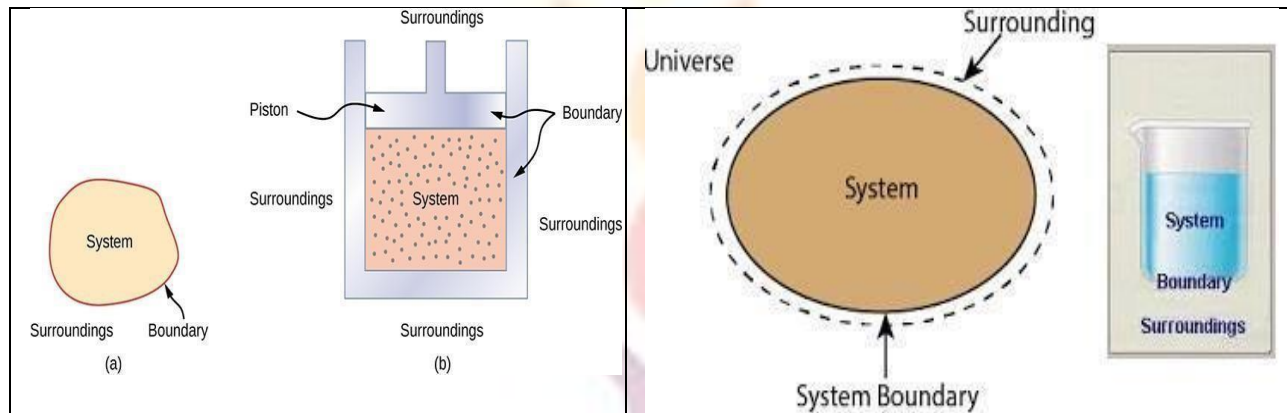


System: A thermodynamic system is defined as a quantity of matter or a region in space which is selected for the study.

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.



Types of thermodynamic system

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

1. Closed system 2. Open system 3. Isolated system

Closed system: A system in which the transfer of energy but not mass can take place across the boundary is called closed system. The mass inside the closed system remains constant.

For example: Boiling of water in a closed vessel. Since the water is boiled in a closed vessel, so the mass of water cannot escape out of the boundary of the system but heat energy continuously enters and leaves the boundary of the vessel. It is an example of a closed system.

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.

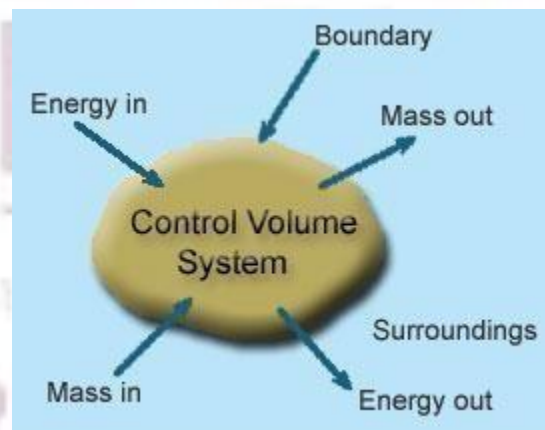
For example: Boiling of water in an open vessel is an example of an open system because the water and heat energy both enter and leave the boundary of the vessel.

Isolated system: A system in which the transfer of mass and energy cannot take place is called an isolated system.

For example: Tea present in a thermos flask. In this, the heat and the mass of the tea cannot cross the boundary of the thermos flask. Hence, the thermos flask is an isolated system.

Control Volume:

- Its a system of fixed volume.
- This type of system is usually referred to as "open system" or a "control volume"
- Mass transfer can take place across a control volume.
- Energy transfer may also occur into or out of the system.
- Control Surface- Its the boundary of a control volume across which the transfer of both mass and energy takes place.
- The mass of a control volume (open system) may or may not be fixed.
- When the net influx of mass across the control surface equals zero then the mass of the system is fixed and vice-versa.
- The identity of mass in a control volume always changes unlike the case for a control mass system (closed system).
- Most of the engineering devices, in general, represent an open system or control
- □ volume.



Example: **Heat exchanger** - Fluid enters and leaves the system continuously with the transfer of heat across the system boundary. **Pump** - A continuous flow of fluid takes place through the system with a transfer of mechanical energy from the surroundings to the system

Pump - A continuous flow of fluid takes place through the system with a transfer of mechanical energy from the surroundings to the system

Microscopic Approach:

- 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 and energies. The values of these energies are constantly changing with time. This approach to
- 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.
- Large numbers of variables are needed to describe a system. So the approach is complicated.

Macroscopic Approach:

- 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.
- 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.

| .No | Microscopic Approach | Macroscopic Approach |
|-----|---|---|
| 01 | In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level | The matter is considered to be comprised of a large number of tiny particles known as molecules, which moves randomly in chaotic fashion. The effect of molecular motion is considered. |
| 02 | Analysis is concerned with overall behavior of the system. | The Knowledge of the structure of matter is essential in analyzing the behavior of the system |
| 03 | This approach is used in the study of classical thermodynamics. | This approach is used in the study of statistical thermodynamics. |
| 04 | A few properties are required to describe the system. | Large numbers of variables are required to describe the system. |
| 05 | The properties like pressure, temperature, etc. needed to describe the system, can be easily measured. | The properties like velocity, momentum, kinetic energy, etc. needed to describe the system, cannot be measured easily. |
| 06 | The properties of the system are their average values. | The properties are defined for each molecule individually. |
| 07 | This approach requires simple | No. of molecules are very large so it requires |

your tools to success

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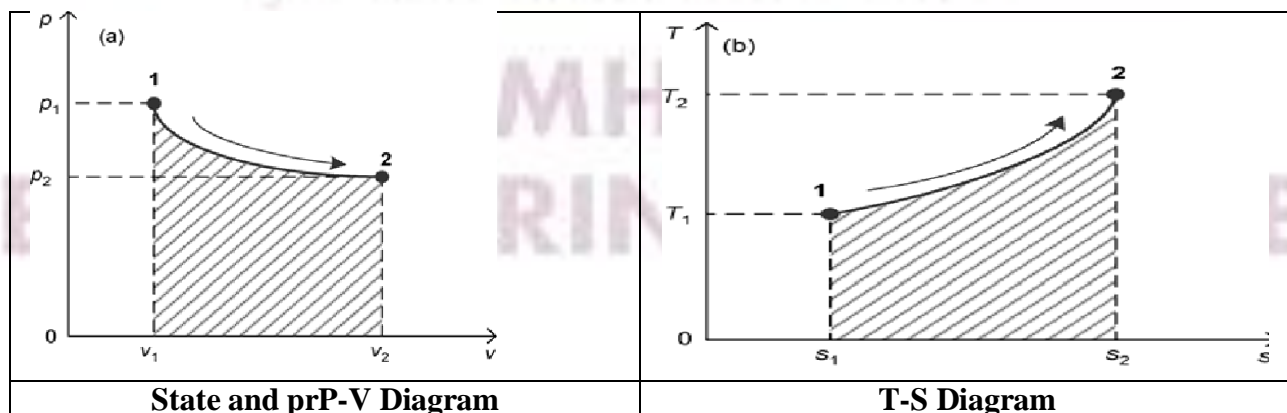
Thermodynamic Equilibrium:

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. Therefore, there can be no spontaneous change in any macroscopic property if the system exists in an equilibrium state. A thermodynamic system will be in a state of thermodynamic equilibrium if the system is the state of Mechanical equilibrium, Chemical equilibrium and Thermal 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: 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. More complex systems may require the specification of more unusual properties. As an example, the state of an electric battery requires the specification of the amount of electric charge it contains.

Property: Properties may be extensive or intensive.



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 mass of the system are called extensive properties. For example: Total mass, total volume and total momentum.

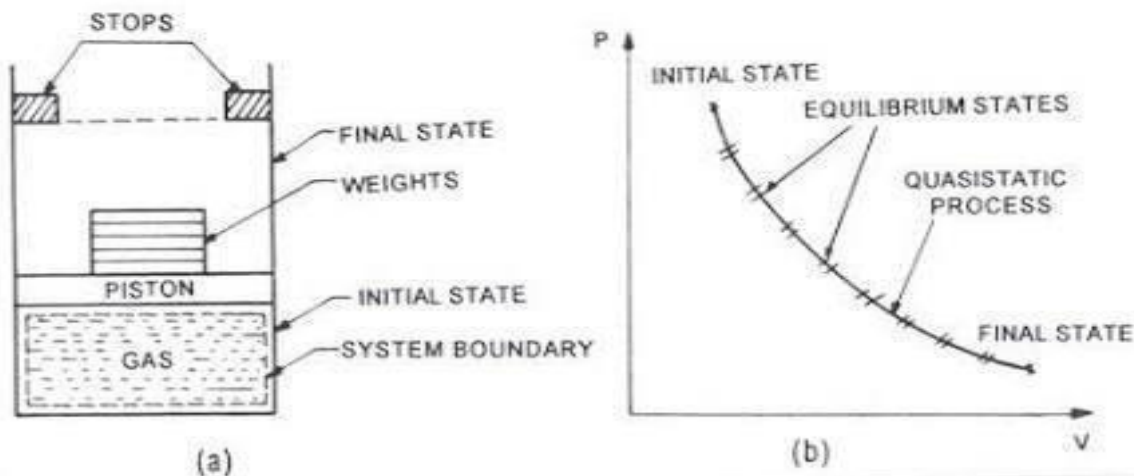
Process: When the system undergoes change from one thermodynamic state to final state due change in properties like temperature, pressure, volume etc, the system is said to have undergone thermodynamic process. Various types of thermodynamic processes are: isothermal process, adiabatic process, isochoric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

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. This cycle is important as it allows for the continuous process of a moving piston seen in heat engines and the expansion/compression of the working fluid in refrigerators, for example. Without the cyclical process, a car wouldn't be able to continuously move when fuel is added, or a refrigerator would not be able to stay cold.

Visually, any thermodynamic cycle will appear as a closed loop on a pressure volume diagram. Examples: Otto cycle, Diesel Cycle, Brayton Cycle etc.

Reversibility: Reversibility, in thermodynamics, a characteristic of certain processes (changes of a system from an initial state to a final state spontaneously or as a result of interactions with other systems) that can be reversed, and the system restored to its initial state, without leaving net effects in any of the systems involved. An example of a reversible process would be a single swing of a frictionless pendulum from one of its extreme positions to the other. The swing of a real pendulum is irreversible because a small amount of the mechanical energy of the pendulum would be expended in performing work against frictional forces, and restoration of the pendulum to its exact starting position would require the supply of an equivalent amount of energy from a second system, such as a compressed spring in which an irreversible change of state would occur.

Quasi static process: When a process is processing in such a way that system will be remained infinitesimally close with equilibrium state at each time, such process will be termed as quasi static process or quasi equilibrium process. 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



We will see one example for understanding the quasi static process, but let us consider one simple example for better understanding of quasi static process. If a person is coming down from roof to ground floor with the help of ladder steps then it could be considered as quasi static process. But if he jumps from roof to ground floor then it will not be a quasi static process. Weight placed over the piston is just balancing the force which is exerted in upward direction by gas. If we remove the weight from the piston, system will have unbalanced force and piston will move in upward direction due to force acting over the piston in upward direction by the gas.

Irreversible Process: The irreversible process is also called the natural process because all the processes occurring in nature are irreversible processes. The natural process occurs due to the finite gradient between the two states of the system. For instance, heat flow between two bodies occurs due to the temperature gradient between the two bodies; this is in fact the natural flow of heat. Similarly, water flows from high level to low level, current moves from high potential to low potential, etc.

- In the irreversible process the initial state of the system and surroundings cannot be restored from the final state.
- During the irreversible process the various states of the system on the path of change from initial state to final state are not in equilibrium with each other.
- During the irreversible process the entropy of the system increases decisively and it cannot be reduced back to its initial value.
- The phenomenon of a system undergoing irreversible process is called as irreversibility

Friction: Friction is invariably present in real systems. It causes irreversibility in the process as work done does not show an equivalent rise in the kinetic or potential energy of the system. The fraction of energy wasted due to frictional effects leads to deviation from reversible states.

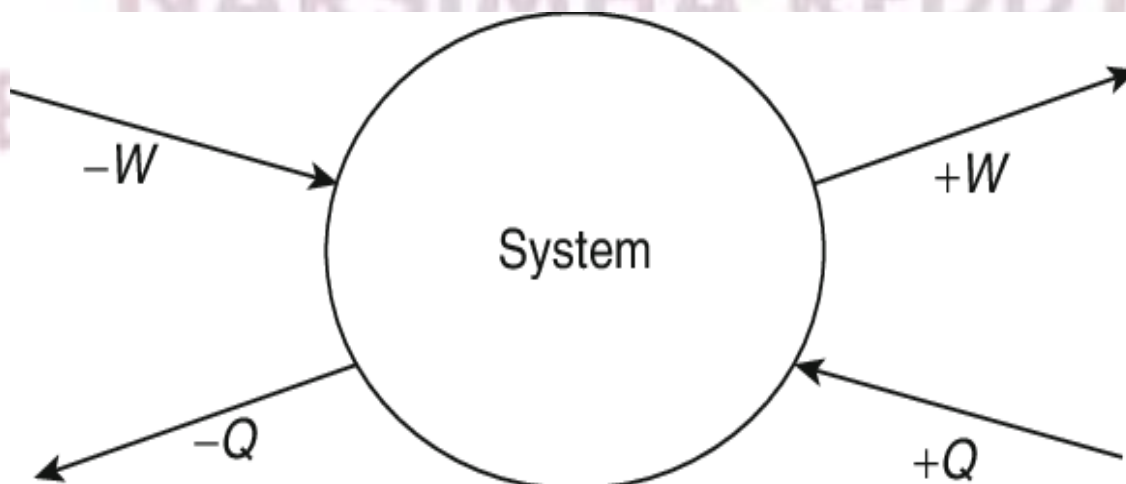
Free expansion: Free expansion refers to the expansion of an unresisted type such as expansion in a vacuum. During this unresisted expansion the work interaction is zero, and without the expense of any work, it is not possible to restore initial states. Thus, free expansion is irreversible.

Heat transfer through a finite temperature difference: Heat transfer occurs only when there exists a temperature difference between bodies undergoing heat transfer. During heat transfer, if heat addition is carried out in a finite number of steps then after every step the new state shall be a non-equilibrium state.

Non equilibrium during the process: Irreversibility's are introduced due to lack of thermodynamic equilibrium during the process. Non-equilibrium may be due to mechanical non-equilibrium, chemical non-equilibrium, thermal non-equilibrium, electrical non-equilibrium, etc. and irreversibility is called mechanical irreversibility, chemical irreversibility, thermal irreversibility, electrical irreversibility respectively. Factors discussed above are also causing non-equilibrium during the process and therefore make process irreversible.

Heat: It is the energy in transition between the system and the surroundings by virtue of the difference in temperature. Heat is energy transferred from one system to another solely by reason of a temperature difference between the systems. Heat exists only as it crosses the boundary of a system and the direction of heat transfer is from higher temperature to lower temperature. For thermodynamics sign convention, heat transferred to a system is positive; Heat transferred from a system is negative.

Work: Thermodynamic definition of work: Positive work is done by a system when the sole effect external to the system could be reduced to the rise of a weight. Work done BY the system is positive and work done ON the system is negative.



Types of work interaction:

- Expansion and compression work (displacement work)
- Work of a reversible chemical cell
- Work in stretching of a liquid surface
- Work done on elastic solids
- Work of polarization and magnetization

Point and Path functions:

- Point function does not depend on the history (or path) of the system. It only depends on the state of the system.
- Examples of point functions are: temperature, pressure, density, mass, volume, enthalpy, entropy, internal energy etc.
- Path function depends on history of the system (or path by which system arrived at a given state).
- Examples for path functions are work and heat.
- Path functions are not properties of the system, while point functions are properties of the system.
- Change in point function can be obtained by from the initial and final values of the function, whereas path has to define in order to evaluate path functions.

Zeroth Law of Thermodynamics:

The Thermodynamics Zeroth Law states that if two systems are at the same time in thermal equilibrium with a third system, they are in equilibrium with each other. If an object with a higher temperature comes in contact with an object of lower temperature, it will transfer heat to the lower temperature object. The objects will approach the same temperature and in the absence of loss to other objects, they will maintain a single constant temperature. Therefore, thermal equilibrium is attained.

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.

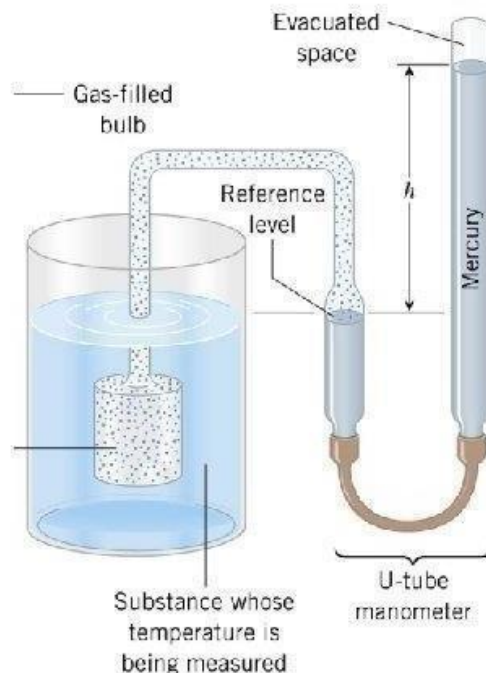
Principles of Thermometry:

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. 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:

When we heat a gas keeping the volume constant, its pressure increases and when we cool the gas its pressure decreases. The relationship between pressure and temperature at constant volume is given by the law of pressure. According to this law, the pressure of a gas changes by $\frac{1}{273}$ of its original pressure at 0°C for each degree centigrade (or Celsius) rise in temperature at constant volume. If P_0 is the pressure of a given volume of a gas at 0°C and P_t is the pressure of the same volume of the gas (i.e., at constant volume) at $t^\circ\text{C}$, then

Constant Volume Gas Thermometer



It consists of a glass bulb B connected to a tube A, through a capillary glass tube 'C'. The tube A is connected to a mercury reservoir R which is clamped on the board and can be lowered or raised whenever required to keep the volume of the air constant. The capillary tube C is provided with a three way stopper S and can be used to connect capillary and bulb as well as to disconnect tube from bulb B. A pointer is provided such that the end P is projecting inside from the upper part of A. A scale calibrated in 0°C is provided between A and R. The whole apparatus is leveled by adjusting the leveling screws. By adjusting the stopper, the bulb 'B' is filled with air or some gas and the pointer is adjusted so that tip of the pointer just touches the level of mercury in the tube A. After filling the bulb, it is kept in an ice bath for some time till the air inside the bulb attains the temperature of ice at which the mercury level becomes stationary. Now the reservoir R is adjusted so that the level of mercury in the tube A just touches the tip of the pointer P.

CONSTANT VOLUME GAS THERMOMETER

If P_0 is the pressure of a given volume of a gas at 0°C and P_t is the pressure of the same volume of the gas (i.e., at constant volume) at $t^{\circ}\text{C}$, then

$$P_t = P_0 + \frac{P_0}{273} \times t$$

$$P_t = P_0 + \left(1 + \frac{t}{273}\right) P_0$$

i.e., (or) $P_t = P_0 + (1 + \gamma_v t) P_0$ (1)

Where $\gamma_v = \frac{1}{273}$ is constant and is known as coefficient of increase of pressure

Scales of Temperature: There are three temperature scales in use 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: $F = \frac{9}{5}C + 32$.

PERPETUAL MOTION MACHINE OF THE FIRST KIND—PMM1

The first law states the general principle of the conservation of energy. *Energy is neither created nor destroyed, but only gets transformed from one form to another.* There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously (Fig. 4.8). Such a *fictitious machine* is called a *perpetual motion machine of the first kind*, or in brief, PMM1. *A PMM1 is thus impossible.*

The converse of the above statement is also true, i.e. there can be no machine which would continuously consume work without some other form of energy appearing simultaneously (Fig. 4.9).

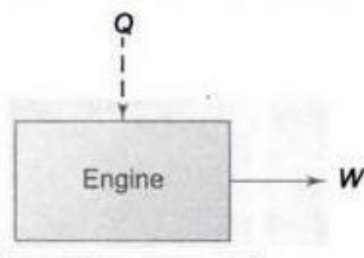


Fig. 4.8 A PMM1

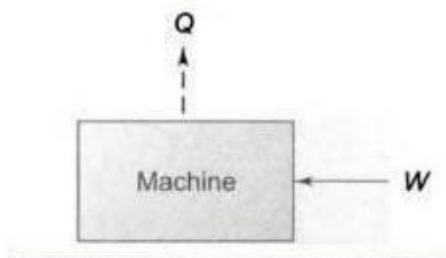


Fig. 4.9 The Converse of PMM1

Example 4.1 A stationary mass of gas is compressed without friction from an initial state of 0.3 m³ and 0.105 MPa to a final state of 0.15 m³ 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
$$Q_{1-2} = U_2 - U_1 + W_{1-2} \quad (1)$$

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)

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

∴
$$U_2 - U_1 = -21.85 \text{ kJ}$$

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

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?

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or
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$$\therefore U_2 - U_1 = -21.85 \text{ kJ}$$

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

Limitations of the First Law:

- 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.
- First law does not provide any information regarding the direction processes will take whether it is a spontaneous or a non-spontaneous process.

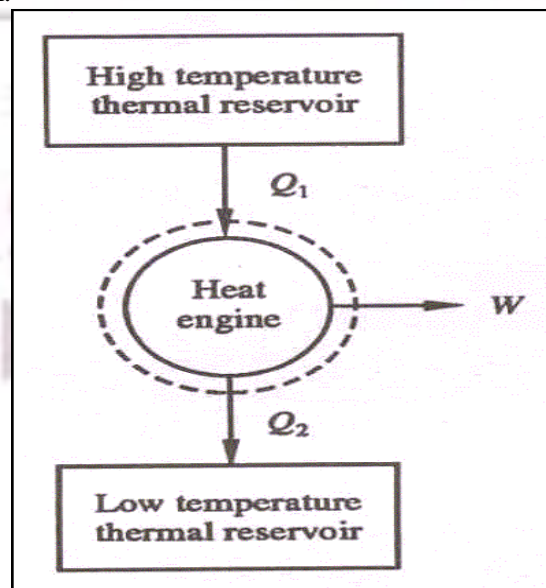
Thermal Reservoir:

A thermal reservoir is a large system (very high mass \times specific heat value) from which a quantity of energy can be absorbed or added as heat without changing its temperature. The atmosphere and sea are examples of thermal reservoirs. Any physical body whose thermal energy capacity is large relative to the amount of energy it supplies or absorbs can be modelled as a thermal reservoir. A reservoir that supplies energy in the form of heat is called a source and one that absorbs energy in the form of heat is called a sink.

Heat Engine:

It is a cyclically operating device which absorbs energy as heat from a high temperature reservoir, converts part of the energy into work and rejects the rest of the energy as heat to a thermal reservoir at low temperature.

The working fluid is a substance, which absorbs energy as heat from a source, and rejects energy as heat to a sink.



Heat pump:

A heat pump is a device that transfers heat energy from a source of heat to what is called a heat sink. Heat pumps move thermal energy in the opposite direction of spontaneous heat transfer, by

absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses a small amount of external power to accomplish the work of transferring energy from the heat source to the heat sink. The most common design of a heat pump involves four main components – a condenser, an evaporator and a compressor. The heat transfer medium circulated through these components is called refrigerant.

COP-

As can be seen, the better (more efficient) the refrigerator is when more heat Q_{cold} can be removed from the inside of the refrigerator for a given amount of work. Since the first law of thermodynamics must be valid also in this case ($Q_{\text{cold}} + W = Q_{\text{hot}}$), we can rewrite the above equation:

Perpetual motion machine of the second kind

The first law of thermodynamics does not stipulate any restriction on the thermal efficiency of a heat engine. However, the second law restricts the thermal efficiency of a heat engine to less than one. It stipulates that some portion of the energy absorbed as heat from a source must always be rejected to a low temperature sink. Wilhelm Ostwald introduced the concept of Perpetual Motion Machine of the Second Kind, that is, of a device which could perform work solely by absorbing energy as heat from a single thermal reservoir (see Fig. 7.4). Clearly, such a device does not violate the first law of thermodynamics because it would perform work at the expense of the internal energy of a body. A Perpetual Motion Machine of the Second Kind (PMMSK) is a hypothetical device which, working cyclically, receives energy as heat from a single thermal reservoir and delivers an equivalent amount of work.

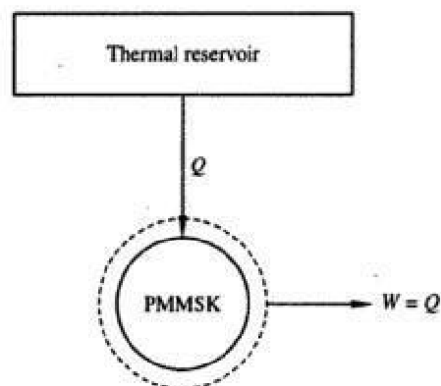


Fig. 7.4 Perpetual motion machine of the second kind

UNIT-III

Puresubstance

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 substances. A pure substance can also be a mixture of various chemical elements or compounds as long as the mixture is homogeneous. 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."

PVT Surface

Pressure can be expressed as a function of temperature and specific volume: $p=p(T,v)$. The plot of $p=p(T,v)$ is a surface called $p-v-T$ surface. Figure 3.1 shows the $p-v-T$ surface of a substance such as water that expands on freezing.

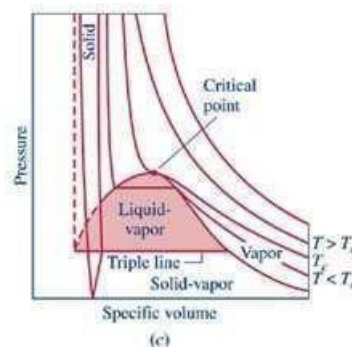
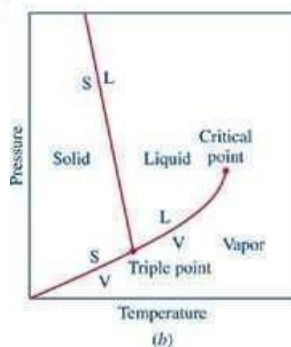
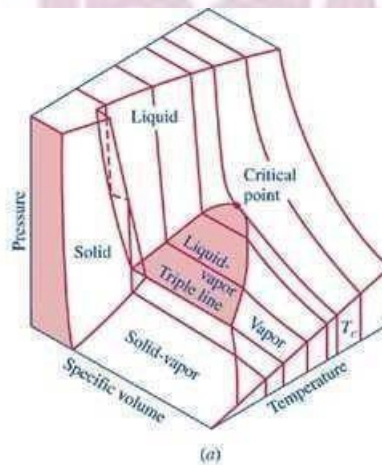


Figure 3.1 $p-v-T$ surface and projections for a substance that expands on freezing.

The location of a point on the $p-v-T$ surface gives the values of pressure, specific volume, and temperature at equilibrium. The regions on the $p-v-T$ surface labeled *solid*, *liquid*, and *vapor* are single-phase regions. The state of a single phase is determined by any two of the properties: pressure, temperature, and specific volume. The two-phase regions where two phases exist in equilibrium separate the single-phase regions. The two-phase regions are: liquid-vapor, solid-liquid, and solid-vapor. Temperature and pressure are dependent within the two-phase regions. Once the temperature is specified, the pressure is determined and vice versa. The states within the two-phase regions can be fixed by specific volume and either temperature or pressure.

The projection of the $p-v-T$ surface onto the $p-T$ plane is known as the phase diagram as shown in Figure 3.1 (b). The two-phase regions of the $p-v-T$ surface reduce to lines in the phase diagram. A point on any of these lines can represent any two-phase mixture at that particular temperature and pressure. The triple line of the $p-v-T$ surface projects onto a point on the phase diagram called the triple point. Three phases coexist on the triple line or the triple point.

The constant temperature lines of the $p-v$ diagram are called the isotherms. For any specified temperature less than the critical temperature, the pressure remains constant within the two-phase region even though specific volume changes. In the single-phase liquid and vapor regions the pressure decreases at fixed temperature as specific volume increases. For temperature greater than or equal to the critical temperature, there is no passage across the two-phase liquid-vapor region.

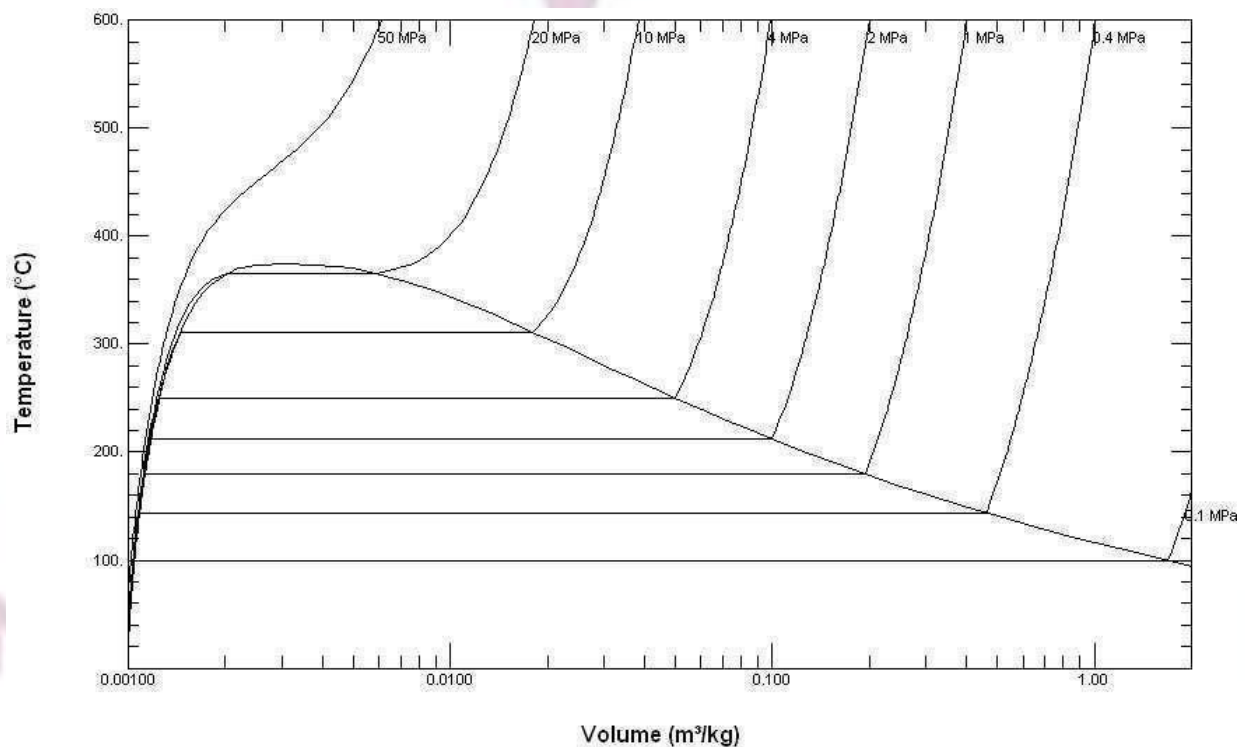


Figure 3.1-2 T-v diagram for water (to scale).

Figure 3.1-2 is a $T-v$ diagram for water. For pressure greater than or equal to the critical pressure, temperature increases continuously at fixed pressure as the specific volume increases and there is no passage across the two-phase liquid-vapor region. The isobaric curve marked 50 MPa in Figure 3.1-2 shows this behavior. For pressure less than the critical value, there is a two-phase region where the temperature remains constant at a fixed pressure as the two-phase region is traversed. The isobaric curve with values of 20 MPa or less in Figure 3.1-2 shows the constant temperature during the phase change.

At 100°C, the saturated volumes of liquid and vapor water are 1.0434 cm³/g and 1,673.6 cm³/g, respectively. The quality of steam is the mass fraction of water vapor in a mixture of liquid and vapor water. The specific volume of 100°C steam with a quality of 0.65 is given by

$$v = (1 - 0.65)v^L + 0.65v^V = (0.35)(1.0434) + (0.65)(1,673.6) = 1088.2 \text{ cm}^3/\text{g}$$

Phase Behavior:

We will consider a phase change of 1 kg of liquid water contained within a piston-cylinder assembly as shown in Figure 3.2-1a. The water is at 20°C and 1.014 bar (or 1 atm) as indicated by point (1) on Figure 3.2-2.

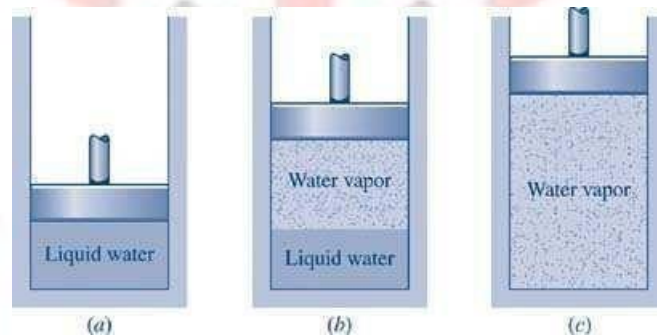


Figure 3.2-1 Phase change at constant pressure for water³

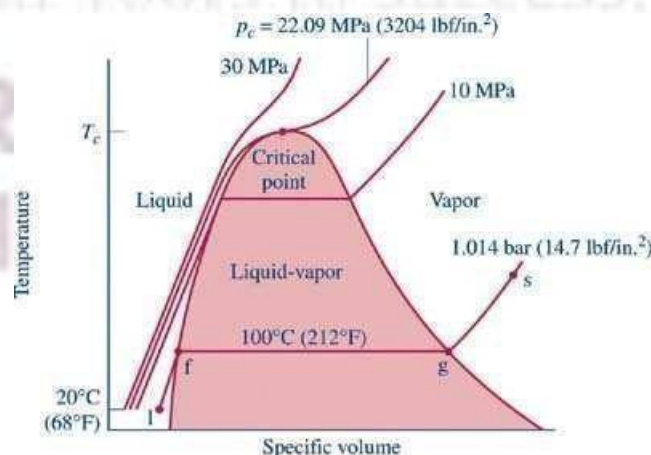


Figure 3.2-2 Sketch of $T-v$ diagram for water

1.014 bar is 100°C. The liquid states along the line segment 1-f are called *subcooled* or *compressed* liquid states. When the system is at the saturated liquid state (point f in Figure 3.2-2) any additional heat will cause the liquid to evaporate at constant pressure as shown in Figure 3.2-1b. When a mixture of liquid and vapor exists in equilibrium, the liquid phase is a saturated liquid and the vapor phase is a saturated vapor.

Liquid water continues to evaporate with additional heat until it becomes all saturated vapor at point (g). Any further heating will cause an increase in both temperature and specific volume and the saturated vapor becomes superheated vapor denoted by point (s) in Figure 3.2-2. For a two-phase liquid-vapor mixture, the quality x is defined as the mass fraction of vapor in the mixture

$$x = \frac{m_{\text{vapor}}}{m_{\text{vapor}} + m_{\text{liquid}}}$$

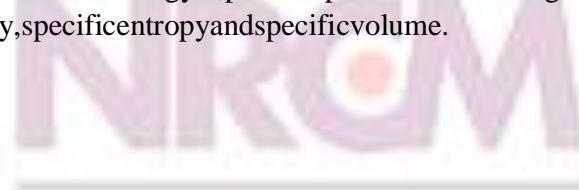
When a substance exists as part liquid and part vapor at saturation conditions, its quality (x) is defined as the ratio of the mass of the vapor to the total mass of both vapor and liquid.

Enthalpy-Entropy Chart An enthalpy-entropy chart, also known as the H-S

chart or Mollier diagram, plots the total heat against entropy, describing the enthalpy of a thermodynamic system. A typical chart covers a pressure range

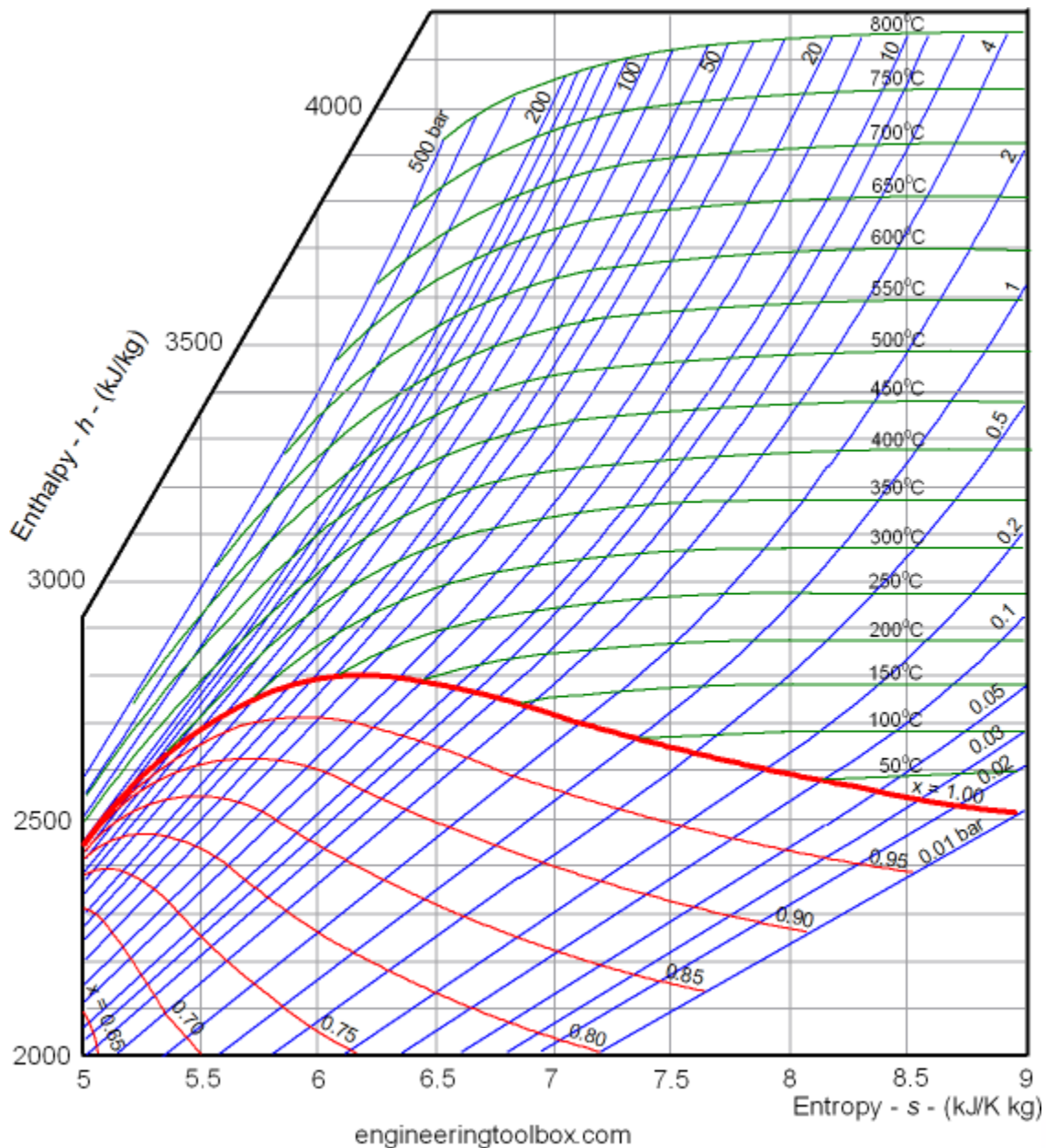
of 0.01–1000 bar, and temperatures up to 800 degrees Celsius.

It shows enthalpy H in terms of internal energy U , pressure p and volume V using the relationship $H = U + pV$ or, in terms of specific enthalpy, specific entropy and specific volume.



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On the diagram, lines of constant pressure, constant temperature and volume are plotted, so in a two-phase region, the lines of constant pressure and temperature coincide. Thus, coordinates on the diagram represent entropy and heat.

A vertical line in the $h-s$ chart represents an isentropic process. The process 3-4 in a Rankine cycle is isentropic when the steam turbine is said to be an ideal one. So the expansion process in a turbine can be easily calculated using the $h-s$ chart when the process is considered to be ideal (which is the case normally when calculating enthalpies, entropies, etc.). Later the deviations from the ideal values and they can be calculated considering the isentropic efficiency of the steam turbine used.

Lines of constant dryness fraction (x), sometimes called the quality, are drawn in the wet region and lines of constant temperature are drawn in the superheated region. x gives the

fraction (by mass) of gaseous substance in the wet region, the remainder being colloidal liquid droplets. Above the heavy line, the temperature is above the boiling point, and the dry (superheated) substance is gas only.

Characteristics of the critical point:

- For saturated phase often its enthalpy is an important property.
- Enthalpy-pressure charts are used for refrigeration cycle analysis.
- Enthalpy-entropy charts for water are used for steam cycle analysis.
- Note: Unlike pressure, volume and temperature which have specified numbers associated with it, in the case of internal energy, enthalpy (and entropy) only changes are required.

Consequently, a base (or datum) is defined - as you have seen in the case of water. Let V be total volume of liquid vapour mixture of quality x , V_f the volume of saturated liquid and V_g the volume of saturated vapour, the corresponding masses being m , m_f and m_g respectively.

$$\text{Now, } m = m_f + m_g$$

$$= V_f + V_g$$

$$m v = m_f v_f + m_g v_g$$

Saturation States

When a liquid and its vapour are in equilibrium at certain pressure and temperature, only the pressure or the temperature is sufficient to identify the saturation state.

If pressure is given, the temperature of the mixture gets fixed, which is known as saturation temperature, or if the temperature is given, the saturation pressure gets fixed.

Saturation liquid or saturated vapour has only one independent variable, i.e. only one property is required to know to fix up the state.

Type of Steam

Wet steam:

Wet steam is defined as steam which is partly vapour and partly liquid suspended in it. It means that evaporation of water is not complete.

Dry saturated steam:

When the wet steam is further heated, and it does not contain any suspended particles of water, it is known as dry saturated steam.

Superheated steam: When the dry steam is further heated at constant pressure, thus raising its temperature, it is called superheated steam.

Measurement of Steam Quality:

The state of a pure substance gets fixed if two independent properties are given. A pure substance is thus said to have two degrees of freedom. Of all thermodynamic properties, it

is easiest to measure the pressure and temperature of a substance. Therefore, whenever pressure and temperature are independent properties, it is the practice to measure them to determine that state of the substance.

Types of Calorimeters used for measurement of Steam Quality

- Barrel Calorimeter
- Separating Calorimeter
- Throttling Calorimeter
- Combined Separating and Throttling calorimeter

Barrel Calorimeter

Dryness fraction of steam can be found out very conveniently by barrel calorimeter as shown in figure. A vessel contains a measured quantity of water. Also water equivalent of the vessel is determined experimentally and stamped platform of weighing machine. Sample of steam is passed through the sampling tube into fine exit holes for discharge of steam into the cold water.

The steam gets condensed and the temperature of water rises. The weighing machine gives the steam condensed.

Heat Lost = Heat Gain

$$m\{xh_{fg} + (t_s - t_2)\} = C_p M(t_2 - t_1) - C_p\{M - m(t_2 - t_1) - (t_s - t_2)\}$$

$$X = \frac{C_p\{M - m(t_2 - t_1) - (t_s - t_2)\}}{h_{fg}}$$

From the law of conservation of energy,

Where, x = quantity of steam in the main

pipe h_{fg} = latent heat of vaporization at pressure

P

C_p = specific heat of water at constant pressure

m = mass of steam condensed

M = Equivalent mass of water at

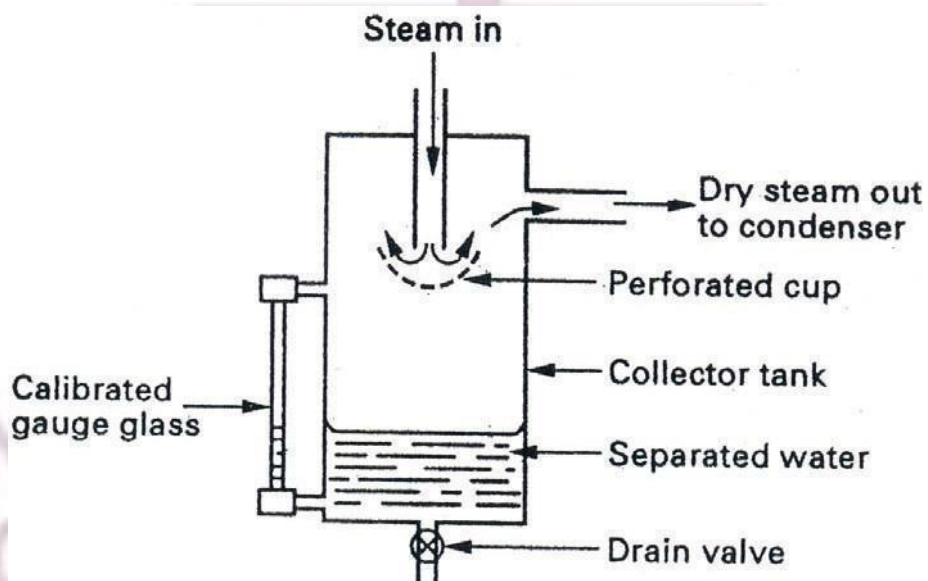
commencement t_s = Sat. temperature;

t_1 = temperature of Water at commencement

t_2 = final temperature after steam has condensed



Separating Calorimeter



The wet steam enters at the top from the main steam pipe through holes in the sampling pipe facing upstream 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 it strikes the perforated cup.

It leads to inaccuracy due to incomplete separation of water

Dryness fraction calculated is always greater than actual dryness fraction

C_p = specific heat of water at constant pressure

m = mass of steam condensed

M = Equivalent mass of water at

commencement T_s = Sat. temperature;

t_1 = temperature of Water at commencement

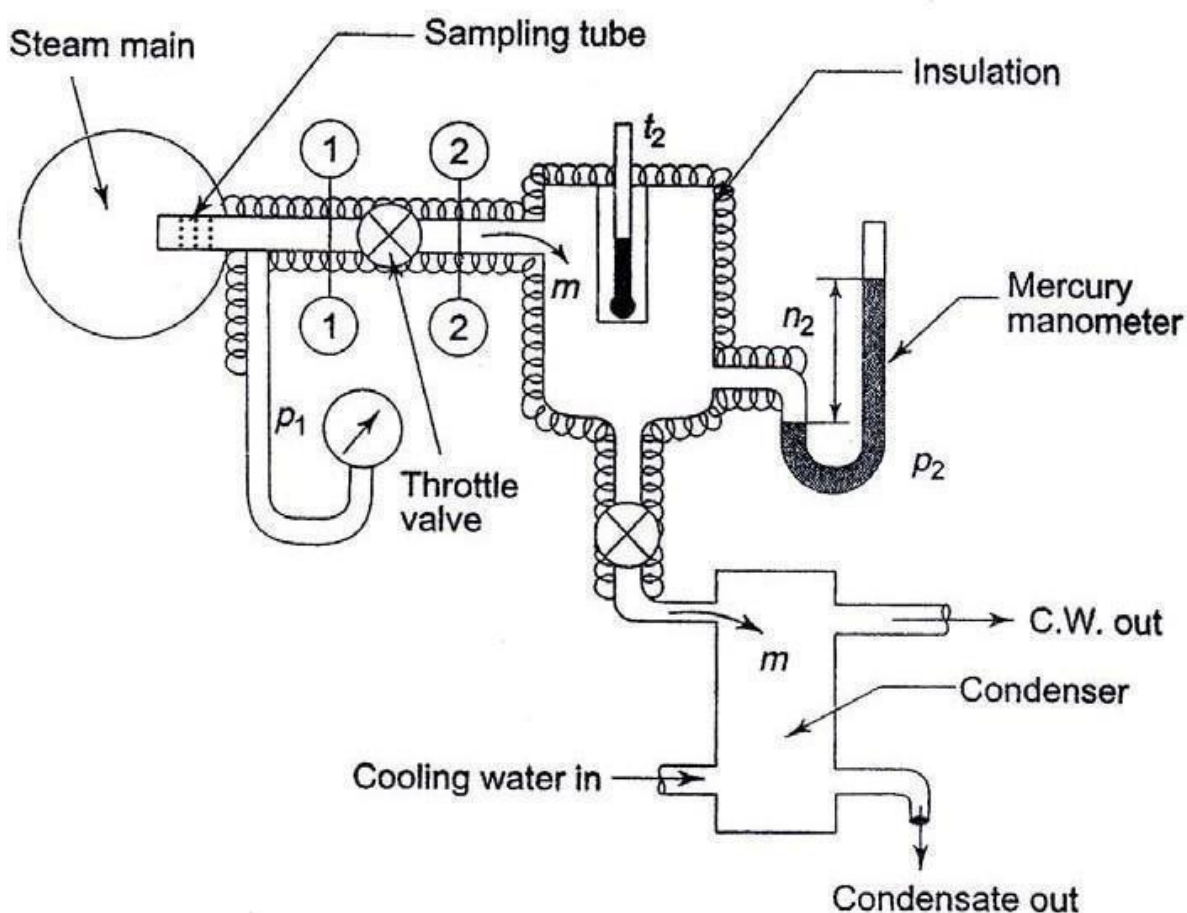
t_2 = final temperature after steam has condensed



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Throttling Calorimeter



In the throttling calorimeter, a sample of wet steam of mass m and at pressure P_1 is taken from the steam main through a perforated sampling tube. Then it is throttled by the partially-opened valve (orifice) to a pressure P_2 measured by mercury manometer, and temperature t_2 , so that after throttling the steam is in the superheated region.

The steady flow energy equation gives the enthalpy after throttling as equal to enthalpy before throttling. The initial and final equilibrium states 1 and 2 are joined by a dotted line since throttling is irreversible (adiabatic but not isentropic) and the intermediate states are non-equilibrium states not describable by thermodynamic coordinates. The initial state (wet) is given by P_1 and x_1 and the final state by P_2 and t_2 .

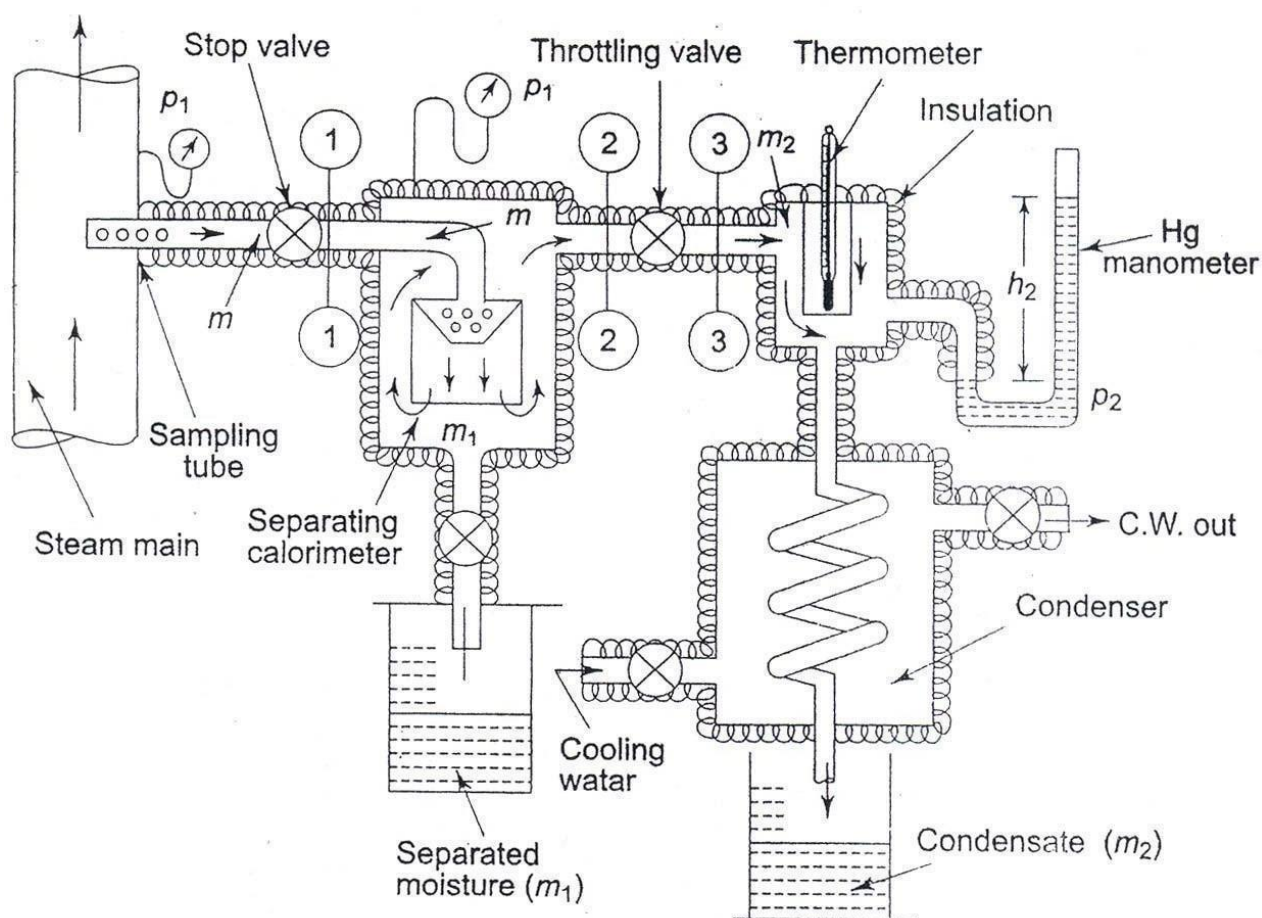
Advantages:

Dryness fraction of very dry steam can be found out easily.

Disadvantages:

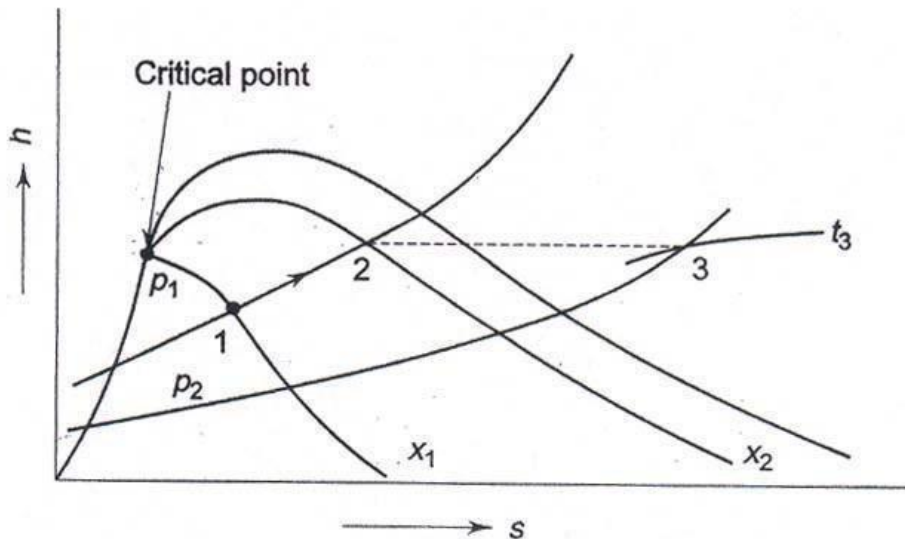
It is not possible to find dryness fraction of very wet steam.

Combined Separating and Throttling calorimeter



When the steam is very wet and the pressure after throttling is not low enough to take the steam to the superheated region, then a combined separating and throttling calorimeter is used for the measurement of quality.

Steam from the main is first passed through a separator where some part of the moisture separates out due to the sudden change in direction and falls by gravity, and the partially dry vapour is then throttled and taken to the superheated region.



Separating and throttling processes on h-s plot

In Fig. process 1-2 represents the moisture separation from the wet sample of steam at constant pressure P_1 and process 2-3 represents throttling to pressure P_2 . With P_2 and t_3 being measured, h_3 can be found out from the superheated steam table.

$$h_3 = h_2 = h_{f,p1} + x_2 h_{fg,p1}$$

Therefore x_2 , the quality of steam after partial moisture separation can be evaluated. If m kg of steam is taken through the sampling tube in t s, m_1 kg of it is separated, and m_2 kg is throttled and then condensed to water and collected, then $m = m_1 + m_2$ and at state 2, the mass of dry vapour will be $x_2 m_2$. Therefore, the quality of the

sample of steam at state 1, x_1 is given by..

$$x_1 = \frac{\text{mass of dry vapour state 1}}{\text{mass of liquid-vapour mixture at state 1}}$$

$$= \frac{m_2}{m_1 + m_2}$$

Mass of water (m_f) = 1.5

kg Mass of steam (m_g) = 50 kg

Required: Dryness fraction (x) Solution

$$\text{Dryness fraction } (x) = \frac{m_g}{m_g + m_f} = \frac{50}{50 + 1.5} = 0.971 \text{ --- Ans}$$

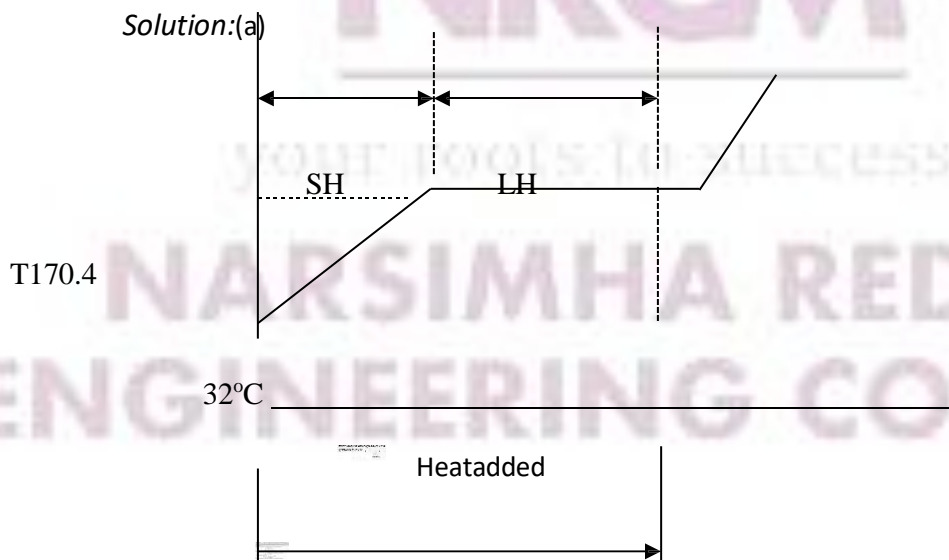
Eg. Steam is generated at 8 bar from water at 32°C. Determine the heat required to produce 1 kg of steam (a) when the dryness fraction is 0.85 (b) when steam is dry saturated and (c) when the steam is superheated to 305°C. The specific heat of superheated steam may be taken as 2.093 kJ/kg-K.

Given:

Steam pressure (p) = 8 bar

Initial temperature of water (T_1) = 32°C Mass of steam (m) = 1 kg

Required: Heat required when (a) $x = 0.85$ (b) $x = 1$ (c) $T_{sup} = 305^\circ\text{C}$



Heat required = Sensible heat addition + Latent heat addition

Sensible heat addition = $m C_{pw} (t_s - T_1)$

t_s = saturation temperature = 170.4°C at 8 bar

from steam table C_{pw} = Specific heat at

constant pressure = 4.186 kJ/kg (Taken)

$$\begin{aligned}\text{Sensible Heat addition} &= 1 \times 4.186 \times (170.4 - 32) \\ &= 79.34 \text{ kJ/kg}\end{aligned}$$

$$\text{Latent heat addition/kg} = x h_{fg}$$

Latent heat (h_{fg})

$$= 2046.5 \text{ kJ/kg from steam table at 8 bar Latent}$$

Latent heat addition for 'm' kg = $m \times h_{fg}$

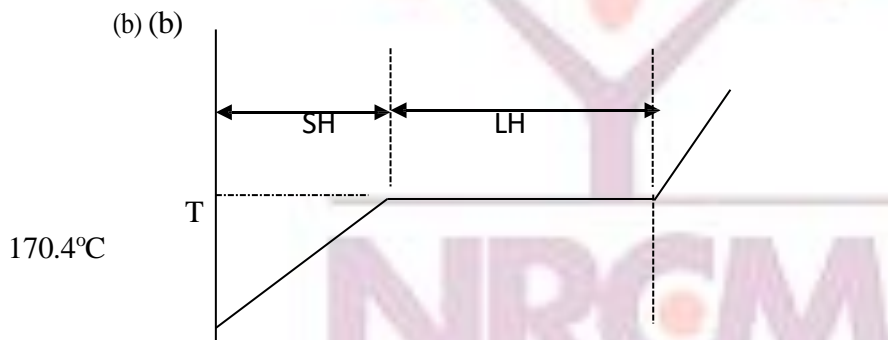
$$= 1 \times 0.85 \times (2046.5)$$

$$= 1739.525 \text{ kJ/kg}$$

Total heat required

$$= 79.34 + 1739.525$$

$$= 2318.865 \text{ kJ/kg --- Ans}$$



$$\begin{aligned} \text{Sensible Heat addition} &= 1 \times 4.186 \times (170.4 - 32) \\ &= 79.34 \text{ kJ/kg} \end{aligned}$$

$$\text{Latent heat addition/kg} = x h_{fg}$$

$$\text{Latent heat (} h_{fg} \text{)}$$

$$= 2046.5 \text{ kJ/kg from steam table at 8 bar Latent}$$

$$\text{Latent heat addition for 'm' kg} = m x h_{fg}$$

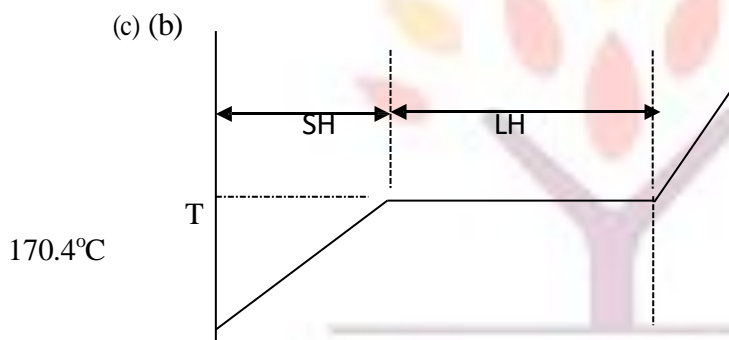
$$= 1 \times 0.85 \times (2046.5)$$

$$= 1739.525 \text{ kJ/kg}$$

$$\text{Total heat required}$$

$$= 79.34 + 1739.525$$

$$= 2318.865 \text{ kJ/kg --- Ans}$$



$$\text{Heat required} = \text{Sensible heat addition} + \text{Latent heat addition} + \text{Sensible heat addition to superheated steam}$$

$$\text{Latent heat (} h_{fg} \text{)} = 2046.5 \text{ kJ/kg from}$$

$$\text{steam table at 8 bar Latent heat addition for 'm' kg} = m x h_{fg}$$

$$= 1 \times 1 \times (2046.5)$$

$$= 2046.5 \text{ kJ/kg Total heat}$$

$$\text{required}$$

$$= 79.34 + 2046.5$$

$$= 2625.84 \text{ kJ/kg --- Ans}$$

$$\text{Heat required} = \text{Sensible heat addition} + \text{Latent heat addition} + \text{Sensible heat addition to superheated steam}$$

$$= m C_{pv} (T_{sup} - t_s)$$

$$= 1 \times 2.093 \times (305 - 170.4)$$

$$= 281.72 \text{ kJ/kg}$$

$$\text{Latent heat addition/kg} = h_{fg}$$

g

$$\begin{aligned} \text{Latent heat (} h_{fg} \text{)} &= 2046.5 \text{ kJ/kg from steam table at } 8 \text{ bar} \\ \text{Total heat required} &= 579.34 + 2046.5 + 281.72 \\ &= 2907.56 \text{ kJ/kg --- Ans} \end{aligned}$$

Ideal Gas:

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

Gas Laws:

Boyle's 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 .

Charles' Law:

Charles' Law Volume is directly proportional to temperature: $V = cT$, where $c > 0$ is constant. Scientist Jacques 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,

$$pV = mRT \quad \text{The Individual Gas Constant - } R$$

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 individual gas constant, R , for a gas can be calculated from the universal gas constant, R_u (given in several units below), and the gas molecular weight, M_{gas} :

$$R = R_u / M_{\text{gas}}$$

In the SI system units are J/kgK.

The Universal Gas Constant - R_u

The Universal Gas Constant - R_u - 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 - M_{gas} - for the gas, and is the same for all ideal or perfect gases:

$$R_u = M_{\text{gas}} R, \quad \text{kJ/(kmol.K)}$$

: 8.3144598 The Molecular weight of a Gas Mixture

ure

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:

$$M_{\text{mixture}} = \sum x_i \cdot M_i = (x_1 \cdot M_1 + \dots + x_n \cdot M_n)$$

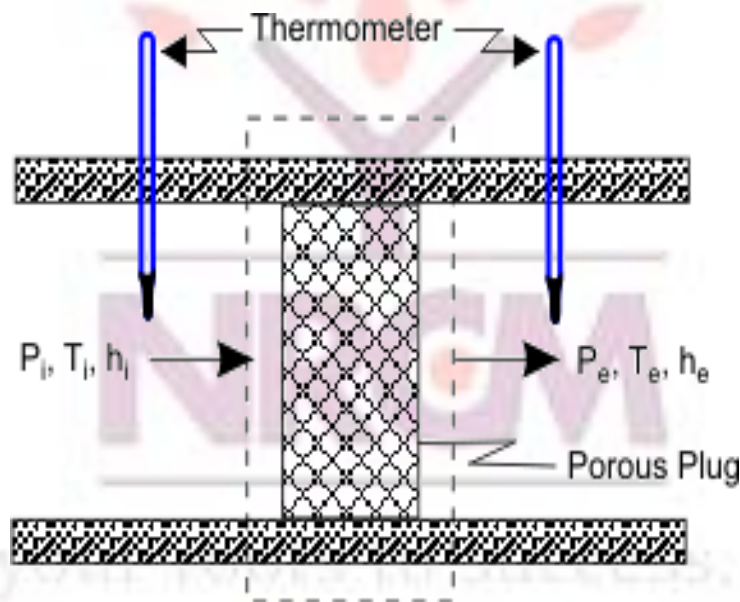
where

x_i = mole fractions of each

gas M_i = the molar mass of each

gas 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



As a gas 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 a control volume.

$$\dot{Q} = 0, \dot{W}_{sh} = 0.$$

These results in $h_i = h_e$

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 (or unresisted expansion) process. A free expansion occurs when a fluid is allowed to expand suddenly into a vacuum 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,

$$Q_{1-2}=0, W_{1-2}=0 \text{ and } dU=0.$$

vander 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 Johannes D. van der Waals in 1873 to take into account 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.

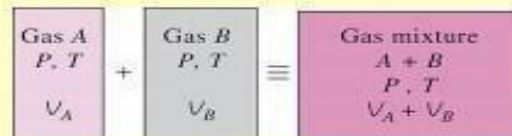
Since the constant b is an indication of molecular volume, it could be used to estimate the radius of an atom or molecule, modeled as a sphere. Fishbane et al. give the value of b for nitrogen gas as $39.4 \times 10^{-6} \text{ m}^3/\text{mol}$.

UNIT-IV

Problem 12-30

P-v-T BEHAVIOR OF GAS MIXTURES

A rigid tank contains 8 kmol of O₂ and 10 kmol of CO₂ gases at 290 K and 150 kPa. Estimate the volume of the tank.



$$V_m = \sum_{i=1}^k V_i(T_m, P_m)$$

$$V_m = \frac{N_m R_u T_m}{P_m} = \frac{(18 \text{ kmol})(8.314 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(290 \text{ K})}{150 \text{ kPa}} = 289.3 \text{ m}^3$$

Answer: 289 m³

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Problem 12-32

P-v-T BEHAVIOR OF GAS MIXTURES

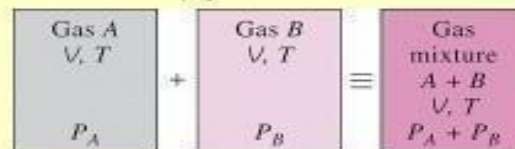
A rigid tank contains 0.5 kmol of Ar and 2 kmol of N₂ at 250 kPa and 280 K. The mixture is now heated to 400 K. Determine the volume of the tank and the final pressure of the mixture.

$$V_m = \frac{N_m R_u T_m}{P_m} = \frac{(2.5 \text{ kmol})(8.314 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(280 \text{ K})}{250 \text{ kPa}} = 23.3 \text{ m}^3$$



$$V_m = \sum_{i=1}^k V_i(T_m, P_m)$$

$$\frac{P_2 V_2}{T_2} = \frac{P_1 V_1}{T_1} \rightarrow P_2 = \frac{T_2}{T_1} P_1 = \frac{400 \text{ K}}{280 \text{ K}} (250 \text{ kPa}) = 357.1 \text{ kPa}$$



$$P_m = \sum_{i=1}^k P_i(T_m, V_m) \quad 14$$



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Example 0.3 m^3 of helium at 20 bar and 30°C is mixed with 0.7 m^3 of oxygen at 5 bar and 5°C by opening the valve between two tanks. Calculate the heat transfer, if the final temperature of the mixture is 25°C .

Solution.

Given: Volume of helium, $v_{\text{He}} = 0.3 \text{ m}^3$

Pressure of helium, $p_{\text{He}} = 20 \text{ bar} = 20 \times 10^2 \text{ kN/m}^2$

Temperature of helium, $T_{\text{He}} = 30^\circ\text{C} = 30 + 273 = 303 \text{ K}$

Volume of oxygen, $v_{\text{O}_2} = 0.7 \text{ m}^3$

Pressure of oxygen, $p_{\text{O}_2} = 5 \text{ bar} = 5 \times 10^2 \text{ kN/m}^2$

Temperature of oxygen, $T_{\text{O}_2} = 5^\circ\text{C} = 5 + 273 = 278 \text{ K}$

Temperature of the mixture,

$$T_{\text{mix}} = 25^\circ\text{C} = 25 + 273 = 298 \text{ K}$$

First of all, let us find the mass and specific heat at constant volume for helium (He) and oxygen (O_2).

We know that gas constant for helium,

$$R_{\text{He}} = \frac{R_u}{\text{Molecular mass of helium } (M_{\text{He}})} = \frac{8.314}{4}$$

$$= 2.0785 \text{ kJ/kg K}$$

and gas constant for oxygen, $R_{\text{O}_2} = \frac{R_u}{M_{\text{O}_2}} = \frac{8.314}{32} = 0.26 \text{ kJ/kg K}$

From the characteristic equation of gas, $p v = m R T$, we have

$$\text{Mass of helium, } m_{\text{He}} = \frac{p_{\text{He}} \cdot v_{\text{He}}}{R_{\text{He}} T_{\text{He}}} = \frac{20 \times 10^2 \times 0.3}{2.0785 \times 303} = 0.9527 \text{ kg}$$



Example . Find the increase in entropy when 2 kg of oxygen at 60°C are mixed with 6 kg of nitrogen at the same temperature. The initial pressure of each constituent is 103 kPa and is same as that of the mixture.

Solution.

Given: Mass of oxygen, $m_{O_2} = 2 \text{ kg}$

Temperature of oxygen, $T_{O_2} = 60^\circ\text{C} = 60 + 273 = 333 \text{ K}$

Mass of nitrogen, $m_{N_2} = 6 \text{ kg}$

Initial pressure of each constituent,

$$p_{O_2} = p_{N_2} = 103 \text{ kPa}$$

We know that number of moles of oxygen,

$$n_{O_2} = \frac{\text{Mass of oxygen } (m_{O_2})}{\text{Molecular mass of oxygen } (M_{O_2})} = \frac{2}{32} = 0.0625$$

and number of moles of nitrogen,

$$n_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{6}{28} = 0.2143$$

Total number of moles in the mixture,

$$n = n_{O_2} + n_{N_2} = 0.0625 + 0.2143 = 0.2768$$

We know that mole fraction of oxygen,

$$x_{O_2} = \frac{n_{O_2}}{n} = \frac{p_{O_2}}{p} = \frac{0.0625}{0.2768} = 0.2258$$

and mole fraction of nitrogen,

$$x_{N_2} = \frac{n_{N_2}}{n} = \frac{p_{N_2}}{p} = \frac{0.2143}{0.2768} = 0.7742$$

We know that increase in entropy,

$$\begin{aligned} ds &= -2.3 n_{O_2} R_u \log \left(\frac{p_{O_2}}{p} \right) - 2.3 n_{N_2} R_u \log \left(\frac{p_{N_2}}{p} \right) \\ &= -2.3 \times 0.0625 \times 8.314 \log (0.2258) - 2.3 \times 0.2143 \times 8.314 \log (0.7742) \\ &= 0.7724 + 0.4555 = 1.2279 \text{ kJ/kg Ans.} \end{aligned}$$

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THERMODYNAMICS (ME2105PC)

Example 11.9. A mixture of gases has the following volumetric composition:

$$CO_2 = 12\%; O_2 = 4\%; N_2 = 82\%; CO = 2\%$$

Calculate: 1. Gravimetric composition; 2. Molecular mass of the mixture; and 3. Gas constant for the mixture.

Solution.

Given: Volume of carbon dioxide (CO_2) in 1 m³ of the mixture = 12% = 0.12

Volume of oxygen (O_2) = 4% = 0.04

Volume of nitrogen (N_2) = 82% = 0.82

Volume of carbon monoxide (CO) = 2% = 0.02

1. Gravimetric composition

We have already discussed in Art. 11.4 that the volume fraction (z) is equal to the mole fraction (x).

We also know that mass of the constituent per mole of the mixture

$$= x \times M, \text{ where } M \text{ is the molecular mass of the constituent.}$$

Using these relations, the results may be tabulated as follows:

| Constituent | % by volume or % by mole (a) | Volume fraction or mole fraction (x) (b) | Molecular mass (M) (c) | Mass of the constituent per mole of the mixture $m = x \times M$ (d) | % Mass $\frac{(d)}{\Sigma(d)} \times 100$ |
|--------------|---|---|----------------------------------|---|--|
| CO_2 | 14 | 0.14 | 44 | 6.16 | $\frac{6.16}{30.44} \times 100 = 20.2$ |
| O_2 | 5 | 0.05 | 32 | 1.6 | $\frac{1.6}{30.44} \times 100 = 5.3$ |
| N_2 | 81 | 0.81 | 28 | 22.68 | $\frac{22.68}{30.44} \times 100 = 74.5$ |
| Total | 100 | 1.00 | | $\Sigma(d) = 30.44$ | 100 |

Partial pressure of the gases in the mixture

We know that volume fraction is equal to the mole fraction.

∴ Partial pressure of carbon dioxide,

$$p_{CO_2} = x_{CO_2} \times p = 0.14 \times 4 = 0.56 \text{ bar Ans.}$$

Partial pressure of oxygen,

$$p_{O_2} = x_{O_2} \times p = 0.05 \times 4 = 0.20 \text{ bar Ans.}$$

THERMODYNAMICS (ME2105PC)

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 air¹. Assuming both water vapour and dry air to be perfect gases², the humidity ratio is given by:

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

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:

$$W = 0.622 \frac{P_v}{P_t - P_v}$$

For a given barometric pressure p_t , given the DBT, we can find the saturated vapour pressure p_{sat} from the thermodynamic property tables on steam. Then using the above equation, we can find the humidity ratio at saturated conditions, W_{sat} .

It is to be noted that, W is a function of both total barometric pressure and vapor pressure of water.

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:

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

where ϕ is the relative humidity (in fraction). DBT & DPT are in °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

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UNIT-V

Gas Power CYCLES

For the purpose of thermodynamic analysis of the internal combustion engines, the following approximations are made:

- The engine is assumed to operate on a closed cycle with a fixed mass of air which does not undergo any chemical change.
- The combustion process is replaced by an equivalent energy addition process from an external source.
- The exhaust process is replaced by an equivalent energy rejection process to external surroundings by means of which the working fluid is restored to the initial state.
- The air is assumed to behave like an ideal gas with constant specific heat. These cycles are usually referred to as air standard cycle.

Otto Cycle

The Air Standard Otto cycle is named after its inventor **Nikolaus A. Otto**. Figures 5.1 (a), (b) and (c) illustrate the working principles of an Otto cycle. The Otto cycle consists of the following processes.

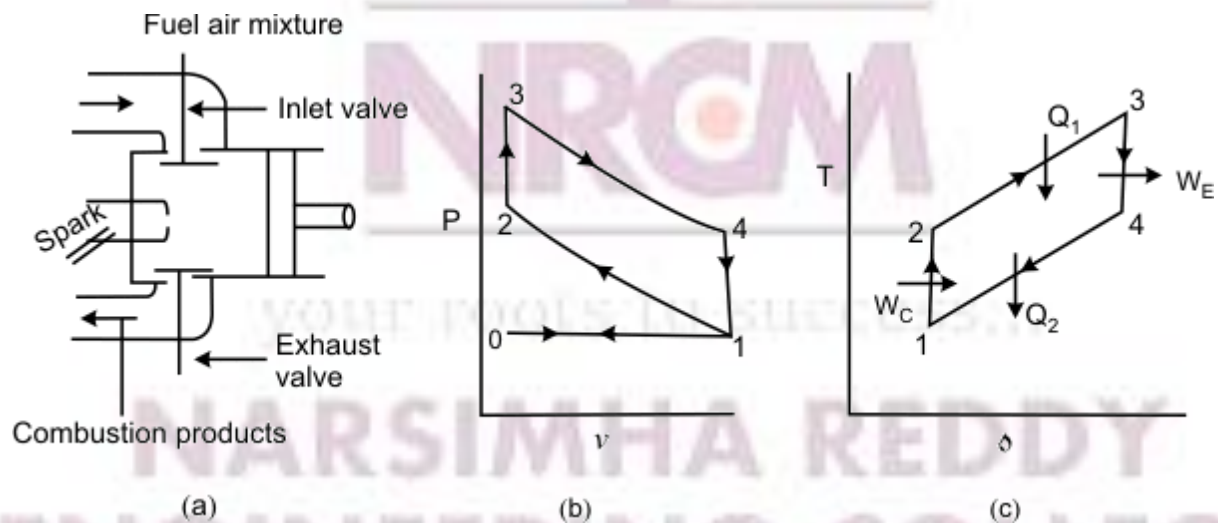


Figure 5.1

0-1: Constant pressure suction during which a mixture of fuel vapour and air is drawn into the cylinder as the piston executes an outward stroke.

1-2: The mixture is compressed isentropically due to the inward motion of the piston. Because of the **isentropic compression**, the temperature of the gas increases.

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2-3: The hot fuel vapour-air mixture is ignited by means of an electric spark. Since the combustion is instantaneous, there is not enough time for the piston to move outward. This process is approximated as a **constant volume energy addition process**.

3-4: The hot combustion products undergo **isentropic expansion** and the piston executes an outward motion.

4-

1: The exhaust port opens and the combustion products are exhausted into the atmosphere. The process is conveniently approximated as a **constant-volume energy rejection process**.

1-0: The remaining combustion products are exhausted by an inward motion of the piston at constant pressure.

Effectively there are four strokes in the cycle. These are suction, compression, expansion, and exhaust strokes, respectively. From the P-V diagram it can be observed that the work done during the process 0-1 is exactly balanced by the work done during 1-0. Hence for the purpose of thermodynamic analysis we need to consider only the cycle 1-2-3-4, which is air-standard Otto Cycle.

$$\eta_{\text{Otto Cycle}} = \frac{Q_1 - Q_2}{Q_1} \quad (5.1)$$

Where Q_1 and Q_2 denote the energy absorbed and energy rejected in the form of heat. Application of the first law of thermodynamics to process 2-3 and 4-1 gives:

$$Q_1 = U_3 - U_2 = m(u_3 - u_2) = mc_v(T_3 - T_2) \quad (5.2)$$

$$Q_2 = U_4 - U_1 = m(u_4 - u_1) = mc_v(T_4 - T_1) \quad (5.3)$$

Therefore,

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} \quad (5.4)$$

1-2 and 3-4 are isentropic processes for which

$$TV^{r-1} = \text{constant}$$

Therefore,

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and

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} \quad (5.6)$$

But

Hence $V_1 = V_4$ and $V_2 = V_3$ (5.7)

So, $\frac{T_3}{T_4} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$ (5.8)

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad \text{or} \quad \frac{T_3}{T_2} = \frac{T_4}{T_1} \quad (5.9)$$

or

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

and

$$\frac{T_3 - T_2}{T_2} = \frac{T_4 - T_1}{T_1} \quad \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2} \quad (5.11)$$

or

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{1}{r_0}\right)^{\gamma-1} \quad (5.12)$$

THERMODYNAMICS (ME2105PC)

1-7-4-

5:Dieselcycle 1-2-

3-45Dualcycle

Forthesame Q_2 ,thehigherthe Q_1 ,thehigheristhecycleefficiency

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

Forthesamemaximumpressureandtemperature(Figures5.6(a)and(b))

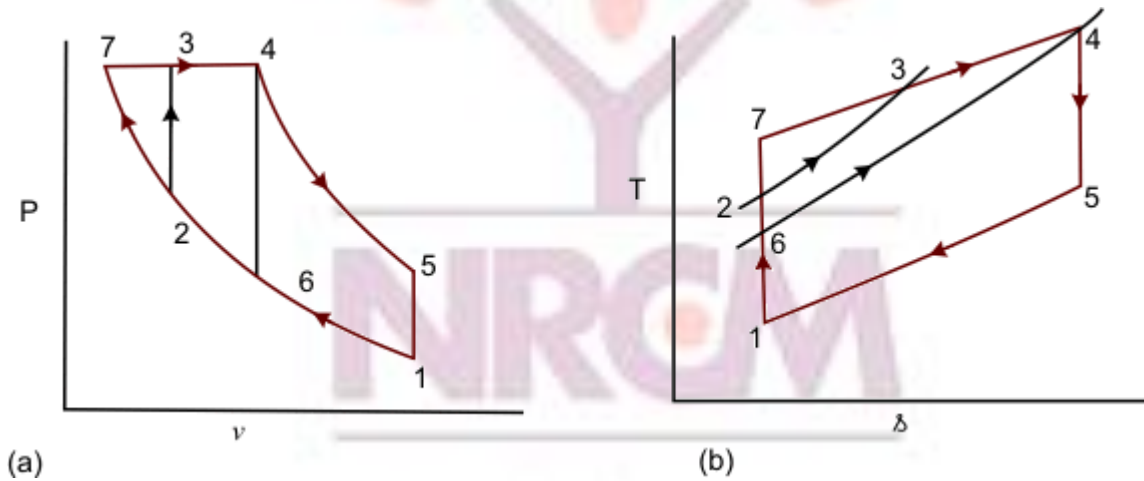


Figure 5.6(a) and (b)

1-6-4-5:Otto cycle

1-7-4-

5:Dieselcycle 1-2-

3-45 Dual

cycle Q_1 isrepresentedb

y:

Area under 6-4 → for Otto cycle
area under 7-4 for Diesel cycle



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and
 are under 2-3-4 → for Dual cycle and Q_2 is same for all the cycles

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

Where

$$r_0 = \frac{V_1}{V_2} = \text{Compression ratio} \quad (5.14)$$

Since $\gamma > 1$ the efficiency of the Otto cycle increases with increasing compression ratio. However, in an actual engine, the compression ratio cannot be increased indefinitely since higher compression ratios give high values of $\frac{T_2}{T_1}$ and this leads to **spontaneous** and **uncontrolled** combustion of the gasoline-air mixture in the cylinder. Such a condition is usually called knocking.

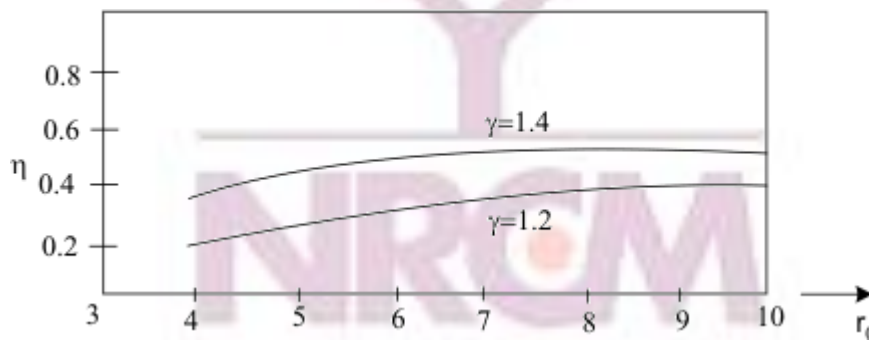


Figure 5.2

Performance of an engine is evaluated in terms of the efficiency (see Figure 5.2). However, sometime it is convenient to describe the performance in terms of mean effective pressure, an imaginary pressure obtained by equating the cycle work to the work evaluated by the following relation

$$W_{\text{net}} = P_{\text{me}} \int dV = P_{\text{me}} (V_1 - V_2) \quad (5.15)$$

The mean effective pressure is defined as the net work divided by the displacement volume. That is

THERMODYNAMICS (ME2105PC)

Where

$$r_0 = \frac{V_1}{V_2} = \text{Compression ratio} \quad (5.14)$$

Since $\eta \uparrow$ the efficiency of the Otto cycle increases with increasing compression ratio. However, in an actual engine, the compression ratio cannot be increased indefinitely since higher compression ratios give high values of T and this leads to **spontaneous** and **uncontrolled** combustion of the gasoline-air mixture in the cylinder. Such a condition is usually called knocking.

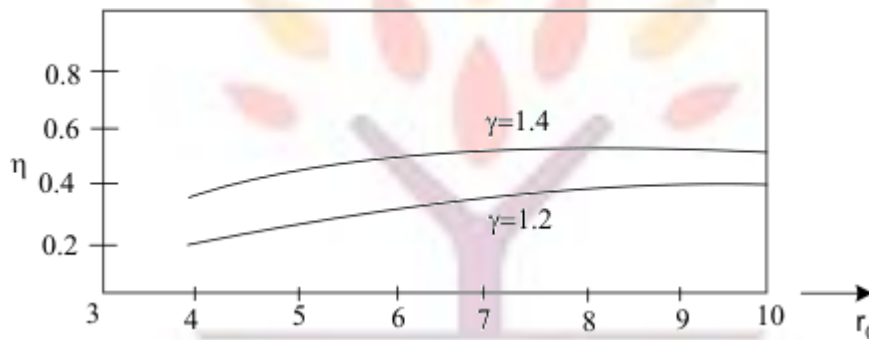


Figure 5.2

Performance of an engine is evaluated in terms of the efficiency (see Figure 5.2). However, sometime it is convenient to describe the performance in terms of mean effective pressure, an imaginary pressure obtained by equating the cycle work to the work evaluated by the following relation

$$W_{net} = P_m \int dV = P_m (V_1 - V_2) \quad (5.15)$$

The mean effective pressure is defined as the network divided by the displacement volume. That is

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$$P_m = \frac{W_{net}}{(V_1 - V_2)}$$

DIESEL CYCLE

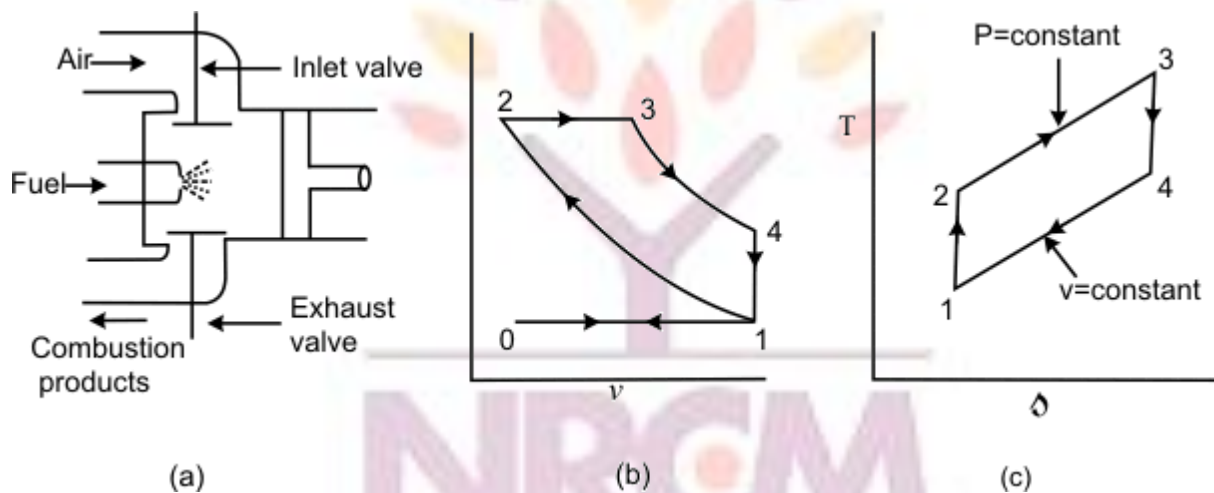


Figure 5.3(a), (b) and (c)

The Diesel cycle was developed by Rudolf Diesel in Germany. Figures 5.3(a), (b) and (c) explain the working principle of an Air Standard Diesel cycle. The following are the processes.

0-1: Constant pressure suction during which fresh air is drawn into the cylinder as the piston executes the outward motion.

1-2: The air is compressed isentropically. Usually the compression ratio in the **Diesel cycle is much higher than that of Otto cycle**. Because of the high compression ratio, the temperature of the gas at the end of isentropic compression is so high that when fuel is injected, it gets ignited immediately.

2-3: The fuel is injected into the hot compressed air at state 2 and the fuel undergoes a chemical reaction. The combustion of Diesel oil in air is not as spontaneous as the combustion of gasoline and the combustion is relatively slow. Hence the piston starts moving outward as combustion takes place. The combustion process is conveniently approximated as **a constant pressure energy addition process**.

3-4: The combustion products undergo isentropic expansion and the piston executes an outward motion.

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4-

1: The combustion products are exhausted at constant volume when the discharge port opens. This is replaced by a **constant-volume energy rejection process**.

1-0: The remaining combustion products are exhausted at constant pressure by the inward motion of the piston.

In the analysis of a Diesel cycle, two important parameters are: compression

ratio ($r_0 = V_1/V_2$) and the cut-off ratio (r_c). The cut-off ratio is defined as the ratio of the volume at the end of constant-pressure energy addition process to the volume at the beginning of the energy addition process.

$$r_c = \frac{V_3}{V_2} \quad (5.16)$$

$$\text{Energy added} = Q_1 = mc_p (T_3 - T_2) \quad (5.17)$$

$$\text{Energy rejected} = Q_2 = mc_v (T_4 - T_1) \quad (5.18)$$

$$\eta = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{T_4 - T_1}{\gamma(T_3 - T_2)} \quad (5.19)$$

or

$$\eta = 1 - \frac{\{(T_4/T_1) - 1\} T_1}{\{(T_3/T_2) - 1\} \gamma T_2} \quad (5.20)$$

1-2 is entropic:

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{1}{r_0}\right)^{\gamma-1}$$

4-1 is Constant volume:

$$\frac{T_4}{T_1} = \frac{P_4}{P_1} = \frac{P_4}{P_3} \times \frac{P_3}{P_1}$$

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But $P_2 = P_3$ Hence

$$\frac{T_4}{T_1} = \frac{P_4}{P_3} \times \frac{P_2}{P_1}$$

Since **1-2** and **3-4** are isentropic processes ($PV^\gamma = C$)

$$\frac{P_4}{P_3} = \left(\frac{V_3}{V_4}\right)^\gamma \quad \text{and} \quad \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^\gamma$$

Hence

$$\frac{T_4}{T_1} = \left(\frac{V_3}{V_4}\right)^\gamma \left(\frac{V_1}{V_2}\right)^\gamma = \left(\frac{V_3}{V_2}\right)^\gamma = (r_c)^\gamma$$

(5.21)

(5.22)

$$\eta = 1 - \frac{\{(r_c)^\gamma - 1\}}{\gamma(r_0)^{\gamma-1} \{r_c - 1\}}$$

(5.23)

Also to be noted $\frac{T_3}{T_2} = \frac{P_3 V_3}{P_2 V_2} = \frac{V_3}{V_2} = r_c$

The compression ratios normally in the Diesel engines vary between 14 and 1

7.

AIR STANDARD DUAL CYCLE

Figures 5.4 (a) and (b) shows the working principles of a Dual cycle. In the dual cycle, the energy addition is accomplished in two stages: Part of the energy is added at constant volume and part of the energy is added at constant pressure. The remaining processes are similar to those of the Otto cycle and the Diesel cycle. The efficiency of the cycle can be estimated in the following way

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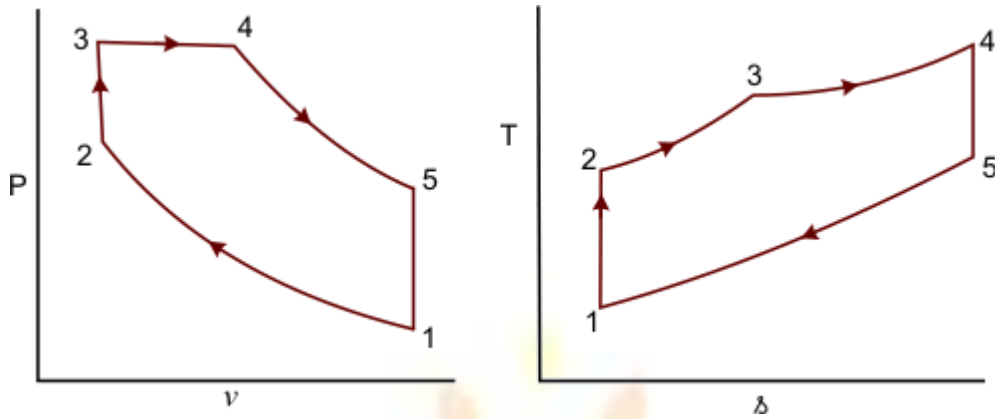


Figure 5.4.1(a) and (b)

Energy added

$$q_1 = c_v (T_3 - T_2) + c_p (T_4 - T_3) \quad (5.24)$$

Energy rejected

$$q_2 = c_v (T_5 - T_1) \quad (5.25)$$

$$\eta = 1 - \frac{c_v (T_5 - T_1)}{c_v (T_3 - T_2) + c_p (T_4 - T_3)} \quad (5.26)$$

or

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

The efficiency of the cycle can be expressed in terms of the following ratios

Compression ratio, $r_0 = \frac{r_1}{V_2} \quad (5.27)$

Cut-off ratio, $r_c = \frac{V_4}{V_3} \quad (5.28)$

THERMODYNAMICS (ME2105PC)

$$\text{Expansion ratio } r_e = \frac{V_5}{V_4} \quad (5.28)$$

$$\text{Constant volume pressure ratio, } r_{vp} = \frac{P_3}{P_2} \quad (5.29)$$

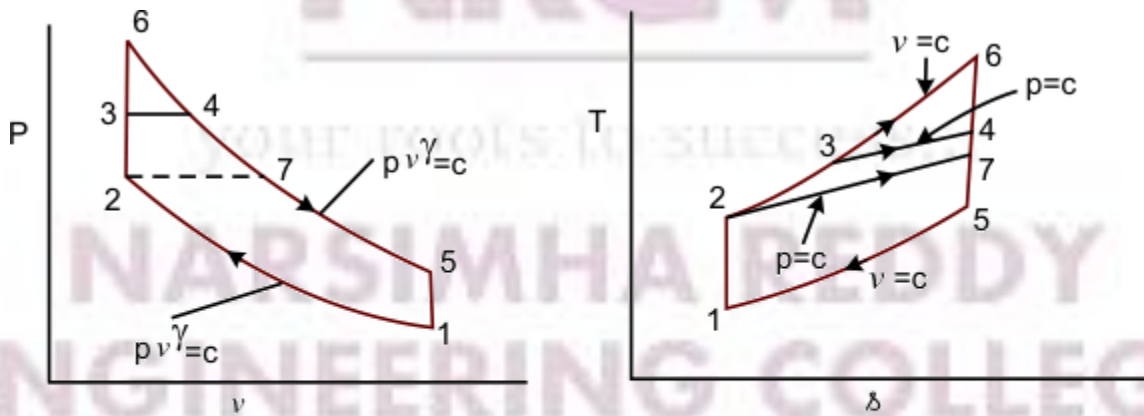
$$\eta_{Dual} = 1 - \frac{1}{(r_0)^{\gamma-1}} \frac{r_{vp} (r_c)^\gamma - 1}{(r_{vp} - 1) + \gamma r_{vp} (r_c - 1)} \quad (5.30)$$

If $r_c = 1$, $\eta_{Dual} \rightarrow \eta_{Otto}$

If $r_{vp} = 1$, $\eta_{Dual} \rightarrow \eta_{Diesel}$

Comparison of Otto, Diesel & Dual Cycles

For same compression ratio and heat rejection (Figures 5.5(a) and (b))



(a)

(b)

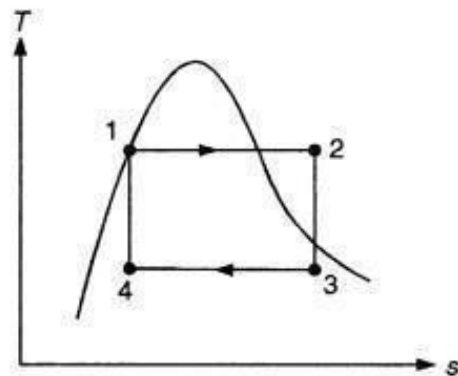
Figure 5.5(a) and (b)
1-2-3-4-5: Otto cycle

EXAMPLE 9.1

A steam power plant operates between a boiler pressure of 4 MPa and 300°C and a condenser pressure of 50 kPa. Determine the thermal efficiency of the cycle, the work ratio, and the specific steam flow rate, assuming (a) the cycle to be a Carnot cycle, and (b) a simple ideal Rankine cycle.

Solution

(a) The T - s diagram of a Carnot cycle is shown in the adjacent figure.



Process 1–2 is reversible and isothermal heating of water in the boiler.

Process 2–3 is isentropic expansion of steam at state 2 in the turbine.

Process 3–4 is reversible and isothermal condensation of steam in the condenser.

Process 4–1 is isentropic compression of steam to initial state.

At state 1: $P_1 = 4 \text{ MPa}$, $T_1 = 300^\circ\text{C}$

At state 2: $P_2 = 50 \text{ kPa}$, the steam is in a saturated state.

From the saturated water-pressure table (Table 4 of the Appendix), at 50 kPa, we get $T_2 = T_{\min} = T_{\text{sat}} = 81.33^\circ\text{C}$



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