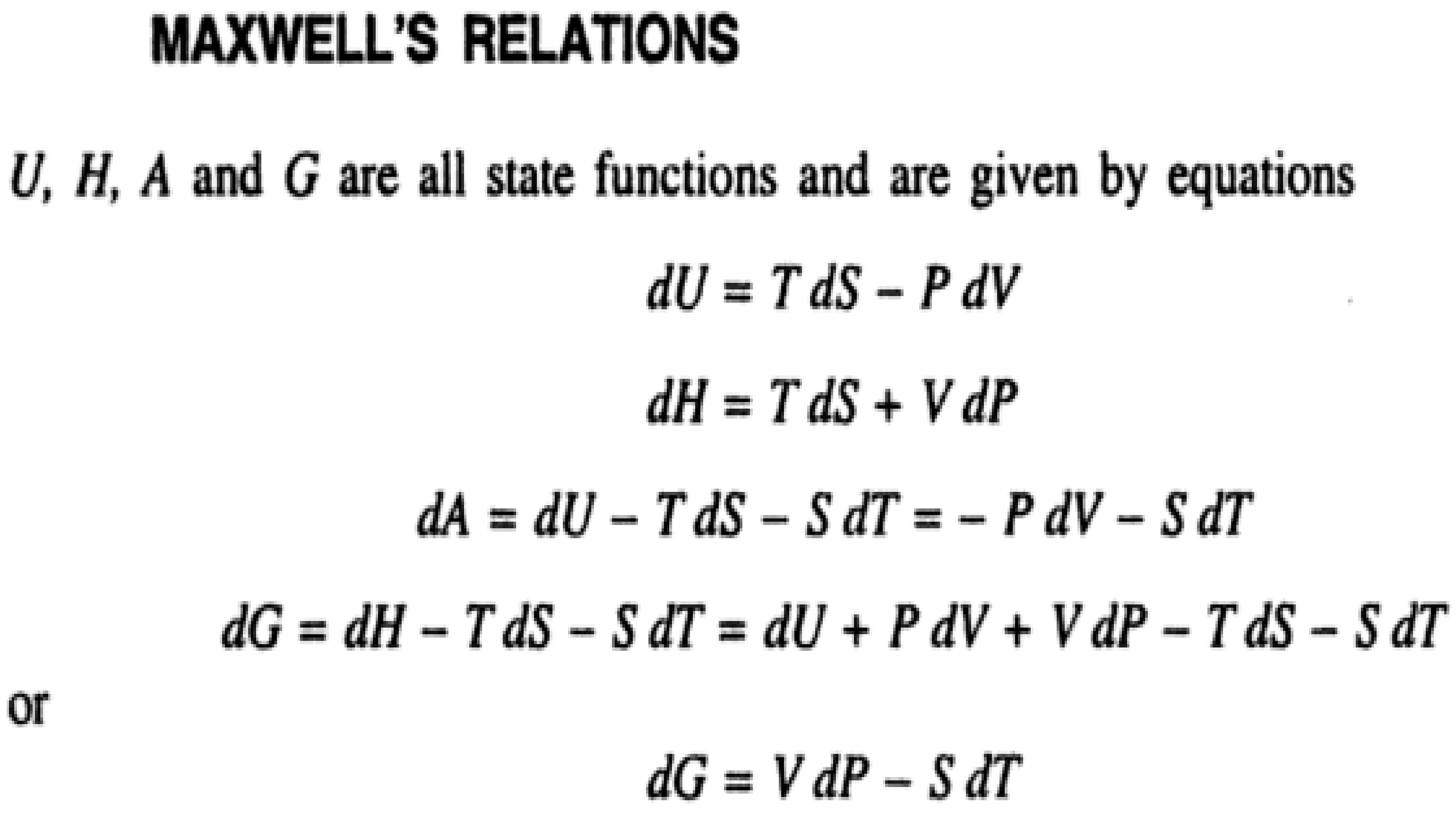
$$b = u + pv - T_0 s$$

$$g = u + pv - Ts$$

When state 1 proceeds to *dead state* (zero state)

$$a = b = g.$$

MAXWELL’S RELATIONS



MAXWELL’S RELATIONS

U, H, A and G are all state functions and are given by equations

$$dU = T\,dS - P\,dV$$

$$dH = T\,dS + V\,dP$$

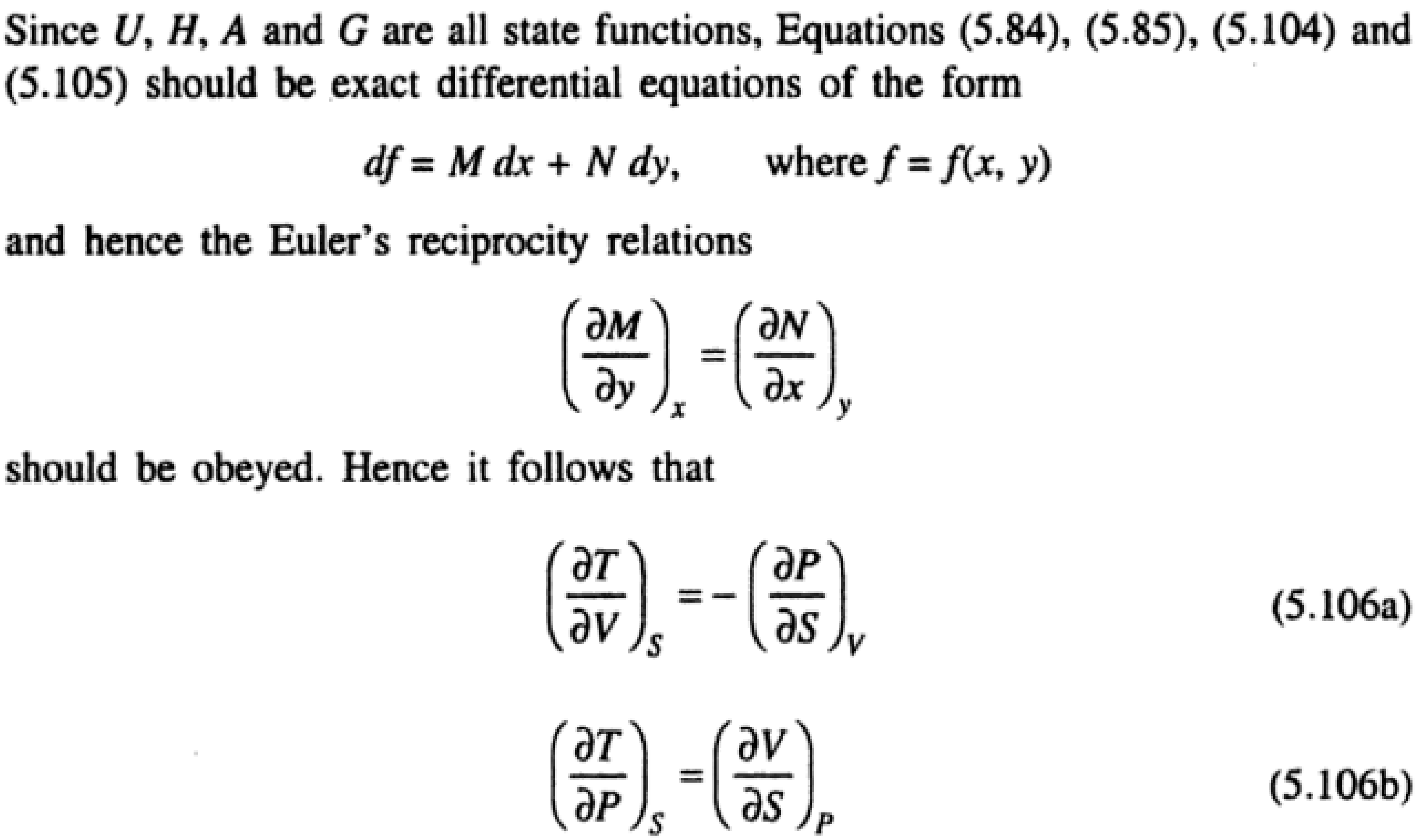
$$dA = dU - T\,dS - S\,dT = -P\,dV - S\,dT$$

$$dG = dH - T\,dS - S\,dT = dU + P\,dV + V\,dP - T\,dS - S\,dT$$

or

$$dG = V\,dP - S\,dT$$

MAXWELL'S RELATIONS



Since U, H, A and G are all state functions, Equations (5.84), (5.85), (5.104) and (5.105) should be exact differential equations of the form

$$df = M\,dx + N\,dy, \qquad \text{where } f = f(x, y)$$

and hence the Euler's reciprocity relations

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

should be obeyed. Hence it follows that

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V \tag{5.106a}$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P \tag{5.106b}$$

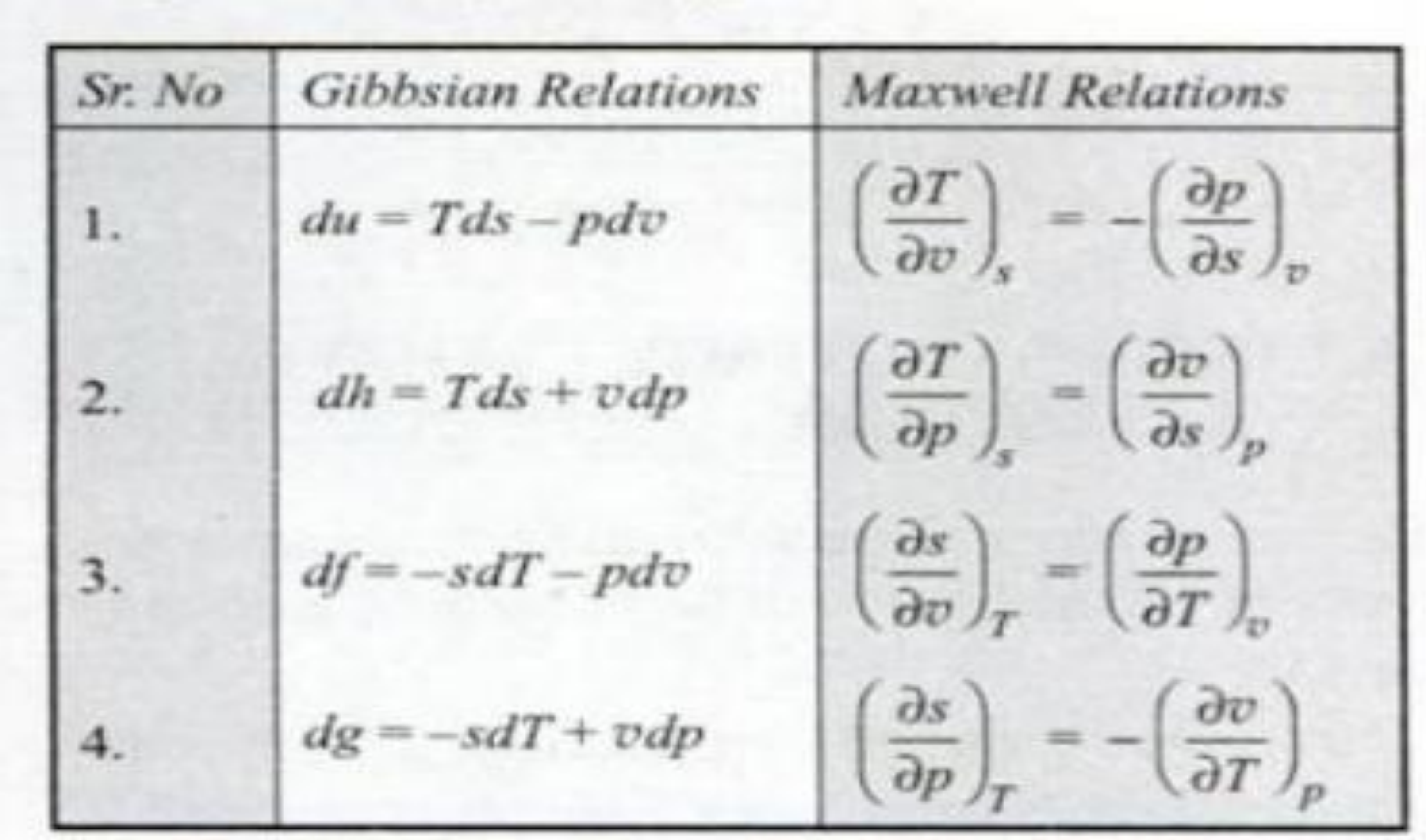
MAXWELL’S RELATIONS

$$\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T \qquad (5.106c)$$

$$\left(\frac{\partial V}{\partial T}\right)_P = -\left(\frac{\partial S}{\partial P}\right)_T \qquad (5.106d)$$

Equations (5.106a)–(5.106d) are well-known Maxwell’s relations and are very helpful in deducing a number of thermodynamic relationships. This will be illustrated a short while from now.

MAXWELL'S RELATIONS

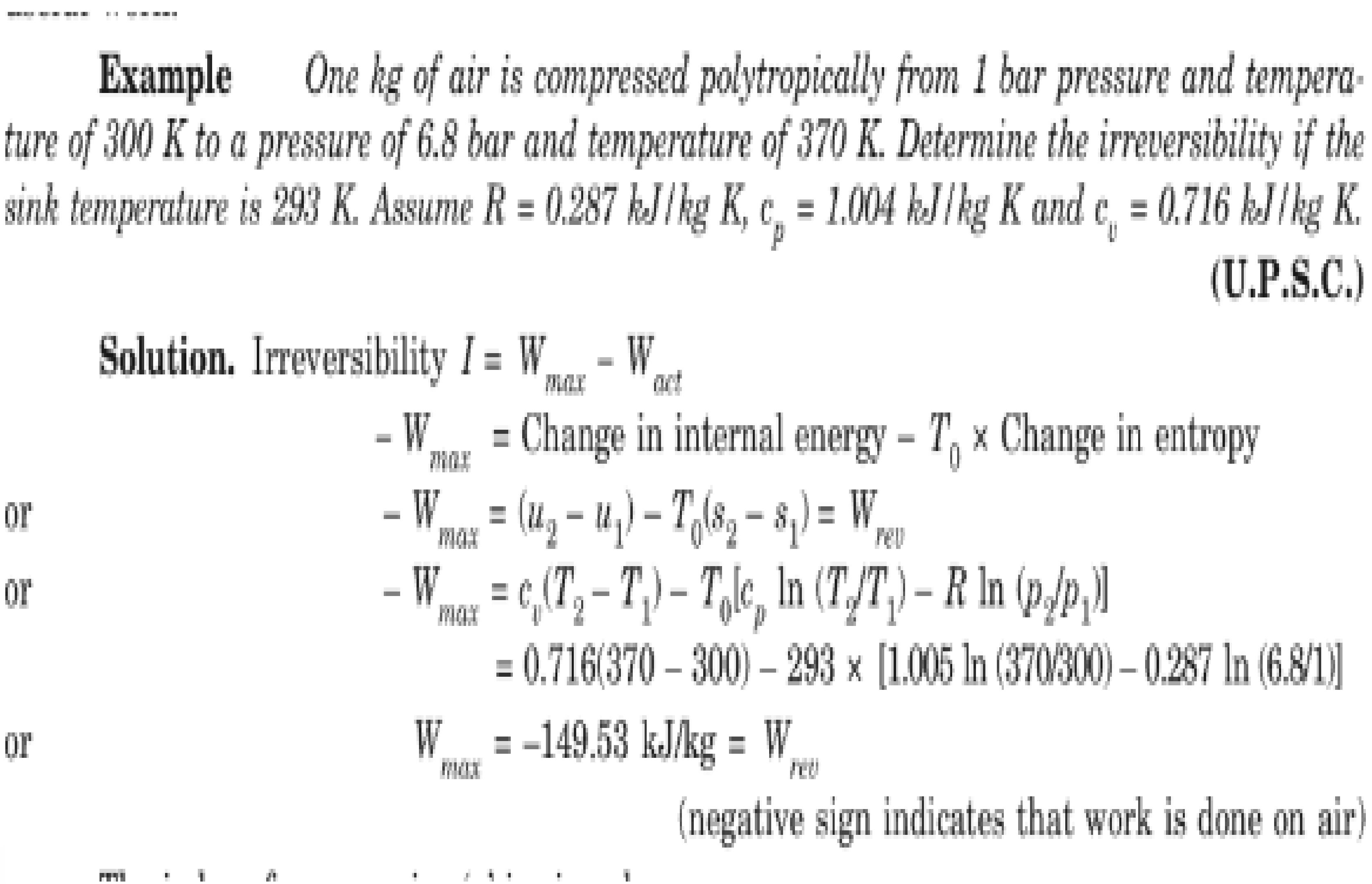


Sr. No	Gibbsian Relations	Maxwell Relations
1.	$du = Tds - pdv$	$\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial p}{\partial s}\right)_v$
2.	$dh = Tds + vdp$	$\left(\frac{\partial T}{\partial p}\right)_s = \left(\frac{\partial v}{\partial s}\right)_p$
3.	$df = -sdT - pdv$	$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial p}{\partial T}\right)_v$
4.	$dg = -sdT + vdp$	$\left(\frac{\partial s}{\partial p}\right)_T = -\left(\frac{\partial v}{\partial T}\right)_p$

THIRD LAW OF THERMODYNAMICS

- It is impossible to attain absolute zero temperature

SOLVED PROBLEMS



Example *One kg of air is compressed polytropically from 1 bar pressure and temperature of 300 K to a pressure of 6.8 bar and temperature of 370 K. Determine the irreversibility if the sink temperature is 293 K. Assume $R = 0.287$ kJ/kg K, $c_p = 1.004$ kJ/kg K and $c_v = 0.716$ kJ/kg K.*

(U.P.S.C.)

Solution. Irreversibility $I = W_{max} - W_{act}$

$$-W_{max} = \text{Change in internal energy} - T_0 \times \text{Change in entropy}$$

or $$-W_{max} = (u_2 - u_1) - T_0(s_2 - s_1) = W_{rev}$$

or $$-W_{max} = c_v(T_2 - T_1) - T_0[c_p \ln (T_2/T_1) - R \ln (p_2/p_1)]$$

$$= 0.716(370 - 300) - 293 \times [1.005 \ln (370/300) - 0.287 \ln (6.8/1)]$$

or $$W_{max} = -149.53 \text{ kJ/kg} = W_{rev}$$

(negative sign indicates that work is done on air)

SOLVED PROBLEMS

The index of compression 'n' is given by

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{[(n-1)/n]}$$

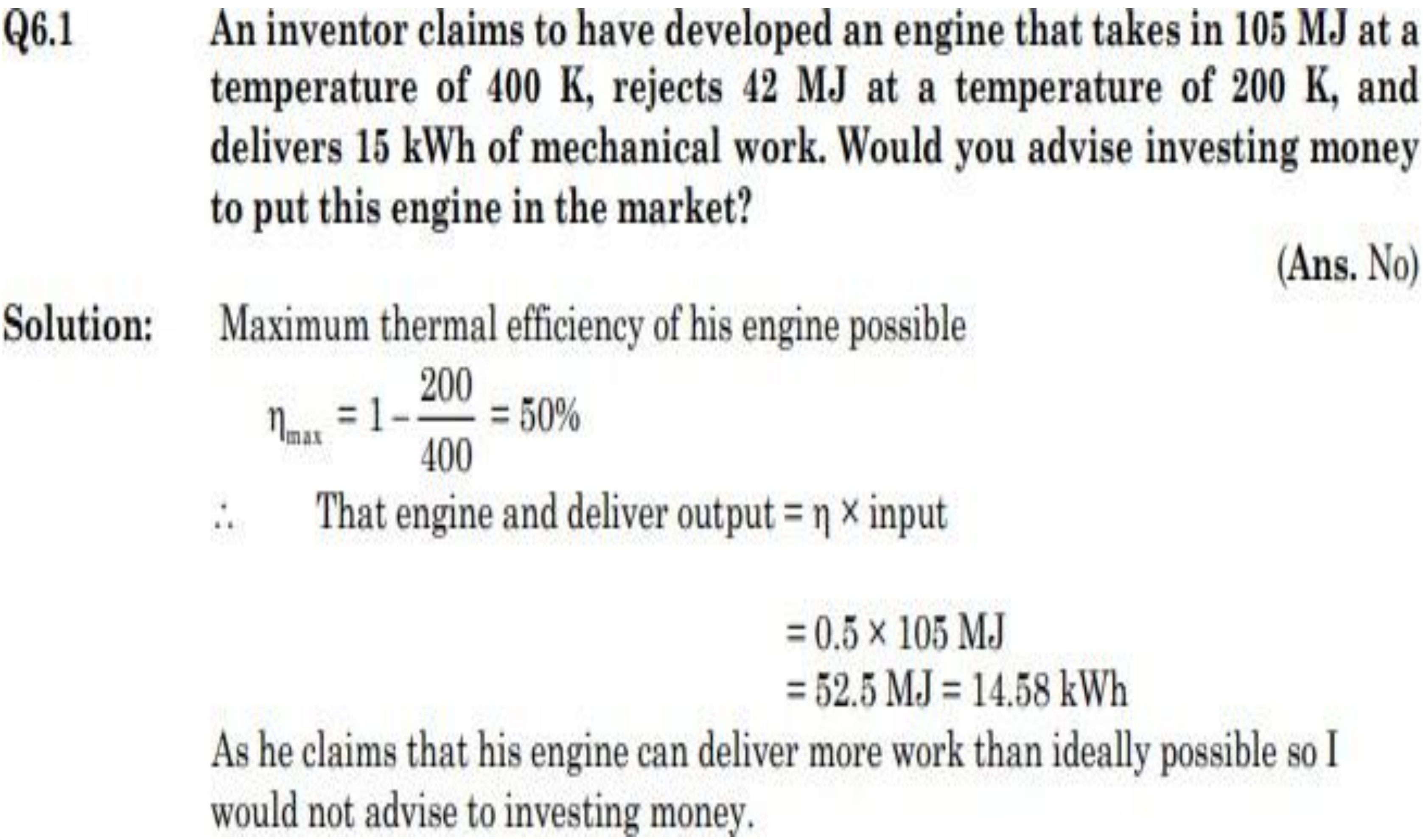
$$\frac{n-1}{n} = \frac{\ln(T_2/T_1)}{\ln(p_2/p_1)} = \frac{\ln(370/300)}{\ln(6.8/1)}$$

$$n = 1.123$$

$$W_{actual} = \frac{mR(T_1 - T_2)}{n-1} = \frac{1 \times 0.287(300-370)}{1.123-1} = -163.33 \text{ kJ/kg}$$

$$I = W_{rev} - W_{act} = -149.53 - (-163.33) = \mathbf{13.8\ kJ/kg.} \quad \textbf{(Ans.)}$$

SOLVED PROBLEMS



Q6.1 An inventor claims to have developed an engine that takes in 105 MJ at a temperature of 400 K, rejects 42 MJ at a temperature of 200 K, and delivers 15 kWh of mechanical work. Would you advise investing money to put this engine in the market?

(Ans. No)

Solution: Maximum thermal efficiency of his engine possible

$$\eta_{max} = 1 - \frac{200}{400} = 50\%$$

∴ That engine and deliver output = $\eta \times$ input

$$= 0.5 \times 105 \text{ MJ}$$
$$= 52.5 \text{ MJ} = 14.58 \text{ kWh}$$

As he claims that his engine can deliver more work than ideally possible so I would not advise to investing money.

SOLVED PROBLEMS

Q6.2 **If a refrigerator is used for heating purposes in winter so that the atmosphere becomes the cold body and the room to be heated becomes the hot body, how much heat would be available for heating for each kW input to the driving motor? The COP of the refrigerator is 5, and the electromechanical efficiency of the motor is 90%. How does this compare with resistance heating?**

(**Ans.** 5.4 kW)

Solution:

$$\text{COP} = \frac{\text{desired effect}}{\text{input}}$$

$$(\text{COP})_{\text{ref.}} = (\text{COP})_{\text{H.P}} - 1$$

or $6 = \dfrac{H}{W}$ $\qquad \therefore (\text{COP})_{\text{H.P.}} = 6$

So input $(W) = \dfrac{H}{6}$

But motor efficiency 90% so

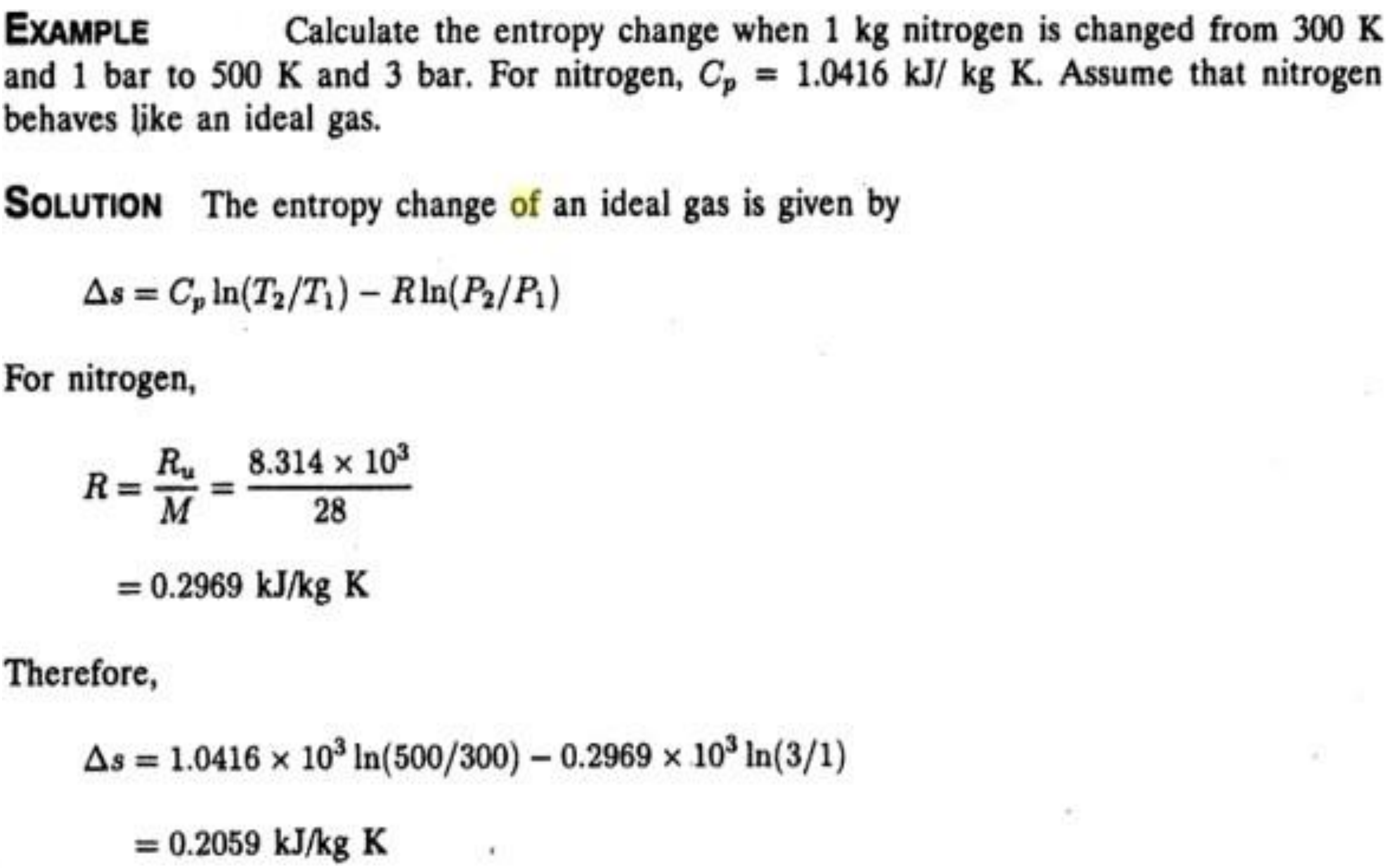
Electrical energy require $(E) = \dfrac{W}{0.9} = \dfrac{H}{0.9 \times 6}$

$= 0.1852\ H$

$= 18.52\%$ of Heat (direct heating)

$$H = \frac{100}{18.52} \frac{\text{kW}}{\text{kW of work}} = 5.3995\,\text{kW}$$

SOLVED PROBLEMS



EXAMPLE Calculate the entropy change when 1 kg nitrogen is changed from 300 K and 1 bar to 500 K and 3 bar. For nitrogen, C_p = 1.0416 kJ/ kg K. Assume that nitrogen behaves like an ideal gas.

SOLUTION The entropy change of an ideal gas is given by

$$\Delta s = C_p \ln(T_2/T_1) - R \ln(P_2/P_1)$$

For nitrogen,

$$R = \frac{R_u}{M} = \frac{8.314 \times 10^3}{28}$$

$$= 0.2969 \text{ kJ/kg K}$$

Therefore,

$$\Delta s = 1.0416 \times 10^3 \ln(500/300) - 0.2969 \times 10^3 \ln(3/1)$$

$$= 0.2059 \text{ kJ/kg K}$$

SOLVED PROBLEMS

Example 6.1 A cyclic heat engine operates between a source temperature of 800°C and a sink temperature of 30°C. What is the least rate of heat rejection per kW net output of the engine?

Solution For a reversible engine, the rate of heat rejection will be minimum (Fig. Ex. 6.1).

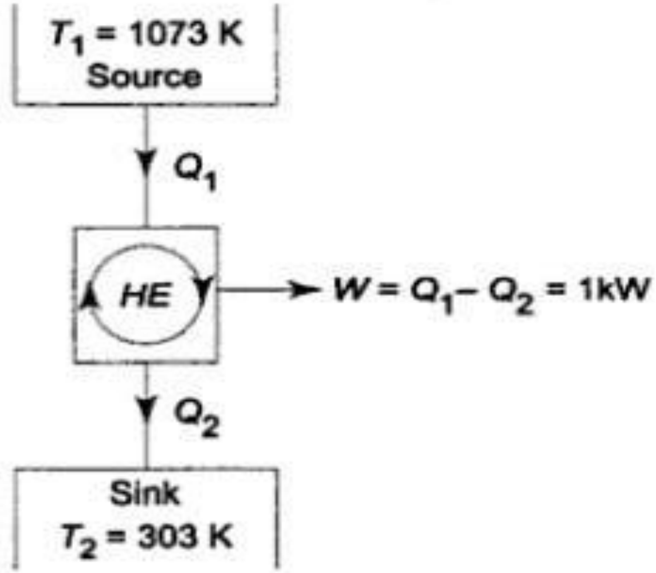


Fig. Ex. 6.1

$$\eta_{\max} = \eta_{\text{rev}} = 1 - \frac{T_2}{T_1}$$

SOLVED PROBLEMS

$$= 1 - \frac{30 + 273}{800 + 273}$$

$$= 1 - 0.282 = 0.718$$

Now $$\frac{W_{\text{net}}}{Q_1} = \eta_{\max} = 0.718$$

∴ $$Q_1 = \frac{1}{0.718} = 1.392 \text{ kW}$$

Now $$Q_2 = Q_1 - W_{\text{net}} = 1.392 - 1$$

$$= 0.392 \text{ kW}$$

This is the least rate of heat rejection.

SOLVED PROBLEMS

Example A fluid undergoes a reversible adiabatic compression from 0.5 MPa, 0.2 m^3 to 0.05 m^3 according to the law, $pv^{1.3}$ = constant. Determine the change in enthalpy, internal energy and entropy, and the heat transfer and work transfer during the process.

Solution

$$TdS = dH - Vdp$$

For the reversible adiabatic process (Fig. Ex. 7.7)

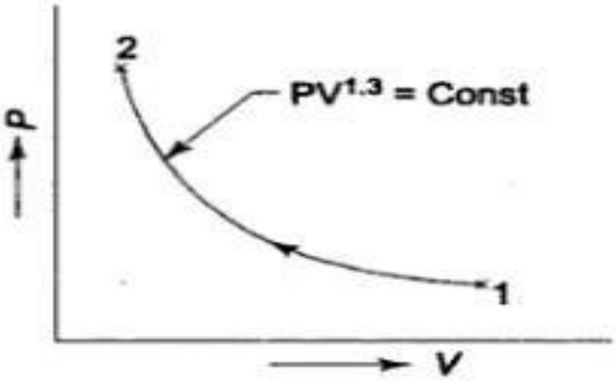


Fig. Ex. 7.7

$$dH = Vdp$$

$$p_1 = 0.5 \text{ MPa}, \; V_1 = 0.2 \text{ m}^3$$

$$V_2 = 0.05 \text{ m}^3, \; p_1 V_1^n = p_2 V_2^n$$

$$\therefore \quad p_2 = p_1 \left(\frac{V_1}{V_2} \right)^n$$

SOLVED PROBLEMS

$$= 0.5 \times \left(\frac{0.20}{0.05}\right)^{1.3} \text{ MPa}$$

$$= 0.5 \times 6.061 \text{ MPa}$$

$$= 3.0305 \text{ MPa}$$

$$p_1 V_1^n = p V^n$$

$$V = \left(\frac{p_1 V_1^n}{p}\right)^{1/n}$$

$$\int_{H_1}^{H_2} dH = \int_{p_1}^{p_2} V dp$$

$$H_2 - H_1 = \int_{p_1}^{p_2} \left[\left(\frac{p_1 V_1^n}{p}\right)^{1/n}\right] dp$$

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SOLVED PROBLEMS

$$
\begin{aligned}
&= (p_1 V_1^{n})^{1/n} \left(\frac{p_1^{1-1/n} - p_1^{1-n/n}}{1 - 1/n} \right) \\
&= \frac{n(p_2 V_2 - p_1 V_1)}{n-1} \\
&= \frac{1.3(3030.5 \times 0.05 - 500 \times 0.2)}{1.3 - 1} \\
&= 223.3 \text{ kJ} \\
H_2 - H_1 &= (U_2 + p_2 V_2) - (U_1 + p_1 V_1) \\
&= (U_2 - U_1) + (p_2 V_2 - p_1 V_1) \\
U_2 - U_1 &= (H_2 - H_1) - (p_2 V_2 - p_1 V_1) \\
&= 223.3 - 51.53 \\
&= 171.77 \text{ kJ} && \textit{Ans.} \\
S_2 - S_1 &= 0 && \textit{Ans.} \\
Q_{1-2} &= 0 && \textit{Ans.} \\
Q_{1-2} &= U_2 - U_1 + W_{1-2} \\
W_{1-2} &= U_1 - U_2 = -171.77 \text{ kJ} && \textit{Ans.}
\end{aligned}
$$

SOLVED PROBLEMS

Example 2.20. *To a closed system 150 kJ of work is supplied. If the initial volume is 0.6 m³ and pressure of the system changes as p = 8 – 4V, where p is in bar and V is in m³, determine the final volume and pressure of the system.*

Solution. Amount of work supplied to a closed system = 150 kJ

Initial volume = 0.6 m³

Pressure-volume relationship, $p = 8 - 4V$

The work done during the process is given by

$$W = \int_{V_1}^{V_2} p\,dV$$

$$= 10^5 \int_{0.6}^{V_2} (8 - 4V)\,dV = 10^5 \left[8V - 4 \times \frac{V^2}{2} \right]_{0.6}^{V}$$

$$= 10^5[8(V_2 - 0.6) - 2(V_2^2 - 0.6^2)]$$

$$= 10^5[8V_2 - 4.8 - 2V_2^2 + 0.72]$$

$$= 10^5[8V_2 - 2V_2^2 - 4.08] \text{ Nm or J}$$

SOLVED PROBLEMS

But this work is equal to – 150 × 10^3 J as this work is supplied to the system.

$$\therefore \quad -150 \times 10^3 = 10^5[8V_2 - 2V_2^{\,2} - 4.08]$$

$$2V_2^{\,2} - 8V_2 + 2.58 = 0$$

$$V_2 = \frac{8 \pm \sqrt{64 - 4 \times 2 \times 2.58}}{4} = \frac{8 \pm 6.585}{4} = 0.354 \text{ m}^3$$

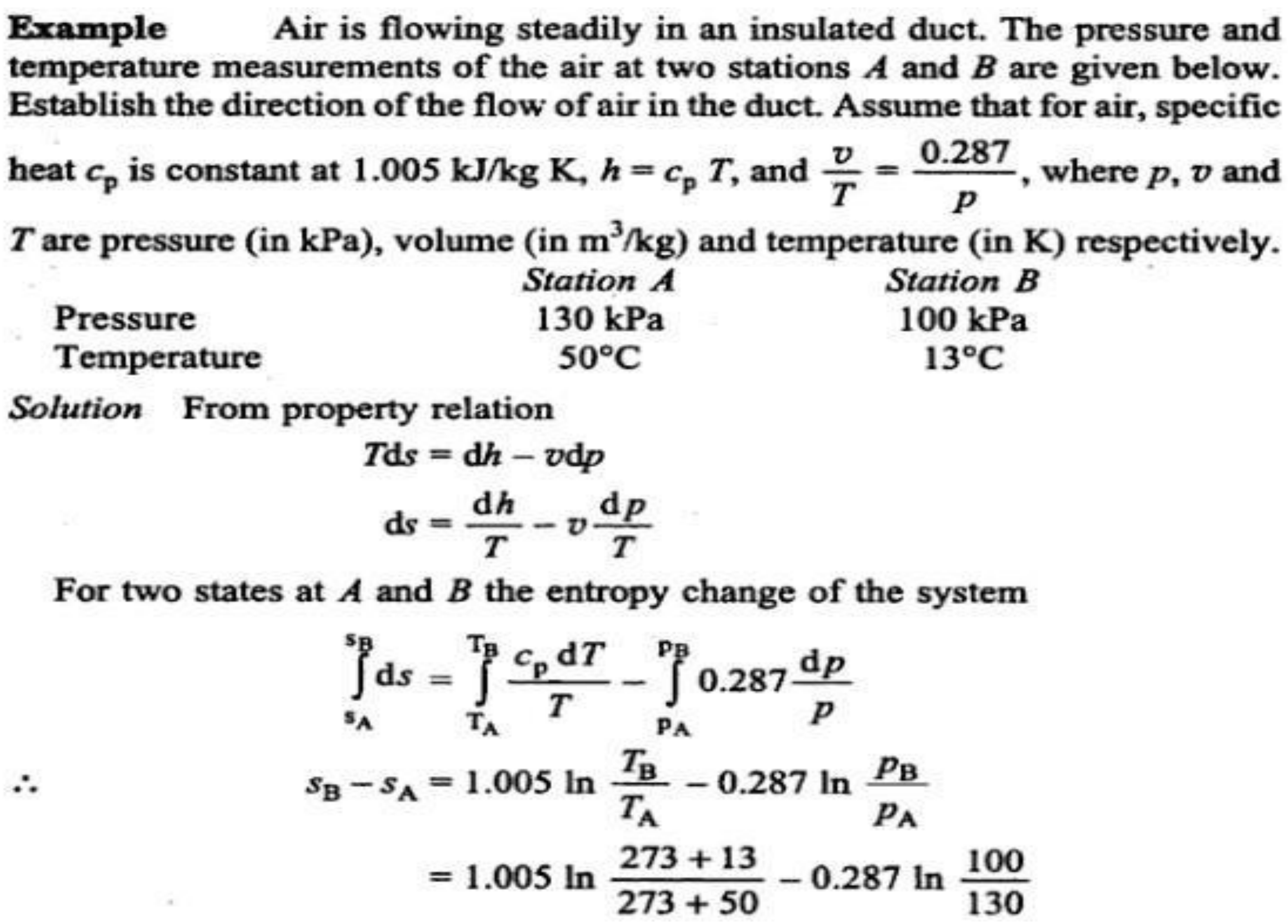
Positive sign is incompatible with the present problem, therefore it is not considered.

∴ **Final volume, V_2 = 0.354 m^3. (Ans.)**

final pressure, $p_2 = 8 - 4V = 8 - 4 \times 0.354$

$= 6.584$ bar = **6.584 × 10^5 N/m^2 or Pa. (Ans.)**

SOLVED PROBLEMS



Example Air is flowing steadily in an insulated duct. The pressure and temperature measurements of the air at two stations *A* and *B* are given below. Establish the direction of the flow of air in the duct. Assume that for air, specific heat c_p is constant at 1.005 kJ/kg K, $h = c_p T$, and $\frac{v}{T} = \frac{0.287}{p}$, where p, v and T are pressure (in kPa), volume (in m^3/kg) and temperature (in K) respectively.

	Station A	*Station B*
Pressure	130 kPa	100 kPa
Temperature	50°C	13°C

Solution From property relation

$$Tds = dh - vdp$$

$$ds = \frac{dh}{T} - v\frac{dp}{T}$$

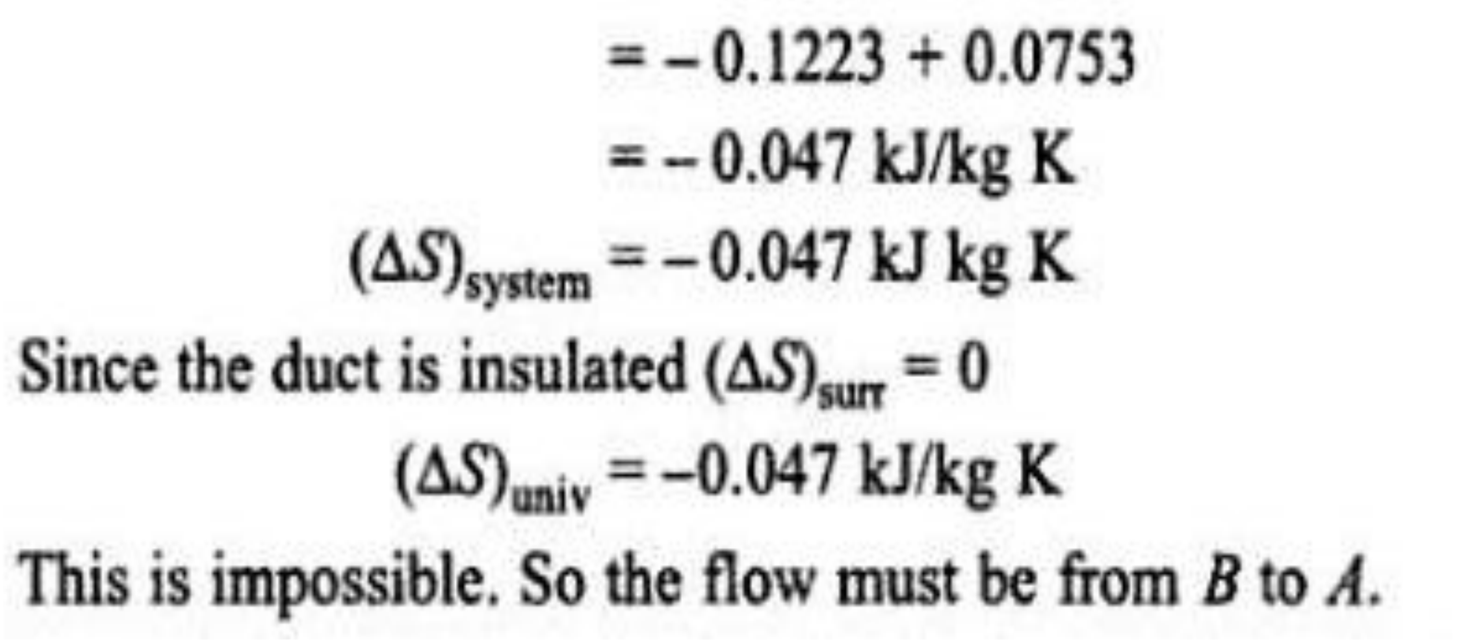
For two states at *A* and *B* the entropy change of the system

$$\int_{s_A}^{s_B} ds = \int_{T_A}^{T_B} \frac{c_p\, dT}{T} - \int_{p_A}^{p_B} 0.287\frac{dp}{p}$$

$$\therefore \quad s_B - s_A = 1.005 \ln \frac{T_B}{T_A} - 0.287 \ln \frac{p_B}{p_A}$$

$$= 1.005 \ln \frac{273 + 13}{273 + 50} - 0.287 \ln \frac{100}{130}$$

SOLVED PROBLEMS



$$= -0.1223 + 0.0753$$

$$= -0.047 \text{ kJ/kg K}$$

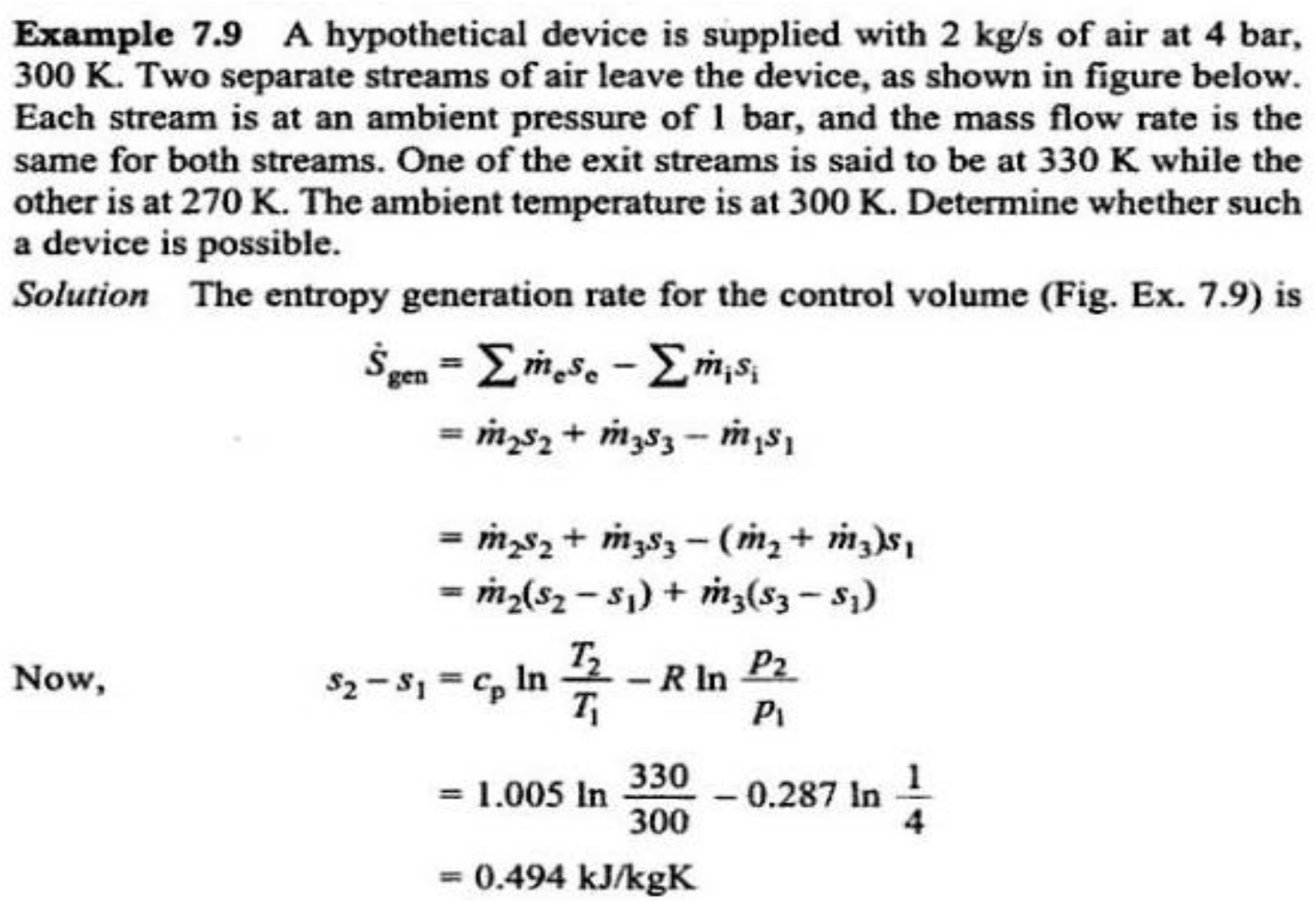
$$(\Delta S)_{\text{system}} = -0.047 \text{ kJ kg K}$$

Since the duct is insulated $(\Delta S)_{\text{surr}} = 0$

$$(\Delta S)_{\text{univ}} = -0.047 \text{ kJ/kg K}$$

This is impossible. So the flow must be from *B* to *A*.

SOLVED PROBLEMS



Example 7.9 A hypothetical device is supplied with 2 kg/s of air at 4 bar, 300 K. Two separate streams of air leave the device, as shown in figure below. Each stream is at an ambient pressure of 1 bar, and the mass flow rate is the same for both streams. One of the exit streams is said to be at 330 K while the other is at 270 K. The ambient temperature is at 300 K. Determine whether such a device is possible.

Solution The entropy generation rate for the control volume (Fig. Ex. 7.9) is

$$\dot{S}_{\text{gen}} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i$$

$$= \dot{m}_2 s_2 + \dot{m}_3 s_3 - \dot{m}_1 s_1$$

$$= \dot{m}_2 s_2 + \dot{m}_3 s_3 - (\dot{m}_2 + \dot{m}_3) s_1$$

$$= \dot{m}_2 (s_2 - s_1) + \dot{m}_3 (s_3 - s_1)$$

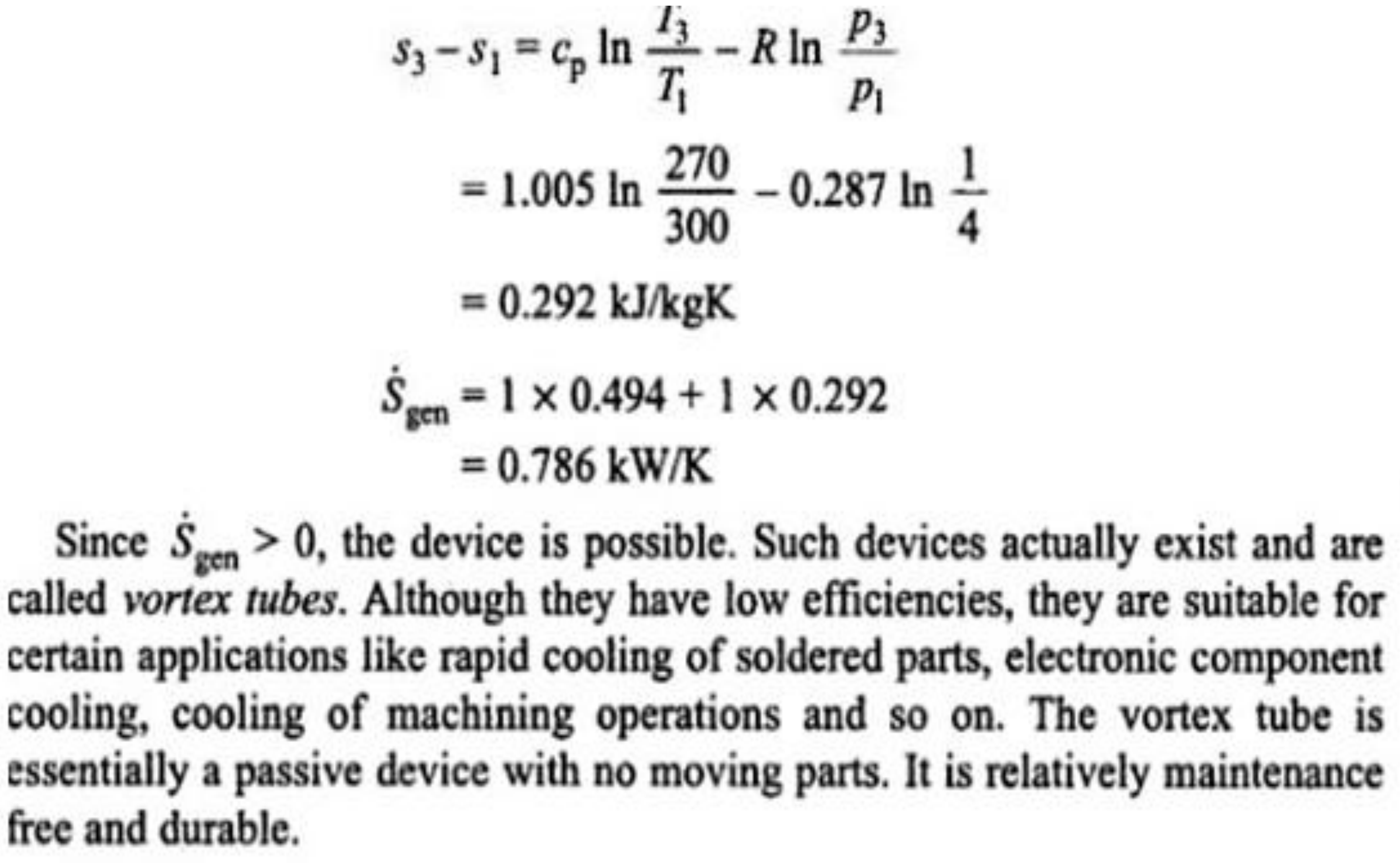
Now,

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

$$= 1.005 \ln \frac{330}{300} - 0.287 \ln \frac{1}{4}$$

$$= 0.494 \text{ kJ/kgK}$$

SOLVED PROBLEMS



$$s_3 - s_1 = c_p \ln \frac{T_3}{T_1} - R \ln \frac{p_3}{p_1}$$

$$= 1.005 \ln \frac{270}{300} - 0.287 \ln \frac{1}{4}$$

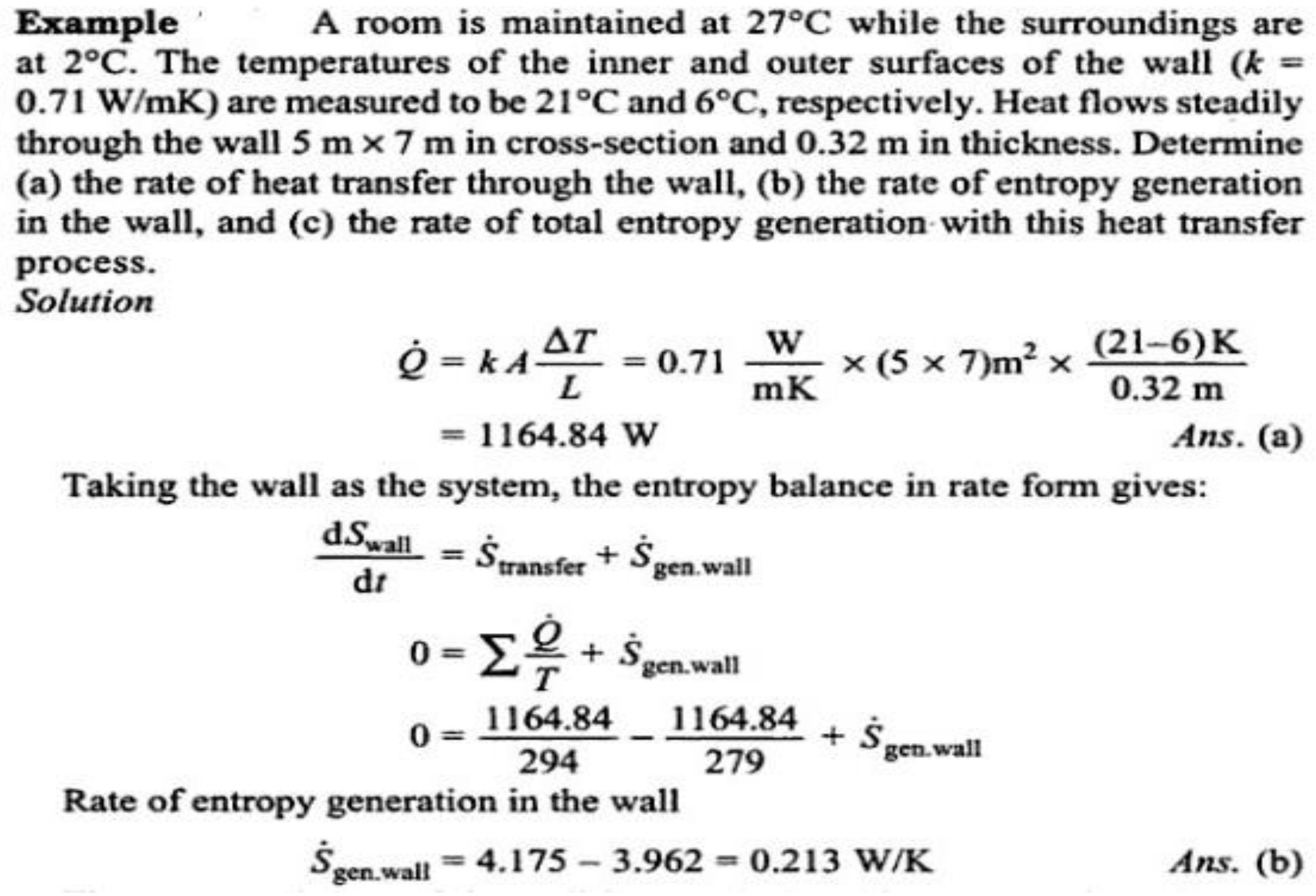
$$= 0.292 \text{ kJ/kgK}$$

$$\dot{S}_{gen} = 1 \times 0.494 + 1 \times 0.292$$

$$= 0.786 \text{ kW/K}$$

Since $\dot{S}_{gen} > 0$, the device is possible. Such devices actually exist and are called *vortex tubes*. Although they have low efficiencies, they are suitable for certain applications like rapid cooling of soldered parts, electronic component cooling, cooling of machining operations and so on. The vortex tube is essentially a passive device with no moving parts. It is relatively maintenance free and durable.

SOLVED PROBLEMS



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

Solution

$$\dot{Q} = kA\frac{\Delta T}{L} = 0.71\ \frac{\text{W}}{\text{mK}} \times (5 \times 7)\text{m}^2 \times \frac{(21-6)\,\text{K}}{0.32\ \text{m}}$$

$$= 1164.84\ \text{W} \qquad \textit{Ans.}\ \text{(a)}$$

Taking the wall as the system, the entropy balance in rate form gives:

$$\frac{dS_{\text{wall}}}{dt} = \dot{S}_{\text{transfer}} + \dot{S}_{\text{gen.wall}}$$

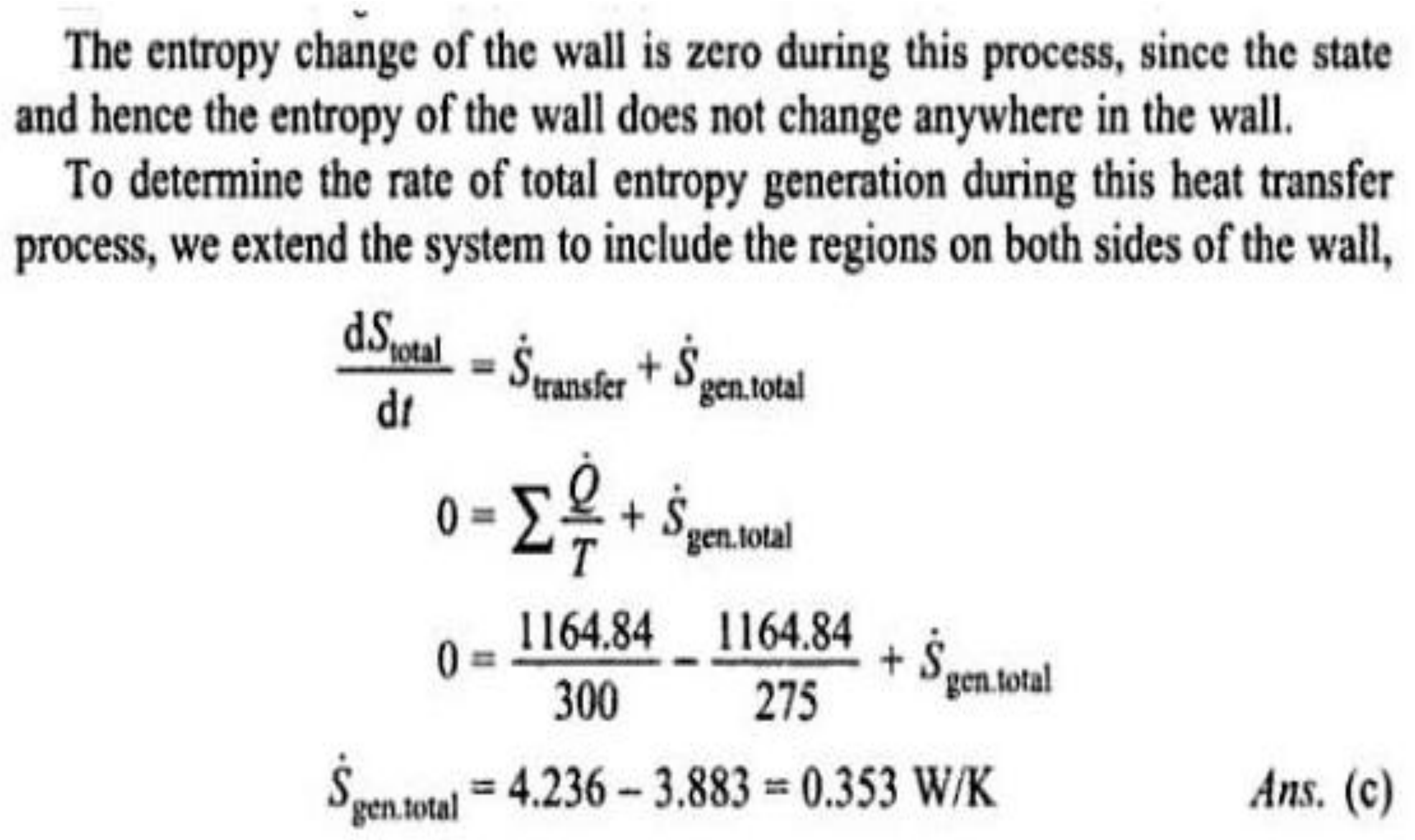
$$0 = \sum\frac{\dot{Q}}{T} + \dot{S}_{\text{gen.wall}}$$

$$0 = \frac{1164.84}{294} - \frac{1164.84}{279} + \dot{S}_{\text{gen.wall}}$$

Rate of entropy generation in the wall

$$\dot{S}_{\text{gen.wall}} = 4.175 - 3.962 = 0.213\ \text{W/K} \qquad \textit{Ans.}\ \text{(b)}$$

SOLVED PROBLEMS



The entropy change of the wall is zero during this process, since the state and hence the entropy of the wall does not change anywhere in the wall.

To determine the rate of total entropy generation during this heat transfer process, we extend the system to include the regions on both sides of the wall,

$$\frac{dS_{total}}{dt} = \dot{S}_{transfer} + \dot{S}_{gen.total}$$

$$0 = \sum \frac{\dot{Q}}{T} + \dot{S}_{gen.total}$$

$$0 = \frac{1164.84}{300} - \frac{1164.84}{275} + \dot{S}_{gen.total}$$

$$\dot{S}_{gen.total} = 4.236 - 3.883 = 0.353 \text{ W/K} \qquad \textit{Ans.} \text{ (c)}$$

INDUSTRIAL APPLICATIONS

- Automobile industries.
- Refrigeration industries
- Air craft applications
- Defense industries
- Thermal power plants
- Chemical industries
- Textile industries etc.

SELF LEARNING QUESTIONS

- Describe briefly about the second law of thermodynamics with its corollaries.
- State the limitations of first law of thermodynamics? State PMM 2?
- Discuss briefly about Clausius inequality.
- Discuss the significance of Third law of thermodynamics
- Derive the expression for the efficiency of Carnot cycle with p-V and T-s diagrams.
- Solve one T -dS equation by using Maxwell’s relations?

ASSIGNMENT EXERCISES

- 0.5 kg of air executes a Carnot power cycle having a thermal efficiency of 50%. The heat transfer to the air during isothermal expansion is 40 kJ. At the beginning of the isothermal expansion the pressure is 7 bar and the volume is 0.12 m3. Determine the maximum and minimum temperatures for the cycle in Kelvin, the volume at the end of isothermal expansion in m3 and the work, heat transfer for each of the four processes in kJ. cp=1.008 kJ/kgK and cv=0.721 kJ/kgK for air.
- Water is heated at a constant pressure of 0.7 MPa. The boiling point is 164.970C. The initial temperature of water is 00C. The latent heat of evaporation is 2066.3 kJ/kg. Find the increase of entropy of water if the final temperature is steam.

ASSIGNMENT EXERCISES

- 1kg of ice at -50C expose to the atmosphere which, is at 200C. The ice melts and comes into thermal equilibrium with the atmosphere. Determine the entropy increase of Universe. Cp for ice is 2.039 kJ/kgK, and the enthalpy of fusion of ice is 333.3kJ/kg.
- A heat engine is operating between two reservoirs 1000K and 300K is used to drive a heat pump which extracts heat from the reservoir at 300K at A heat engine is operating between two reservoirs 1000K and 300K is used to drive a heat pump which extracts heat from the reservoir at 300K. The efficiency of both the engines is equal. What is the value of temperature T2.

THANK YOU

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ENGINEERING THERMODYNAMICS

2nd Year B. Tech I- sem, Mechanical Engineering

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COURSE OBJECTIVES

UNIT - 1	CO1:To understand the concepts of energy transformation, conversion of heat into work.
UNIT - 2	CO2:To acquire knowledge about the fundamentals of thermodynamic laws, the concept of entropy, and principles
UNIT - 3	CO3: To understand how the change of state results in a process.
UNIT - 4	CO4: To understand the various gas laws, psychrometric properties and chart.
UNIT - 5	CO5: To learn the importance of thermodynamic cycles, and the derivation of efficiency.

UNIT III

PURE SUBSTANCES

CO3: **To understand how the change of state results in a process.**

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UNIT – III (SYLLABUS)

Properties of Pure Substances

- p-V-T- surfaces, T-S and h-s diagrams
- Mollier Charts, Phase Transformations
- Triple point at critical state properties
- Dryness Fraction energy Transfer
- Steam Calorimetry.
- Perfect Gas Laws – Equation of State
- Throttling and Free Expansion Processes
- Deviations from perfect Gas Model – Vander Waals Equation of State.

COURSE OUTLINE

UNIT -3

LECTURE	LECTURE TOPIC	KEY ELEMENTS	Learning objectives (2 to 3 objectives)
1	Pure Substances: p-V-T- surfaces	Properties of pure substances	Phase change properties of pure substances (B2)
2	T-S and h-s diagrams, Phase Transformations	Enthalpy and entropy diagrams	Applications of Mollier chart (B3)
3	Triple point at critical state properties during change of phase	Concept of triple point	Understanding triple point temperature (B2)
4	Dryness Fraction – Mollier charts	Concept of quality of steam	Measurement of dryness fraction (B3)
5	Various Thermodynamic processes and energy Transfer	Isobaric process, Isothermal process	Energy transfer in different processes (B4)
6	Steam Calorimetry	Throttling calorimeter	Working principles of different steam calorimeters (B4)
7	Perfect Gas Laws, Equation of State	Boyles law, Charles law	Understanding of gas laws (B2)
8	Flow processes – Deviations from perfect Gas Model – Vander Waals Equation of State.	Vander Waals Equation	Understanding different flow processes (B2)

LECTURE 3

Properties of Pure substances

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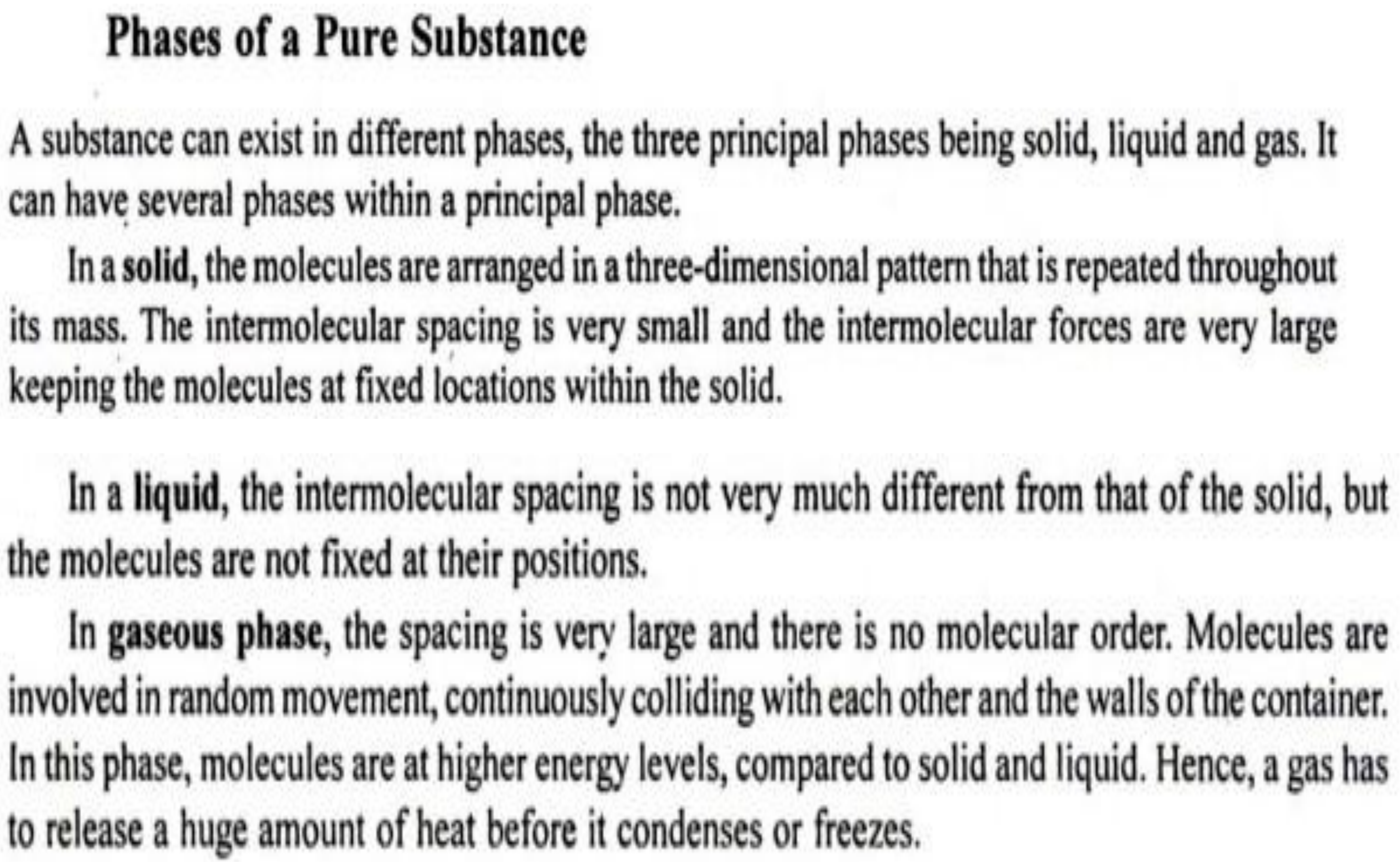
PURE SUBSTANCE

- A substance that has a fixed chemical composition throughout the system is called a pure substance.
- Water, hydrogen, nitrogen, and carbon monoxide, for example, are all pure substance.
- A pure substance can also be a mixture of various chemical elements or compounds as long as the mixture is homogeneous.

PURE SUBSTANCE

- Air, a mixture of several compounds, is often considered to be a pure substance because it has a uniform chemical composition.
- “A mixture of two or more phases of a pure substance is still a pure substance as long as the chemical composition of all phases is the same.
- A mixture of ice and liquid water, for example, is a pure substance because both phases have the same chemical composition.”

PHASES OF A PURE SUBSTANCE



Phases of a Pure Substance

A substance can exist in different phases, the three principal phases being solid, liquid and gas. It can have several phases within a principal phase.

In a **solid**, the molecules are arranged in a three-dimensional pattern that is repeated throughout its mass. The intermolecular spacing is very small and the intermolecular forces are very large keeping the molecules at fixed locations within the solid.

In a **liquid**, the intermolecular spacing is not very much different from that of the solid, but the molecules are not fixed at their positions.

In **gaseous phase**, the spacing is very large and there is no molecular order. Molecules are involved in random movement, continuously colliding with each other and the walls of the container. In this phase, molecules are at higher energy levels, compared to solid and liquid. Hence, a gas has to release a huge amount of heat before it condenses or freezes.

Phase Change Processes

Two phases of a pure substance often coexist in equilibrium in many practical situations. For example, water exists as a liquid–vapour mixture in the boiler and the condenser in the steam power plant. The refrigerant remains as a two-phase fluid in the evaporator and the condenser in a vapour compression refrigeration system.

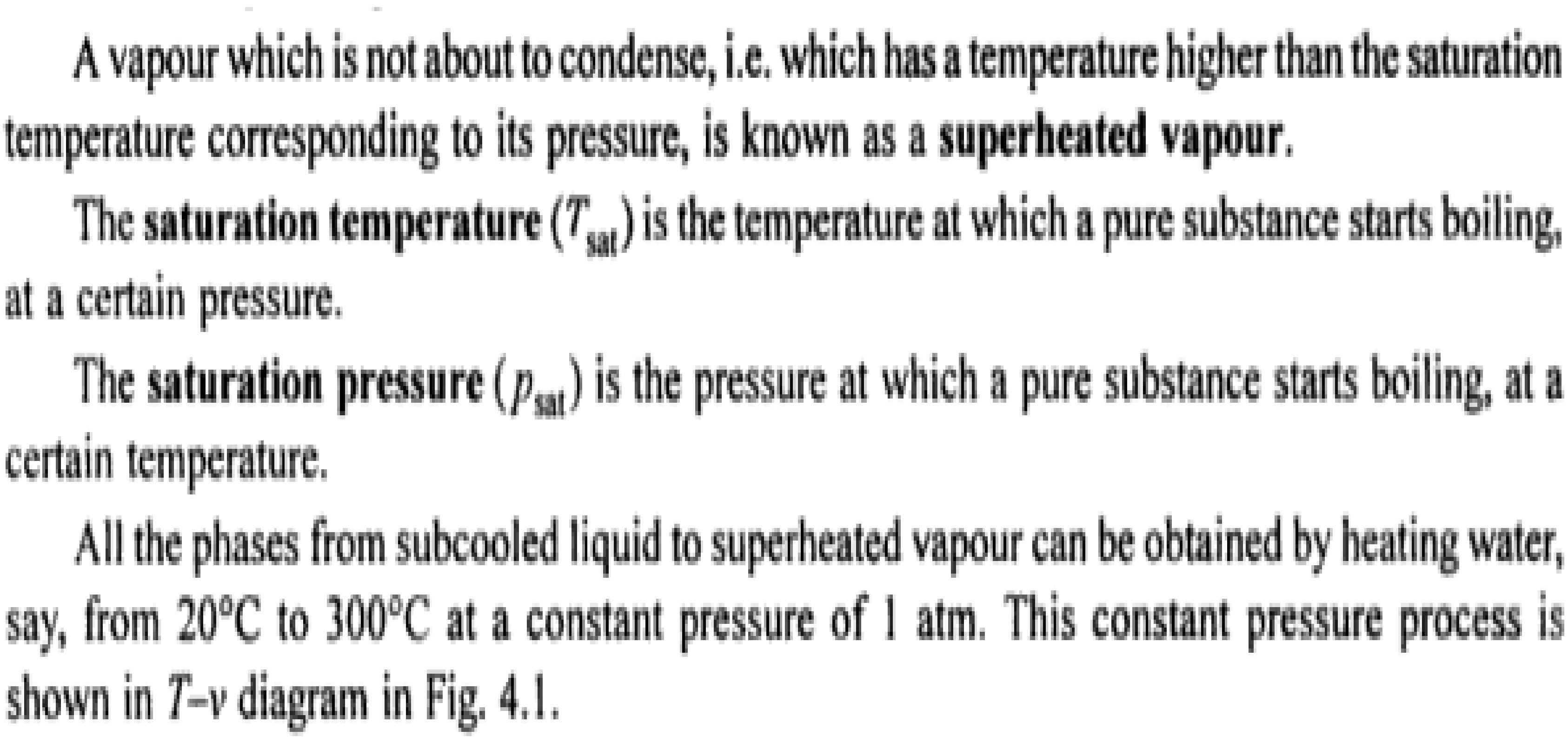
A liquid at a state where it is not about to vaporise is known as a **compressed liquid** or a **subcooled liquid**. Say, for example, water at 1 atm and 30°C is an example of subcooled liquid.

A liquid that is about to vaporise is known as a **saturated liquid**. For example, water at 1 atm and 100°C is a saturated liquid.

A vapour that is just about to condense is known as a **saturated vapour**.

A substance that is at states between the saturated liquid and the saturated vapour is known as a **saturated liquid–vapour mixture**.

PHASES OF A PURE SUBSTANCE



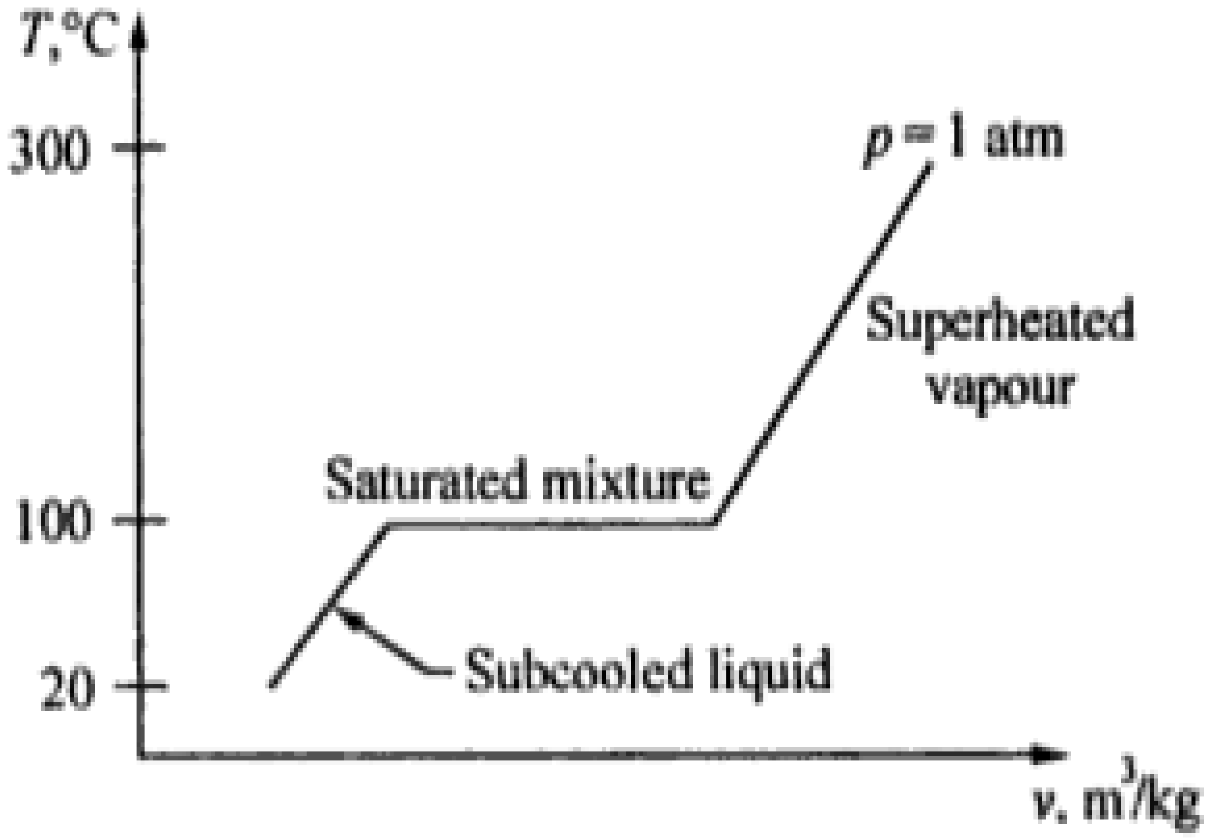
A vapour which is not about to condense, i.e. which has a temperature higher than the saturation temperature corresponding to its pressure, is known as a **superheated vapour**.

The **saturation temperature** (T_{sat}) is the temperature at which a pure substance starts boiling, at a certain pressure.

The **saturation pressure** (p_{sat}) is the pressure at which a pure substance starts boiling, at a certain temperature.

All the phases from subcooled liquid to superheated vapour can be obtained by heating water, say, from 20°C to 300°C at a constant pressure of 1 atm. This constant pressure process is shown in T–v diagram in Fig. 4.1.

PHASES OF A PURE SUBSTANCE



T–v diagram for the constant pressure heating process of water.

Let us consider 1 kg of liquid water at a temperature of 20°C in a cylinder fitted with a piston, which exerts on the water a constant pressure of one atmosphere (1.0132 bar) as shown in Fig. 2 (*i*).

— As the water is heated slowly its temperature rises until the temperature of the liquid water becomes 100°C. During the process of heating, the *volume slightly increases* as indicated by the line 1–2 on the temperature-specific volume diagram (Fig. 3). The piston starts moving upwards.

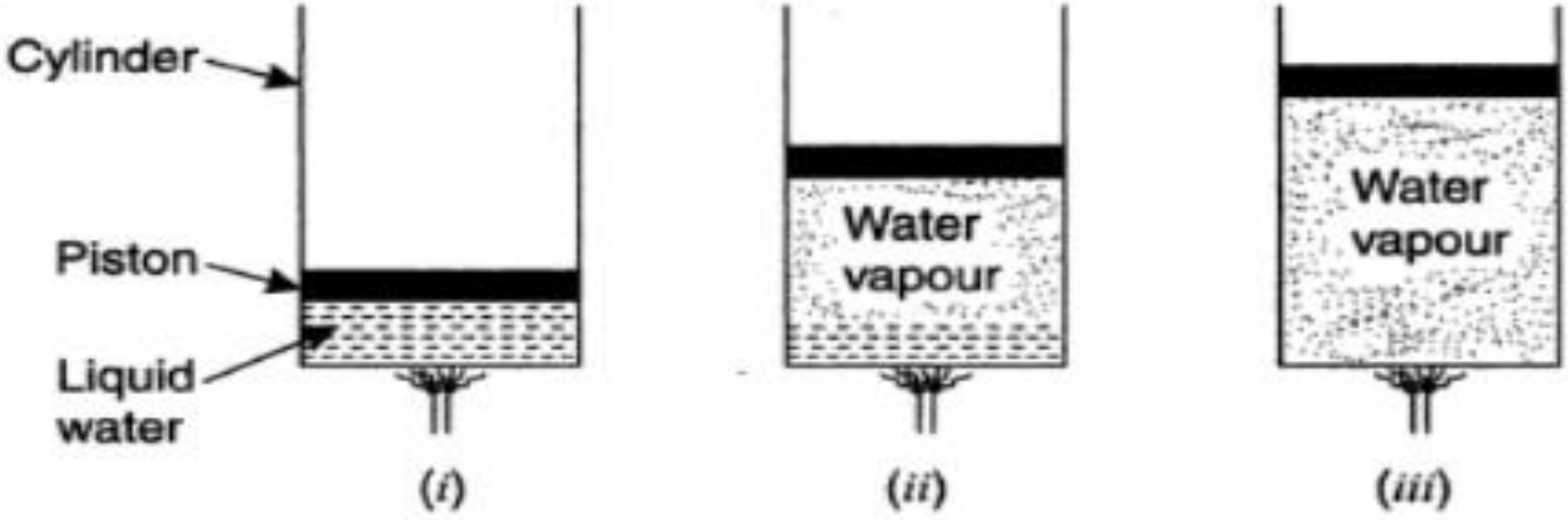
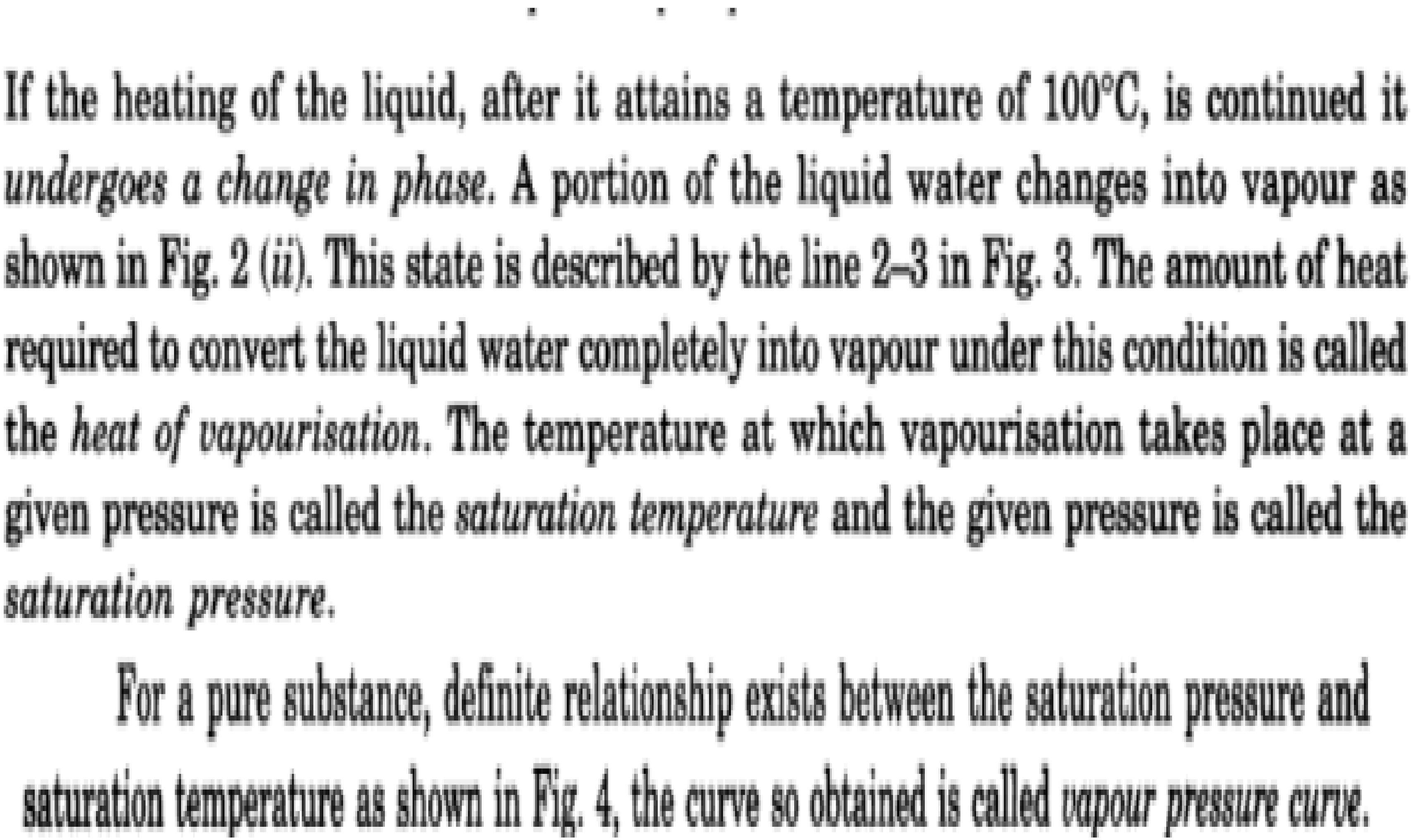


Fig. 2. Phase change of water at constant pressure from liquid to vapour phase.

PHASES OF A PURE SUBSTANCE



If the heating of the liquid, after it attains a temperature of 100°C, is continued it *undergoes a change in phase*. A portion of the liquid water changes into vapour as shown in Fig. 2 (*ii*). This state is described by the line 2–3 in Fig. 3. The amount of heat required to convert the liquid water completely into vapour under this condition is called the *heat of vapourisation*. The temperature at which vapourisation takes place at a given pressure is called the *saturation temperature* and the given pressure is called the *saturation pressure*.

For a pure substance, definite relationship exists between the saturation pressure and saturation temperature as shown in Fig. 4, the curve so obtained is called *vapour pressure curve*.

PHASES OF A PURE SUBSTANCE

During the process represented by the line 2–3 (Fig. 3) the volume increases rapidly and piston moves upwards Fig. 2 (*iii*).

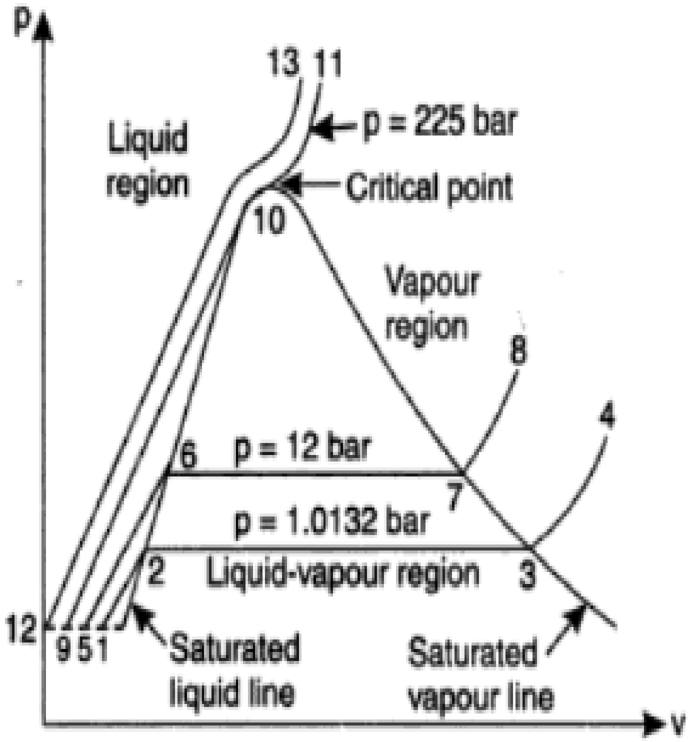


Fig. 3

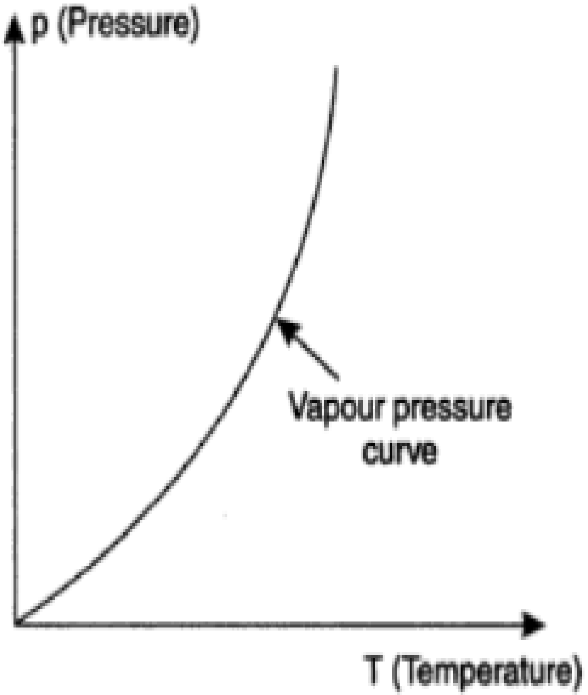


Fig. 4. Vapour pressure curve for water.

PHASES OF A PURE SUBSTANCE

It may be noted that if the temperature of the liquid water on cooling becomes lower than the saturation temperature for the given pressure, the liquid water is called a *sub-cooled liquid*. The point '1' (in Fig. 3) illustrates this situation, when the liquid water is cooled under atmospheric pressure to a temperature of 20°C, which is below the saturation temperature (100°C).

Further, at point '1' the temperature of liquid is 20°C and corresponding to this temperature, the saturation pressure is 0.0234 bar, which is lower than the pressure on the liquid water, which is 1 atmosphere. Thus the pressure on the liquid water is greater than the saturation pressure at a given temperature. In this condition, the liquid water is known as the *compressed liquid*.

p-T (Pressure-Temperature) DIAGRAM FOR A PURE SUBSTANCE

If the vapour pressure of a solid is measured at various temperatures until the *triple point* is reached and then that of the liquid is measured until the critical point is reached, the result when plotted on a *p-T* diagram appears as in Fig. 5.

If the substance at the triple point is compressed until there is no vapour left and the pressure on the resulting mixture of liquid and solid is increased, the temperature will have to be changed for equilibrium to exist between the solid and the liquid.

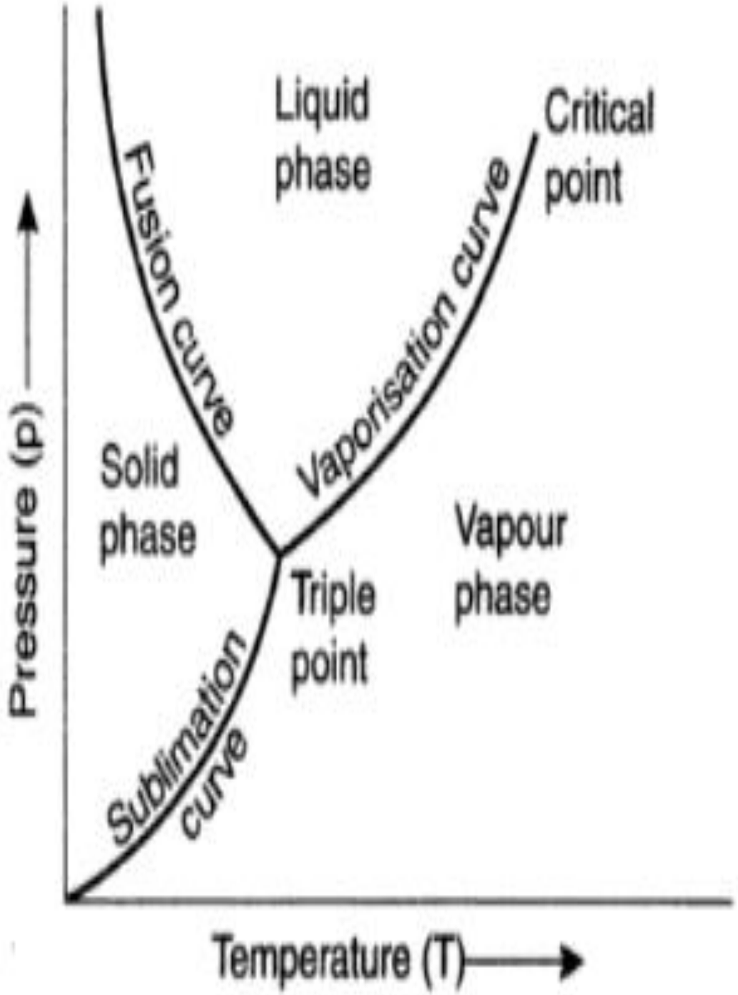
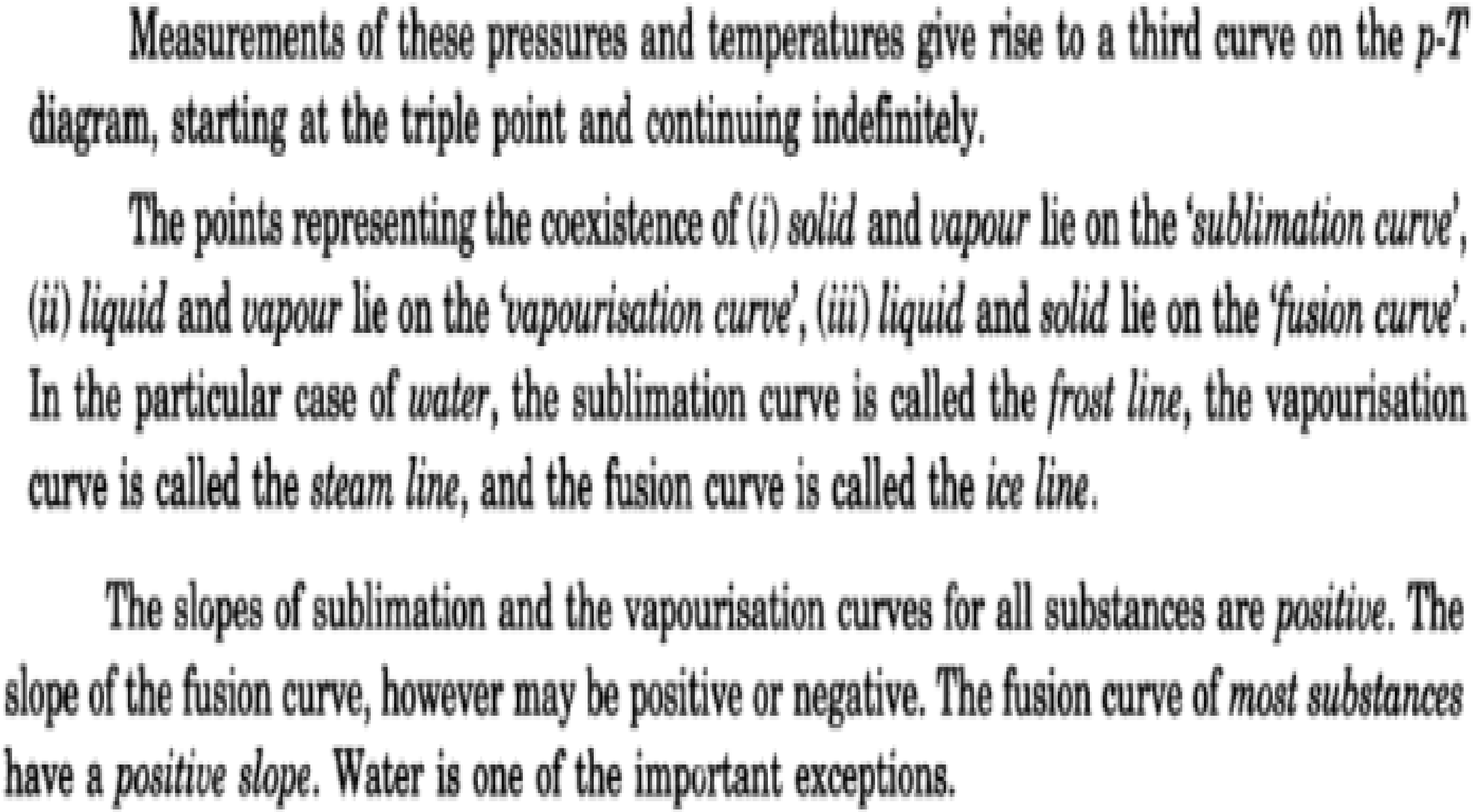


Fig. 5. *p*-T diagram for a substance such as water.

PHASES OF A PURE SUBSTANCE

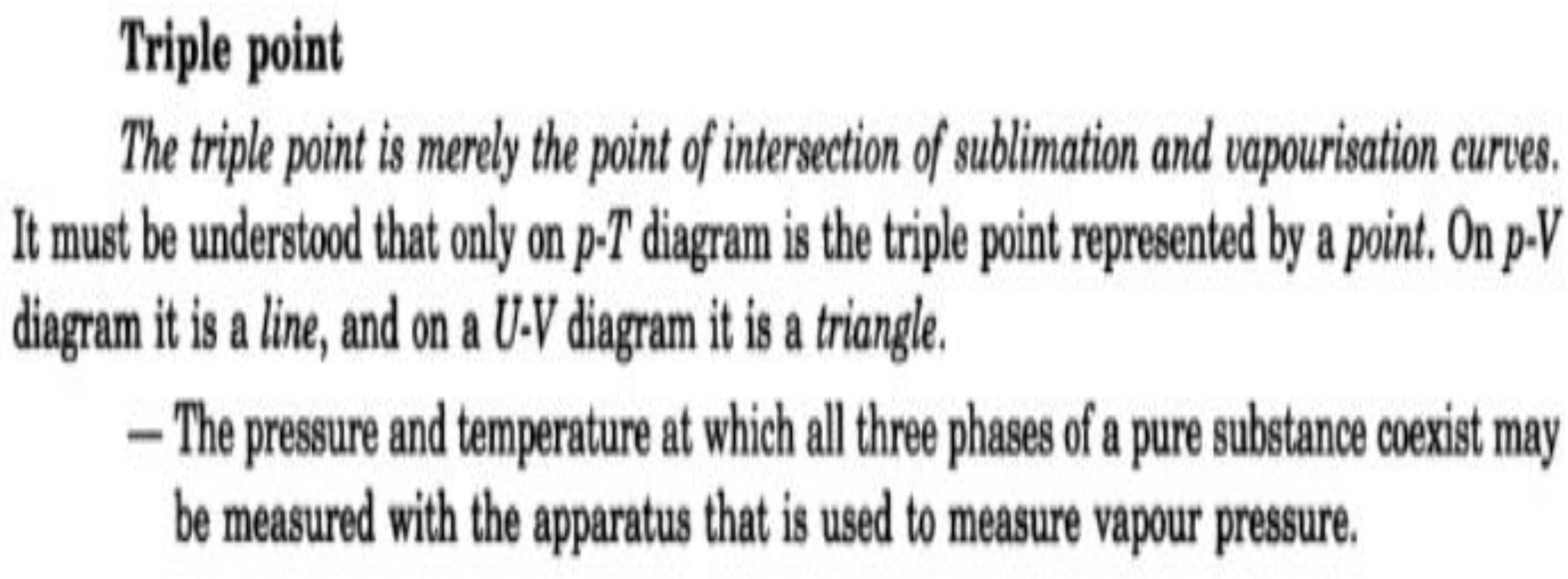


Measurements of these pressures and temperatures give rise to a third curve on the p-T diagram, starting at the triple point and continuing indefinitely.

The points representing the coexistence of (*i*) *solid* and *vapour* lie on the '*sublimation curve*', (*ii*) *liquid* and *vapour* lie on the '*vapourisation curve*', (*iii*) *liquid* and *solid* lie on the '*fusion curve*'. In the particular case of *water*, the sublimation curve is called the *frost line*, the vapourisation curve is called the *steam line*, and the fusion curve is called the *ice line*.

The slopes of sublimation and the vapourisation curves for all substances are *positive*. The slope of the fusion curve, however may be positive or negative. The fusion curve of *most substances* have a *positive slope*. Water is one of the important exceptions.

TRIPLE POINT



Triple point

The triple point is merely the point of intersection of sublimation and vapourisation curves. It must be understood that only on p-T diagram is the triple point represented by a *point*. On p-V diagram it is a *line*, and on a U-V diagram it is a *triangle*.

– The pressure and temperature at which all three phases of a pure substance coexist may be measured with the apparatus that is used to measure vapour pressure.

p-V-T (Pressure-Volume-Temperature) SURFACE

A detailed study of the heating process reveals that the temperature of the solid rises and then during the change of phase from solid to liquid (or solid to vapour) the temperature remains constant. This phenomenon is common to all phase changes. Since the temperature is constant, pressure and temperature are not independent properties and cannot be used to specify state during a change of phase.

The combined picture of change of pressure, specific volume and temperature may be shown on a three dimensional state model. Fig. 6 illustrates the equilibrium states for a pure substance which expands on fusion. Water is an example of a substance that exhibits this phenomenon.

All the equilibrium states lie on the surface of the model. States represented by the space above or below the surface are not possible. It may be seen that the *triple point appears as a line in this representation*. The point *C.P.* is called the *critical*

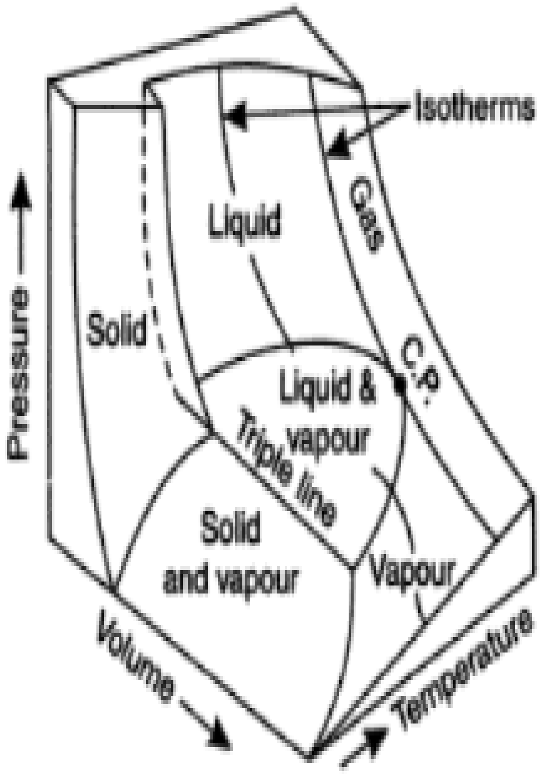
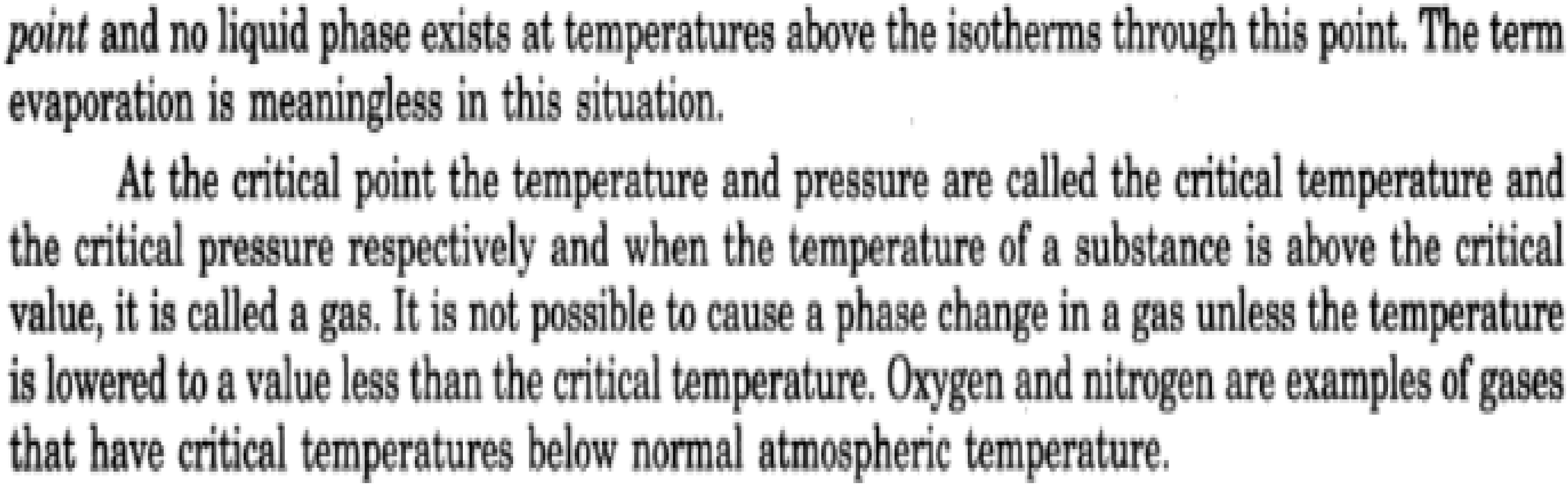


Fig. 6. A pressure-volume-temperature (*p-V-T*) surface.

PHASES OF A PURE SUBSTANCE



point and no liquid phase exists at temperatures above the isotherms through this point. The term evaporation is meaningless in this situation.

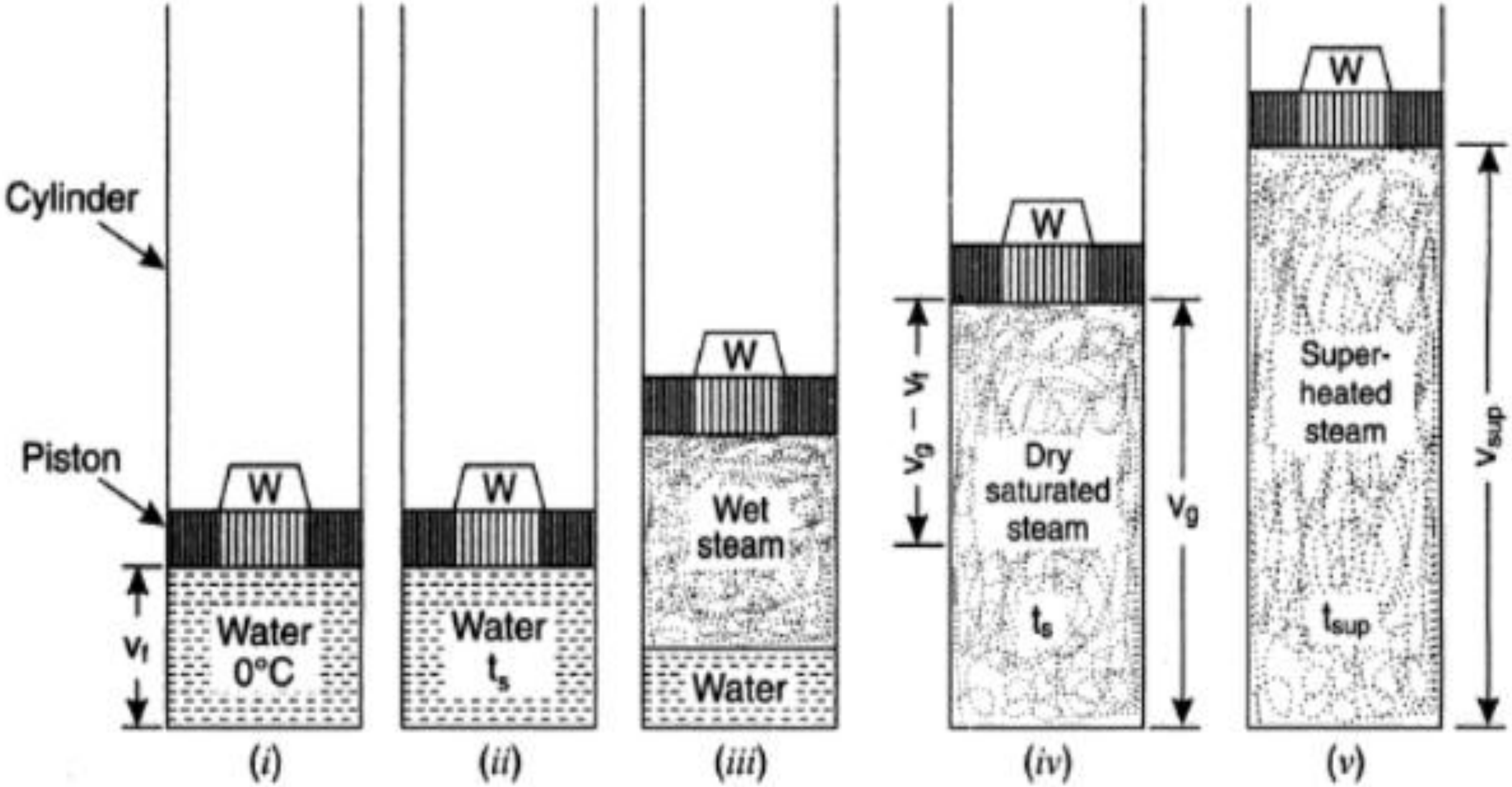
At the critical point the temperature and pressure are called the critical temperature and the critical pressure respectively and when the temperature of a substance is above the critical value, it is called a gas. It is not possible to cause a phase change in a gas unless the temperature is lowered to a value less than the critical temperature. Oxygen and nitrogen are examples of gases that have critical temperatures below normal atmospheric temperature.

FORMATION OF STEAM

The process of formation of steam is discussed in detail in the following few pages :

Consider a cylinder fitted with a piston which can move freely upwards and downwards in it. Let, for the sake of simplicity, there be 1 kg of water at 0°C with volume v_f m^3 under the piston [Fig. 9 (*i*)]. Further let the piston is loaded with load W to ensure heating at constant pressure. Now if the heat is imparted to water, a rise in temperature will be noticed and this rise will continue till boiling point is reached. The temperature at which water starts boiling depends upon the pressure and as such for *each pressure* (under which water is heated) *there is a different boiling point*. This boiling temperature is known as the temperature of formation of steam or *saturation temperature*.

It may be noted during heating up to boiling point that there will be slight increase in volume of water due to which piston moves up and hence work is obtained as shown in Fig. 9 (*ii*). This work, however, is so *small* that is can be *neglected*.



t_s = Saturation temp.

t_{sup} = Temperature of superheated steam

v_f = Volume of water

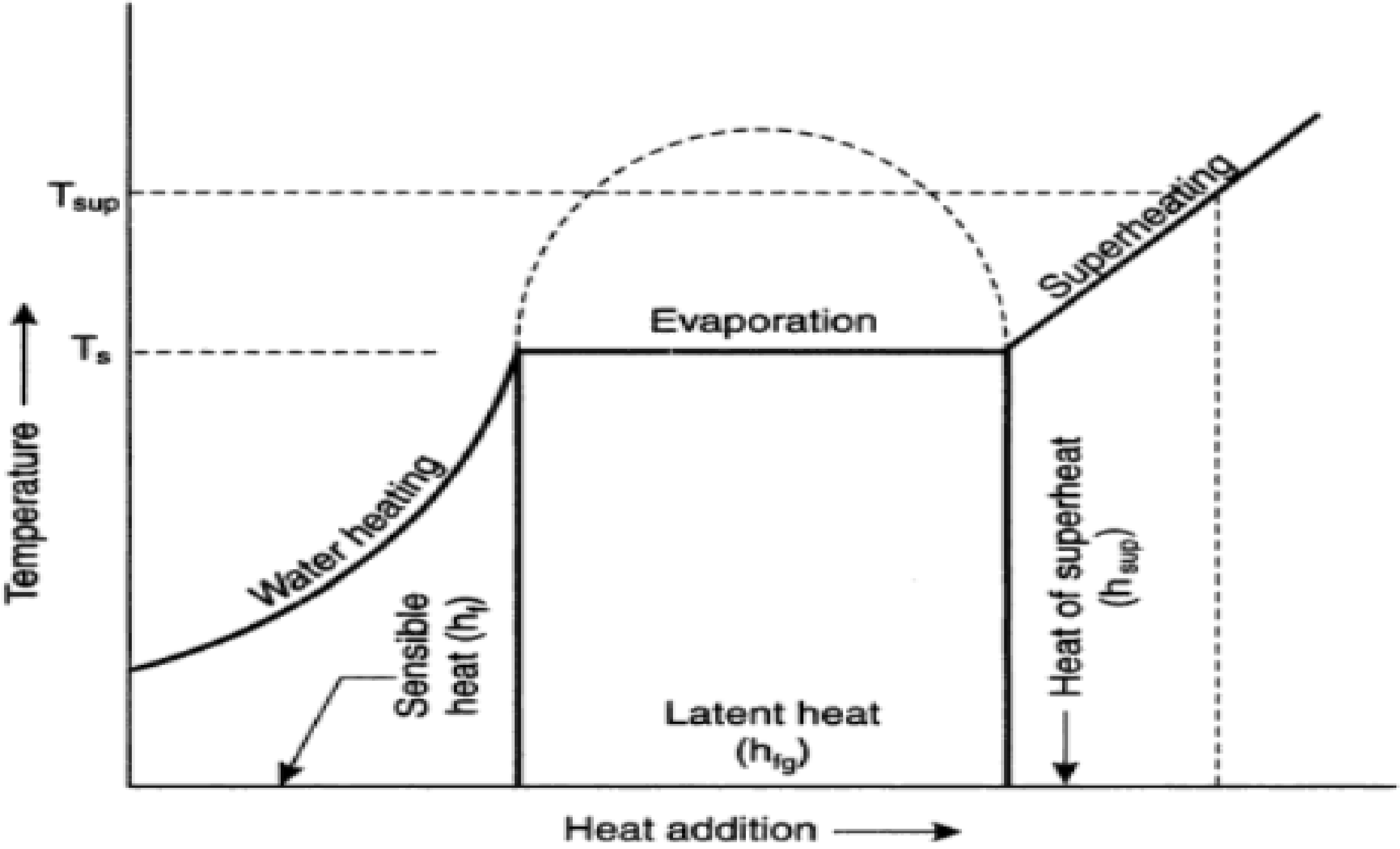
v_g = Volume of dry and saturated steam

v_{sup} = Volume of superheated steam

Fig. 9. Formation of steam.

FORMATION OF STEAM

graphical representation of formation of steam.



Graphical representation of formation of steam.

1. Sensible heat of water (h_f). *It is defined as the quantity of heat absorbed by 1 kg of water when it is heated from 0°C (freezing point) to boiling point.* It is also called total heat (or enthalpy) of water or liquid heat invariably. It is reckoned from 0°C where sensible heat is taken as zero. If 1 kg of water is heated from 0°C to 100°C the sensible heat added to it will be 4.18 × 100 = 418 kJ but if water is at say 20°C initially then sensible heat added will be 4.18 × (100 – 20) = 334.4 kJ. This type of heat is denoted by letter h_f and its value can be directly read from the steam tables.

Note. The value of specific heat of water may be taken as 4.18 kJ/kg K at low pressures but at high pressures it is different from this value.

2. Latent heat or hidden heat (h_{fg}). *It is the amount of heat required to convert water at a given temperature and pressure into steam at the same temperature and pressure.* It is expressed by the symbol h_{fg} and its value is available from steam tables. *The value of latent heat is not constant and varies according to pressure variation.*

3. Dryness fraction (x). The term dryness fraction is related with wet steam. *It is defined as the ratio of the mass of actual dry steam to the mass of steam containing it*. It is usually expressed by the symbol 'x' or 'q'.

If m_s = Mass of dry steam contained in steam considered, and

m_w = Weight of water particles in suspension in the steam considered,

Then,

$$x = \frac{m_s}{m_s + m_w} \quad \text{...(2)}$$

Thus if in 1 kg of wet steam 0.9 kg is the dry steam and 0.1 kg water particles then $x = 0.9$.

Note. No steam can be completely dry and saturated, so long as it is in contact with the water from which it is being formed.

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Note. No steam can be completely dry and saturated, so long as it is in contact with the water from which it is being formed.

The total heat of superheated steam is given by

$$h_{sup} = h_f + h_{fg} + c_{ps}\,(T_{sup} - T_s) \qquad \ldots(4)$$

Superheated steam behaves like a gas and therefore it follows the gas laws. The value of n for this type of steam is 1.3 and the law for the adiabatic expansion is $pv^{1.3}$ = constant.

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$h_{fg} = h_g - h_f$ …… Change of enthalpy during evaporation

$s_{fg} = s_g - s_f$ …… Change of entropy during evaporation

$v_{fg} = v_g - v_f$ …… Change of volume during evaporation.

The internal energy of steam ($u = h - pv$) is also tabulated in some steam tables.

STEAM TABLES

Absolute pressure bar, p	*Temperature* °C t_s	*Specific enthalpy* kJ/kg h_f	h_{fg}	h_g	*Specific entropy* kJ/kg K s_f	s_{fg}	s_g	*Specific volume* m³/kg v_f	v_g
1.0	99.6	417.5	2257.9	2675.4	1.3027	6.0571	7.3598	0.001043	1.6934
50.0	263.9	1154.9	1639.7	2794.2	2.9206	3.0529	5.9735	0.001286	0.00394
100.0	311.1	1408.0	1319.7	2727.7	3.3605	2.2593	5.6198	0.001452	0.01811

ENTROPY OF SUPERHEATED STEAM

Let 1 kg of dry saturated steam at T_s (saturation temperature of steam) be heated to T_{sup}. If specific heat at constant pressure is c_{ps}, then change of entropy during superheating at constant pressure p

$$= c_{ps} \log_e \left(\frac{T_{sup}}{T_s}\right).$$

Total entropy of superheated steam above the freezing point of water.

s_{sup} = Entropy of dry saturated steam + change of entropy during superheating

$$= s_f + \frac{h_{fg}}{T_s} + c_{ps} \log_e \left(\frac{T_{sup}}{T_s}\right) = s_g + c_{ps} \log_e \left(\frac{T_{sup}}{T_s}\right) \quad \text{...(18)}$$

MOLLIER CHART/ ENTHALPY- ENTROPY DIAGRAM

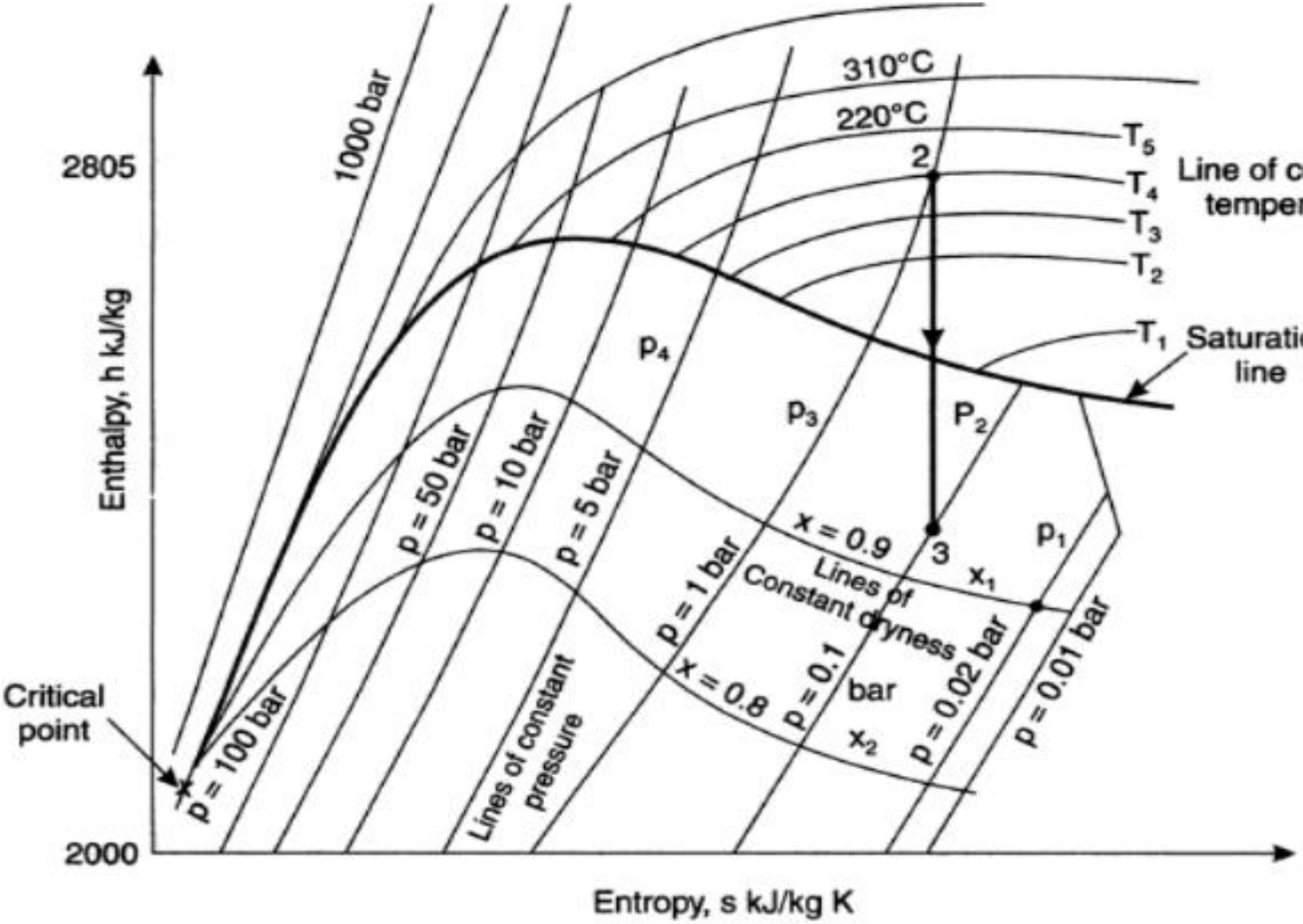
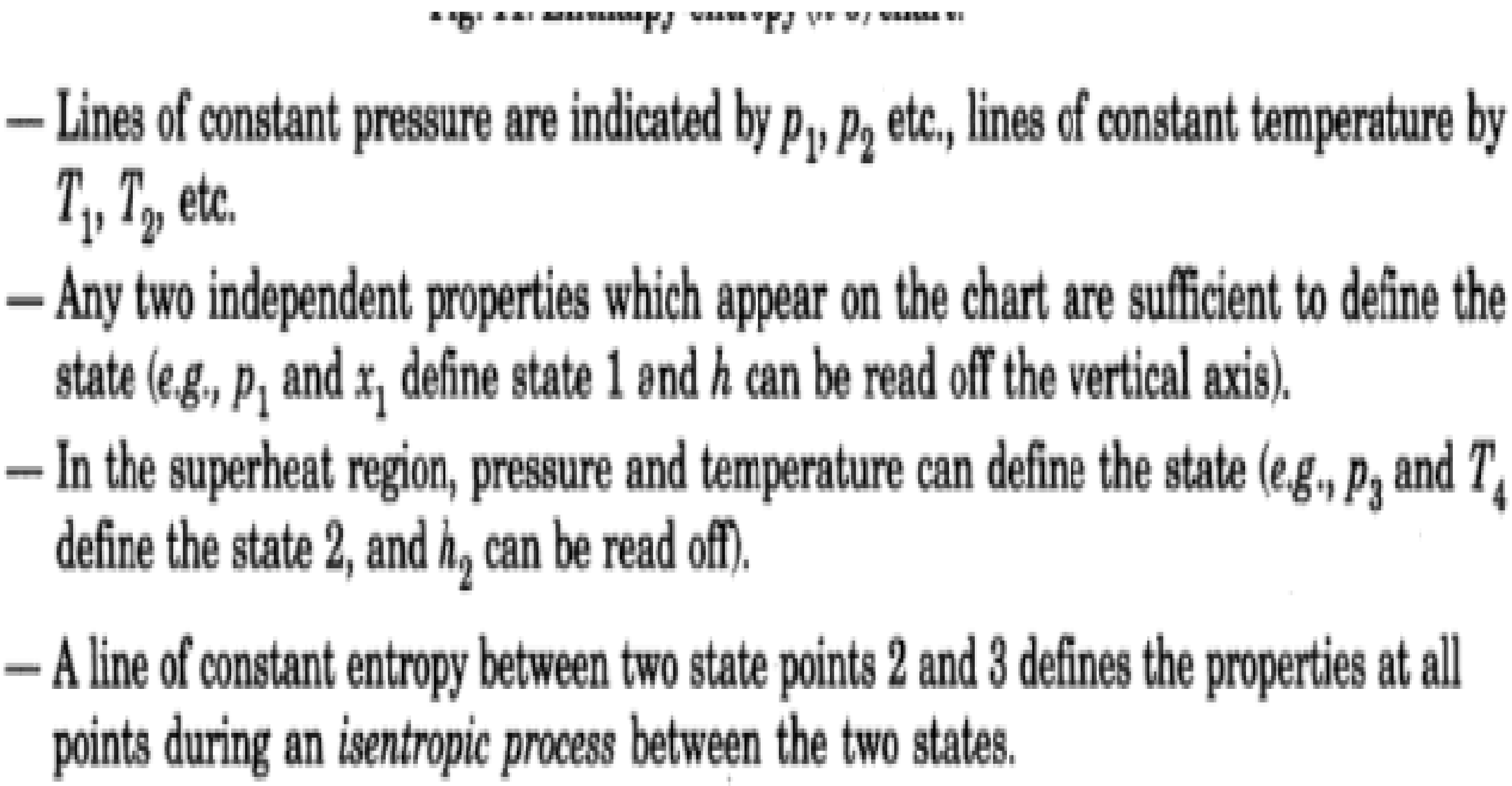


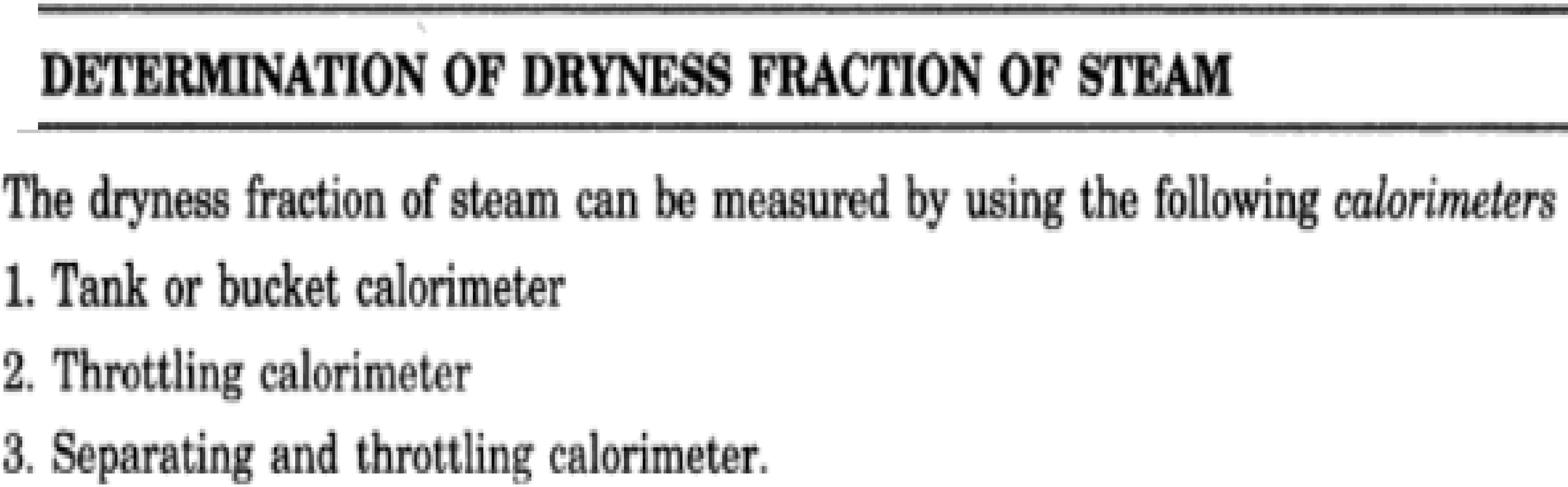
Fig. 11. Enthalpy-entropy (*h-s*) chart.

MOLLIER CHART/ ENTHALPY- ENTROPY DIAGRAM



- Lines of constant pressure are indicated by p_1, p_2 etc., lines of constant temperature by T_1, T_2, etc.
- Any two independent properties which appear on the chart are sufficient to define the state (*e.g.*, p_1 and x_1 define state 1 and h can be read off the vertical axis).
- In the superheat region, pressure and temperature can define the state (*e.g.*, p_3 and T_4 define the state 2, and h_2 can be read off).
- A line of constant entropy between two state points 2 and 3 defines the properties at all points during an *isentropic process* between the two states.

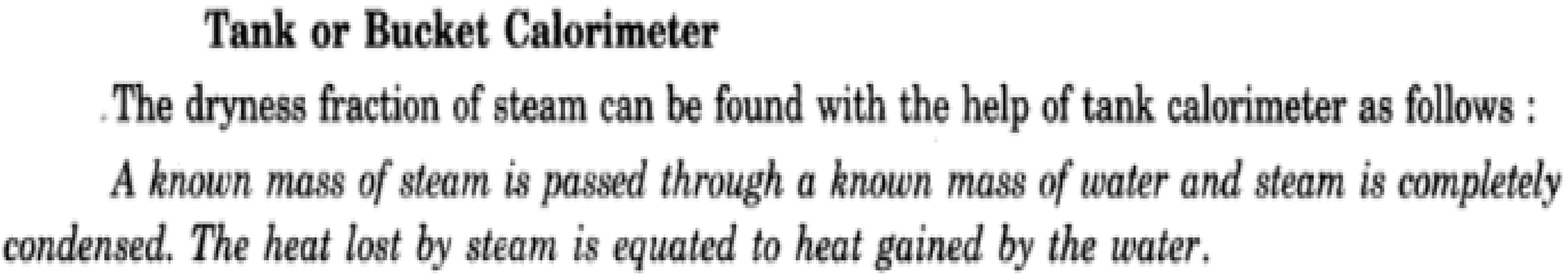
STEAM CALORIMETRY



DETERMINATION OF DRYNESS FRACTION OF STEAM

The dryness fraction of steam can be measured by using the following *calorimeters*

1. Tank or bucket calorimeter
2. Throttling calorimeter
3. Separating and throttling calorimeter.

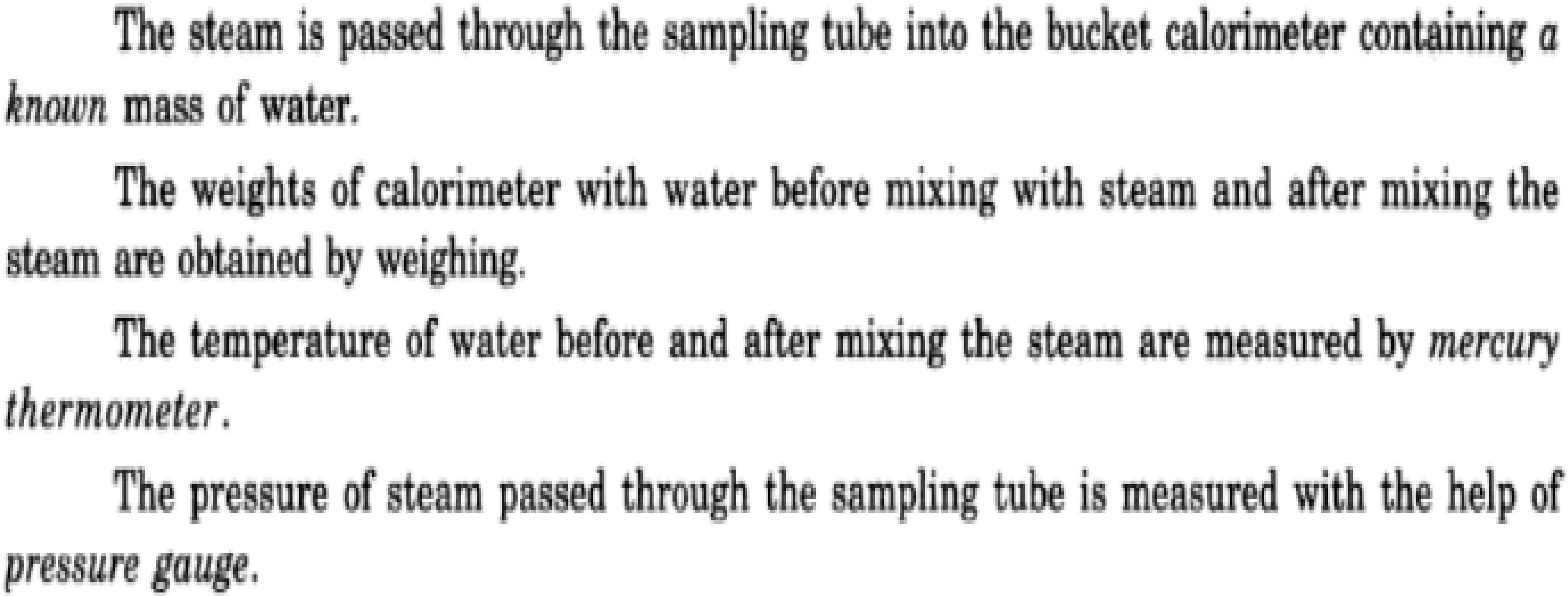


Tank or Bucket Calorimeter

The dryness fraction of steam can be found with the help of tank calorimeter as follows :

A known mass of steam is passed through a known mass of water and steam is completely condensed. The heat lost by steam is equated to heat gained by the water.

STEAM CALORIMETRY



The steam is passed through the sampling tube into the bucket calorimeter containing *a known* mass of water.

The weights of calorimeter with water before mixing with steam and after mixing the steam are obtained by weighing.

The temperature of water before and after mixing the steam are measured by *mercury thermometer*.

The pressure of steam passed through the sampling tube is measured with the help of *pressure gauge*.

STEAM CALORIMETRY

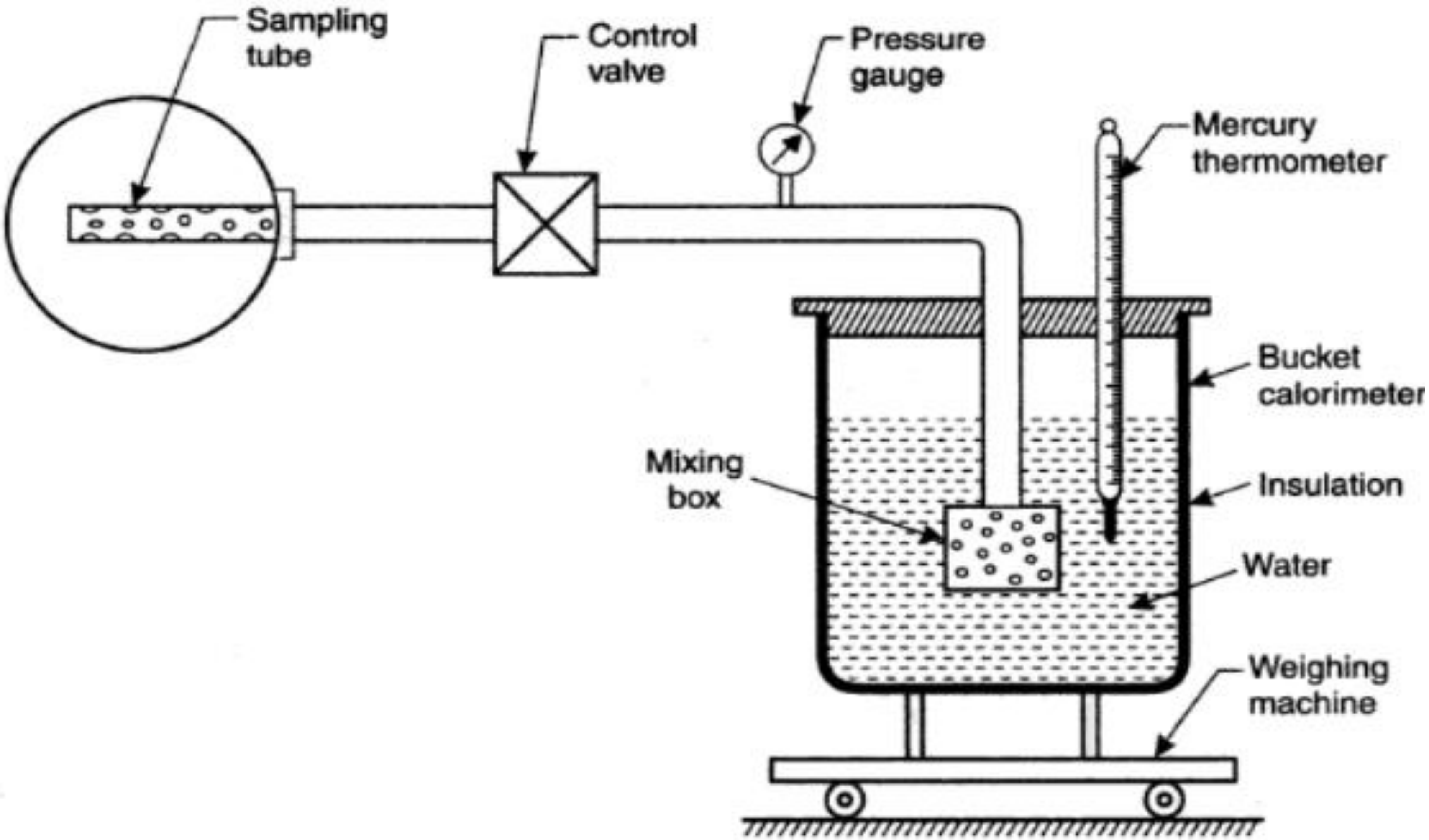
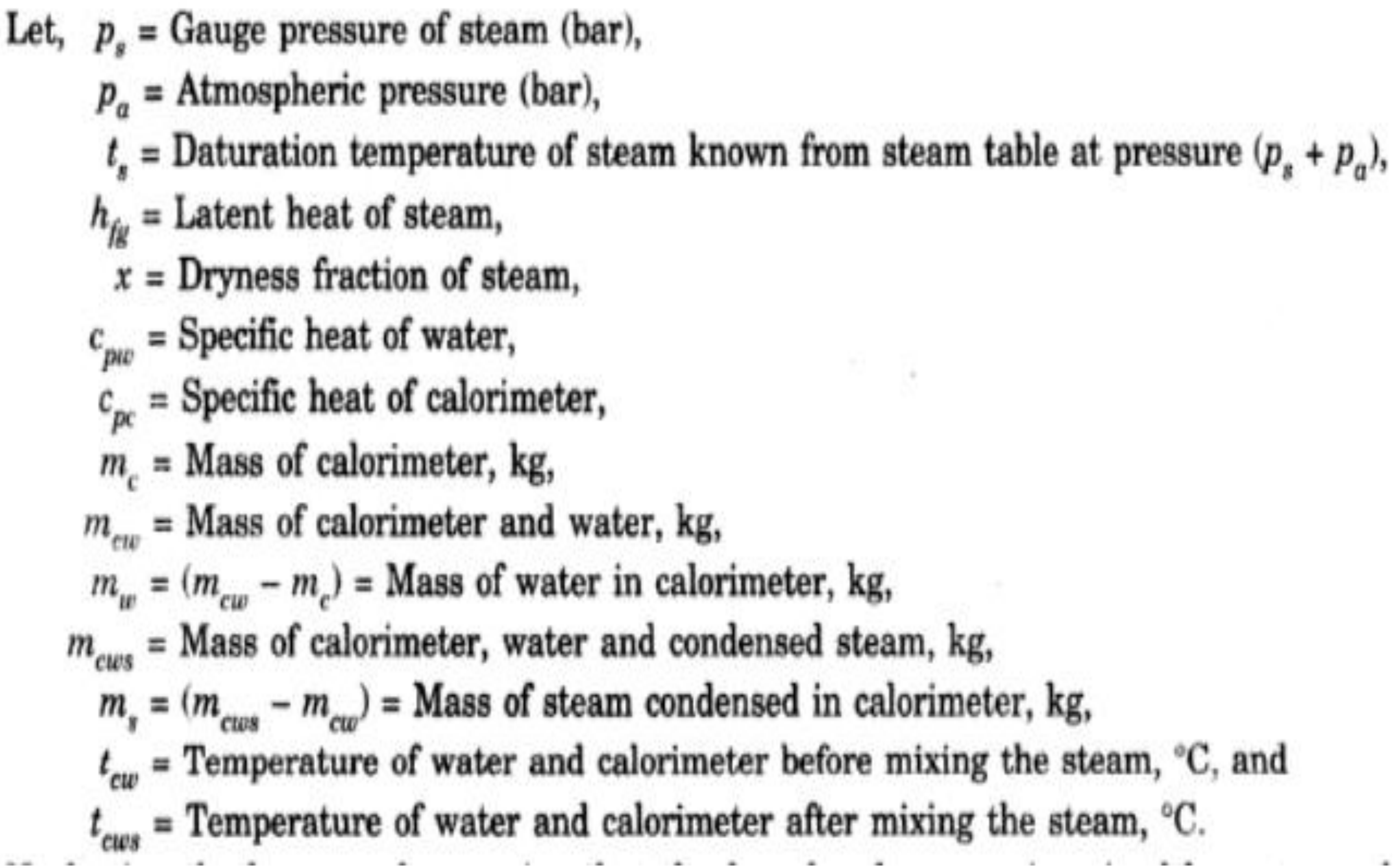


Fig. 14. Tank or bucket calorimeter.

STEAM CALORIMETRY



Let, p_g = Gauge pressure of steam (bar),

p_a = Atmospheric pressure (bar),

t_s = Daturation temperature of steam known from steam table at pressure $(p_s + p_a)$,

h_{fg} = Latent heat of steam,

x = Dryness fraction of steam,

c_{pw} = Specific heat of water,

c_{pc} = Specific heat of calorimeter,

m_c = Mass of calorimeter, kg,

m_{cw} = Mass of calorimeter and water, kg,

$m_w = (m_{cw} - m_c)$ = Mass of water in calorimeter, kg,

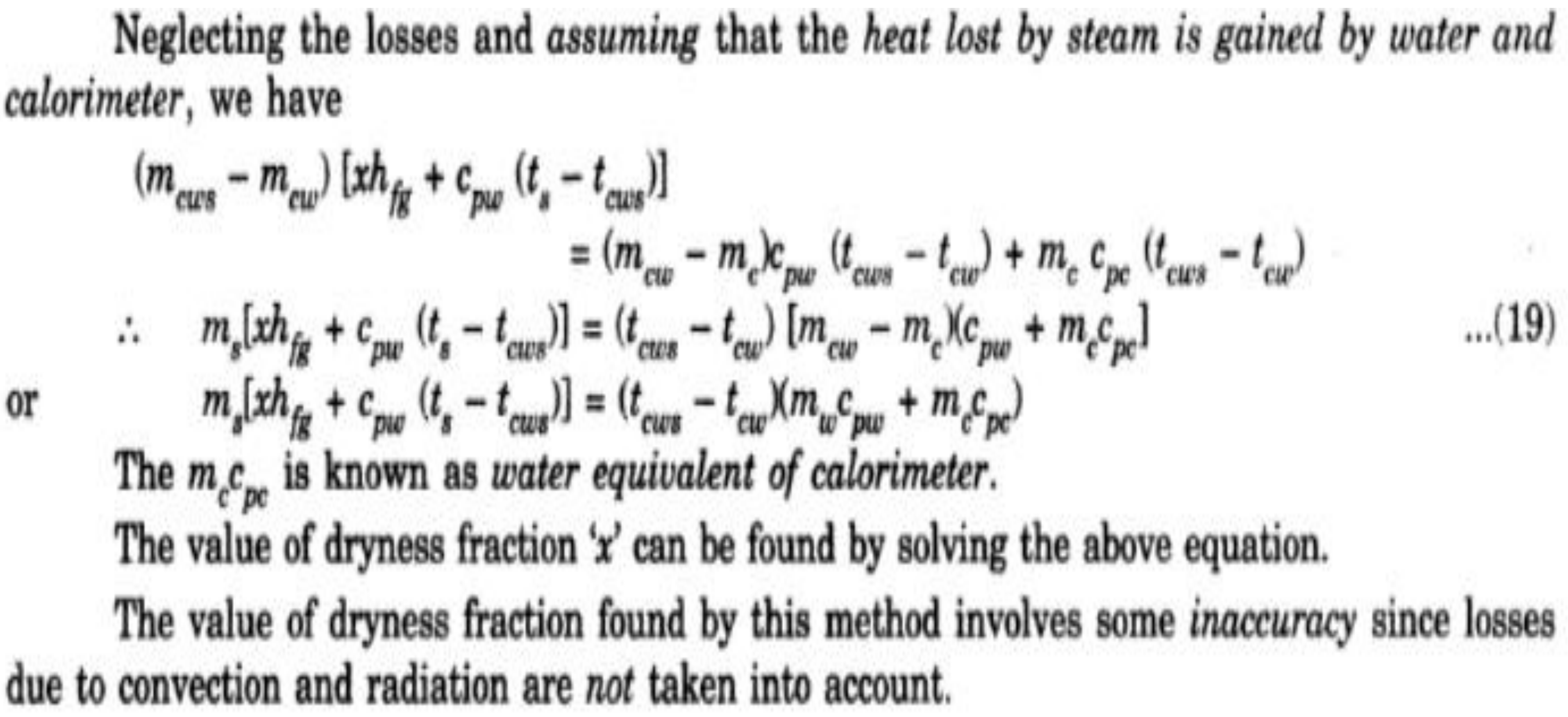
m_{cws} = Mass of calorimeter, water and condensed steam, kg,

$m_s = (m_{cws} - m_{cw})$ = Mass of steam condensed in calorimeter, kg,

t_{cw} = Temperature of water and calorimeter before mixing the steam, °C, and

t_{cws} = Temperature of water and calorimeter after mixing the steam, °C.

STEAM CALORIMETRY



Neglecting the losses and *assuming* that the *heat lost by steam is gained by water and calorimeter*, we have

$$(m_{cws} - m_{cw})\,[xh_{fg} + c_{pw}\,(t_s - t_{cws})]$$
$$= (m_{cw} - m_c)c_{pw}\,(t_{cws} - t_{cw}) + m_c\,c_{pc}\,(t_{cws} - t_{cw})$$

$$\therefore \quad m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (t_{cws} - t_{cw})\,[m_{cw} - m_c)(c_{pw} + m_c c_{pc}] \qquad \text{...(19)}$$

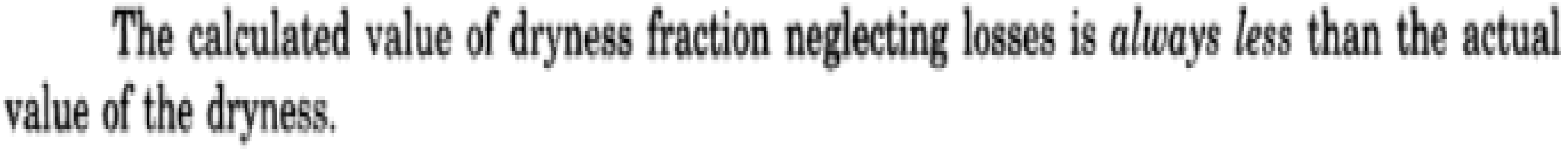
or

$$m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (t_{cws} - t_{cw})(m_w c_{pw} + m_c c_{pc})$$

The $m_c c_{pc}$ is known as *water equivalent of calorimeter.*

The value of dryness fraction 'x' can be found by solving the above equation.

The value of dryness fraction found by this method involves some *inaccuracy* since losses due to convection and radiation are *not* taken into account.

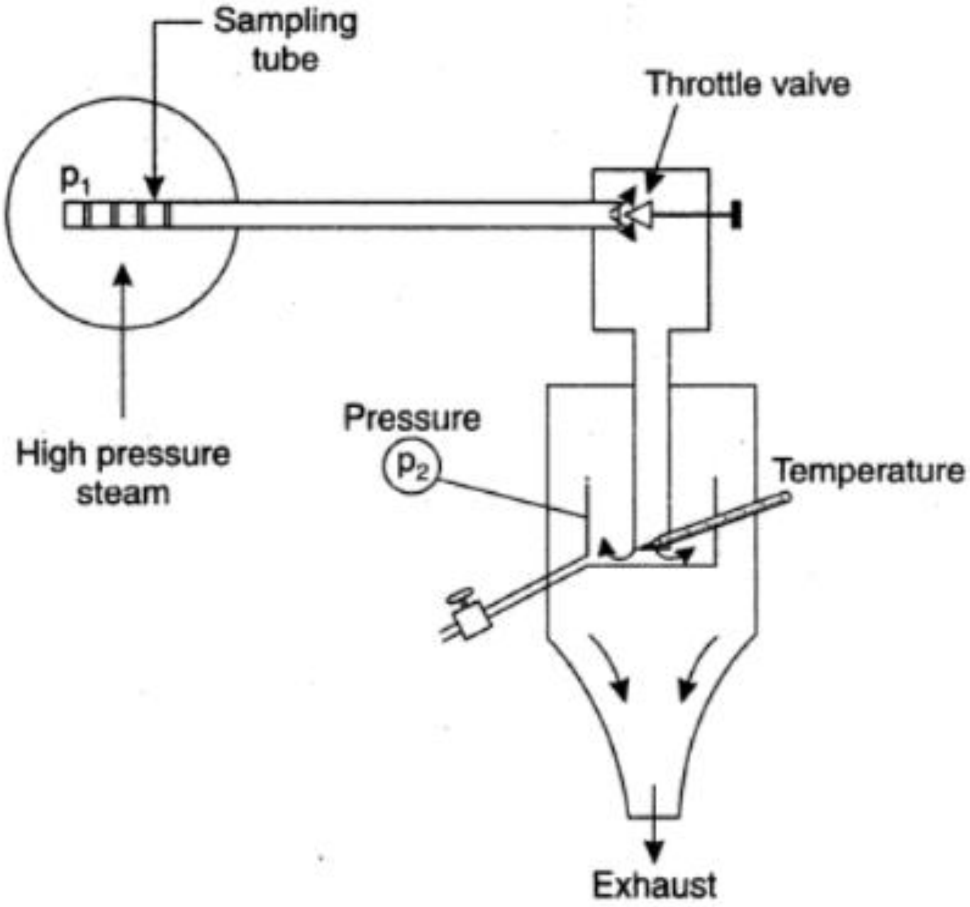


The calculated value of dryness fraction neglecting losses is *always less* than the actual value of the dryness.

STEAM CALORIMETRY

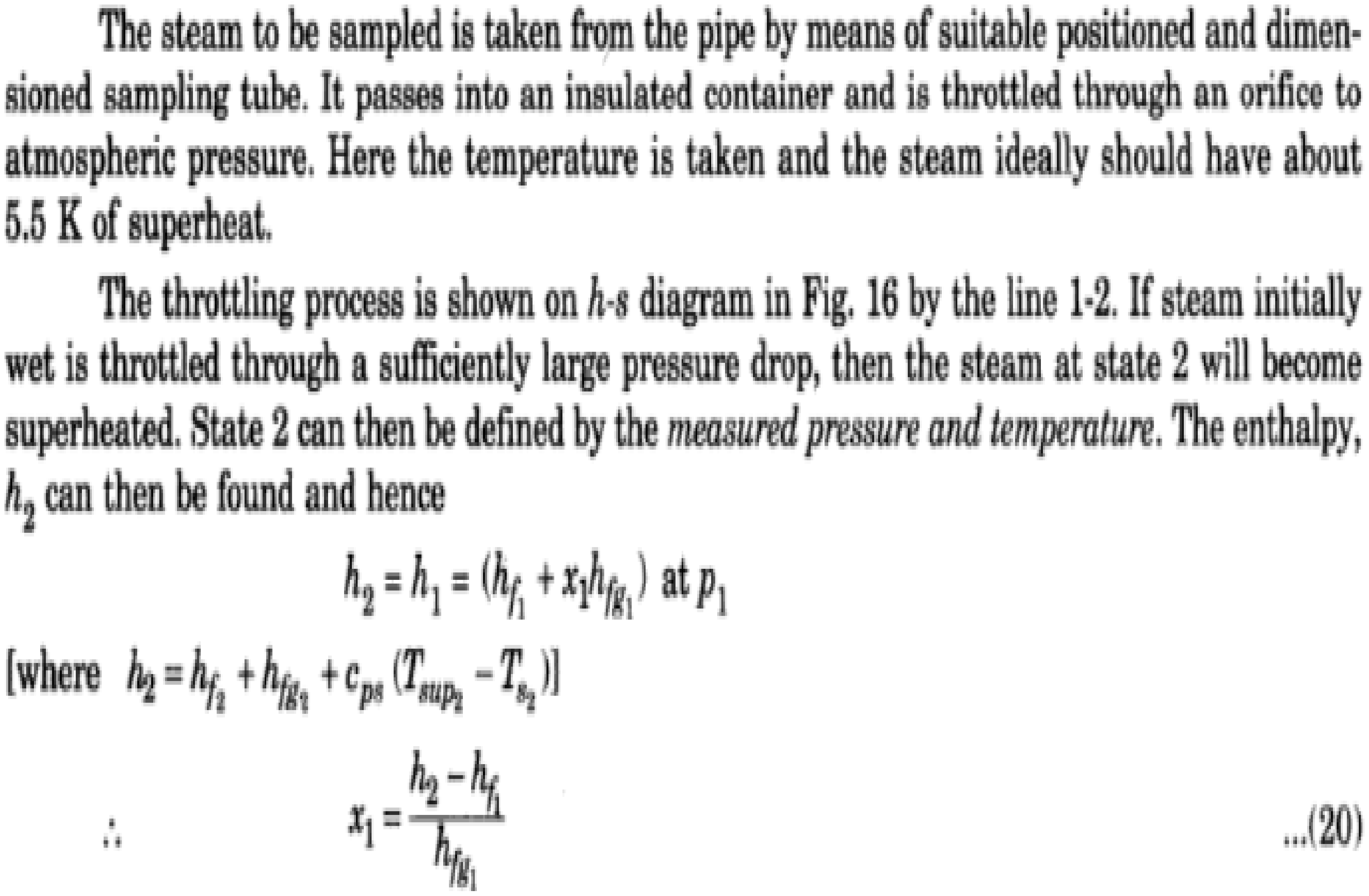
Throttling Calorimeter

The dryness fraction of wet steam can be determined by using a throttling calorimeter which is illustrated diagrammatically in Fig. 15.



Throttling calorimeter.

STEAM CALORIMETRY



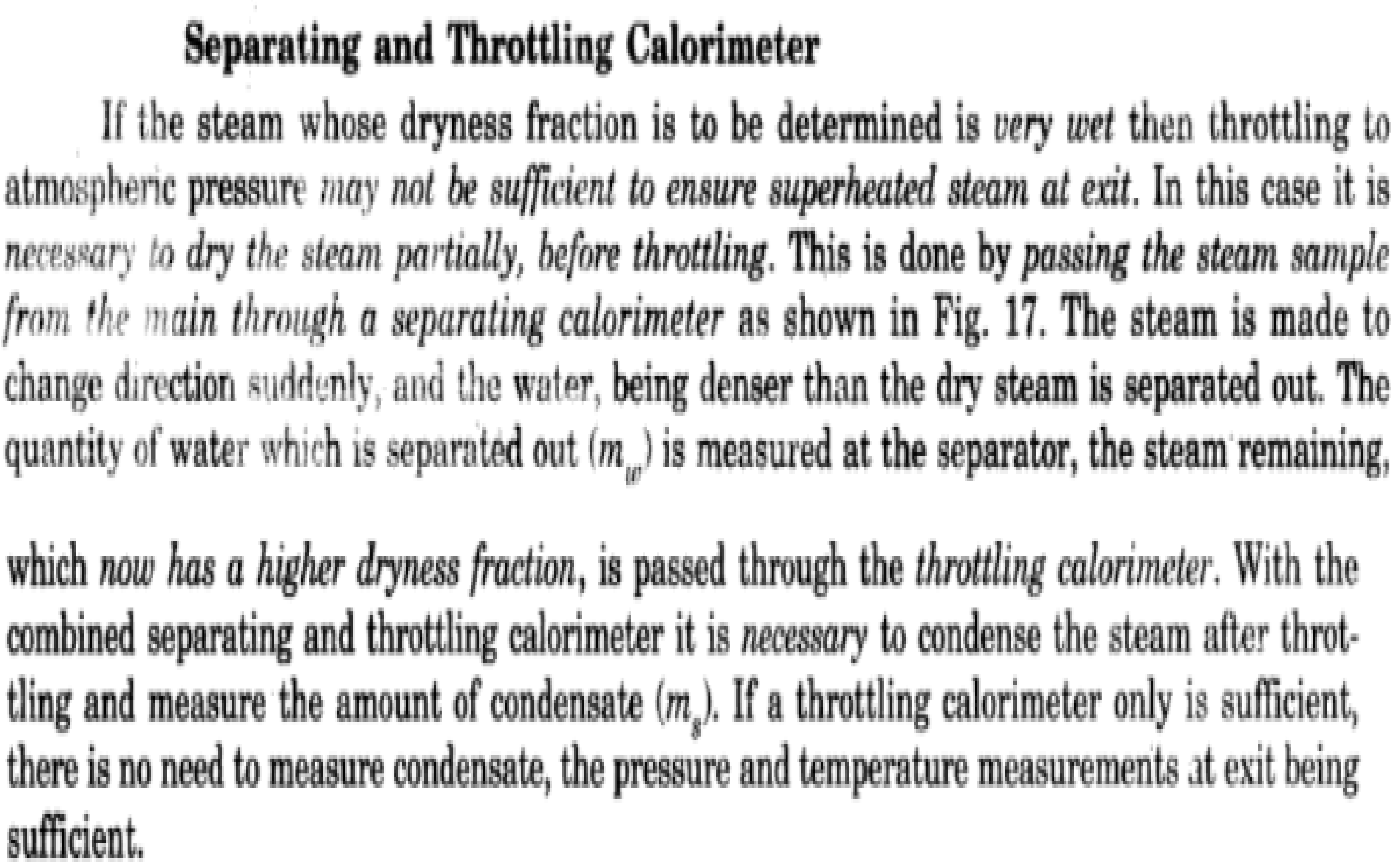
The steam to be sampled is taken from the pipe by means of suitable positioned and dimensioned sampling tube. It passes into an insulated container and is throttled through an orifice to atmospheric pressure. Here the temperature is taken and the steam ideally should have about 5.5 K of superheat.

The throttling process is shown on *h-s* diagram in Fig. 16 by the line 1-2. If steam initially wet is throttled through a sufficiently large pressure drop, then the steam at state 2 will become superheated. State 2 can then be defined by the *measured pressure and temperature*. The enthalpy, h_2 can then be found and hence

$$h_2 = h_1 = (h_{f_1} + x_1 h_{fg_1}) \text{ at } p_1$$

[where $h_2 = h_{f_2} + h_{fg_2} + c_{ps}(T_{sup_2} - T_{s_2})$]

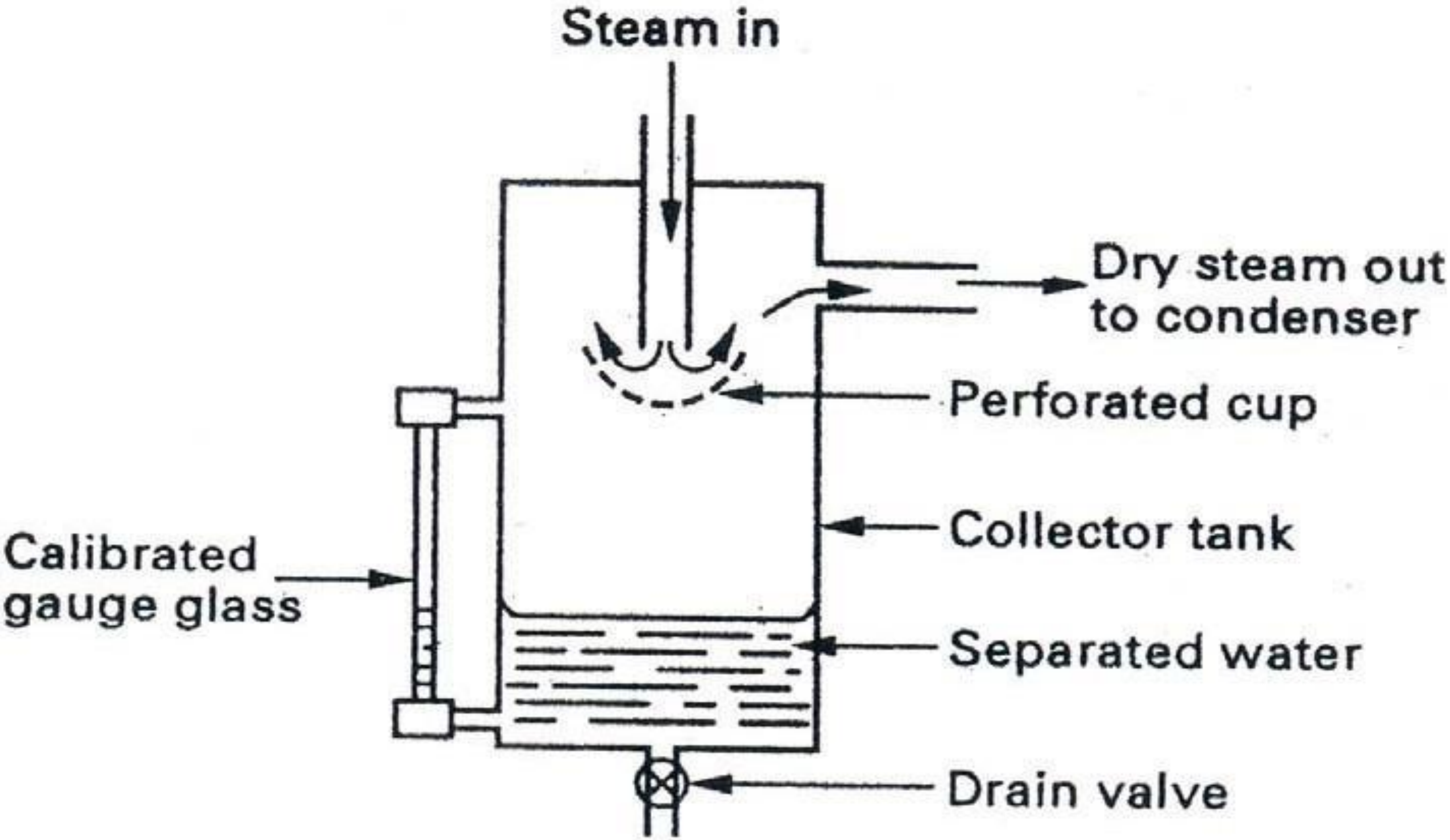
$$\therefore \qquad x_1 = \frac{h_2 - h_{f_1}}{h_{fg_1}} \qquad \text{...(20)}$$



Separating and Throttling Calorimeter

If the steam whose dryness fraction is to be determined is *very wet* then throttling to atmospheric pressure *may not be sufficient to ensure superheated steam at exit*. In this case it is *necessary to dry the steam partially, before throttling*. This is done by *passing the steam sample from the main through a separating calorimeter* as shown in Fig. 17. The steam is made to change direction suddenly, and the water, being denser than the dry steam is separated out. The quantity of water which is separated out (m_w) is measured at the separator, the steam remaining, which *now has a higher dryness fraction*, is passed through the *throttling calorimeter*. With the combined separating and throttling calorimeter it is *necessary* to condense the steam after throttling and measure the amount of condensate (m_g). If a throttling calorimeter only is sufficient, there is no need to measure condensate, the pressure and temperature measurements at exit being sufficient.

SEPARATING CALORIMETER



SEPARATING CALORIMETER

- The wet steam enters at the top from the main steam pipe through holes in the sampling pipe facing up stream which should be as far as possible downstream from elbows and valves to ensure representative sample of steam when in operation the wet steam entering passes down the central passage and undergoes a sudden reversal of direction of motion when strikes perforated cup.
- The weight of steam passing through the jacket may also be readily determined by passing the escaping steam into a bucket of water where it is condensed, the increase in the weight of the bucket and its contents giving the value of W.

SEPARATING CALORIMETER

- In that case gauge G is not required, but it used its reading may be taken as a check.
- This calorimeter will give better results when the dryness fraction of steam to be determined is above 0.95.

Advantages:

- Quick determination of dryness fraction of very wet steam

Disadvantages:

- It leads to inaccuracy due to incomplete separation of water
- Dryness fraction calculated is always greater than actual dryness fraction.

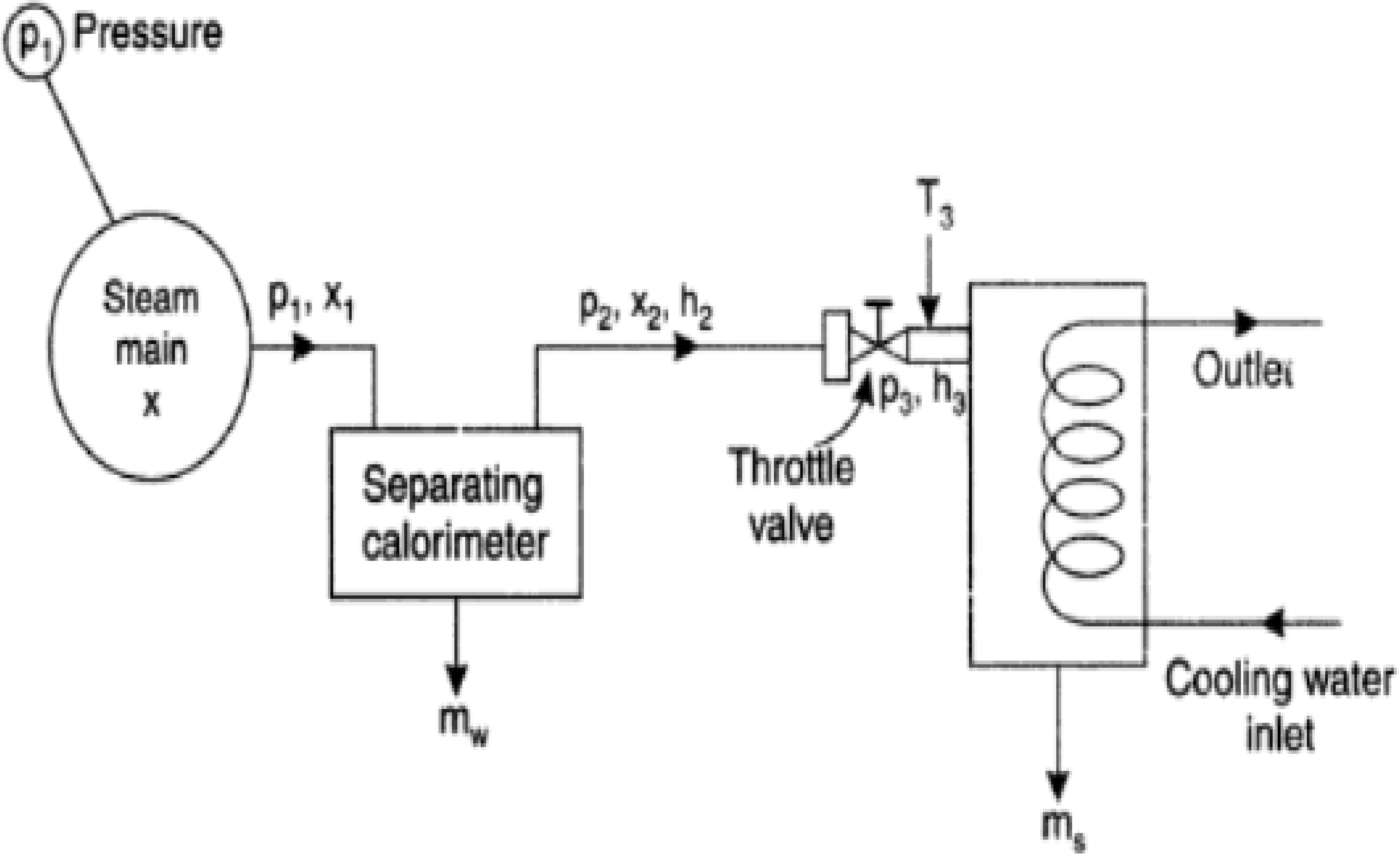
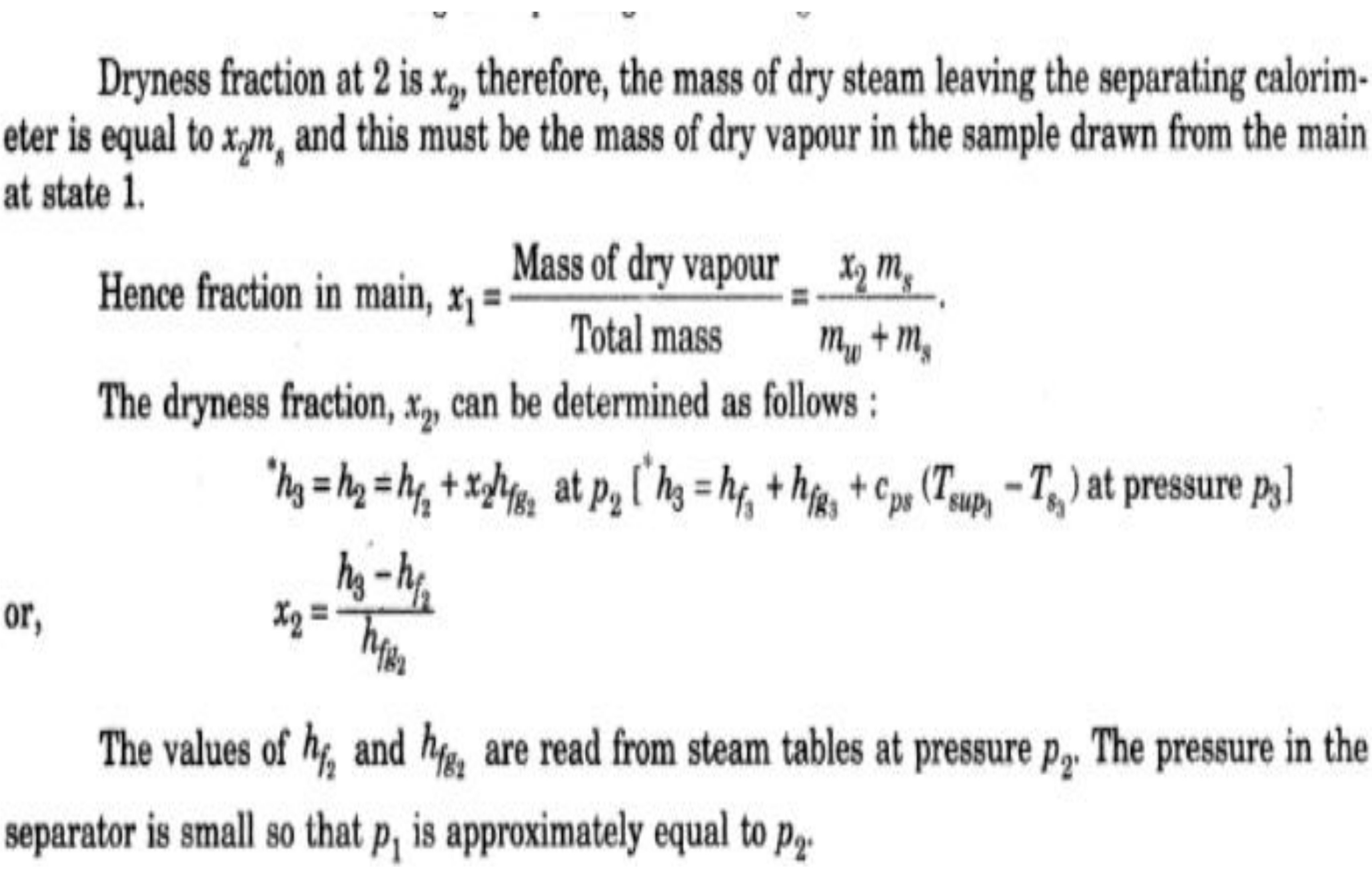


Fig. 17. Separating and throttling calorimeter.

SEPARATING AND THROTTLING CALORIMETER



Dryness fraction at 2 is x_2, therefore, the mass of dry steam leaving the separating calorimeter is equal to $x_2 m_s$ and this must be the mass of dry vapour in the sample drawn from the main at state 1.

Hence fraction in main, $x_1 = \frac{\text{Mass of dry vapour}}{\text{Total mass}} = \frac{x_2\, m_s}{m_w + m_s}$.

The dryness fraction, x_2, can be determined as follows :

$$^{*}h_3 = h_2 = h_{f_2} + x_2 h_{fg_2} \text{ at } p_2 \; [^{*}h_3 = h_{f_3} + h_{fg_3} + c_{ps}(T_{sup_3} - T_{s_3}) \text{ at pressure } p_3]$$

or,
$$x_2 = \frac{h_3 - h_{f_2}}{h_{fg_2}}$$

The values of h_{f_2} and h_{fg_2} are read from steam tables at pressure p_2. The pressure in the separator is small so that p_1 is approximately equal to p_2.

GAS LAWS

- **Ideal Gas:**

  Perfect gas, also called ideal gas, a gas that conforms, in physical behaviour, to a particular, idealized relation between pressure, volume, and temperature called the general gas law.

- Boyle's Law

  Pressure is inversely proportional to volume: $p \propto 1/v$ Robert Boyle noticed that when the volume of a container holding an amount of gas is increased, pressure decreases, and vice versa (while the temperature is held constant). Note that this is not a linear relationship between p and V.

GAS LAWS

- **Charles' Law:**

  Charles' Law Volume is directly proportional to temperature: $V = cT$, where $c > 0$ is constant. Scientist Jacque Charles noticed that if air in a balloon is heated, the balloon expands. For an ideal gas, this relationship between V and T should be linear (as long as pressure is constant).

- **Charles' and Boyle's Laws combined**

  Combine the two laws above: $pV/T = K$, where k is a constant, $= pV=mRT$

GAS LAWS

➢ The Individual Gas Constant - R

- The Individual Gas Constant depends on the particular gas and is related to the molecular weight of the gas.
- The value is independent of temperature. The induvidual gas constant, R, for a gas can be calculated from the universal gas constant, Ru (given in several units below), and the gas molecular weight, Mgas:
- R = Ru/Mgas
- In the SI system units are J/kg K.

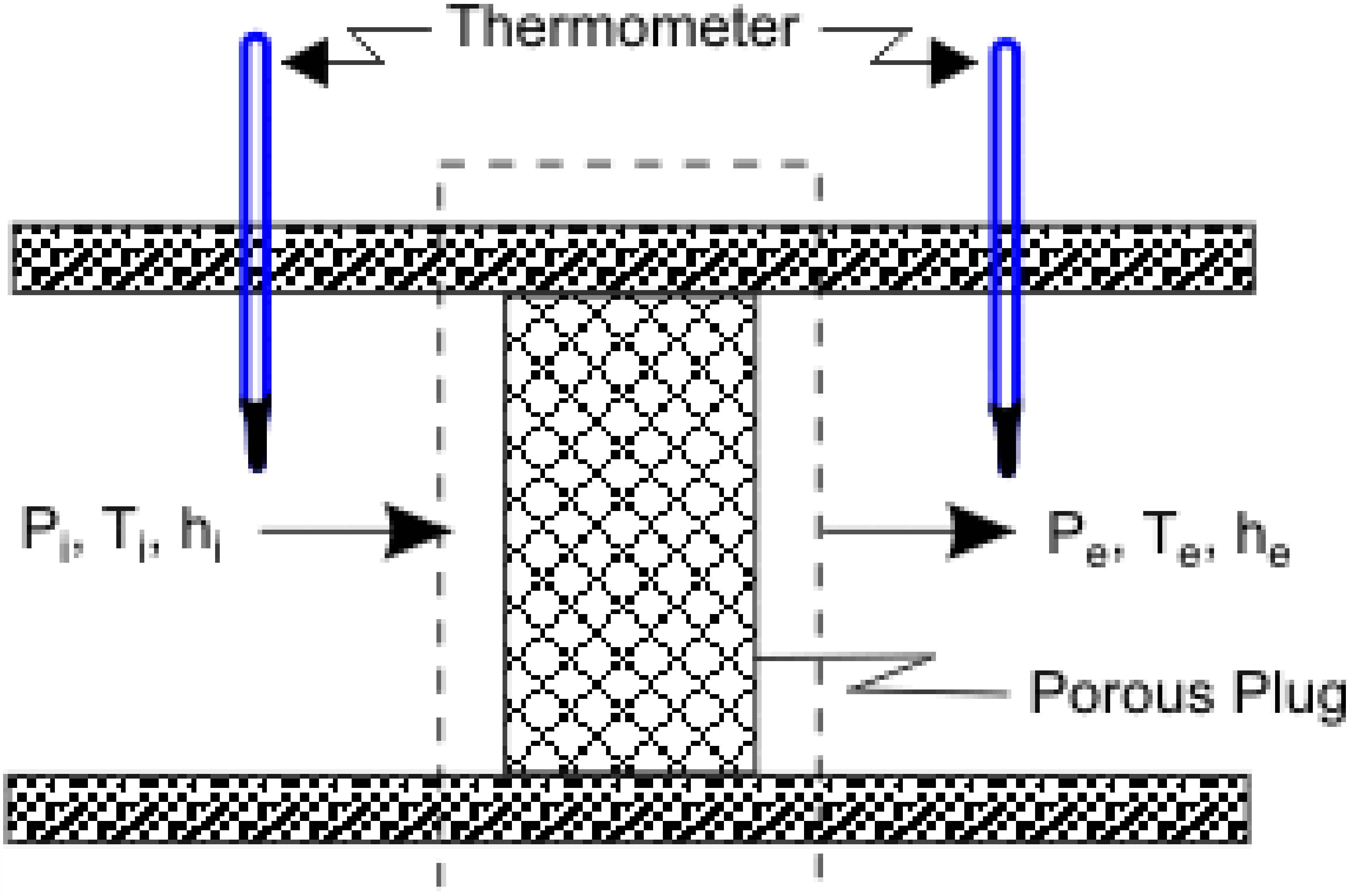
GAS LAWS

- The Universal Gas Constant - Ru
- The Universal Gas Constant - Ru - appears in the ideal gas law and can be expressed as the product between the Individual Gas Constant - R - for the particular gas - and the Molecular Weight - Mgas - for the gas, and is the same for all ideal or perfect gases:
- Ru = MR
- The Molecular weight of a Gas Mixture
  The average molecular weight of a gas mixture is equal to the sum of the mole fractions of each gas multiplied by the molecular weight of that particular gas:
- gas R, kJ/(kmol.K) : 8.3144598

THROTTLING PROCESS

- The porous plug experiment was designed to measure temperature changes when a fluid flows steadily through a porous plug which is inserted in a thermally insulated, horizontal pipe. The apparatus used by Joule and Thomson is shown in Figure
- A gas at pressure and temperature flows continuously through a porous plug in a tube and emerges into a space which is maintained at a constant pressure. The device is thermally insulated and kept horizontal. Consider the dotted portion as control volume.

THROTTLING PROCESS



THROTTLING PROCESS

$$h_i = h_e \qquad \dot{Q} = 0,\ W_{sh} = 0.$$

Therefore, whenever a fluid expands from a region of high pressure to a region of low pressure through a porous plug, partially opened valve or some obstruction, without exchanging any energy as heat and work with the surrounding (neglecting, the changes in PE and KE), the enthalpy of the fluid remains constant, and the fluid is said to have undergone a throttling process.

FREE EXPANSION PROCESS

- A free expansion occurs when a fluid is allowed to expand suddenly into a vaccum chamber through an orifice of large dimensions.
- In this process, no heat is supplied or rejected and no external work is done.
- Hence the total heat of the fluid remains constant. This type of expansion may also be called as constant total heat expansion.
- It is thus obvious, that in a free expansion process,
- $Q_{1-2} = 0$, $W_{1-2} = 0$ and $dU = 0$.

VAN DER WAALS EQUATION OF STATE

- The ideal gas law treats the molecules of a gas as point particles with perfectly elastic collisions. This works well for dilute gases in many experimental circumstances.
- But gas molecules are not point masses, and there are circumstances where the properties of the molecules have an experimentally measurable effect. A modification of the ideal gas law was proposed by van der Waal on molecular size and molecular interaction forces.
- It is usually referred to as the van der Waals equation of state.

$$\left[P + a\left(\frac{n}{V}\right)^2\right]\left(\frac{V}{n} - b\right) = RT$$

The constants a and b have positive values and are characteristic of the individual gas. The van der Waals equation of state approaches the ideal gas law PV=nRT as the values of these constants approach zero. The constant a provides a correction for the intermolecular forces. Constant b is a correction for finite molecular size and its value is the volume of one mole of the atoms or molecules.

INDUSTRIAL APPLICATIONS

- Automobile industries.
- Refrigeration industries
- Air craft applications
- Defense industries
- Thermal power plants
- Chemical industries
- Textile industries etc.

SELF LEARNING QUESTIONS

- Draw the phase equilibrium diagram for a pure substance on T-s plot with relevant constant property line?
- Define dryness fraction of steam. Describe method of finding dryness fraction of steam using separating and throttling calorimeter
- Describe briefly about throttling and free expansion processes.
- Describe briefly about “Mollier diagram”.
- State Vander Waals equation, what is the importance of it?

ASSIGNMENT EXERCISES

- Determine the enthalpy and entropy of steam and the pressure is 2MPa and the specific volume is 0.09m3/kg.
- 10 kg of feed water is heated in a boiler at a constant pressure of 1.5 MN/m2 from 40 C. Calculate the enthalpy required and change of entropy when water is converted into following qualities of steam in each case i) Wet steam at x=0.95 and ii) Super heated steam at 300 C
- Air at 16oC and 1.2 bar occupies a volume of 0.03m3.the air is heated at constant volume until the pressure is 4.3 bar and then cooled at constant pressure back to the original temperature. Calculate the net heat flow to or from the air and the net entropy change.
- 5 kg of steam with a dryness fraction of 0.9 expands adiabatically to the Law PV1.13constant. from a pressure of 8 bar to 1.5 bar determine final dryness fraction ii)heat transferred iii)work done

THANK YOU

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COURSE OBJECTIVES

UNIT - 1	CO1:To understand the concepts of energy transformation, conversion of heat into work.
UNIT - 2	CO2:To acquire knowledge about the fundamentals of thermodynamic laws, the concept of entropy, and principles
UNIT - 3	CO3: To understand how the change of state results in a process.
UNIT - 4	CO4: To understand the various gas laws, psychrometric properties and chart.
UNIT - 5	CO5: To learn the importance of thermodynamic cycles, and the derivation of efficiency.

UNIT 1

MIXTURES OF PERFECT GASES

CO4: To understand the various gas laws, psychrometric properties and chart.

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UNIT – IV (SYLLABUS)

Mixtures of perfect Gases

- Mole Fraction, Mass fraction
- Gravimetric and volumetric Analysis
- Dalton’s Law of partial pressure, Amagat’s Law of additive volumes
- Enthalpy, sp. Heats and Entropy of Mixture of perfect Gases
- Psychrometric Properties
- Thermodynamic Wet Bulb Temperature, Specific Humidity, Relative Humidity
- Degree of saturation – Adiabatic Saturation – Psychrometric chart.

COURSE OUTLINE

UNIT - 4

LECTURE	LECTURE TOPIC	KEY ELEMENTS	Learning objectives (2 to 3 objectives)
1	Mixtures of perfect Gases: Mole Fraction, Mass friction	Mole fraction, mass fraction	Understanding of mixture of gases (B2)
2	Gravimetric and volumetric Analysis	Concepts of gravimetric and volumetric analysis	Knowledge on gravimetric and volumetric analysis (B3)
3	Dalton's Law of partial pressure, Avogadro's Laws of additive volumes	Concept of Dalton's law, Avogadro's law	Understanding the principles of different laws (B2)
4	Mole fraction, Volume fraction and partial pressure,	Definition of partial pressure	Knowledge of fractions like mole, volume (B3)
5	Equivalent Gas constant, Enthalpy, sp. Heats and Entropy of Mixture of perfect Gases	Entropy of gases	Understanding the different types of constants (B2)
6	Vapour and Atmospheric air – Psychrometric Properties	Definition of vapour pressure and atmospheric pressure	Understanding the various vapour pressures (B2)
7	Dry bulb Temperature, Wet Bulb Temperature, Dew point Temperature	Concept of DBT, WBT, RH etc	Knowledge on different Psychrometric Properties (B4)
8	Adiabatic Saturation – Psychrometric chart	Psychrometric chart	Understanding the use of Psychrometric chart (B2)

LECTURE 4

Mixtures of perfect Gases

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MIXTURES OF PERFECT GASES

- A mixture, consisting of several pure substances, is referred to as a solution. Examples of pure substances are water, ethyl alcohol, nitrogen, ammonia, sodium chloride, and iron.
- Examples of mixtures are air, consisting of nitrogen, oxygen and a number of other gases, aqueous ammonia solutions, aqueous solutions of ethyl alcohol, various metal alloys.
- The pure substances making up a mixture are called components or constituents.

MIXTURES OF PERFECT GASES

Basic assumption is that the gases in the mixture do not interact with each other.

Consider a mixture with components $I = 1,2,3$... with masses m_1, m_2, m_3 ...m_i and with number of moles.

The total mixture occupies a volume V, has a total pressure P and temperature T (which is also the temperature of each of the component species)

Mole Fraction

Mole fraction represents the number of molecules of a particular component in a mixture divided by the total number of moles in the given mixture. It's a way of expressing the concentration of a solution.

$$Y_i = \frac{N_i}{N}$$

The mass and number of moles of species *i* are related by

$$m_i = N_i M_i$$

N_i = is the number of moles of species i and Mi is the molar mass of species i.

MOLE FRACTION

- The mole fraction of a substance in the mixture is the ratio of the mole of the substance in the mixture to the total mole of the mixture.
- Since it is the ratio of moles to moles, it is a dimensionless quantity.
- The mole fraction is sometimes called the amount fraction.

For solutions and liquid mixtures, the symbol x is used to denote and for a gaseous component, the symbol y is used to denote it.

For a mixture of the i^{th} component,

$$x_i = \frac{n_i}{n_{\text{mix}}}$$

Here, x_i is the molar fraction of the i^{th} component, n_i is the mole of the i^{th} component in the mixture, and n_{mix} is the total mole of the mixture. But we also know, the total mole of a mixture is the sum of the mole of each component in the mixture.

MOLE FRACTION

From the above two equations,

$$x_i = \frac{n_i}{\sum n_i}$$

Note: The sum of the mole fraction of each component is always equal to one.

$$x_1 + x_2 + x_3 + \ldots = \sum x_i = 1$$

MASS FRACTION

- The mass fraction of a substance in a mixture is the ratio of the mass of the substance to the total mass of the mixture.
- It is also known as mass per cent or percentage by mass when expressing in percentage.
- Since the mass fraction is a ratio of mass to mass, it is a dimensionless quantity.

MASS FRACTION

For a mixture,

$$w_i = \frac{m_i}{m_\mathrm{T}}$$

Here, w_i is the mass fraction of the i^{th} component, m_i is the mass of the i^{th} component, and m_T is the total mass of the mixture.

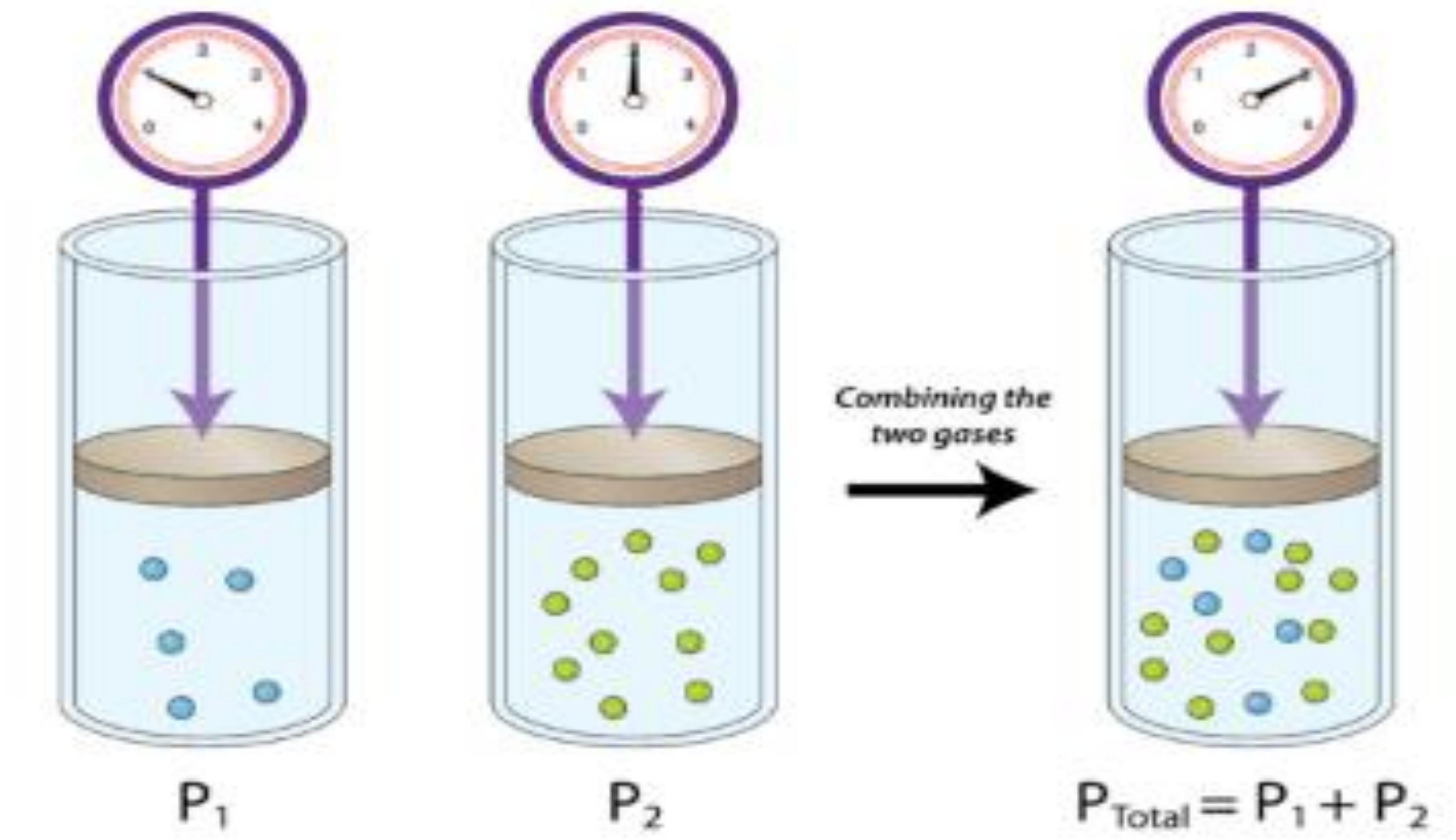
The total mass of a mixture is the sum of the mass of each component.

$$\begin{aligned} m_\mathrm{T} &= m_1 + m_2 + m_3 + \ldots \\ &= \sum m_i \end{aligned}$$

DALTON'S LAW OF PARTIAL PRESSURES

- Dalton's law of partial pressures is a gas law which states that the total pressure exerted by a mixture of gases is equal to the sum of the partial pressures exerted by each individual gas in the mixture.
- For example, the total pressure exerted by a mixture of two gases A and B is equal to the sum of the individual partial pressures exerted by gas A and gas B (as illustrated below).

DALTON’S LAW OF PARTIAL PRESSURES



DALTON’S LAW OF PARTIAL PRESSURES

- Dalton’s Law Formula
- Dalton’s law of partial pressures can be mathematically expressed as follows:
- P_{total} = ∑ni=1pi (or) $P_{total} = P_1 + P_2 + P_3 + \ldots. + P_n$

Where,

- P_{total} is the total pressure exerted by the mixture of gases
- $P_1, P_2, \ldots, P_n$ are the partial pressures of the gases 1, 2,…, ‘n’ in the mixture of ‘n’ gases

DALTON’S LAW OF PARTIAL PRESSURES

- Expressing Partial Pressures in Terms of Mole Fraction
- The mole fraction of a specific gas in a mixture of gases is equal to the ratio of the partial pressure of that gas to the total pressure exerted by the gaseous mixture.
- This mole fraction can also be used to calculate the total number of moles of a constituent gas when the total number of moles in the mixture is known.
- Furthermore, the volume occupied by a specific gas in a mixture can also be calculated with this mole fraction with the help of the equation provided below.
- Xi=Pi/Ptotal=Vi/Vtotal=ni/ntotal
- Where X_i is the mole fraction of a gas ‘i’ in a mixture of ‘n’ gases, ‘n’ denotes the number of moles, ‘P’ denotes pressure, and ‘V’ denotes volume.

- P is the total pressure of the mixture P_i is the partial pressure of species *i*= pressure of the species if it existed alone in the given temperature T and volume V

$$P_i = \frac{N_i \hat{R} T}{V}$$

R_u is the universal gas constant = 8.314 kJ/k mol K

Amagat's Law of Additive volumes

Volume of an ideal gas mixture is equal to the sum of the partial volumes

$$V = \sum V_i$$

AMAGAT'S LAW OF ADDITIVE VOLUMES

- Amagat's law of additive volumes is the law of partial volumes.
- The law relates the total volume of a mixture with the volumes of individual components.
- Amagat's law is very similar to Dalton's law of partial pressure.
- The law is only valid for ideal gases.

Statement

- For a mixture of non-reacting ideal gases, the total volume of the mixture equals the sum of the partial volumes of individual components at constant pressure and temperature.
- As per Amagat's law, the volume of an ideal mixture is

$$V_{\text{mix}} = \sum_{i=1}^{k} V_i = V_1 + V_2 + V_3 + \ldots + V_k$$

- where V_{mix} is the volume of the ideal mixture, k is the last component of the mixture, V_i is the volume of the ith component.

IDEAL GAS LAW OR EQUATION OF STATE

- The Ideal Gas Law
- The volume (*V*) occupied by *n* moles of any gas has a pressure (*P*) at temperature (*T*) in Kelvin.
- The relationship for these variables,
- $PV=nRT$
- where *R* is known as the gas constant, is called the **ideal gas law** or **equation of state**

ENTHALPY

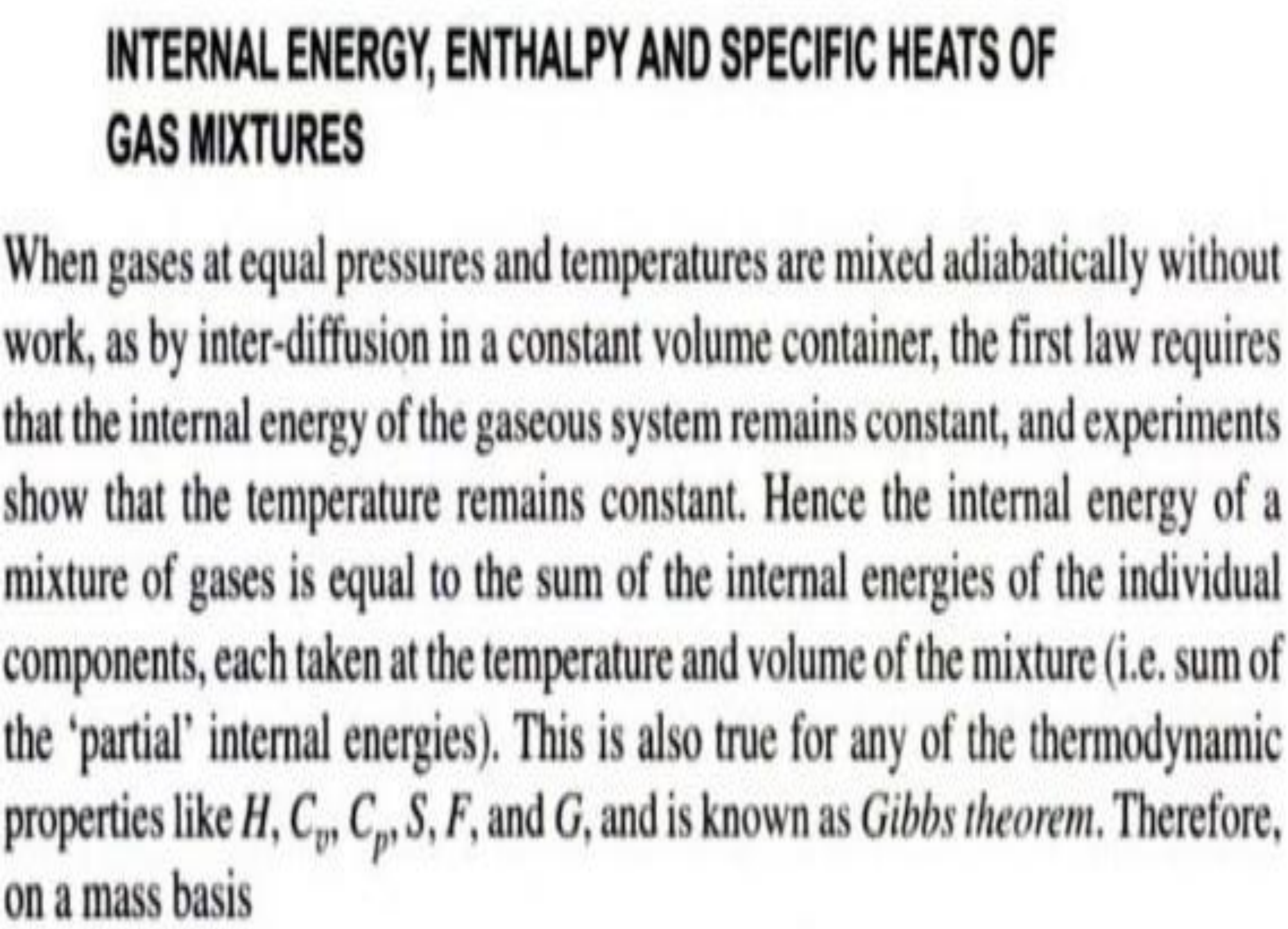
- The enthalpy H of a thermodynamic system is defined as the sum of its internal energy U and the work required to achieve its pressure and volume.
- When a process occurs at constant pressure, the heat evolved (either released or absorbed) is equal to the change in enthalpy. Enthalpy (H) is the sum of the internal energy (U) and the product of pressure and volume (PV) given by the equation:
- $H = U + pV$

ENTHALPY

- Enthalpy is a state function which depends entirely on the state functions T, P and U.
- Enthalpy is usually expressed as the change in enthalpy ($\Delta H\Delta H$) for a process between initial and final states:
- $\Delta H=\Delta U+\Delta PV$
- If temperature and pressure remain constant through the process and the work is limited to pressure-volume work, then the enthalpy change is given by the equation:
- $\Delta H=\Delta U+P\Delta V$

ENTHALPY

- Also at constant pressure the heat flow (q) for the process is equal to the change in enthalpy defined by the equation:
- $\Delta H = q$
- At constant temperature and pressure, by the equation above, if q is positive then ΔH is also positive.
- If q is negative, then ΔH will also be negative.



INTERNAL ENERGY, ENTHALPY AND SPECIFIC HEATS OF GAS MIXTURES

When gases at equal pressures and temperatures are mixed adiabatically without work, as by inter-diffusion in a constant volume container, the first law requires that the internal energy of the gaseous system remains constant, and experiments show that the temperature remains constant. Hence the internal energy of a mixture of gases is equal to the sum of the internal energies of the individual components, each taken at the temperature and volume of the mixture (i.e. sum of the 'partial' internal energies). This is also true for any of the thermodynamic properties like H, C_v, C_p, S, F, and G, and is known as *Gibbs theorem*. Therefore, on a mass basis

$$mu_m = m_1u_1 + m_2u_2 + \ldots + m_cu_c$$

$$u_m = \frac{m_1u_1 + m_2u_2 + \ldots + m_cu_c}{m_1 + m_2 + \ldots + m_c} \tag{10.92}$$

which is the average specific internal energy of the mixture.

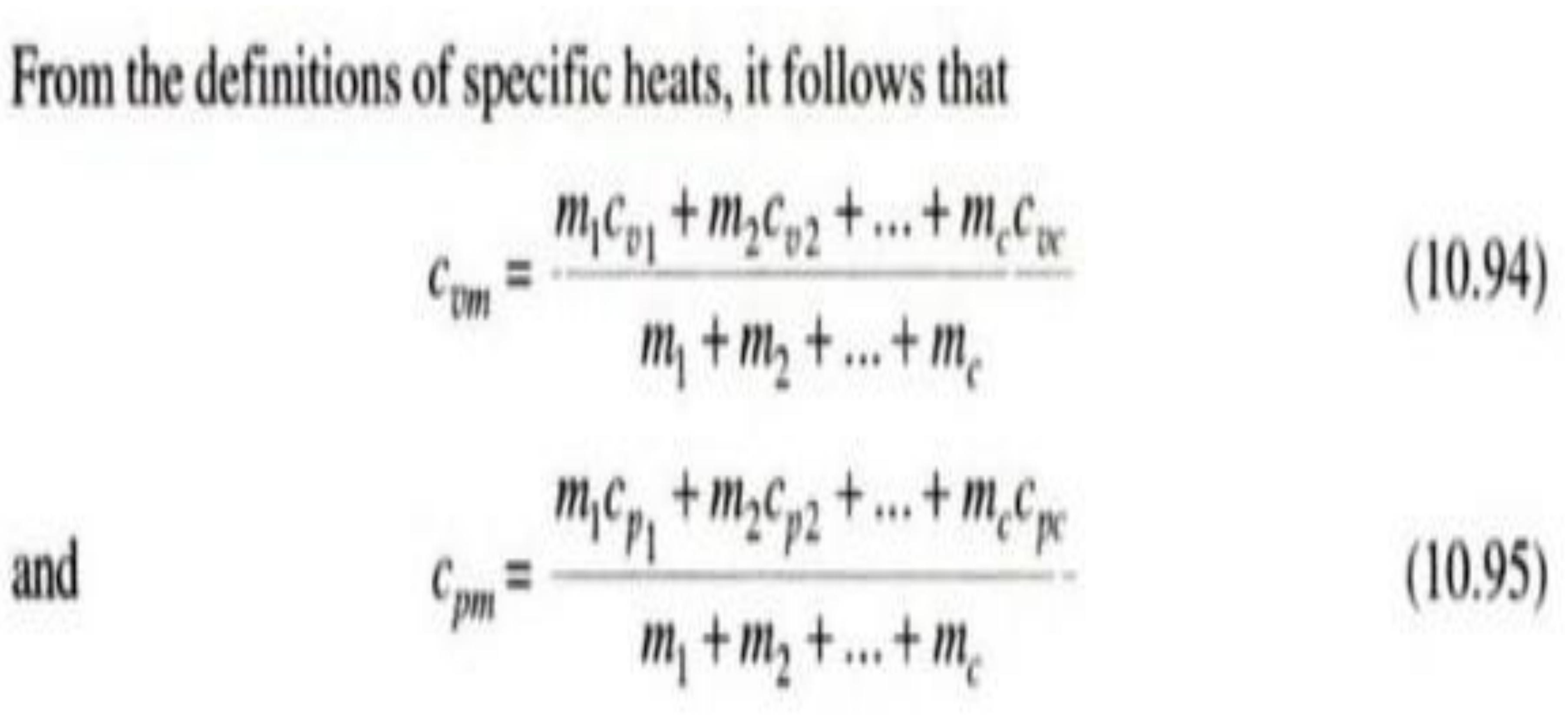
Similarly, the total enthalpy of a gas mixture is the sum of the 'partial' enthalpies

$$mh_m = m_1h_1 + m_2h_2 + \ldots + m_ch_c$$

and

$$h_m = \frac{m_1h_1 + m_2h_2 + \ldots + m_ch_c}{m_1 + m_2 + \ldots + m_c} \tag{10.93}$$

INTERNAL ENERGY ENTHALPY AND SPECIFIC HEATS OF GAS

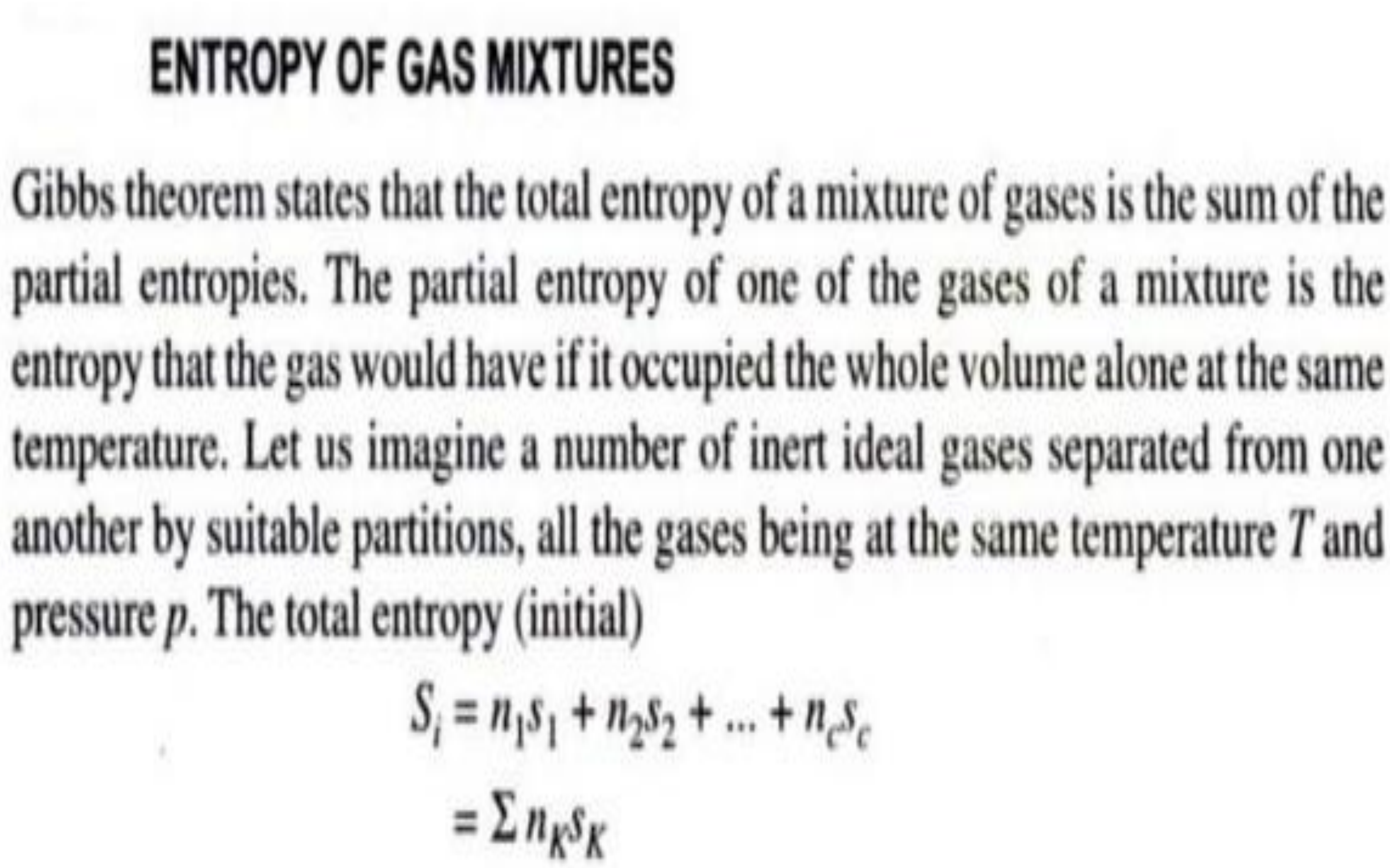


From the definitions of specific heats, it follows that

$$c_{vm} = \frac{m_1 c_{v1} + m_2 c_{v2} + \ldots + m_c c_{vc}}{m_1 + m_2 + \ldots + m_c} \quad (10.94)$$

and

$$c_{pm} = \frac{m_1 c_{p1} + m_2 c_{p2} + \ldots + m_c c_{pc}}{m_1 + m_2 + \ldots + m_c} \quad (10.95)$$



ENTROPY OF GAS MIXTURES

Gibbs theorem states that the total entropy of a mixture of gases is the sum of the partial entropies. The partial entropy of one of the gases of a mixture is the entropy that the gas would have if it occupied the whole volume alone at the same temperature. Let us imagine a number of inert ideal gases separated from one another by suitable partitions, all the gases being at the same temperature T and pressure p. The total entropy (initial)

$$\begin{aligned} S_i &= n_1 s_1 + n_2 s_2 + \ldots + n_c s_c \\ &= \Sigma\, n_K s_K \end{aligned}$$

ENTROPY

- When two pure substances mix under normal conditions there is usually an increase in the entropy of the system.
- Since the molecules of ideal gases do not interact the increase in entropy must simply result from the extra volume available to each gas on mixing.
- Thus, for gas A the available volume has increased from V_A to $(V_A + V_B)$.
- By calculating the entropy of expansion of each gas we can calculate the entropy of mixing as shown in the panel below.

PSYCHROMETRY

- **Atmospheric air** makes up the environment in almost every type of air conditioning system.
- Hence a thorough understanding of the properties of atmospheric air and the ability to analyze various processes involving air is fundamental to air conditioning design.
- Atmospheric air is a mixture of many gases plus water vapour and a number of pollutants
- **Psychrometry** is the study of the properties of mixtures of air and water vapour.

PSYCHROMETRY

- A mixture of various gases that constitute air and water vapour. This mixture is known as moist air.
- The moist air can be thought of as a mixture of dry air and moisture.
- At a given temperature and pressure the dry air can only hold a certain maximum amount of moisture.
- When the moisture content is maximum, then the air is known as saturated air.

PSYCHROMETRY

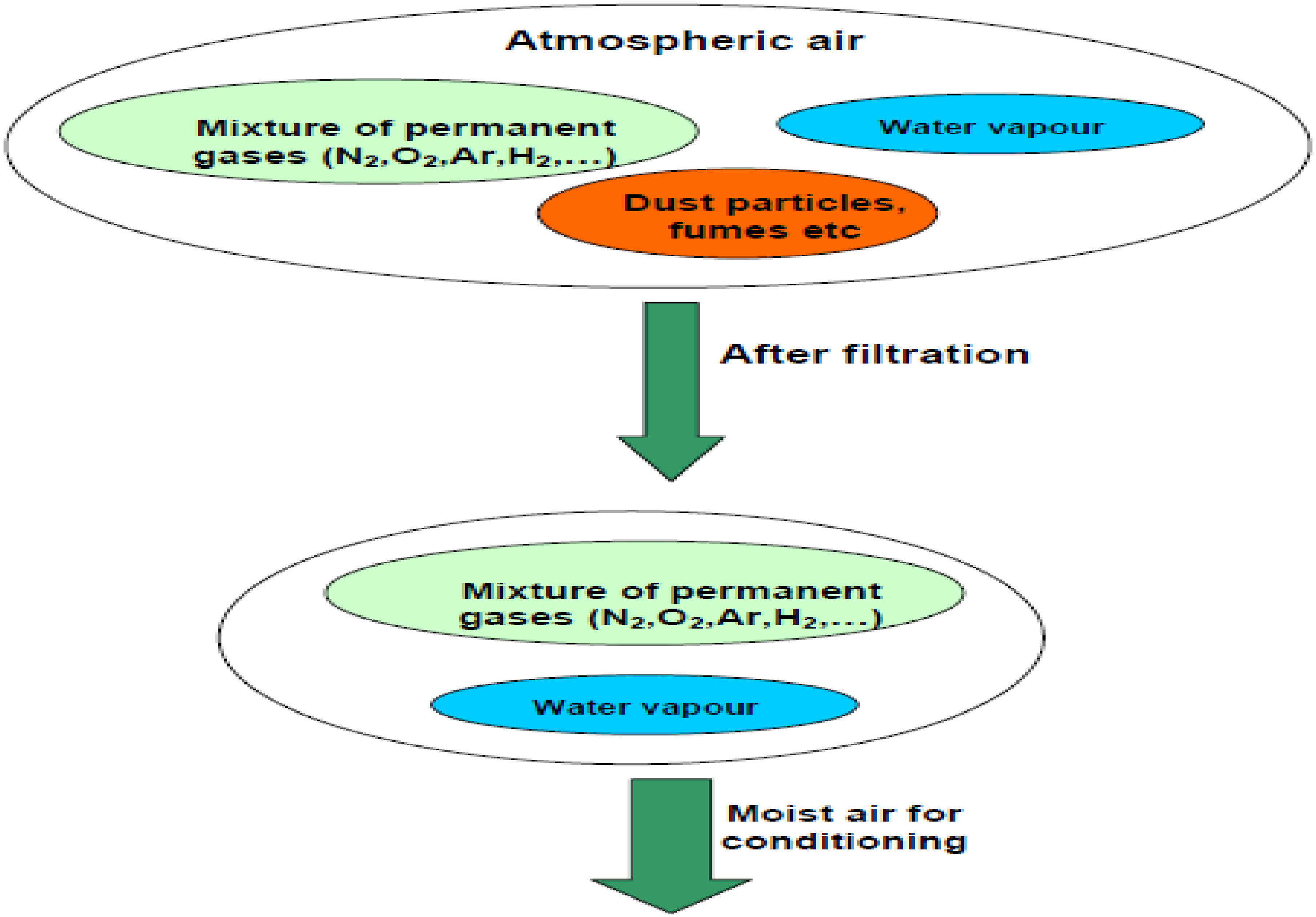
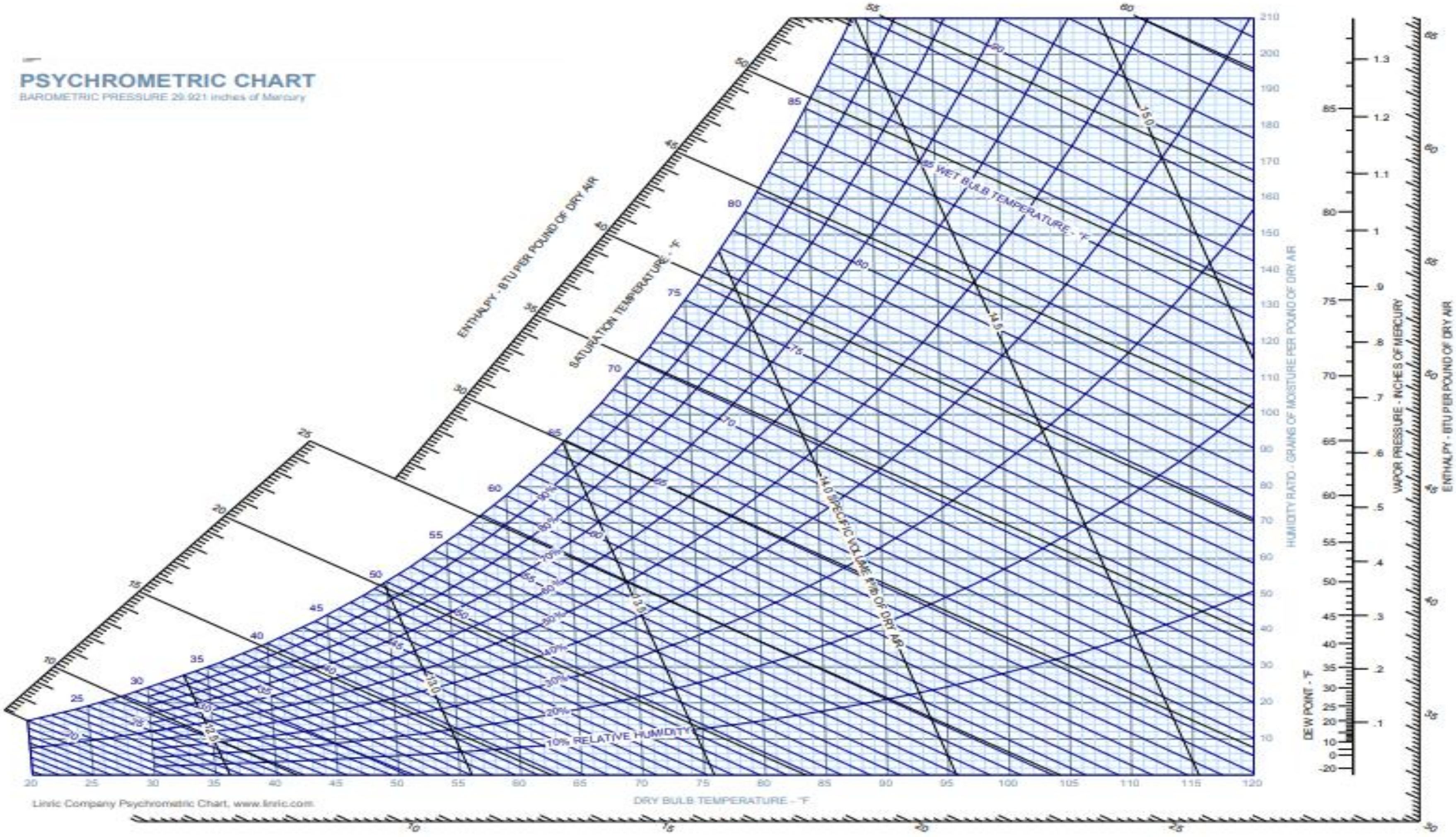


Fig.27.1: Atmospheric air

PSYCHROMETRY



PSYCHROMETRIC PROPERTIES

- Dry bulb temperature (DBT) is the temperature of the moist air as measured by a standard thermometer or other temperature measuring instruments.
- Saturated vapour pressure (psat) is the saturated partial pressure of water vapour at the dry bulb temperature.
- Relative humidity (Φ) is defined as the ratio of the mole fraction of water vapour in moist air to mole fraction of water vapour in saturated air at the same temperature and pressure.

$$\phi = \frac{\text{partial pressure of water vapour}}{\text{saturation pressure of pure water vapour at same temperature}} = \frac{p_v}{p_{sat}} \qquad (27.4)$$

Relative humidity is normally expressed as a percentage. When Φ is 100 percent, the air is saturated.

Humidity ratio (W): The humidity ratio (or specific humidity) W is the mass of water associated with each kilogram of dry air[1]. Assuming both water vapour and dry air to be perfect gases[2], the humidity ratio is given by:

$$W = \frac{\text{kg of water vapour}}{\text{kg of dry air}} = \frac{p_v V / R_v T}{p_a V / R_a T} = \frac{p_v / R_v}{(p_t - p_v) / R_a} \qquad (27.5)$$

Substituting the values of gas constants of water vapour and air R_v and R_a in the above equation; the humidity ratio is given by:

$$W = 0.622 \frac{p_v}{p_t - p_v} \qquad (27.6)$$

Dew-point temperature: If unsaturated moist air is cooled at constant pressure, then the temperature at which the moisture in the air begins to condense is known as *dew-point temperature (DPT)* of air. An approximate equation for dew-point temperature is given by:

$$\mathrm{DPT} = \frac{4030(\mathrm{DBT}+235)}{4030-(\mathrm{DBT}+235)\ln\phi} - 235 \qquad (27.7)$$

where Φ is the relative humidity (in fraction). DBT & DPT are in ^{o}C. Of course, since from its definition, the dew point temperature is the saturation temperature corresponding to the vapour pressure of water vapour, it can be obtained from steam tables or using Eqn.(27.3).

Degree of saturation μ: The degree of saturation is the ratio of the humidity ratio W to the humidity ratio of a saturated mixture W_s at the same temperature and pressure, i.e.,

$$\mu = \left|\frac{W}{W_s}\right|_{t,P} \qquad (27.8)$$

Enthalpy: The enthalpy of moist air is the sum of the enthalpy of the dry air and the enthalpy of the water vapour. Enthalpy values are always based on some reference value. For moist air, the enthalpy of dry air is given a zero value at 0°C, and for water vapour the enthalpy of saturated water is taken as zero at 0°C.

The enthalpy of moist air is given by:

$$h = h_a + Wh_g = c_p t + W(h_{fg} + c_{pw} t) \qquad (27.9)$$

where c_p = specific heat of dry air at constant pressure, kJ/kg.K

c_{pw} = specific heat of water vapor, kJ/kg.K

t = Dry-bulb temperature of air-vapor mixture, °C

W = Humidity ratio, kg of water vapor/kg of dry air

h_a = enthalpy of dry air at temperature t, kJ/kg

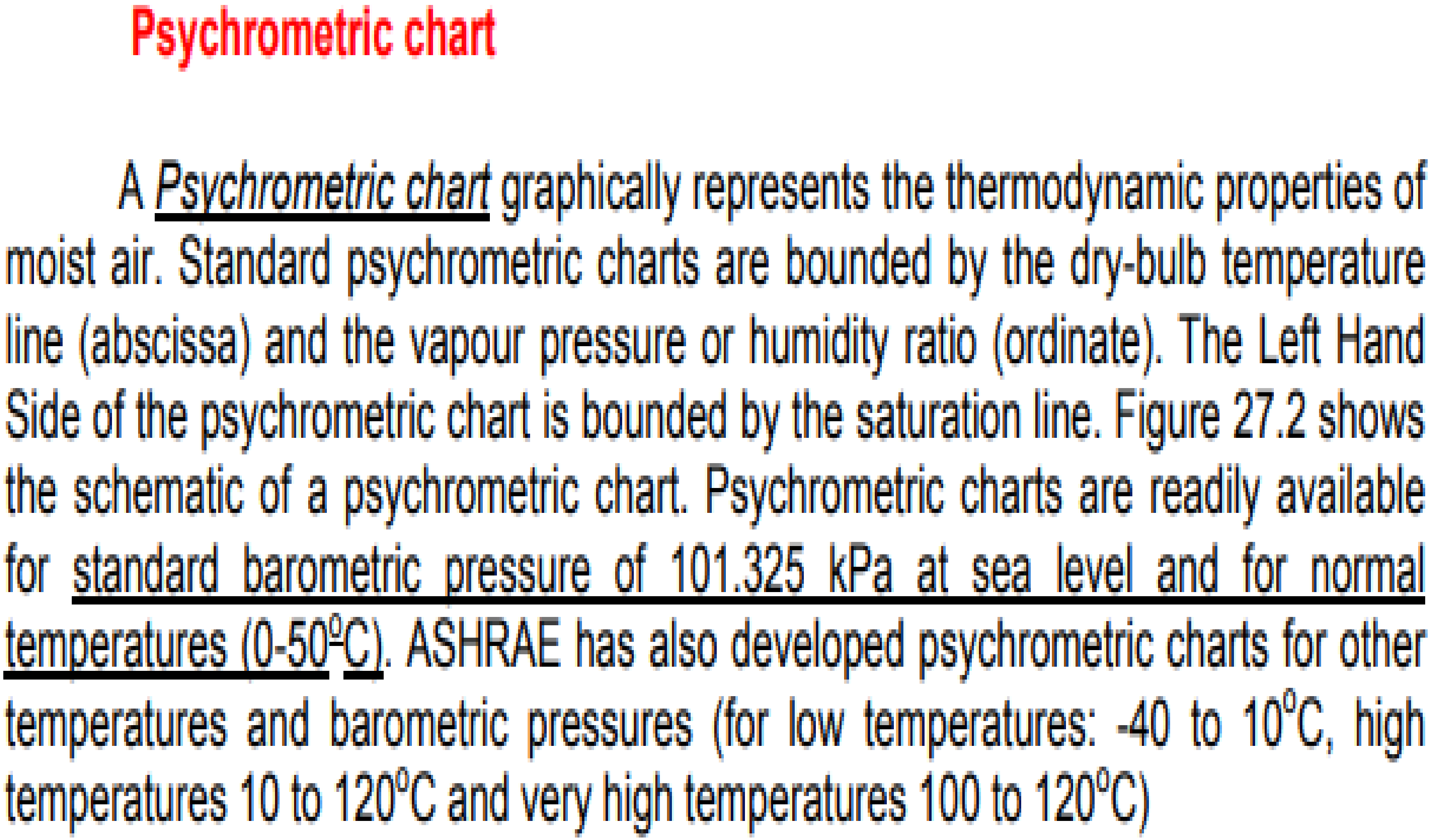
h_g = enthalpy of water vapor^3 at temperature t, kJ/kg

h_{fg} = latent heat of vaporization at 0°C, kJ/kg

The unit of h is kJ/kg of dry air. Substituting the approximate values of c_p and h_g, we obtain:

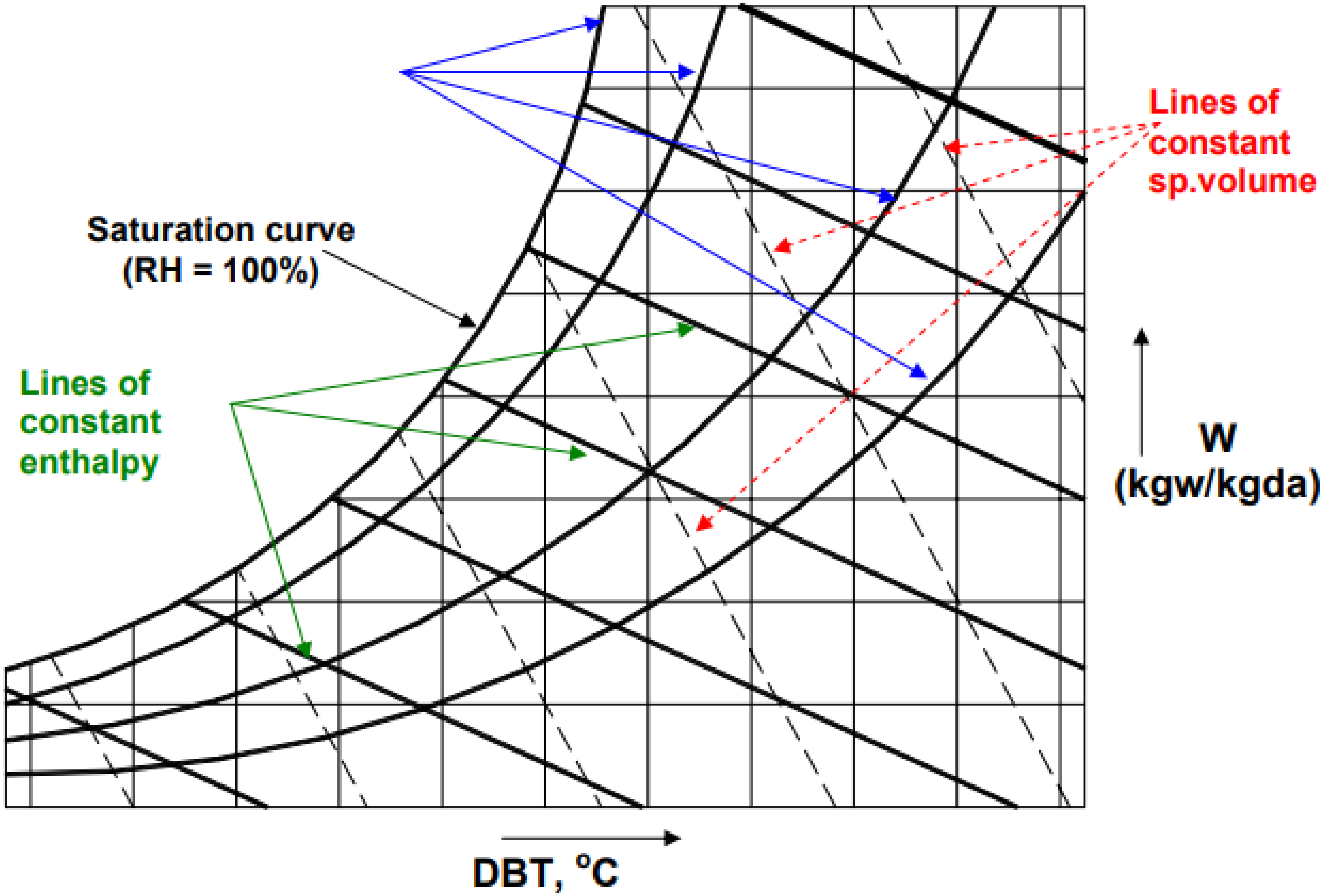
$$h = 1.005\,t + W(2501 + 1.88t) \qquad (27.10)$$

PSYCHROMETRIC CHART



Psychrometric chart

A *Psychrometric chart* graphically represents the thermodynamic properties of moist air. Standard psychrometric charts are bounded by the dry-bulb temperature line (abscissa) and the vapour pressure or humidity ratio (ordinate). The Left Hand Side of the psychrometric chart is bounded by the saturation line. Figure 27.2 shows the schematic of a psychrometric chart. Psychrometric charts are readily available for standard barometric pressure of 101.325 kPa at sea level and for normal temperatures (0-50°C). ASHRAE has also developed psychrometric charts for other temperatures and barometric pressures (for low temperatures: -40 to 10°C, high temperatures 10 to 120°C and very high temperatures 100 to 120°C)



Schematic of a psychrometric chart for a given barometric pressure

Adiabatic saturation and thermodynamic wet bulb temperature:

Adiabatic saturation temperature is defined as that temperature at which water, by evaporating into air, can bring the air to saturation at the same temperature adiabatically. An adiabatic saturator is a device using which one can measure theoretically the adiabatic saturation temperature of air.

As shown in Fig.27.4, an adiabatic saturator is a device in which air flows

water in the duct, there will be heat and mass transfer between water and air. If the duct is infinitely long, then at the exit, there would exist perfect equilibrium between air and water at steady state. Air at the exit would be fully saturated and its temperature is equal to that of water temperature. The device is adiabatic as the walls of the chamber are thermally insulated. In order to continue the process, make-up water has to be provided to compensate for the amount of water evaporated into the air. The temperature of the make-up water is controlled so that it is the same as that in the duct.

After the adiabatic saturator has achieved a steady-state condition, the temperature indicated by the thermometer immersed in the water is the *thermodynamic wet-bulb temperature*. The thermodynamic wet bulb temperature will be less than the entering air DBT but greater than the dew point temperature.

Certain combinations of air conditions will result in a given sump temperature, and this can be defined by writing the energy balance equation for the adiabatic saturator. Based on a unit mass flow rate of dry air, this is given by:

$$h_1 = h_2 - (W_2 - W_1)h_f \qquad (27.13)$$

where h_f is the enthalpy of saturated liquid at the sump or thermodynamic wet-bulb temperature, h_1 and h_2 are the enthalpies of air at the inlet and exit of the adiabatic saturator, and W_1 and W_2 are the humidity ratio of air at the inlet and exit of the adiabatic saturator, respectively.

It is to be observed that the thermodynamic wet-bulb temperature is a thermodynamic property, and is independent of the path taken by air. Assuming the humid specific heat to be constant, from the enthalpy balance, the thermodynamic wet-bulb temperature can be written as:

$$t_2 = t_1 - \frac{h_{fg,2}}{c_{pm}}(w_2 - w_1) \qquad (27.14)$$

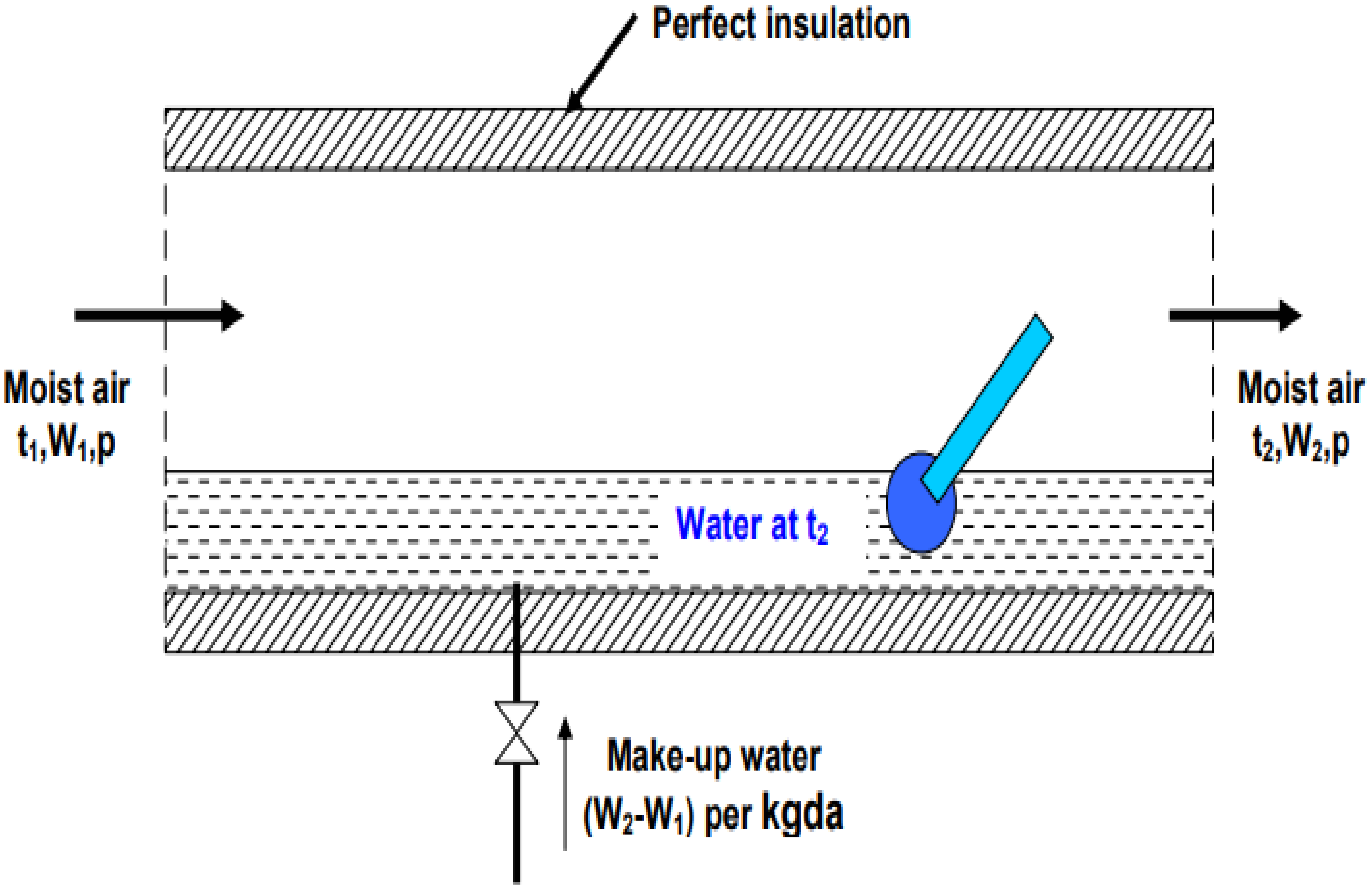


Fig.27.4: The process of adiabatic saturation of air

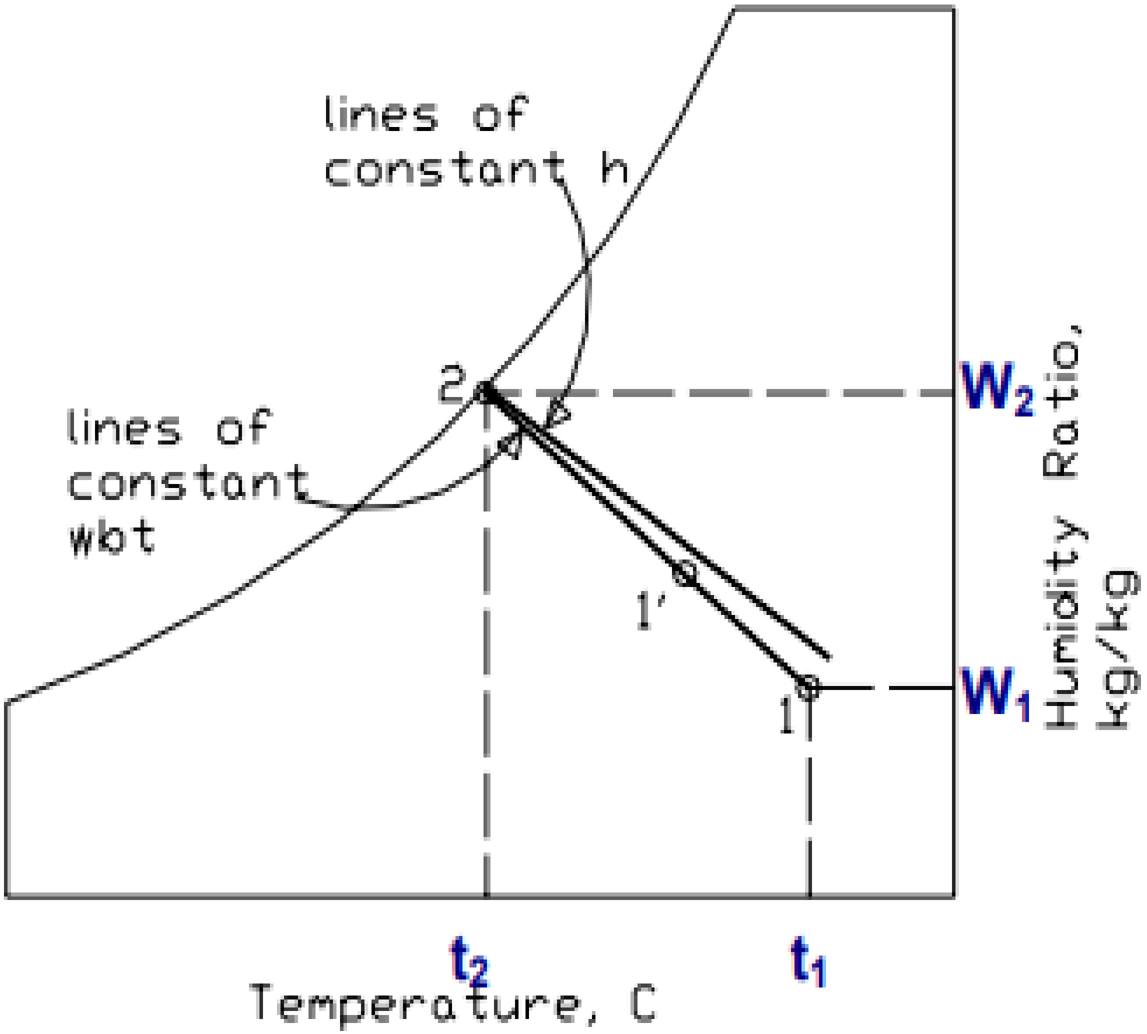


Fig.27.5: Adiabatic saturation process 1-2 on psychrometric chart

PSYCHROMETER

- Any instrument capable of measuring the psychrometric state of air is called a psychrometer.
- As mentioned before, in order to measure the psychrometric state of air, it is required to measure three independent parameters.
- Generally two of these are the barometric pressure and air dry-bulb temperature as they can be measured easily and with good accuracy.

PSYCHROMETER

- The sling psychrometer is widely used for measurements involving room air or other applications where the air velocity inside the room is small.
- The sling psychrometer consists of two thermometers mounted side by side and fitted in a frame with a handle for whirling the device through air.
- The required air circulation (≈ 3 to 5 m/s) over the sensing bulbs is obtained by whirling the psychrometer (≈ 300 RPM).
- Readings are taken when both the thermometers show steady-state readings.

SOLVED PROBLEMS

7. Moist air at 1 atm. pressure has a dry bulb temperature of 32°C and a wet bulb temperature of 26°C. Calculate a) the partial pressure of water vapour, b) humidity ratio, c) relative humidity, d) dew point temperature, e) density of dry air in the mixture, f) density of water vapour in the mixture and g) enthalpy of moist air using perfect gas law model and psychrometric equations.

Ans.:

a) Using modified Apjohn equation and the values of DBT, WBT and barometric pressure, the vapour pressure is found to be:

$p_v = 2.956$ kPa **(Ans.)**

b) The humidity ratio W is given by:

$W = 0.622 \times 2.956/(101.325-2.956) = 0.0187$ kgw/kgda **(Ans.)**

c) Relative humidity RH is given by:

RH = (p_v/p_s) x 100 = (p_v/saturation pressure at 32°C) x 100

From steam tables, the saturation pressure of water at 32°C is **4.7552 kPa**, hence,

RH = (2.956/4.7552) x 100 = 62.16% (Ans.)

d) Dew point temperature is the saturation temperature of steam at 2.956 kPa. Hence using steam tables we find that:

DPT = T_{sat}(2.956 kPa) = 23.8°C (Ans.)

e) Density of dry air and water vapour

Applying perfect gas law to dry air:

Density of dry air $\rho_a = (p_a/R_aT) = (p_t - p_v)/R_aT = (101.325 - 2.956)/(287.035 \times 305) \times 10^3$

$= 1.1236\ kg/m^3$ of dry air (Ans.)

f) Similarly the density of water vapour in air is obtained using perfect gas law as:

Density of water vapour $\rho v = (p_v/R_vT) = 2.956 \times 10^3/(461.52 \times 305) = 0.021\ kg/m^3$

(Ans.)

g) Enthalpy of moist air is found from the equation:

$h = 1.005 \times t + W(2501 + 1.88 \times t) = 1.005 \times 32 + 0.0187(2501 + 1.88 \times 32)$

h= 80.05 kJ/kg of dry air (Ans.)

5. On a particular day the weather forecast states that the dry bulb temperature is $37^{\circ}C$, while the relative humidity is 50% and the barometric pressure is 101.325 kPa. Find the humidity ratio, dew point temperature and enthalpy of moist air on this day.

Ans.:

At $37^{\circ}C$ the saturation pressure (p_s) of water vapour is obtained from steam tables as **6.2795 kPa.**

Since the relative humidity is 50%, the vapour pressure of water in air (p_v) is:

$$\mathbf{p_v = 0.5 \times p_s = 0.5 \times 6.2795 = 3.13975\ kPa}$$

the humidity ratio W is given by:

$$\mathbf{W = 0.622 \times p_v/(p_t - p_v) = 0.622 \times 3.13975/(101.325 - 3.13975) = 0.01989\ kgw/kgda}$$

(Ans.)

The enthalpy of air (h) is given by the equation:

$$\mathbf{h = 1.005t + W(2501 + 1.88t) = 1.005 \times 37 + 0.01989(2501 + 1.88 \times 37) = 88.31\ kJ/kgda}$$

(Ans.)

Q 3. A sample of air contains 39.05 mol of nitrogen, 10.47 mol of oxygen, 0.45 mol of argon, and 0.03 mol of argon. Determine the mole fractions.

- Solution: Let n_{N2}, n_{O2}, n_{Ar}, and n_{CO2} be moles of nitrogen, oxygen, argon, and carbon dioxide.
- The mole fraction of nitrogen, oxygen, argon, and carbon dioxide in the given of air be y_{N2}, y_{O2}, y_{Ar}, and y_{CO2}.

$$y_{N_2} = \frac{n_{N_2}}{n_{N_2} + n_{O_2} + n_{Ar} + n_{CO_2}} = \frac{39.05}{39.05 + 10.47 + 0.45 + 0.03} = \frac{39.05}{50.00} = 0.7810$$

$$y_{O_2} = \frac{n_{O_2}}{n_{N_2} + n_{O_2} + n_{Ar} + n_{CO_2}} = \frac{10.47}{39.05 + 10.47 + 0.45 + 0.03} = \frac{10.47}{50.00} = 0.2094$$

$$y_{\mathrm{Ar}} = \frac{n_{\mathrm{Ar}}}{n_{\mathrm{N}_2} + n_{\mathrm{O}_2} + n_{\mathrm{Ar}} + n_{\mathrm{CO}_2}} = \frac{0.45}{39.05 + 10.47 + 0.45 + 0.03} = \frac{0.45}{50.00} = 0.0090$$

$$y_{\mathrm{CO}_2} = \frac{n_{\mathrm{CO}_2}}{n_{\mathrm{N}_2} + n_{\mathrm{O}_2} + n_{\mathrm{Ar}} + n_{\mathrm{CO}_2}} = \frac{0.03}{39.05 + 10.47 + 0.45 + 0.03} = \frac{0.03}{50.00} = 0.0006$$

Thus, the sample of air consists of 0.7810 of nitrogen, 0.2094 of oxygen, 0.0090 of argon, and 0.0006 of carbon dioxide.

SOLVED PROBLEMS

Q4. A mixture of hydrogen gas and oxygen gas exerts a total pressure of 1.5 atm on the walls of its container. If the partial pressure of hydrogen is 1 atm, find the mole fraction of oxygen in the mixture.

- Given, $P_{hydrogen}$ = 1 atm, P_{total} = 1.5 atm
- Applying Dalton's law formula,
- $P_{total} = P_{hydrogen} + P_{oxygen}$
- Therefore, P_{oxygen} = 0.5 atm
- Now, the mole fraction of oxygen,
- $X_{oxygen} = (P_{oxygen}/P_{total}) = 0.5/1.5 = 0.33$
- Therefore, the mole fraction of oxygen in the mixture is 0.33

INDUSTRIAL APPLICATIONS

- Automobile industries.
- Refrigeration industries
- Air craft applications
- Defense industries
- Thermal power plants
- Chemical industries
- Textile industries etc.

SELF LEARNING QUESTIONS

1. Define mole fraction, and mass fraction. Explain about volumetric and gravimetric analysis?
2. Explain adiabatic saturation temperature?
3. Explain psychrometric charts while representing all the properties?
4. Locate i) sensible heating ii) sensible cooling iii) heating and humidification iv) heating and dehumidification on psychrometric chart?
5. Compare degree of saturation and adiabatic saturation.

ASSIGNMENT EXERCISES

1. 1.8 kg of oxygen at 48^0 C is mixed with 6.2 kg of nitrogen at the same temperature. Both oxygen and nitrogen are at the pressure of 102 k Pa before and after mixing. Find the increase in entropy.
2. A mixture of ideal air and water vapour at a dbt of 220C and a total pressure of 730 mm Hg abs. has a temperature of adiabatic saturation of 150C. Calculate: i. the speci_c humidity in gms per kg of dry air. ii. the partial pressure of water vapour the relative humidity, and iv. enthalpy of the mixture per kg of dry air.
3. Atmospheric air at 1.0132 bar has a DBT of 30°C and WBT of 24°C. Compute, (i) The partial pressure of water vapour (ii) Specific humidity (iii) The dew point temperature (iv) Relative humidity (v) Degree of saturation (vi) Density of air in the mixture (vii) Density of the vapour in the mixture (viii) The enthalpy of the mixture.

THANK YOU

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ENGINEERING THERMODYNAMICS

2nd Year B. Tech I- sem, Mechanical Engineering

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COURSE OBJECTIVES

UNIT - 1	CO1:To understand the concepts of energy transformation, conversion of heat into work.
UNIT - 2	CO2:To acquire knowledge about the fundamentals of thermodynamic laws, the concept of entropy, and principles
UNIT - 3	CO3: To understand how the change of state results in a process.
UNIT - 4	CO4: To understand the various gas laws, psychrometric properties and chart.
UNIT - 5	CO5: To learn the importance of thermodynamic cycles, and the derivation of efficiency.

UNIT 5

BASICS OF THERMODYNAMICS

CO5: **To learn the importance of thermodynamic cycles, and the derivation of efficiency.**

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UNIT – V (SYLLABUS)

Power Cycles

- Otto cycle
- Diesel cycle
- Dual Combustion cycle
- P–V and T-S diagram
- Thermal Efficiency
- Comparison of Cycles
- Basic Rankine cycle

COURSE OUTLINE

UNIT -5

LECTURE	LECTURE TOPIC	KEY ELEMENTS	Learning objectives (2 to 3 objectives)
1	Power Cycles	Concepts of power cycles	Knowledge on power cycles (B2)
2	Otto cycle	Efficiency of Otto cycle	Understanding the working of Otto cycle (B2)
3	Diesel cycle	Performance of Diesel cycle	Knowledge on the applications of Diesel engine (B2)
4	Dual Combustion cycle	Efficiency of dual combustion engine	Understanding the performance of Dual combustion cycle (B3)
5	Brayton cycle	Gas turbine	Knowledge on the applications of Brayton cycle (B5)
6	Thermal Efficiency	Cycle efficiency	Calculation of efficiency of different cycles (B6)
7	Comparison of Cycles	Differences of cycles	Understanding the different cycles (B2)
8	Basic Rankine cycle Performance Evaluation.	Power plant, Rankine cycle	Understanding the applications of Rankine cycle (B3)

LECTURE 5

Power Cycles

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POWER CYCLES

- A cycle is defined as a *repeated series of operations occurring in a certain order.*
- *It may be* repeated by repeating the processes in the same order.
- The cycle may be of *imaginary perfect engine or actual engine.*
- *The former is called ideal cycle and the latter actual cycle.*
- *In ideal cycle all accidental heat losses are prevented and the working substance is assumed to behave like a perfect working substance.*

AIR STANDARD EFFICIENCY

- To compare the effects of different cycles, it is of paramount importance that the effect of the calorific value of the fuel is altogether eliminated and this can be achieved by considering air (which is assumed to behave as a perfect gas) as the working substance in the engine cylinder. *The efficiency of engine using air as the working medium is known as an “**Air standard efficiency**”.*
- This efficiency is oftenly called ***ideal efficiency.***

THERMAL EFFICIENCY

- The actual efficiency of a cycle is always *less than the air-standard efficiency of that cycle* under ideal conditions.
- This is taken into account by introducing a new term “***Relative efficiency***”

which is defined as :

- ηrelative = Actual thermal efficiency/Air standard efficiency
- **Assumptions :**

1. The gas in the engine cylinder is a *perfect gas i.e., it obeys the gas laws and has constant* specific heats.

THERMAL EFFICIENCY

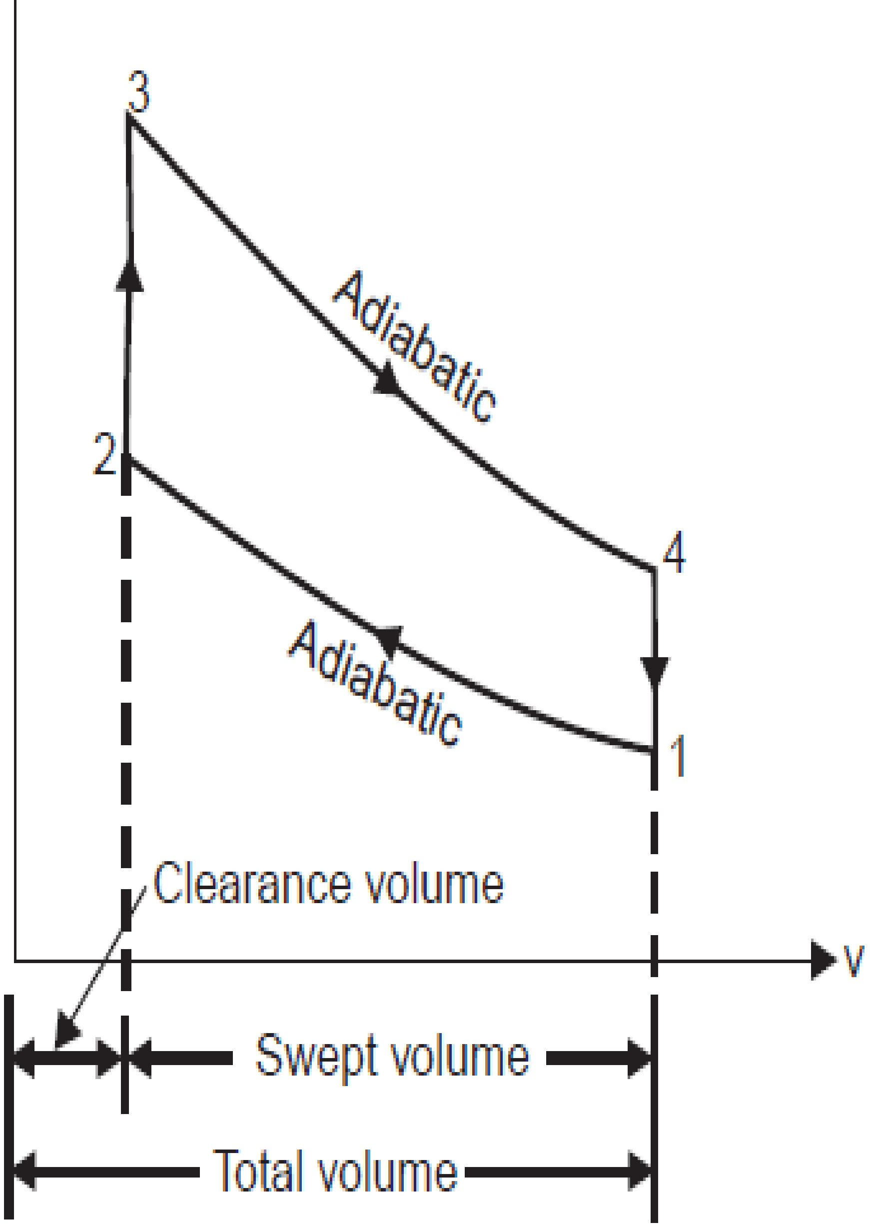
2. The physical constants of the gas in the cylinder are the same as those of air at moderate temperatures *i.e., the molecular weight of cylinder gas is 29.*

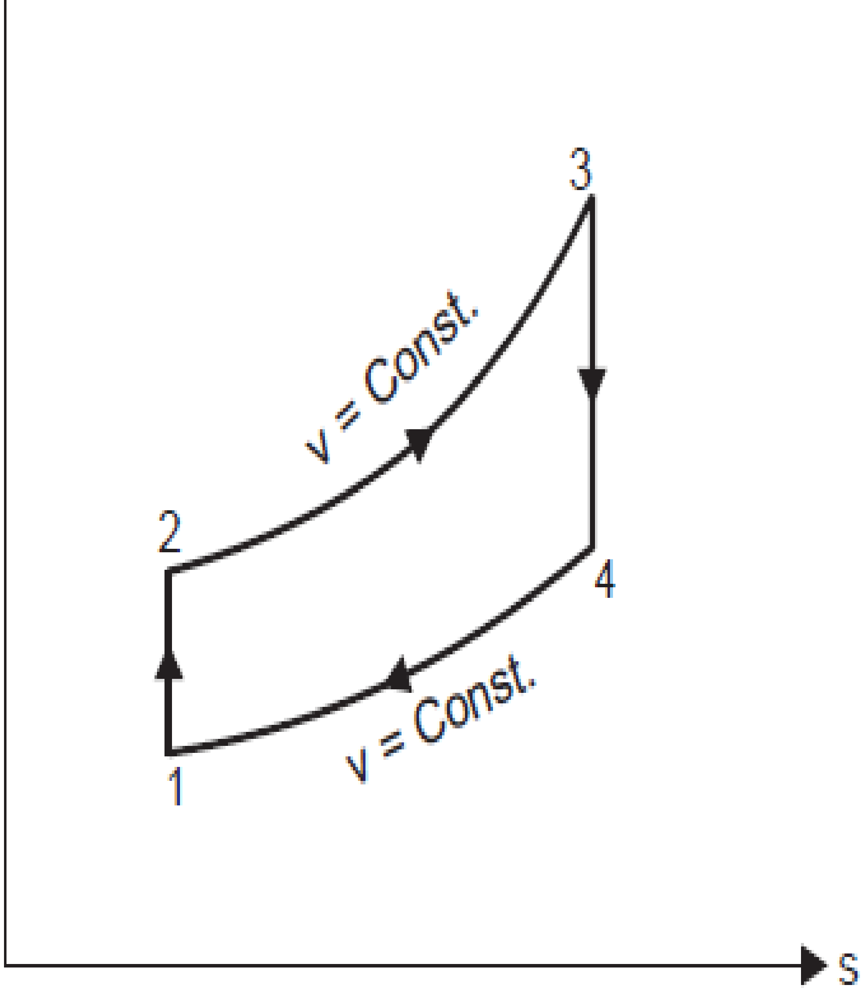
- *cp = 1.005 kJ/kg-K, cv = 0.718 kJ/kg-K.*

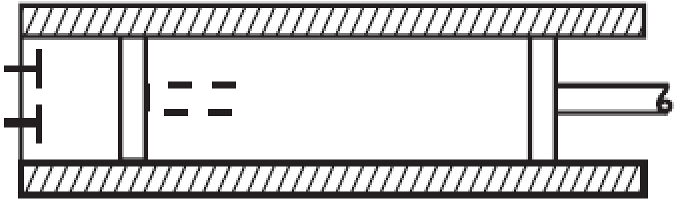
3. The compression and expansion processes are adiabatic and they take place without internal friction, *i.e., these processes are isentropic.*

OTTO CYCLE OR CONSTANT VOLUME CYCLE

- Otto cycle is so named as it was conceived by the scientist 'Otto'. On this cycle, petrol, gas and many types of oil engines work.
- It is the standard of comparison for internal combustion engines.
- Figs. 13.5 (*a) and (b) shows the theoretical p-V diagram and T-s diagrams of this cycle* respectively.


3
Adiabatic
2
4
Adiabatic
1
Clearance volume
v
Swept volume
Total volume


3
v = Const.
2
4
v = Const.
1
s



(a)

OTTO CYCLE OR CONSTANT VOLUME CYCLE

Process 1-2 Adiabatic Compression:

- The piston moves from BDC to TDCV compression of the fuel-air mixture takes place.
- The compression causes the mixture to increase slightly in pressure and temperature—however, no heat is exchanged.
- In terms of thermodynamics, this is referred to as an adiabatic process.

OTTO CYCLE OR CONSTANT VOLUME CYCLE

- When the cycle reaches point 2, that is when the fuel is met by the spark plug to be ignited.
- The point 1 represents that cylinder is full of air with volume *V1, pressure p1 and absolute* temperature *T1.*
- Line 1-2 represents the *adiabatic compression of air due to which p1, V1 and T1 change to p2, V2 and T2, respectively.*

OTTO CYCLE OR CONSTANT VOLUME CYCLE

- **Process 2-3 Constant volume heat addition:**
- This is where combustion occurs due to the ignition of fuel by the spark plug.
- The combustion of the gas is complete at point 3, which results in a highly pressurized chamber that has a lot of heat (thermal energy).
- In terms of thermodynamics, this is referred to as an isochoric process.
- Line 2-3 shows the *supply of heat to the air at constant volume so that p2 and T2 change to*
- *p3 and T3 (V3 being the same as V2).*

OTTO CYCLE OR CONSTANT VOLUME CYCLE

Process 3 to 4: Adiabatic Expansion

- The thermal energy in the chamber as a result of combustion is used to do work on the piston—which pushes the piston down—increasing the volume of the chamber.
- This is also known as the power stoke because it is when the thermal energy is turned into motion to power the machine or vehicle.
- During expansion *p3, V3 and T3*
- change to a final value of *p4, V4 or V1 and T4, respectively.*

OTTO CYCLE OR CONSTANT VOLUME CYCLE

Process 4-1: Constant volume heat rejection

- All the waste heat is expelled from the engine chamber.
- As the heat leaves the gas, the molecules lose kinetic energy causing the decrease in pressure.
- Then the exhaust phase occurs when the remaining mixture in the chamber is compressed by the piston to be "exhausted" out, without changing the pressure.

OTTO CYCLE OR CONSTANT VOLUME CYCLE

Total Cylinder Volume:

- It is the total volume (maximum volume) of the cylinder in which Otto cycle takes place. In Otto cycle,
- Total cylinder volume = $V_1 = V_4 = V_c + {}_s$
- (Refer p-V diagram above)
- where,
- V_c → Clearance Volume
- V_s → Stroke Volume

OTTO CYCLE OR CONSTANT VOLUME CYCLE

Clearance Volume (V_c):

- At the end of the compression stroke, the piston approaches the Top Dead Center (TDC) position. The minimum volume of the space inside the cylinder, at the end of the compression stroke, is called clearance volume (V_c).
- In Otto cycle,
- Clearance Volume, $V_c = V_2$

Stroke Volume (V_s):

- In Otto cycle, stroke volume is the difference between total cylinder volume and clearance volume.
- Stroke Volume, V_s = Total Cylinder Volume – Clearance Volume = $V_1 - V_2 = V_4 - V_3$

Compression Ratio:

- Compression ratio (r) is the ratio of total cylinder volume to the clearance volume.

$$r = \frac{\text{Total Cylinder Volume}}{\text{Clearance Volume}}$$

OTTO CYCLE OR CONSTANT VOLUME CYCLE

Consider **1 kg of air** (working substance) :

Heat supplied at constant volume = $c_v(T_3 - T_2)$.

Heat rejected at constant volume = $c_v(T_4 - T_1)$.

But, work done = Heat supplied – Heat rejected

$$= c_v(T_3 - T_2) - c_v(T_4 - T_1)$$

$$\therefore \quad \text{Efficiency} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{c_v(T_3 - T_2) - c_v(T_4 - T_1)}{c_v(T_3 - T_2)}$$

$$= 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

Let compression ratio, $r_c\ (= r) = \frac{v_1}{v_2}$

expansion ratio, $r_e\ (= r) = \frac{v_4}{v_3}$

(These *two ratios are same* in this cycle)

As
$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1}$$

Then,
$$T_2 = T_1 \, . \, (r)^{\gamma - 1}$$

Similarly,
$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma - 1}$$

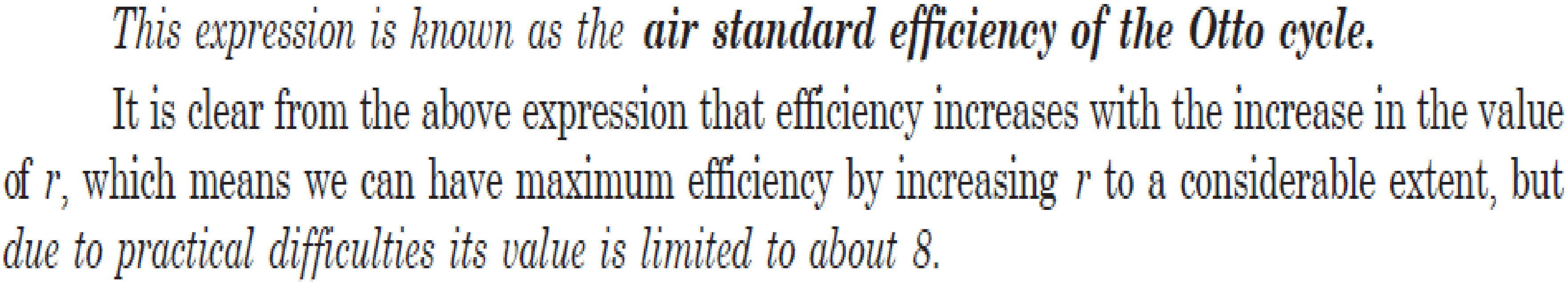
$$T_3 = T_4 \, . \, (r)^{\gamma - 1}$$

Inserting the values of T_2 and T_3 in equation (i), we get

$$\eta_{otto} = 1 - \frac{T_4 - T_1}{T_4 \, . (r)^{\gamma - 1} - T_1 \, . (r)^{\gamma - 1}} = 1 - \frac{T_4 - T_1}{r^{\gamma - 1}(T_4 - T_1)}$$

$$= 1 - \frac{1}{(r)^{\gamma - 1}}$$

OTTO CYCLE OR CONSTANT VOLUME CYCLE



This expression is known as the ***air standard efficiency of the Otto cycle.***

It is clear from the above expression that efficiency increases with the increase in the value of r, which means we can have maximum efficiency by increasing r to a considerable extent, but *due to practical difficulties its value is limited to about 8.*

DIESEL CYCLE OR CONSTANT PRESSURE

- This cycle was introduced by Dr. R. Diesel in 1897. It differs from Otto cycle in that *heat is supplied at constant pressure instead of at constant volume. Fig. 13.15 (a and b) shows the p-v* and *T-s diagrams of this cycle respectively.*

This cycle comprises of the following ***operations :***

(i) 1-2......Adiabatic compression.

(ii) 2-3......Addition of heat at constant pressure.

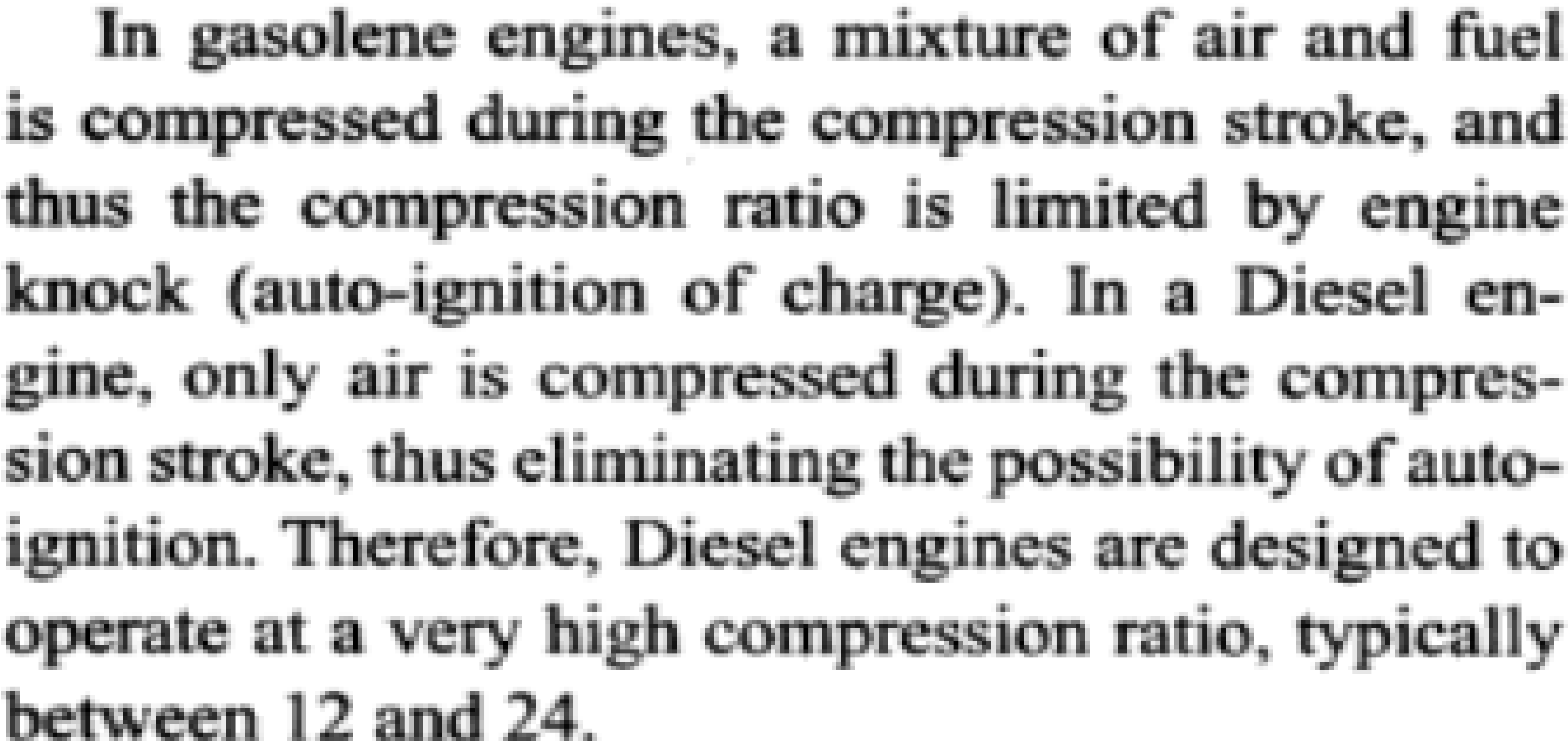
(iii) 3-4......Adiabatic expansion.

(iv) 4-1......Rejection of heat at constant volume.

DIESEL CYCLE OR CONSTANT PRESSURE

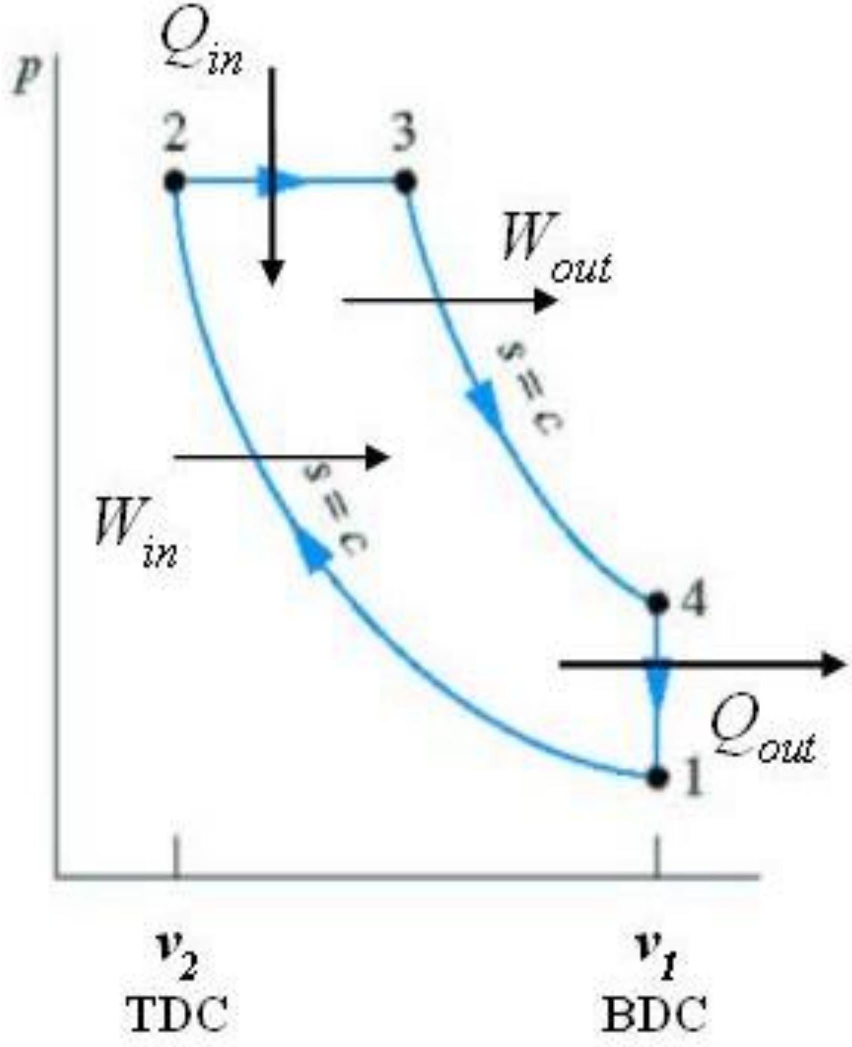
- Diesel cycle is an ideal cycle for Diesel engines or compression ignition engines.
- There is no fuel in the cylinder at the beginning of the compression stroke, therefore an autoignition does not occur in Diesel engines.

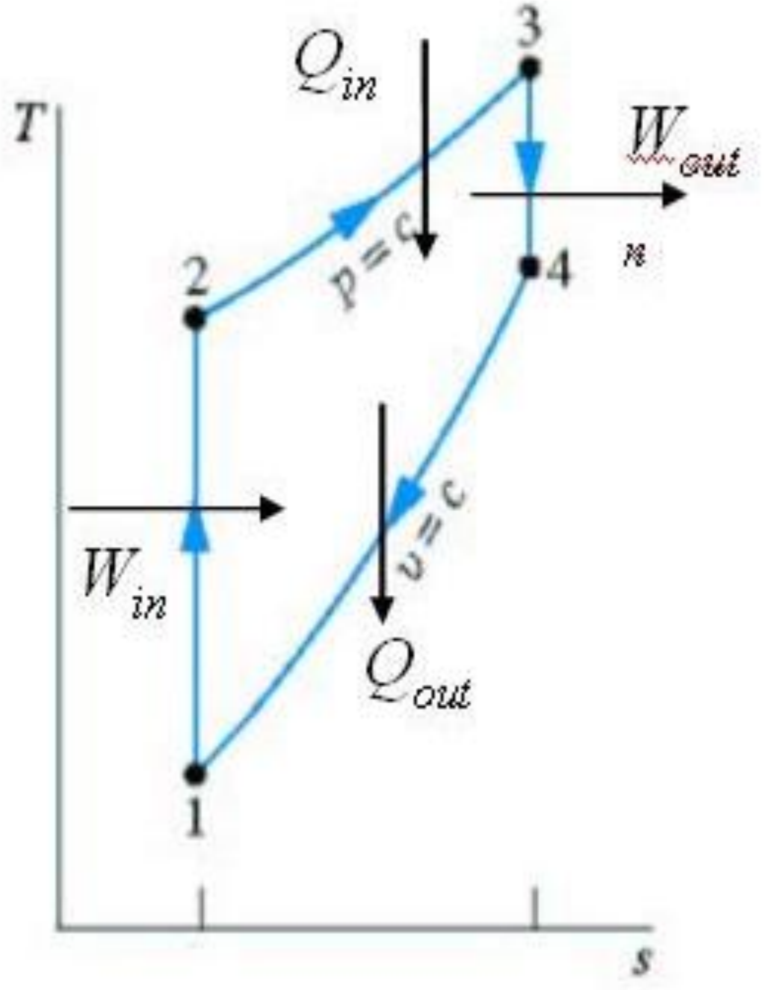
DIESEL CYCLE OR CONSTANT PRESSURE



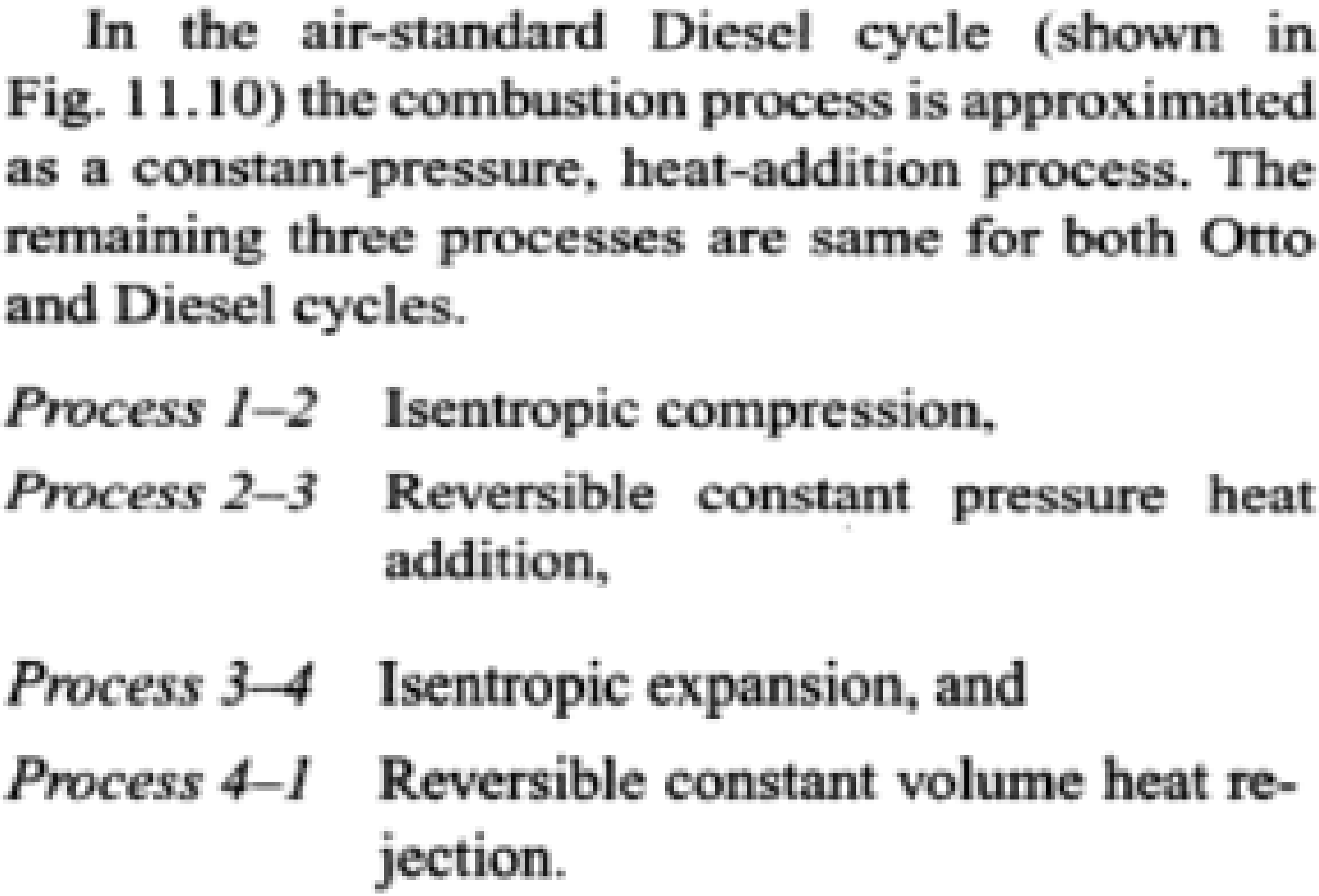
In gasolene engines, a mixture of air and fuel is compressed during the compression stroke, and thus the compression ratio is limited by engine knock (auto-ignition of charge). In a Diesel engine, only air is compressed during the compression stroke, thus eliminating the possibility of auto-ignition. Therefore, Diesel engines are designed to operate at a very high compression ratio, typically between 12 and 24.

DIESEL CYCLE OR CONSTANT PRESSURE





DIESEL CYCLE OR CONSTANT PRESSURE



In the air-standard Diesel cycle (shown in Fig. 11.10) the combustion process is approximated as a constant-pressure, heat-addition process. The remaining three processes are same for both Otto and Diesel cycles.

Process 1–2	Isentropic compression,
Process 2–3	Reversible constant pressure heat addition,
Process 3–4	Isentropic expansion, and
Process 4–1	Reversible constant volume heat rejection.

Analysis

For 1 kg of air undergoing a Diesel cycle,

Heat supplied $q_{in} = q_{2-3} = C_p(T_3 - T_2)$

Heat rejected $q_{out} = q_{4-1} = C_v(T_4 - T_1)$

The efficiency of the cycle

$$\eta = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)}$$

$$\eta_{Diesel} = 1 - \left(\frac{T_4 - T_1}{\gamma(T_3 - T_2)}\right) \qquad \text{...(11.11)}$$

The efficiency of the Diesel cycle may be expressed in the following terms:

Compression ratio

$$r = \frac{V_1}{V_2} = \frac{v_1}{v_2}$$

$$= \frac{\text{Volume before compression}}{\text{Volume after compression}}$$

Cut-off ratio

$$\rho = \frac{V_3}{V_2} = \frac{v_3}{v_2}$$

$$= \frac{\text{Volume after heat supply}}{\text{Volume after compression}}$$

Expansion ratio

$$r_e = \frac{V_4}{V_3} = \frac{v_4}{v_3}$$

$$= \frac{\text{Volume after expansion}}{\text{Volume before expansion}}$$

It can be proved that

$$r = r_e\,\rho \text{ as } \left(\frac{v_4}{v_3} \times \frac{v_3}{v_2} = \frac{v_1}{v_2} = r\right) \quad \text{...(11.12)}$$

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Now for the isentropic process 1–2,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = r^{\gamma-1}$$

or $$T_2 = T_1 r^{\gamma-1} \qquad \text{...(i)}$$

For the constant-pressure heat-addition process 2–3,

$$\frac{T_3}{T_2} = \frac{v_3}{v_2} = \rho$$

or $$T_3 = \rho T_2 = \rho r^{\gamma-1} T_1 \qquad \text{...(ii)}$$

For the isentropic process 3–4

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1}$$

$$= \left(\frac{v_3}{v_1}\right)^{\gamma-1} = \left(\frac{v_3}{v_2} \times \frac{v_2}{v_1}\right)^{\gamma-1}$$

or $$T_4 = \left(\frac{\rho}{r}\right)^{\gamma-1} T_3 = \left(\frac{\rho}{r}\right)^{\gamma-1} \rho r^{\gamma-1}\; T_1$$

$$= \rho^{\gamma} T_1 \qquad \text{...(iii)}$$

Using the values of T_2, T_3 and T_4 from Eqs. (i), (ii) and (iii), respectively in Eq. (11.11), we get

$$\eta_{Diesel} = 1 - \frac{(\rho^{\gamma} - 1)T_1}{\gamma(\rho r^{\gamma-1} - r^{\gamma-1})T_1}$$

$$= 1 - \frac{1}{r^{\gamma-1}}\left[\frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)}\right] \quad \text{...(11.13)}$$

11.7.1 Effect of Cut-off Ratio on Diesel Cycle Efficiency

Since the cut-off ratio ρ is always greater than unity then the quantity

$\frac{1}{\gamma}\left(\frac{\rho^{\gamma} - 1}{\rho - 1}\right)$ is also greater than unity. Therefore, the efficiency of the Diesel cycle is less than that of the Otto cycle for the same compression ratio. However, since Diesel engines employ much higher compression ratio, thus their thermal efficiency is higher.

As cut-off ratio decreases, (Fig. 11.13) the efficiency of the Diesel cycle increases. For a cut-off ratio $\rho \approx 1$, the quantity in the bracket of Eq. (11.13) approaches unity and the efficiency of Otto and Diesel cycles becomes identical.

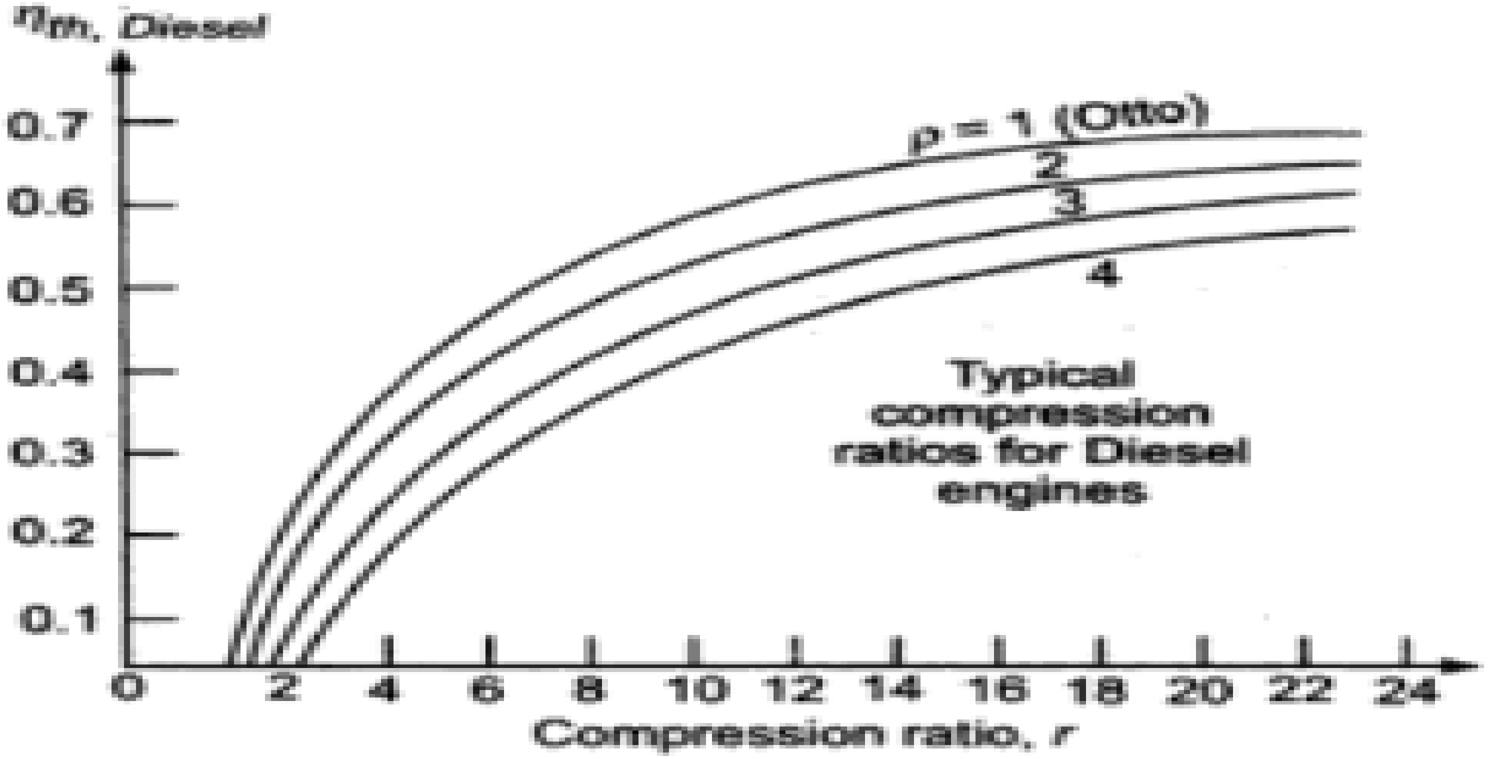
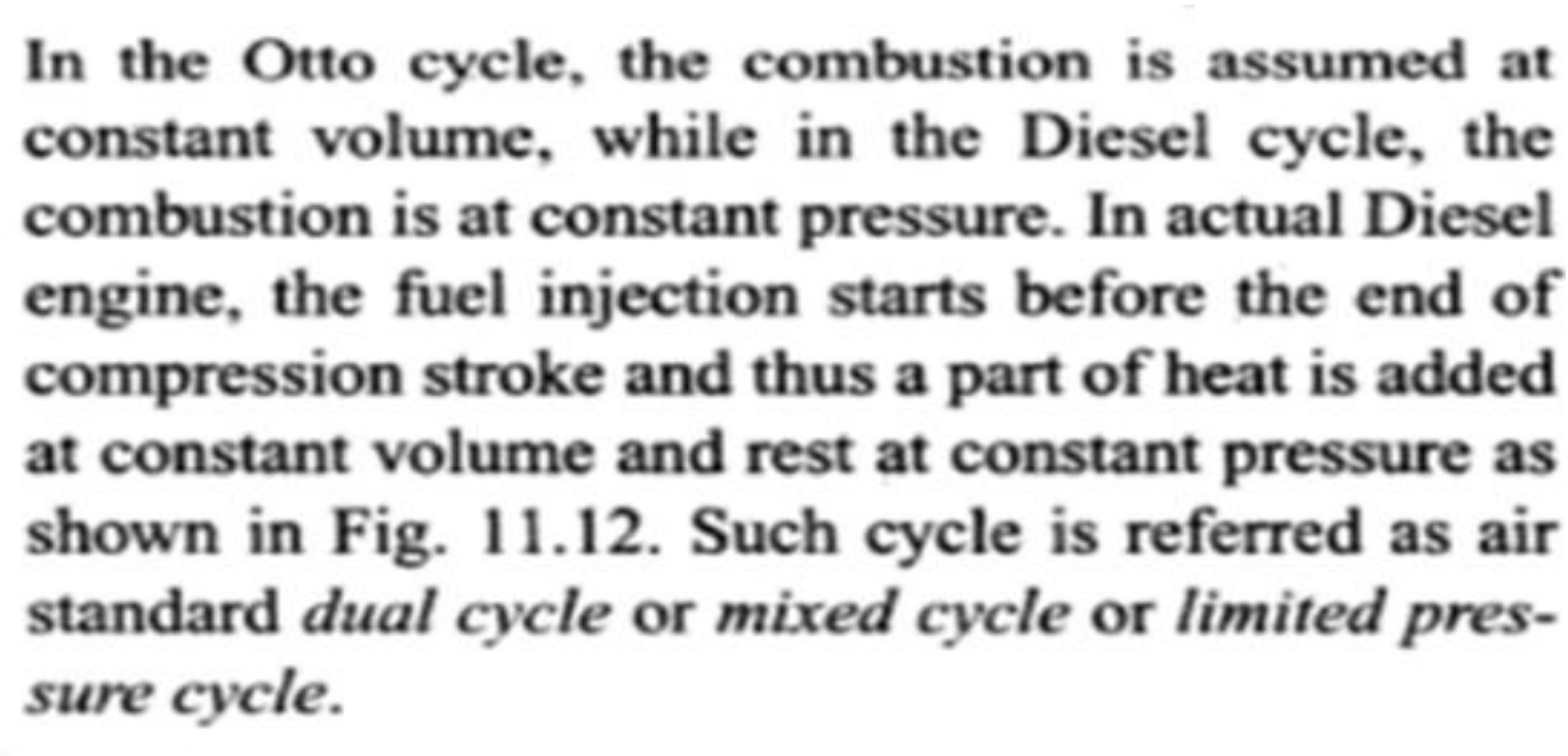
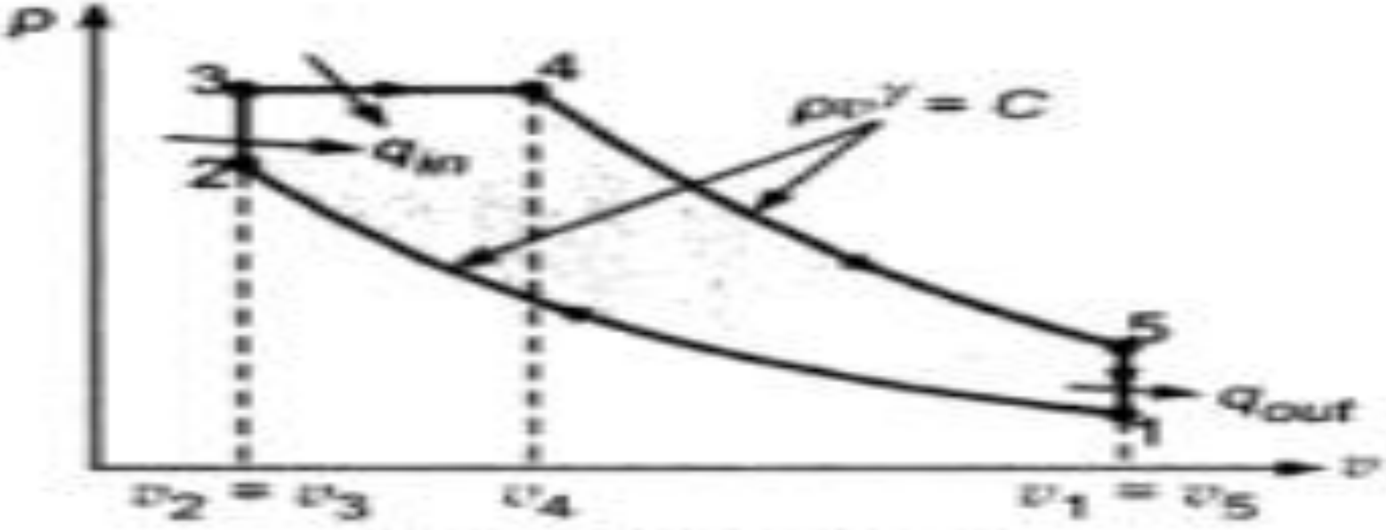


Fig. 11.11 *Effect of cut-off ratio and compression ratio on thermal efficiency of Diesel cycle*

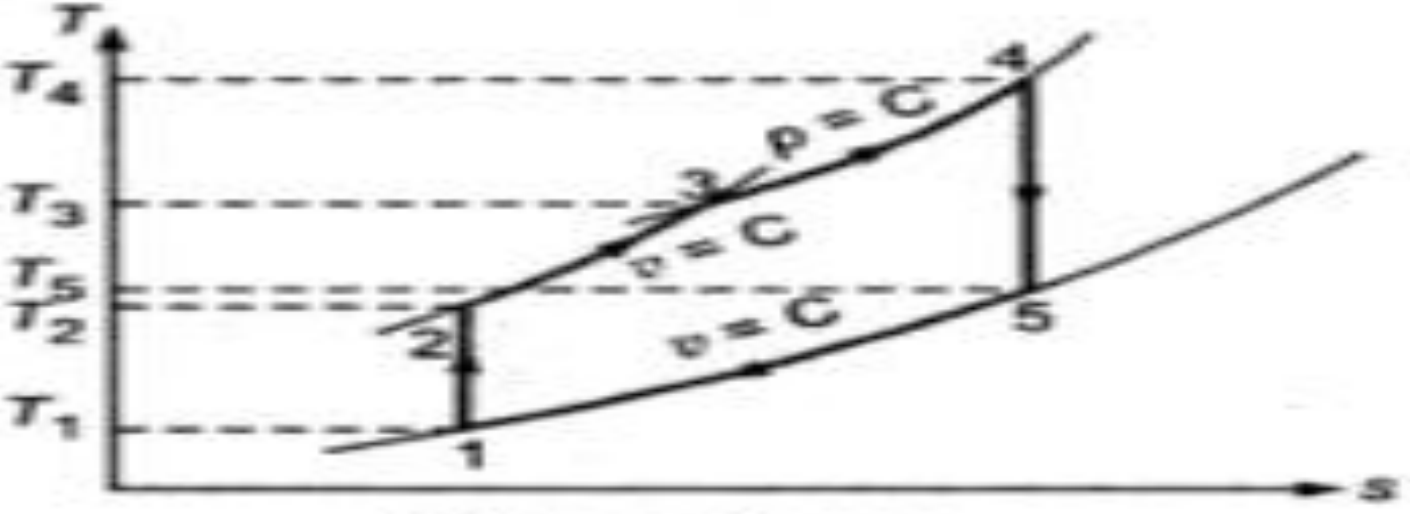
DUAL COMBUSTION CYCLE



In the Otto cycle, the combustion is assumed at constant volume, while in the Diesel cycle, the combustion is at constant pressure. In actual Diesel engine, the fuel injection starts before the end of compression stroke and thus a part of heat is added at constant volume and rest at constant pressure as shown in Fig. 11.12. Such cycle is referred as air standard *dual cycle* or *mixed cycle* or *limited pressure cycle*.



(a) p–v diagram



(b) T–s diagram

Fig. 11.12 *Air Standard Dual cycle*

Heat supplied, $q_{in} = C_v(T_3 - T_2) + C_p(T_4 - T_3)$

Heat rejected, $q_{out} = C_v(T_5 - T_1)$

Thermal efficiency $\eta = 1 - \frac{q_{out}}{q_{in}}$

$$= 1 - \frac{C_v(T_5 - T_1)}{C_v(T_3 - T_2) + C_p(T_4 - T_3)}$$

$$= 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)} \quad \ldots(11.14)$$

Considering the following ratio to express the efficiency of Dual cycle

Compression ratio $r = \frac{v_1}{v_2}$ ...(i)

Cut-off ratio, $\rho = \frac{v_4}{v_3}$ ...(ii)

Pressure ratio, $r_p = \frac{p_3}{p_2}$ ...(iii)

Expansion ratio, $r_e = \frac{v_5}{v_4}$ ...(iv)

For isentropic compression process 1–2;

$$T_2 = T_1 r^{\gamma - 1} \quad \ldots(v)$$

For constant volume process 2–3,

$$\frac{T_3}{T_2} = \frac{p_3}{p_2} = r_p$$

or $T_3 = r_p r^{\gamma-1} T_1$ ...(vi)

For constant pressure process 3—4,

$$\frac{v_4}{T_4} = \frac{v_3}{T_3}$$

or $$T_4 = \frac{v_4}{v_3} T_3 = \rho T_3$$

$$= \rho r_p r^{\gamma-1} T_1 \qquad \ldots(\text{vii})$$

For isentropic expansion process 4—5

$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5}\right)^{\gamma-1} = \left(\frac{v_4}{v_1}\right)^{\gamma-1} = \left(\frac{v_4}{v_3} \times \frac{v_3}{v_2} \times \frac{v_2}{v_1}\right)^{\gamma-1}$$

$$= \left(\frac{\rho}{r}\right)^{\gamma-1} \qquad (\because\ v_3 = v_2)$$

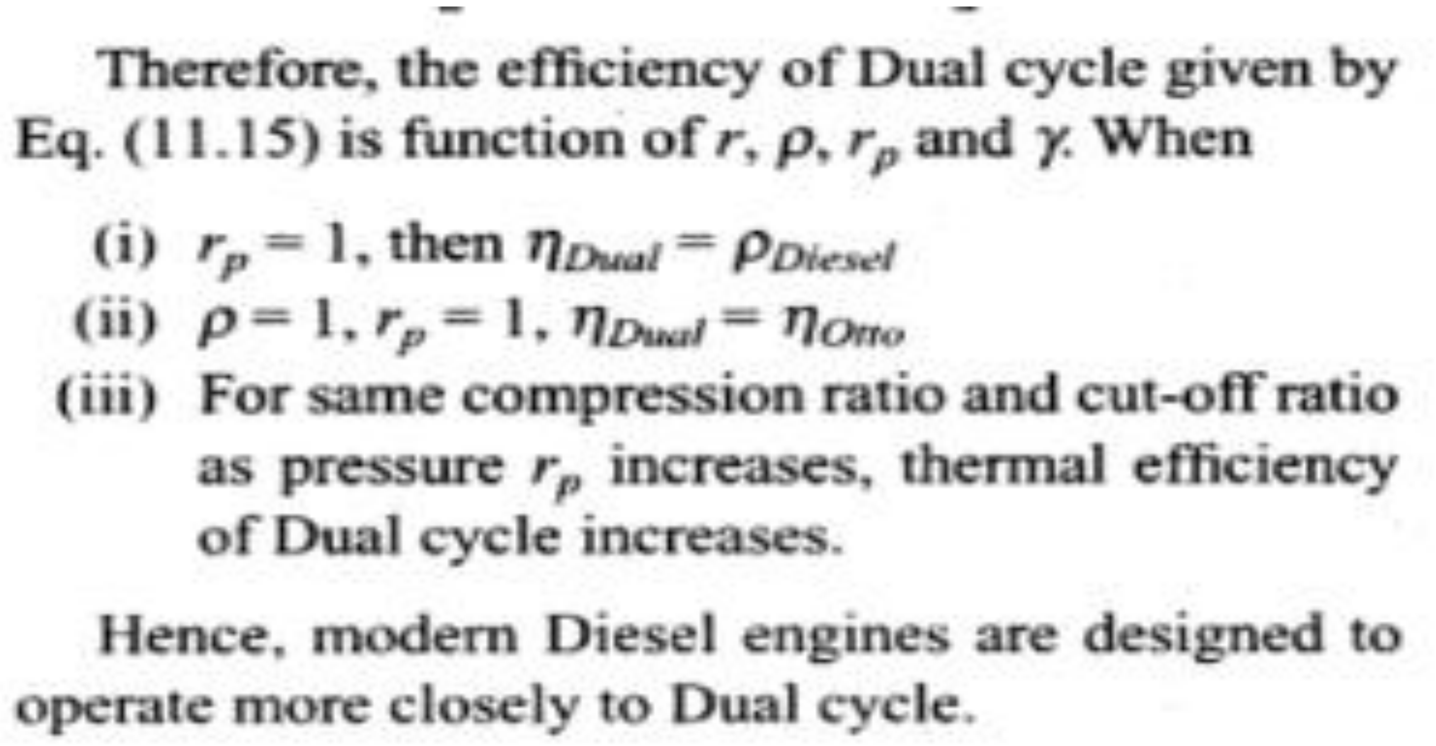
or $$T_5 = \left(\frac{\rho}{r}\right)^{\gamma-1} \rho r_p r^{\gamma-1} T_1 = \rho^{\gamma} r_p T_1 \qquad \ldots(\text{viii})$$

Using the values for T_2, T_3, T_4 and T_5 in Eq. (11.14)

$$\eta_{Dual} = 1 - \frac{T_1(\rho^{\gamma} r_p - 1)}{T_1(r_p r^{\gamma-1} - r^{\gamma-1}) + \gamma T_1(\rho r_p r^{\gamma-1} - r_p r^{\gamma-1})}$$

$$= 1 - \frac{1}{r^{\gamma-1}}\left[\frac{r_p \rho^{\gamma} - 1}{(r_p - 1) + \gamma r_p(\rho - 1)}\right] \qquad \ldots(11.15)$$

DUAL COMBUSTION CYCLE



Therefore, the efficiency of Dual cycle given by Eq. (11.15) is function of r, ρ, r_p and γ. When

(i) $r_p = 1$, then $\eta_{Dual} = \rho_{Diesel}$
(ii) $\rho = 1$, $r_p = 1$, $\eta_{Dual} = \eta_{Otto}$
(iii) For same compression ratio and cut-off ratio as pressure r_p increases, thermal efficiency of Dual cycle increases.

Hence, modern Diesel engines are designed to operate more closely to Dual cycle.

11.9 COMPARISON OF OTTO AND DIESEL CYCLES

The three cycles can be compared on the basis of either the same compression ratio or the same maximum pressure and temperature.

11.9.1 For Same Compression Ratio

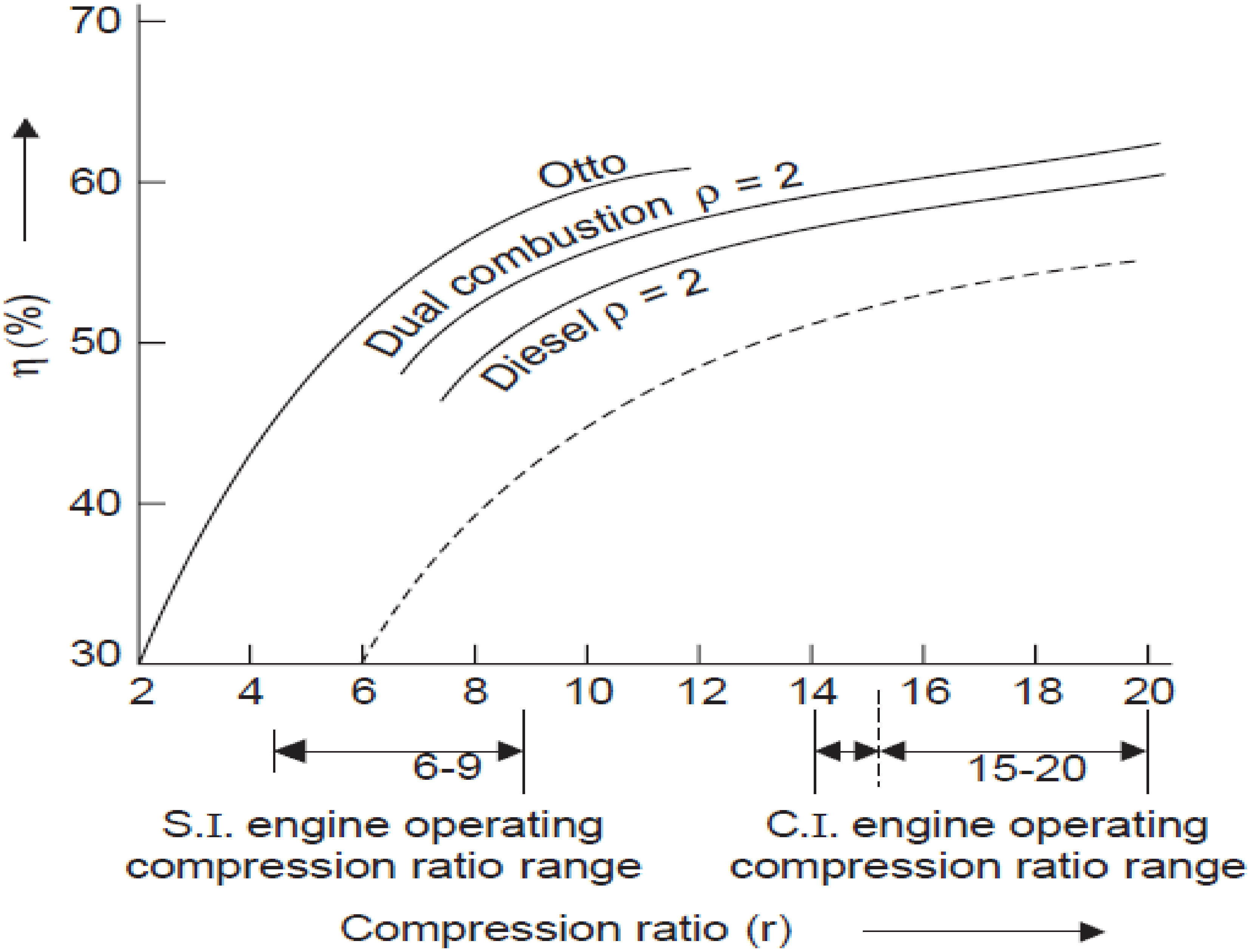
Figure 11.13 shows the comparison of three cycles on p–v and T–s diagrams.

Otto cycle has the **highest work output** (because of minimum heat rejection) and **efficiency**.

Diesel cycle has the least efficiency and **Dual cycle** having the efficiency between the two.

Hence for same compression ratio and heat addition,

$$\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$$


η (%)
70
60
50
40
30
Otto
Dual combustion ρ = 2
Diesel ρ = 2
2
4
6
8
10
12
14
16
18
20
6-9
15-20
S.I. engine operating compression ratio range
C.I. engine operating compression ratio range
Compression ratio (r)

COMPARISON OF THE CYCLES

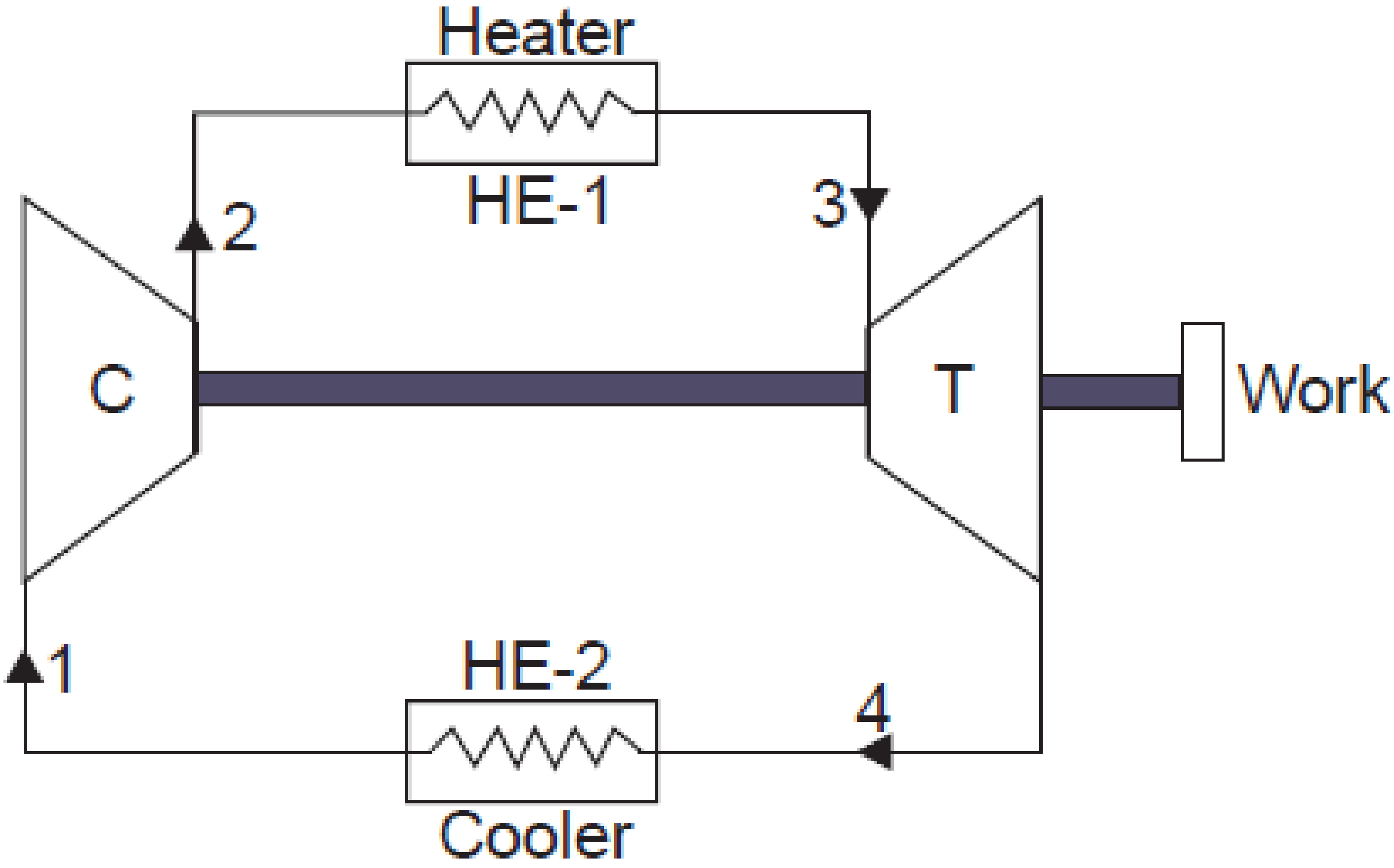
- comparison of the cycles (Otto, Diesel and Dual) on the *p-v and T-s diagrams for the same compression ratio and heat supplied is shown in the Fig.*
- Since all the cycles reject their heat at the same specific volume, process line from state 4 to 1, the quantity of *heat rejected from each cycle is represented by the appropriate area under the line 4 to 1 on the T-s diagram.*

COMPARISON OF THE CYCLES

- The least heat rejected will have the highest efficiency.
- Thus, Otto cycle is the most efficient and Diesel cycle is the least efficient of the three cycles.
- $\eta\text{otto} > \eta\text{dual} > \eta\text{diesel}$
- *For a given compression ratio Otto cycle is the most efficient while the Diesel cycle is the least efficient*

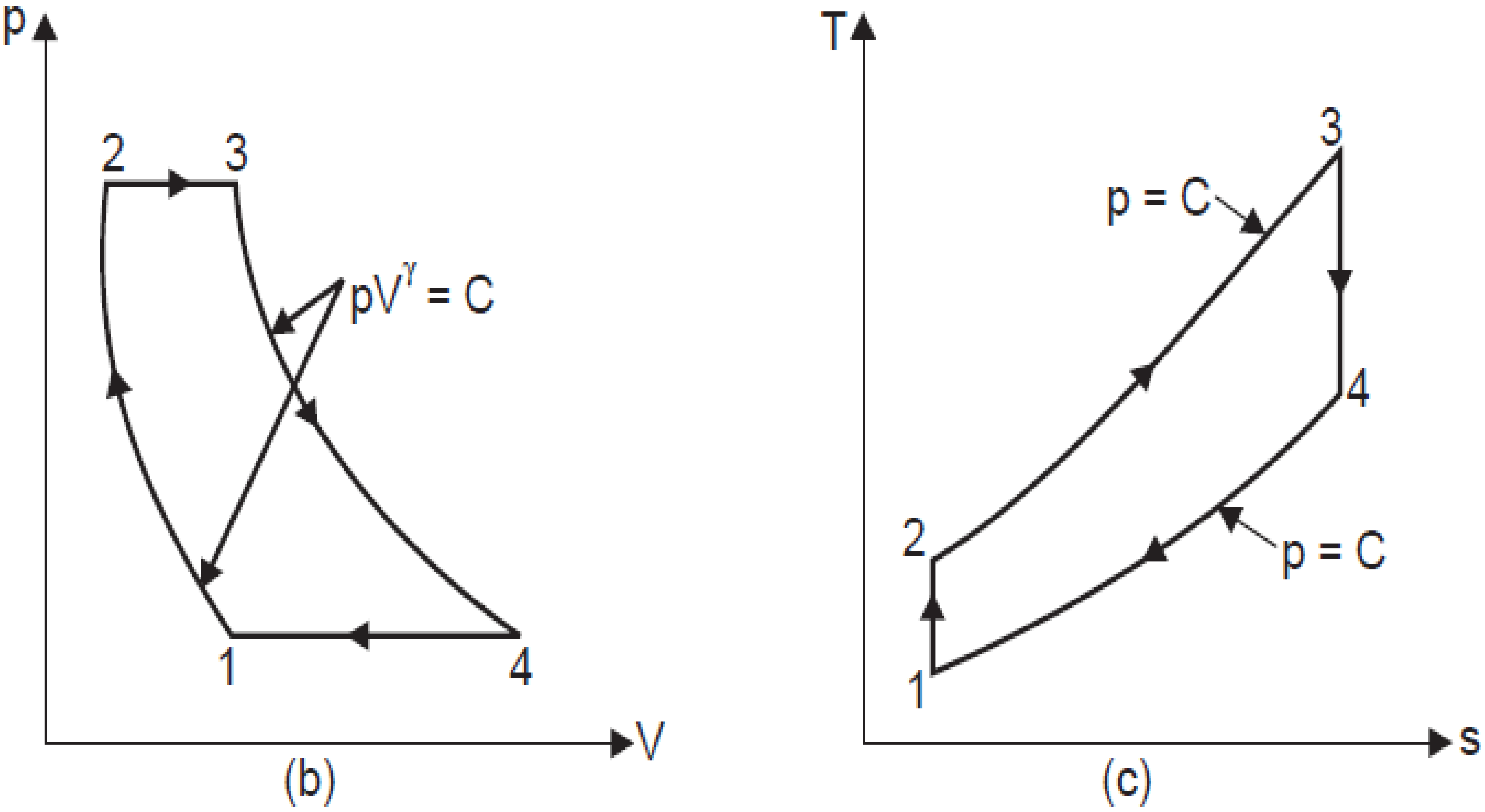
BRAYTON CYCLE

- Brayton cycle is *a constant pressure cycle for a perfect gas. It is also called Joule cycle.*
- The heat transfers are achieved in reversible constant pressure heat exchangers. An ideal gas
- turbine plant would perform the processes that make up a Brayton cycle. The cycle is shown in the
- Fig. 13.33 (*a) and it is represented on p-v and T-s diagrams as shown in Figs. 13.33 (b) and (c).*



C = Compressor T = Turbine

(a)



(b)

(c)

Fig. 13.33. Brayton cycle : (*a*) Basic components of a gas turbine power plant (*b*) *p*-*V* diagram (*c*) *T*-*s* diagram.

BRAYTON CYCLE

The various operations are as follows :

Process 1-2:

The air is compressed isentropically from the lower pressure *p1 to the* upper pressure *p2, the temperature rising from T1 to T2. No heat flow occurs.*

Process 2-3:

Heat flows into the system increasing the volume from *V2 to V3 and temperature* from *T2 to T3 whilst the pressure remains constant at p2. Heat received = mcp (T3 – T2).*

BRAYTON CYCLE

Process 3-4:

- The air is expanded isentropically from *p2 to p1, the temperature falling* from *T3 to T4.*
- *No heat flow occurs.*

Process 4-1:

- Heat is rejected from the system as the volume decreases from *V4 to V1 and* the temperature from *T4 to T1 whilst the pressure remains constant at p1.*
- *Heat rejected = mcp*(*T4 – T1)*

BRAYTON CYCLE

$$\eta_{\text{air-standard}} = \frac{\text{Work done}}{\text{Heat received}}$$

$$= \frac{\text{Heat received/cycle} - \text{Heat rejected/cycle}}{\text{Heat received/cycle}}$$

$$= \frac{mc_p (T_3 - T_2) - mc_p (T_4 - T_1)}{mc_p (T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

Now, from isentropic expansion,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = T_1 (r_p)^{\frac{\gamma-1}{\gamma}}$$, where r_p = pressure ratio.

Similarly $$\frac{T_3}{T_4} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{or} \quad T_3 = T_4 (r_p)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \qquad \eta_{\text{air-standard}} = 1 - \frac{T_4 - T_1}{T_4 (r_p)^{\frac{\gamma-1}{\gamma}} - T_1 (r_p)^{\frac{\gamma-1}{\gamma}}} = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}$$

BRAYTON CYCLE

- The above equation shows that the *efficiency of the ideal joule cycle increases with the pressure ratio.*
- *The absolute limit of upper pressure is determined by the limiting temperature of the material of the turbine at the point at which this temperature is reached by the compression process alone, no further heating of the gas in the combustion chamber would be permissible and the work of expansion would ideally just balance the work of compression so that no excess work would be available for external use.*

RANKINE CYCLE

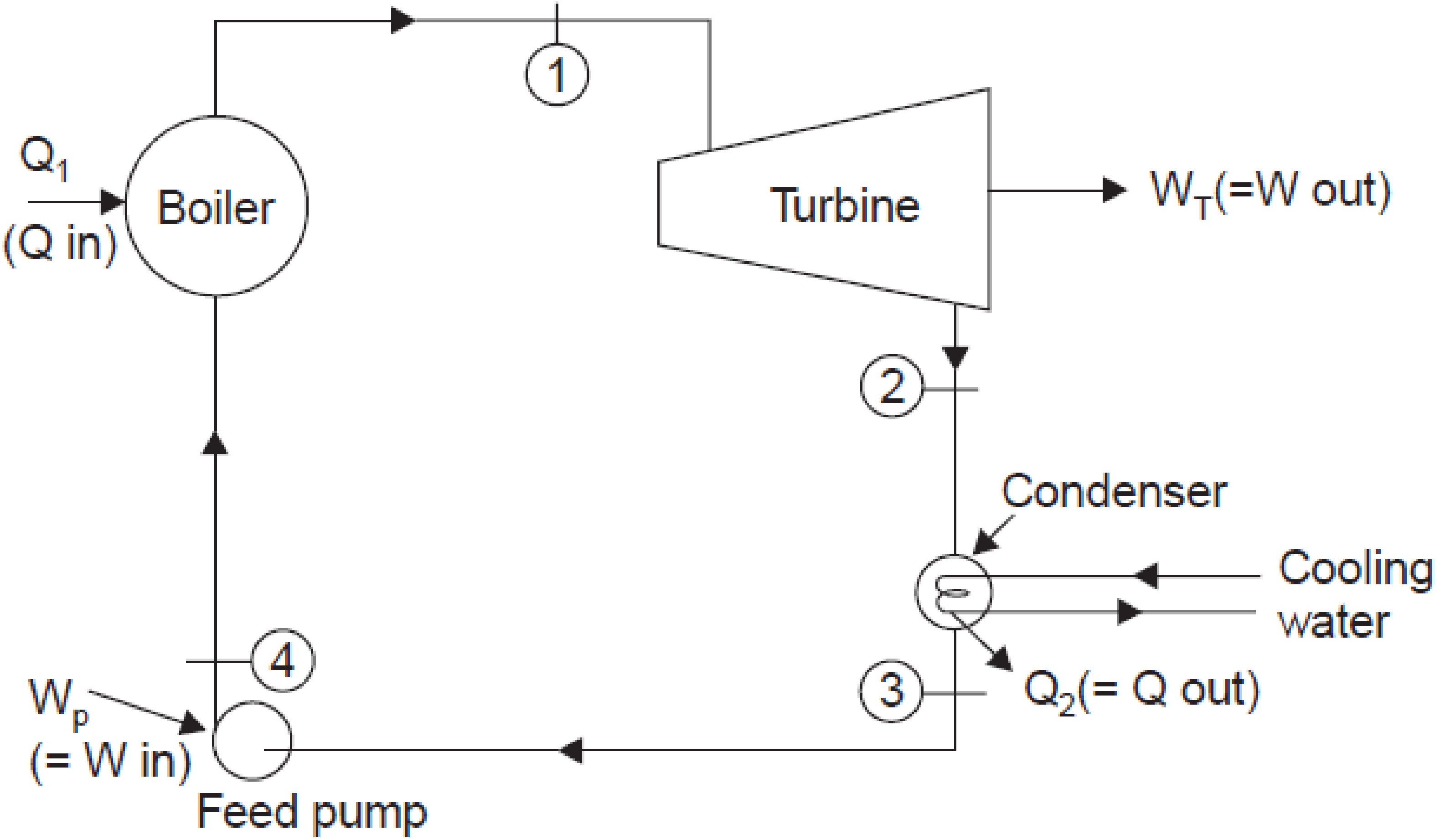
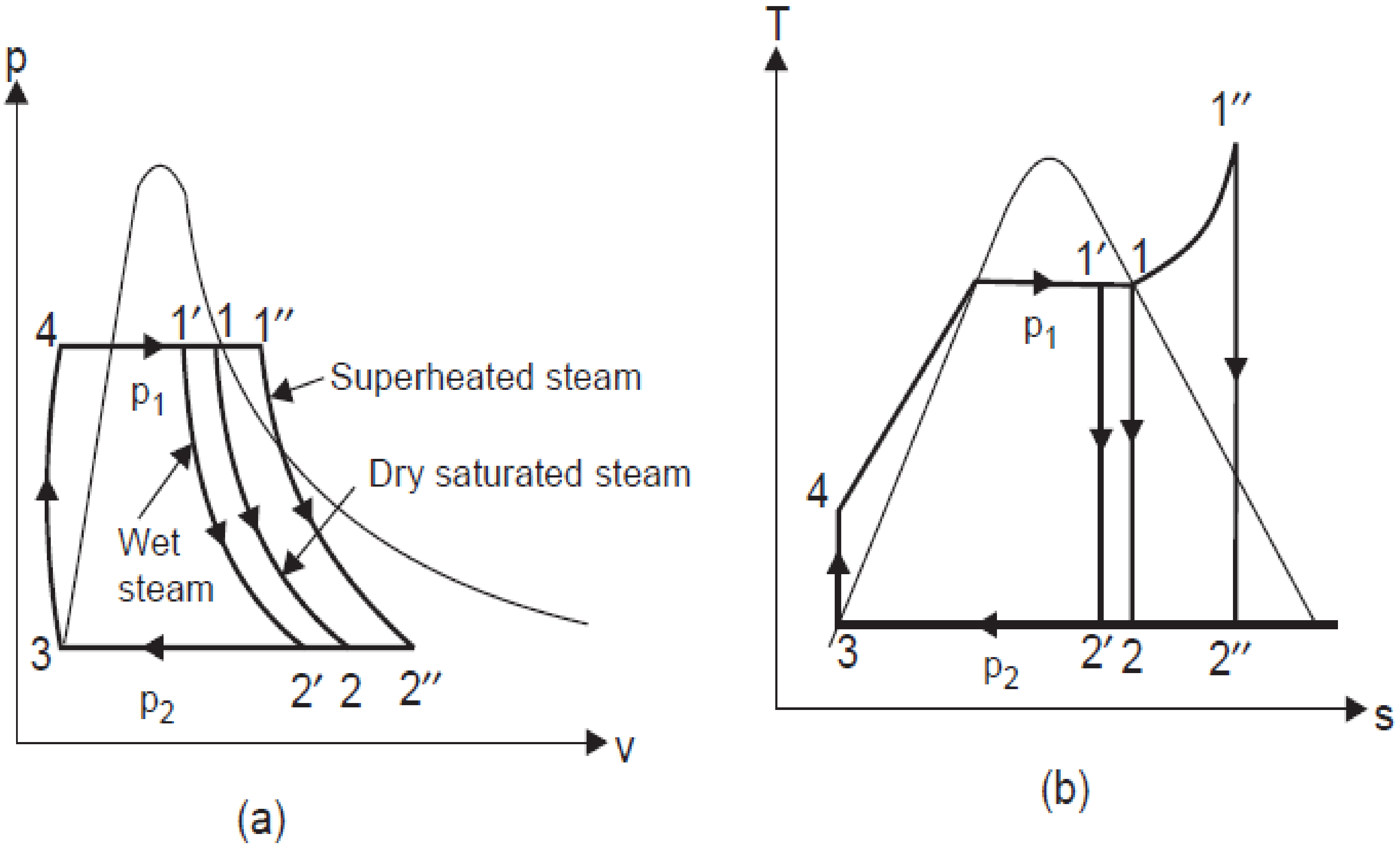
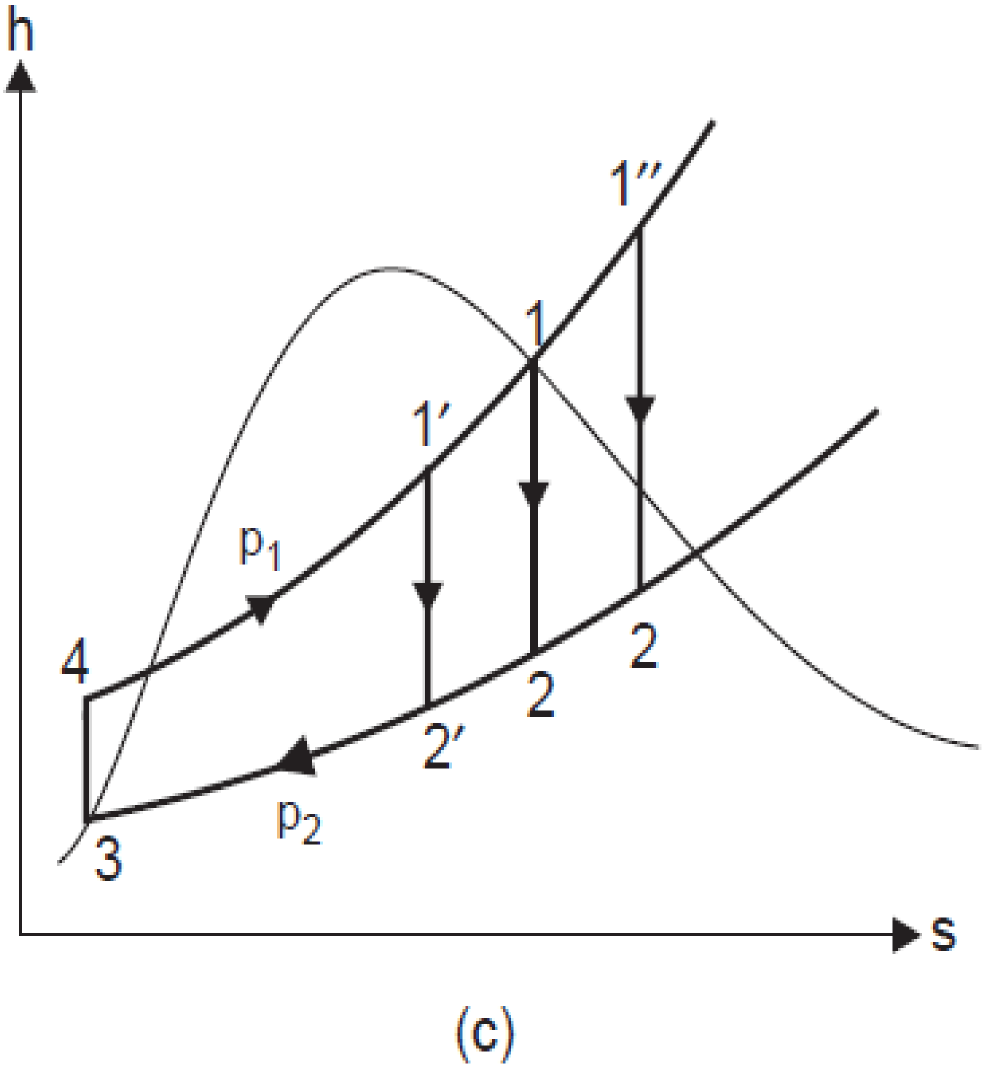


Fig. 12.2. Rankine cycle.

RANKINE CYCLE





ig. 12.3. (*a*) *p*-*v* diagram ; (*b*) *T*-*s* diagram ; (*c*) *h*-*s* diagram for Rankine cycle.

RANKINE CYCLE

- Rankine cycle is the theoretical cycle on which the steam turbine (or engine) works.
- The Rankine cycle is shown in Fig. 12.2. It comprises of the following *processes :*

Process 1-2 :

- Reversible adiabatic expansion in the turbine (or steam engine).

Process 2-3 :

- Constant-pressure transfer of heat in the condenser.

Process 3-4 :

- Reversible adiabatic pumping process in the feed pump.

Process 4-1 :

- Constant-pressure transfer of heat in the boiler.

RANKINE CYCLE

- Fig. 12.3 shows the Rankine cycle on *p-v, T-s and h-s diagrams (when the saturated steam* enters the turbine, the steam can be wet or superheated
- **Considering 1 kg of fluid :**
- Applying *steady flow energy equation (S.F.E.E.) to boiler, turbine, condenser and pump :*

(*i*) ***For boiler (as control volume),***

we get $hf4 + Q1 = h1$

$\therefore Q1 = h1 - hf4$...(12.2)

(*ii*) ***For turbine (as control volume), we get***

$h1 = WT + h2$, *where* WT = *turbine work*

$\therefore WT = h1 - h2$ated also).

RANKINE CYCLE

(*iii*) **For condenser**, we get

$$h_2 = Q_2 + h_{f_3}$$

$$\therefore \quad Q_2 = h_2 - h_{f_3}$$

(*iv*) **For the feed pump**, we get

$$h_{f_3} + W_P = h_{f_4}, \qquad \text{where, } W_P = \text{Pump work}$$

$$\therefore \quad W_P = h_{f_4} - h_{f_3}$$

Now, efficiency of Rankine cycle is given by

$$\eta_{\text{Rankine}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_P}{Q_1}$$

$$= \frac{(h_1 - h_2) - (h_{f_4} - h_{f_3})}{(h_1 - h_{f_4})}$$

The feed pump handles liquid water which is incompressible which means with the increase in pressure its density or specific volume undergoes a little change. Using general property relation for reversible adiabatic compression, we get

$$Tds = dh - vdp$$

$\because$ $ds = 0$

$\therefore$ $dh = vdp$

or $\Delta h = v\,\Delta p$ ...... (since change in specific volume is negligible)

or $h_{f_4} - h_{f_3} = v_3\,(p_1 - p_2)$

When p is in bar and v is in m^3/kg, we have

$$h_{f_4} - h_{f_3} = v_3\,(p_1 - p_2) \times 10^5 \text{ J/kg}$$

The feed pump term ($h_{f_4} - h_{f_3}$) being a small quantity in comparison with turbine work, W_T, is usually neglected, *especially when the boiler pressures are low.*

Then, $$\eta_{\text{Rankine}} = \frac{h_1 - h_2}{h_1 - h_{f_4}} \qquad \text{...[12.5 }(a)]$$

SOLVED PROBLEMS

Example 13.7. *The efficiency of an Otto cycle is 60% and $\gamma = 1.5$. What is the compression ?*

Solution. Efficiency of Otto cycle, $\eta = 60\%$

Ratio of specific heats, $\gamma = 1.5$

Compression ratio, $r = ?$

Efficiency of Otto cycle is given by,

$$\eta_{Otto} = 1 - \frac{1}{(r)^{\gamma - 1}}$$

$$0.6 = 1 - \frac{1}{(r)^{1.5 - 1}}$$

$$\frac{1}{(r)^{0.5}} = 0.4 \quad \text{or} \quad (r)^{0.5} = \frac{1}{0.4} = 2.5 \quad \text{or} \quad r = 6.25$$

Hence, *compression ratio* $=$ **6.25. (Ans.)**

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Example 12.2. *In a steam power cycle, the steam supply is at 15 bar and dry and saturated. The condenser pressure is 0.4 bar. Calculate the Carnot and Rankine efficiencies of the cycle. Neglect pump work.*

Solution. Steam supply pressure, $p_1 = 15$ bar, $x_1 = 1$

Condenser pressure, $p_2 = 0.4$ bar

Carnot and Rankine efficiencies :

From steam tables :

At 15 bar : $t_s = 198.3°\text{C}$, $h_g = 2789.9$ kJ/kg, $s_g = 6.4406$ kJ/kg K

At 0.4 bar : $t_s = 75.9°\text{C}$, $h_f = 317.7$ kJ/kg, $h_{fg} = 2319.2$ kJ/kg,

$$s_f = 1.0261 \text{ kJ/kg K}, \quad s_{fg} = 6.6448 \text{ kJ/kg K}$$

$$T_1 = 198.3 + 273 = 471.3 \text{ K}$$

$$T_2 = 75.9 + 273 = 348.9 \text{ K}$$

$$\eta_{\text{carnot}} = \frac{T_1 - T_2}{T_1} = \frac{471.3 - 348.9}{471.3}$$

$$= 0.259 \text{ or } 25.9\%. \text{ (Ans.)}$$

$$\eta_{\text{Rankine}} = \frac{\text{Adiabatic or isentropic heat drop}}{\text{Heat supplied}} = \frac{h_1 - h_2}{h_1 - h_{f_2}}$$

where $h_2 = h_{f_2} + x_2 h_{fg_2} = 317.7 + x_2 \times 2319.2$

Value of x_2 :

As the steam expands isentropically,

$$\therefore \quad s_1 = s_2$$

$$6.4406 = s_{f_2} + x_2 s_{fg_2} = 1.0261 + x_2 \times 6.6448$$

$$\therefore \quad x_2 = \frac{6.4406 - 1.0261}{6.6448} = 0.815$$

$$\therefore \quad h_2 = 317.7 + 0.815 \times 2319.2 = 2207.8 \text{ kJ/kg}$$

Hence, $\eta_{\text{Rankine}} = \dfrac{2789.9 - 2207.8}{2789.9 - 317.7} =$ **0.2354 or 23.54%. (Ans.)**

Example 12.3. *In a steam turbine steam at 20 bar, 360°C is expanded to 0.08 bar. It then enters a condenser, where it is condensed to saturated liquid water. The pump feeds back the water into the boiler. Assume ideal processes, find per kg of steam the net work and the cycle efficiency.*

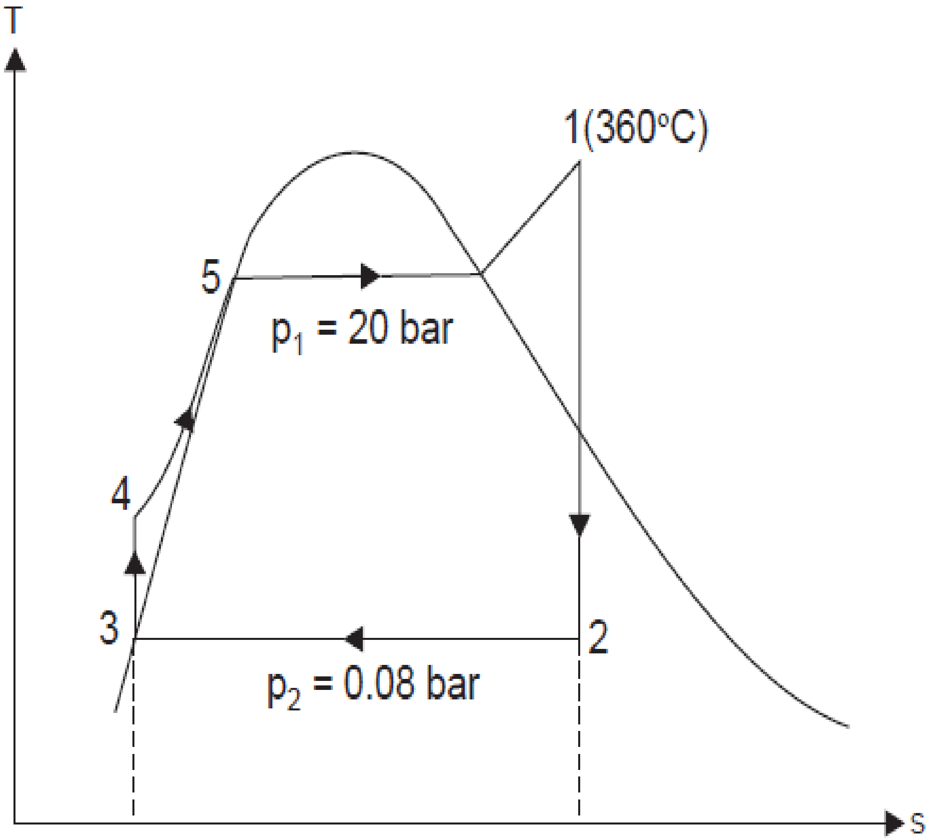

Fig. 12.7

Solution. Boiler pressure, $p_1 = 20$ bar (360°C)

Condenser pressure, $p_2 = 0.08$ bar

From steam tables :

At 20 bar (p_1), 360°C : $h_1 = 3159.3$ kJ/kg

$s_1 = 6.9917$ kJ/kg-K

At 0.08 bar (p_2) : $h_3 = h_{f(p_2)} = 173.88$ kJ/kg,

$s_3 = s_{f(p_2)} = 0.5926$ kJ/kg-K

$h_{fg(p_2)} = 2403.1$ kJ/kg, $s_{g(p_2)} = 8.2287$ kJ/kg-K

$v_{f(p_2)} = 0.001008$ m³/kg $\therefore$ $s_{fg(p_2)} = 7.6361$ kJ/kg-K

Now $s_1 = s_2$

$$6.9917 = s_{f(p_2)} + x_2\, s_{fg(p_2)} = 0.5926 + x_2 \times 7.6361$$

$$\therefore \quad x_2 = \frac{0.69917 - 0.5926}{7.6361} = 0.838$$

$$\therefore \quad h_2 = h_{f(p_2)} + x_2\, h_{fg(p_2)}$$

$$= 173.88 + 0.838 \times 2403.1 = 2187.68 \text{ kJ/kg.}$$

Net work, W_{net} :

$$W_{net} = W_{turbine} - W_{pump}$$

$$W_{pump} = h_{f_4} - h_{f(p_2)} \; (= h_{f_3}) = v_{f(p_2)} \; (p_1 - p_2)$$

$$= 0.00108 \; (m^3/kg) \times (20 - 0.08) \times 100 \text{ kN/m}^2$$

$$= 2.008 \text{ kJ/kg}$$

$$\left[\text{and} \quad h_{f_4} = 2.008 + h_{f(p_2)} = 2.008 + 173.88 = 175.89 \text{ kJ/kg}\right]$$

$$W_{turbine} = h_1 - h_2 = 3159.3 - 2187.68 = 971.62 \text{ kJ/kg}$$

$$\therefore \quad W_{net} = 971.62 - 2.008 = \mathbf{969.61 \text{ kJ/kg.}} \quad \textbf{(Ans.)}$$

Cycle efficiency, η_{cycle} :

$$Q_1 = h_1 - h_{f_4} = 3159.3 - 175.89 = 2983.41 \text{ kJ/kg}$$

$$\therefore \quad \eta_{cycle} = \frac{W_{net}}{Q_1} = \frac{969.61}{2983.41} = \mathbf{0.325 \text{ or } 32.5\%.} \quad \textbf{(Ans.)}$$

INDUSTRIAL APPLICATIONS

- Automobile industries.
- Refrigeration industries
- Air craft applications
- Defense industries
- Thermal power plants
- Chemical industries
- Textile industries etc.

SELF LEARNING QUESTIONS

1. With p-V and T-s diagrams derive the efficiency of otto cycle.
2. With p-V and T-s diagrams derive the efficiency of Diesel cycle.
3. With p-V and T-s diagrams derive the efficiency of dual combustion cycle.
4. Differentiate between Otto cycle, diesel cycle and dual combustion cycle.
5. With p-V and T-s diagrams derive the efficiency of Rankine cycle.

ASSIGNMENT EXERCISES

1. An engine working on Otto cycle has a volume of 0.45 m3, pressure 1 bar and temperature 30°C at the beginning of compression stroke. At the end of compression stroke, the pressure is 11 bar. 210 kJ of heat is added at constant volume. Determine:
   a. Pressures, temperatures and volumes at salient points in the cycle.
   b. Percentage clearance.
   c. Efficiency.
   d. Mean effective pressure.
2. In a Diesel cycle, air a 0.1 MPa and 300 K is compressed adiabatically until the pressure rises to 5 MPa. If 700 kJ/kg of energy in the form of heat is supplied at constant pressure, determine the compression ratio, cutoff ratio, thermal efficiency and mean effective pressure.
3. An air-standard Diesel cycle has a compression ratio of 20, and the heat transferred to the working fluid per cycle is 1800 kJ/kg. At the beginning of the compression process, the pressure is 0.1 MPa and the temperature is 15°C. Consider ideal gas and constant specific heat model. Determine the pressure and temperature at each point in the cycle, The thermal efficiency, The mean effective pressure.

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