

# **4024 THERMAL ENGINEERING**

## **MODULE I**

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# MODULE I

- **1.1.0 Understand the basics of Thermodynamics and thermodynamic processes**
- 1.1.1 Understand the scope and application of Thermal Engineering
- 1.1.2 Explain the terms such as Thermal Engineering, Thermo dynamics and Heat Engines
- **1.2.0 Appreciate the fundamentals of Thermodynamics**
- 1.2.1 Define a system
- 1.2.2 Classify the systems
- 1.2.3 Explain the terms boundary and surroundings
- 1.2.4 Distinguish between intrinsic and extrinsic properties
- 1.2.5 Explain the terms pressure, temperature, enthalpy, entropy etc and their S.I. Units
- 1.2.6 Explain the term thermodynamic equilibrium
- 1.2.7 Describe the Quasistatic process.
- 1.2.8 Explain the specific heat of gases

- 1.2.9 Explain the Zeroth law, First law and Second laws of thermodynamics
- 1.2.10 Explain Boyle's law, Charles's law, Regnault's law, Joule's law and Avogadro's law
- 1.2.11 Derive the characteristic gas equation
- 1.2.12 Explain characteristic gas constant and universal gas constant
- 1.2.13 State the relationship between specific heats of gases
- 1.2.14 Apply the gas equation to solve simple problems
- **1.3.0 Define a thermodynamic process**
- 1.3.1 Explain the importance of P-V diagram
- 1.3.2 Illustrate with p-V, T-S diagrams the thermodynamic processes such as Isochoric, Isobaric, Isothermal, Isentropic, Polytropic and throttling processes
- 1.3.3 Derive the expressions for the expansion work, change in internal energy, heat transferred and enthalpy change in each process listed in 1.3.2
- 1.3.4 Compute the expansion work, change in internal energy, Heat transferred and enthalpy change in each process

# **FUNDAMENTALS OF THERMODYNAMICS**

# INTRODUCTION

- Thermal engineering or heat engineering deals with the applications of heat energy.
- It is a comprehensive term covering fundamentals of thermodynamics, production of heat by the combustion of fuels and applied heat.

# THERMODYNAMICS

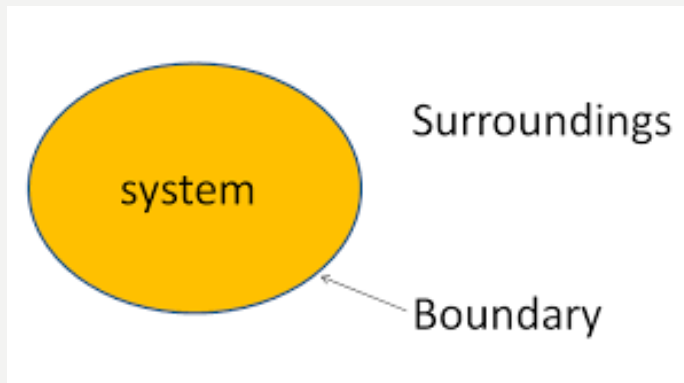
- The word thermodynamics is derived from the Greek words **therme** meaning **heat**, **dynamics** meaning **power**.
- Thermodynamics is the science that deals with **heat and work**.
- It is the science of **energy, entropy and equilibrium**.

# SCOPE OF THERMODYNAMICS

- Study of thermodynamics is important to engineers, since it finds applications in,
  - a) Almost all power producing and power absorbing devices.
  - b) Refrigeration system, air conditioning system and power plants.
  - c) Cooling of electronic components etc.

# SYSTEM

- A system is defined as **an enclosed space which has been selected for the purpose of analysis, observation and inference.**



- It can be any object, any quantity of matter, any region of space etc. selected for study.
- **The matter or region outside the system is termed as surroundings.**
- **The envelope of the system is called boundary of the system.**

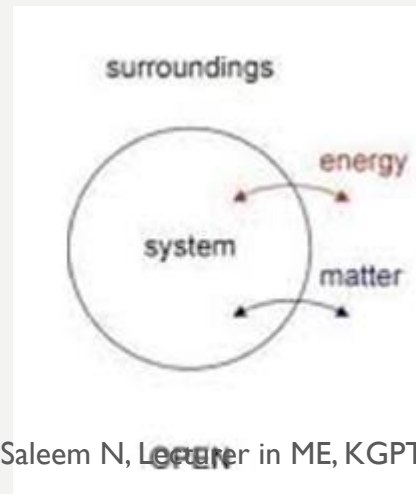


# TYPES OF SYSTEMS

- The thermodynamic systems are classified based on energy and mass interactions of the systems with surroundings.
- Open system.
- Closed system.
- Isolated system.

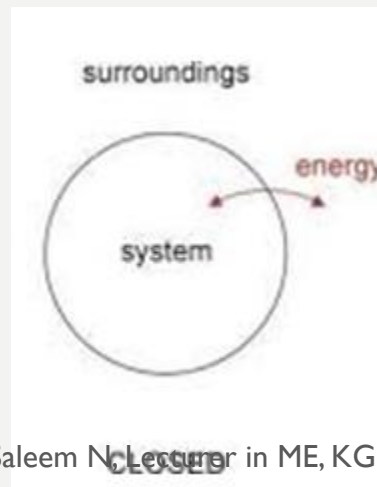
# OPEN SYSTEM

- Open system is a system in which there is mass transfer as well as energy transfer occurs across the boundary of a system.
- Eg:- Water flowing in a pipeline, steam turbines, pumps, a fountain pen while writing etc.



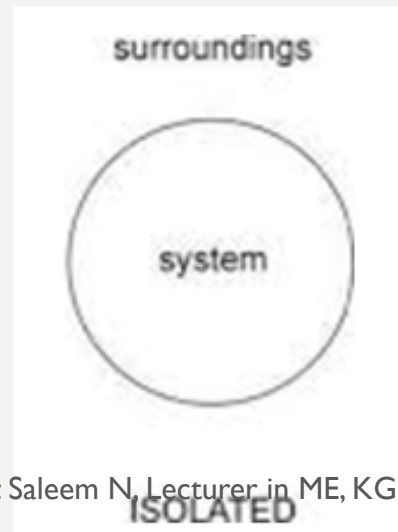
# CLOSED SYSTEM

- A system in which **there is no mass transfers but only energy transfers across the boundary of a system.**
- Eg:- Hot coffee in a cup, sun, human body etc.



# ISOLATED SYSTEM

- A system in which there is no mass transfer as well as energy transfer across the boundary of a system.
- Eg:- Coffee in a thermo flask, universe etc.



# STATE

- The condition of physical existence of a system at any instant is called its state.
- The state of a thermodynamic system is described by specifying its thermodynamic coordinates.
- Pressure, temperature, volume, density etc. are examples of thermodynamic coordinates.

# PROPERTY

- Property can be defined as any quantity that depends on the state of the system and is independent of how the system is arrived at that state.
- Eg:- Temperature, pressure, volume, density etc.
- If the properties are functions of state only, then it is called point function or state functions.

# TYPES OF PROPERTIES

- Classified into two.
  - 1) Intensive or intrinsic property
  - 2) Extensive or extrinsic property

# INTENSIVE OR INTRINSIC PROPERTY

- If the value of a property is independent of the mass of the system, it is called an intensive property.
- Eg:- temperature, pressure, velocity specific volume, density etc.



# EXTENSIVE OR EXTRINSIC PROPERTY

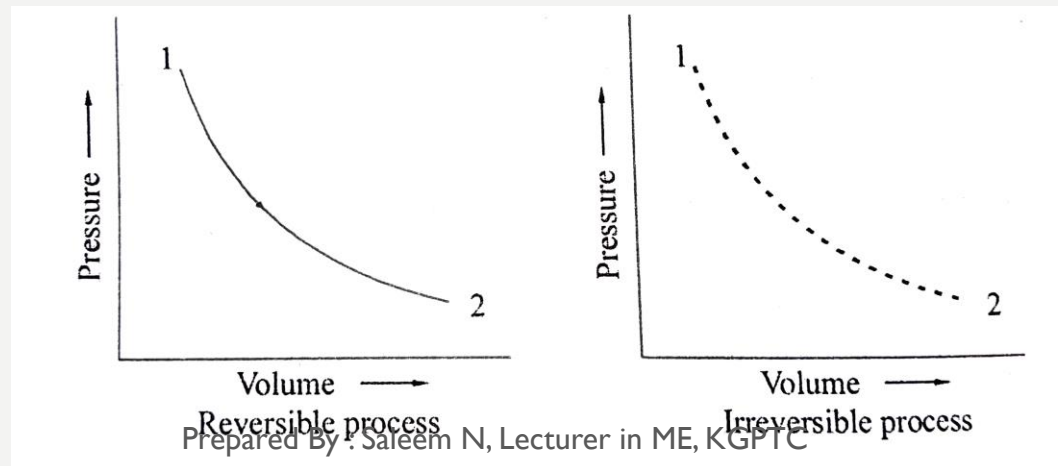
- If the value of a property is dependent of the mass of the system, it is called an extensive property.
- Eg:- Volume, energy, internal energy, enthalpy etc.

# PATH

- If a thermodynamic system passes through a series of states, then it is called path of a system.
- If the value of thermodynamic variable depends on the path followed in going from one state to another, then the variable is a path function.
- Eg:- Heat, work etc.

# PROCESS

- When a thermodynamic system changes from one state to another state it is said to have undergone a process.
- If the process can happen in either direction without any deviation, then the process is known as reversible process.
- If the process suffers a deviation or it can't be able to exactly replace its path, then that process is known as irreversible process.



# CYCLE

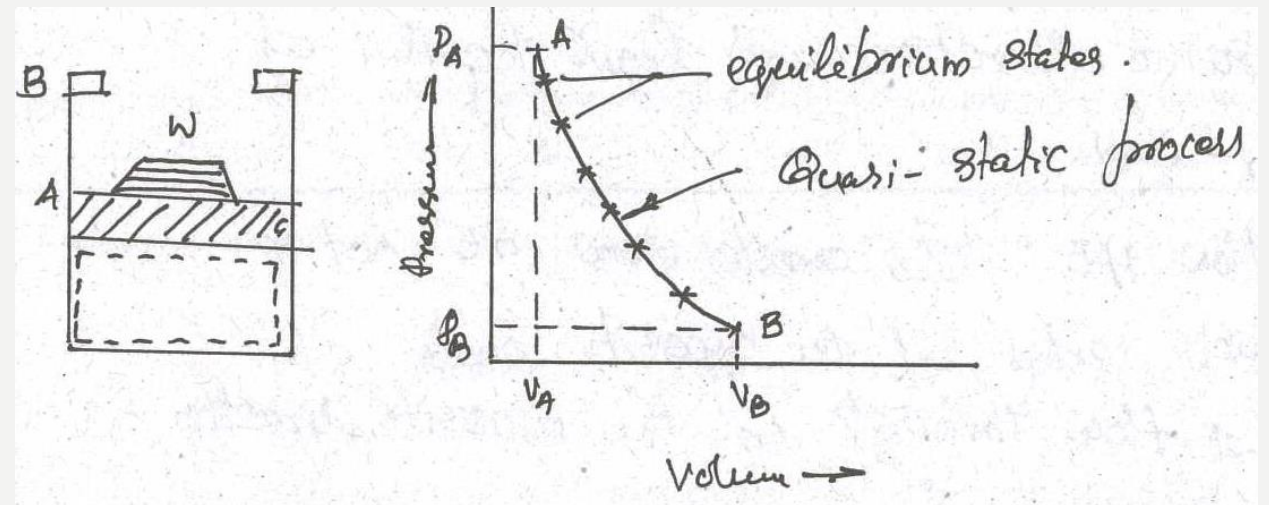
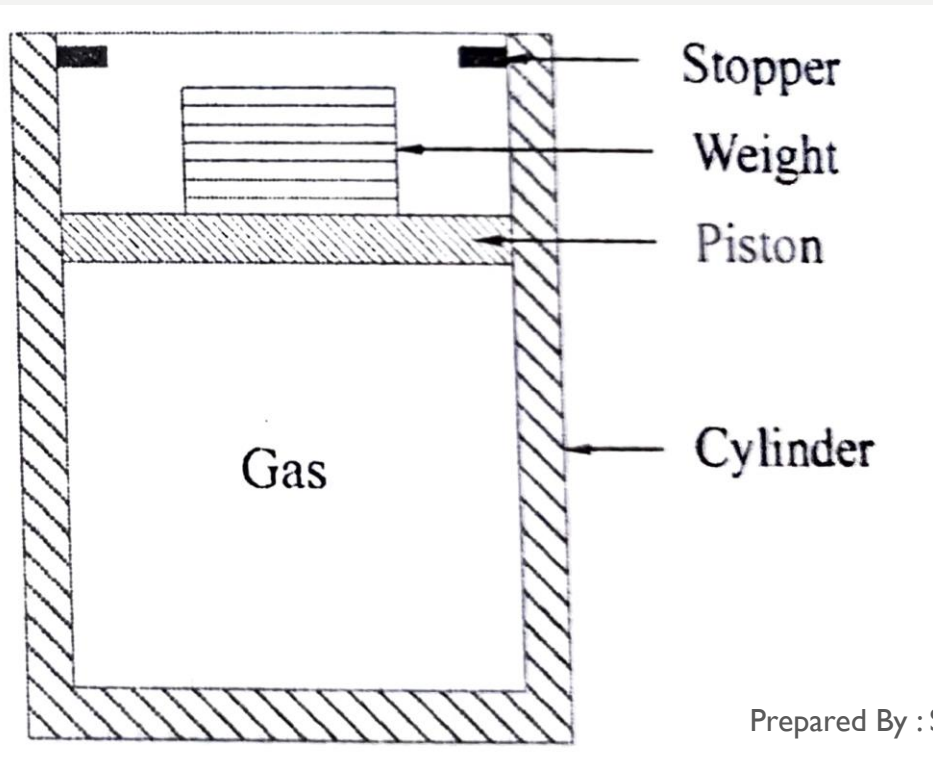
- When a thermodynamic system changes from one state to another state it is said to have undergone a process.
- At the end of the last process if the system returns to its original state it is said to have completed one thermodynamic cycle.
- For a cycle, cyclic integral  $\oint dx = 0$  (ie, net change in any property is zero.), where  $x$  = any property

# THERMODYNAMIC EQUILIBRIUM

- If a system is in **mechanical**, **chemical**, **thermal** equilibrium, then the system is said to be in **thermodynamic equilibrium**.
- If **there is no internal forces acting on the system**, then the system is said to be in **mechanical equilibrium**.
- If **there is no chemical reaction with in the system**, then the system is said to be in **chemical equilibrium**.
- If **there is no variation of temperature in the system**, then the system is said to be in **thermal equilibrium**.

# QUASI-STATIC PROCESS

- It is an ideal process in which the departure of the state of the system from the thermodynamic equilibrium state will be infinitesimally small.



- Consider the gas contained in a cylinder as a system.
- The system is in equilibrium state defined by the properties  $V_1$ ,  $T_1$ ,  $\rho_1$ .
- The upward force exerted by the gas is balanced by the small weights on the piston.
- When the weights on the piston is removed the piston moves upward and a change in state occurs.
- If the entire weights are removed suddenly, the piston will move upward rapidly until it hits the stoppers.

- After the piston stops, a new equilibrium state will be reached.
- The new equilibrium state will be defined by the properties  $V_2$ ,  $T_2$ ,  $\rho_2$ .
- The intermediate states passed through by the system are non-equilibrium states.
- If the weights are removed slowly one by one the departure of the state of the system from the thermodynamic equilibrium state will be infinitesimally small.
- Since every state will be passed through by the system will be in equilibrium state and the process can be considered as **quasi-static**.



# CONCEPT OF TEMPERATURE

- It is defined as the sense of hotness or coldness of a body when we touch the body.

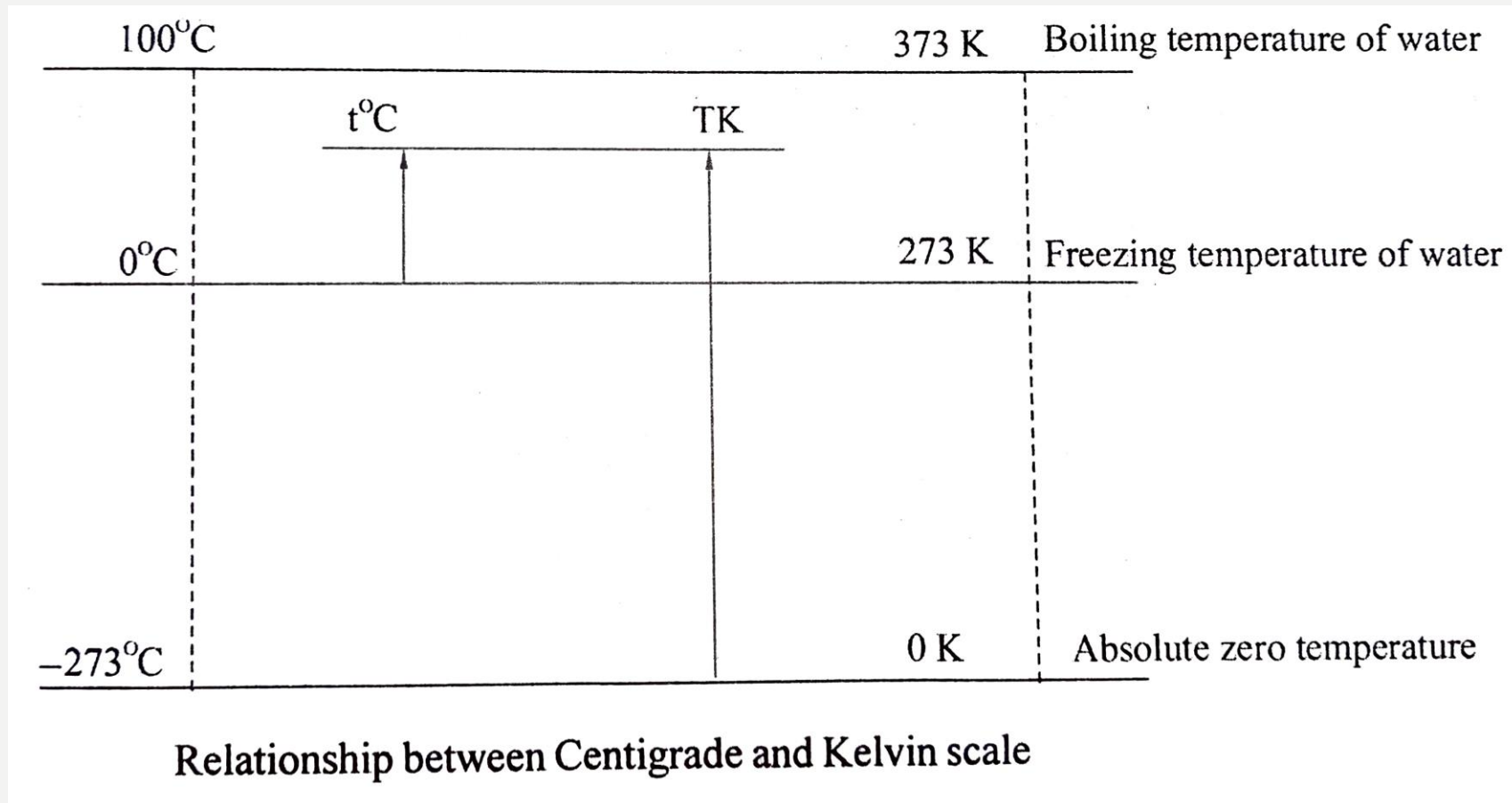
# TEMPERATURE SCALE

- Centigrade scale are commonly used for temperature measurement.
- In centigrade scale the freezing and boiling point of water at atmospheric pressure are taken as  $0^{\circ}\text{C}$ ,  $100^{\circ}\text{C}$  respectively.
- In Farhreh heat scale, freezing and boiling point of water at atmospheric pressure are taken as 32 and 212 respectively.
- The two scales are related by the formula,
- $\text{Temp } ^{\circ}\text{C} = \frac{5}{9} (\text{Temp } ^{\circ}\text{F} - 32)$  or
- $\text{Temp } ^{\circ}\text{F} = \frac{9}{5} (\text{Temp } ^{\circ}\text{C}) + 32$

# ABSOLUTE TEMPERATURE SCALE

- When the temperature of a gas increases with constant pressure its volume changes.
- For one degree change in temperature, the volume changes by  $(1/273)$  times its volume at  $0^{\circ}\text{C}$ .
- This means if a gas is cooled to  $-273^{\circ}\text{C}$  the volume of the gas would become zero.
- This temperature  $-273^{\circ}\text{C}$  is known as absolute zero temperature.
- The absolute temperature is the temperature measured above the absolute zero temperature.

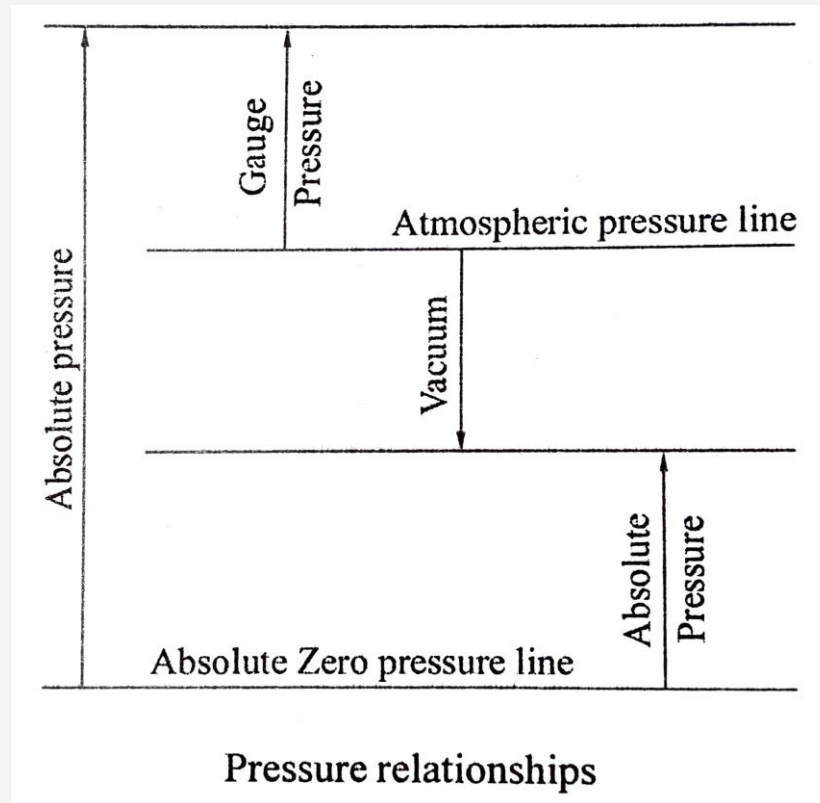
- Absolute temperature corresponding to  $t^{\circ}\text{C}$  is  $(t + 273)$ , denoted by **T K (Kelvin)**.



# PRESSURE

- Absolute pressure of a system is the external force exerted by the system on unit area of its boundaries.
- $P = \frac{\text{Force}}{\text{Area}} = \frac{F}{A}$
- SI unit is  $\text{N/m}^2$  or Pa
- Higher unit is bar,  $1\text{bar} = 10^5 \text{ N/m}^2$
- Atmospheric pressure at sea level is  $1.01325 \times 10^5 \text{ N/m}^2$  ( 1.01 bar) or 760 mm of Hg.

# PRESSURE RELATIONSHIPS



- In the case of positive pressure, **Absolute pressure**,  $P_{abs} = P_{atm} + P_g$
- In the case of negative pressure, **Absolute pressure**,  $P_{abs} = P_{atm} - P_v$
- $P_{atm}$  = Atmospheric pressure,  $P_g$  = Gauge pressure,  $P_v$  = Vacuum pressure

# STANDARD TEMPERATURE AND PRESSURE (STP)

- Standard temperature =  $15^{\circ}\text{C}$  (288 K)
- Standard pressure = 760 mm of Hg

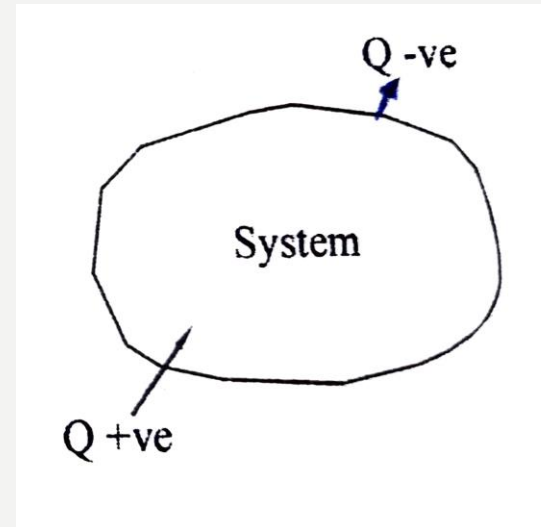
# NORMAL TEMPERATURE AND PRESSURE (NTP)

- Normal temperature =  $0^{\circ}\text{C}$  ( $273\text{ K}$ )
- Normal pressure =  $760\text{ mm of Hg}$



# HEAT (Q)

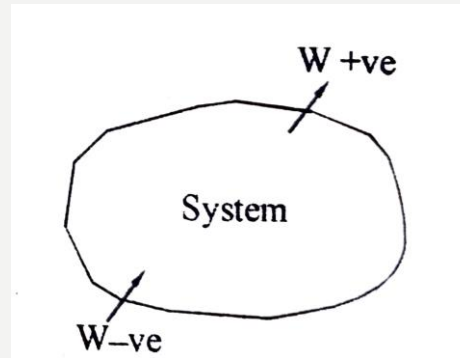
- The energy transfer across the boundary of a system due to the temperature difference between the system and the surroundings is called heat.



- Heat transferred to a system is positive and heat transferred from a system is negative.
- Unit of heat is Joule (J) or kJ

# WORK (W)

- In mechanics, Work,  $W = \text{Force} \times \text{Distance}$  moved in the direction of force.
- In thermodynamics, the energy transfer across the boundary of a system on account of reasons other than temperature difference is called work.



- Work done by the system is positive and work done on the system is negative.
- Unit of work is Nm or J
- Flow work,  ${}_1W_2 = \int_1^2 P dv$

# SPECIFIC HEAT

- Specific heat of a substance is defined as the amount of heat required to raise the temperature of unit mass of a substance by unit degree.

# SPECIFIC HEAT AT CONSTANT PRESSURE ( $C_p$ )

- The amount of heat required to raise the temperature of unit mass of a gas through unit degree, when it is heated at constant pressure is called specific heat at constant pressure.
- $C_p = \frac{Q}{m(T_2 - T_1)}$  J/kgK
- Where,  $Q$  = The amount of heat supplied to a gas at constant pressure in Joule.
- $m$  = Mass of the gas.
- $T_1$  and  $T_2$  = Initial and final temperature of gas in K.
- For air,  $C_p = 1.005$  kJ/kgK

# SPECIFIC HEAT AT CONSTANT VOLUME ( $C_v$ )

- The amount of heat required to raise the temperature of unit mass of a gas through unit degree, when it is heated at constant volume is called specific heat at constant volume.
- $C_v = \frac{Q}{m(T_2 - T_1)} \text{ J/kgK}$
- Where,  $Q$  = The amount of heat supplied to a gas at constant volume in Joule.
- $m$  = Mass of the gas.
- $T_1$  and  $T_2$  = Initial and final temperature of gas in K.
- For air,  $C_v = 0.718 \text{ kJ/kgK}$

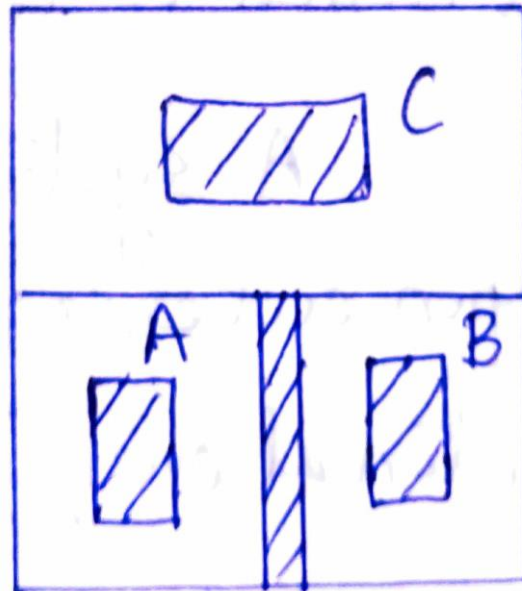
# RATIO OF SPECIFIC HEATS

- $\gamma = \frac{C_p}{C_v}$
- $C_p > C_v$ , since  $\gamma$  is always greater than one.
- For air,  $\gamma = 1.4$

# **LAWS OF THERMODYNAMICS**

# ZEROth LAW OF THERMODYNAMICS

- It states that if two systems are in thermal equilibrium with a 3<sup>rd</sup> system separately, then they are also in thermal equilibrium with each other.



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- Zeroth law of thermodynamics gives **the basis for measuring temperature.**
- Using this law the equality of temperature of two systems can be checked without actually bringing the two systems in contact.
- Let a reference system known as thermometer be brought in contact separately with two systems.
- If the thermometer shows the same reading in both the cases, then the two systems are said to be at the same temperature.

# FIRST LAW OF THERMODYNAMICS

- First law of thermodynamics states that “ for a system operating in a cycle, the net heat transfer is equal to the net work transfer”.
- Or it gives the law of conservation of energy.
- ie,  $\oint dQ = \oint dW$
- $\oint (dQ - dW) = 0$

# ENERGY (E)

- Energy is a property and is equal to the difference between heat supplied and the workdone during any process and is denoted by E.
- ie, Change in energy during any process 1-2,
- $E_2 - E_1 = \Delta E = {}_1Q_2 - {}_1W_2$

# INTERNAL ENERGY (U)

- Internal energy of a substance may be defined as the algebraic sum of internal kinetic energy and internal potential energy of its molecules.
- Total energy,
- $E = PE + KE + U + \text{Electricity} + \text{Magnetism}$
- $E = PE + KE + U$  (Electricity and magnetism are Neglected)
- $\Delta E = \Delta PE + \Delta KE + \Delta U$

- For a stationary closed system,  $\Delta KE$  and  $\Delta PE = 0$
- $\Delta E = \Delta U = {}_1Q_2 - {}_1W_2$
- ${}_1Q_2 = {}_1W_2 + \Delta U$
- ie, when a heat is supplied to a closed system a portion of it is converted into work and remaining portion is used to increase the internal energy of the system.

# ENTHALPY (H)

- Enthalpy is a measure of the total energy of a thermodynamic system.
- It is the sum of internal energy and pressure volume product (flow work).
- $H = U + PV$
- $\Delta H = mC_p (T_2 - T_1)$
- Unit of enthalpy is kJ

# **LIMITATIONS OF FIRST LAW**

- The first law doesn't place any restriction on the direction of work and heat transfer.
- The whole of the heat energy transferred cannot be converted into work energy and a part of heat transferred therefore must be rejected to the surroundings.
- Though mechanical work can fully be converted into heat energy, only a part of heat energy can be converted into mechanical work.

# SECOND LAW OF THERMODYNAMICS

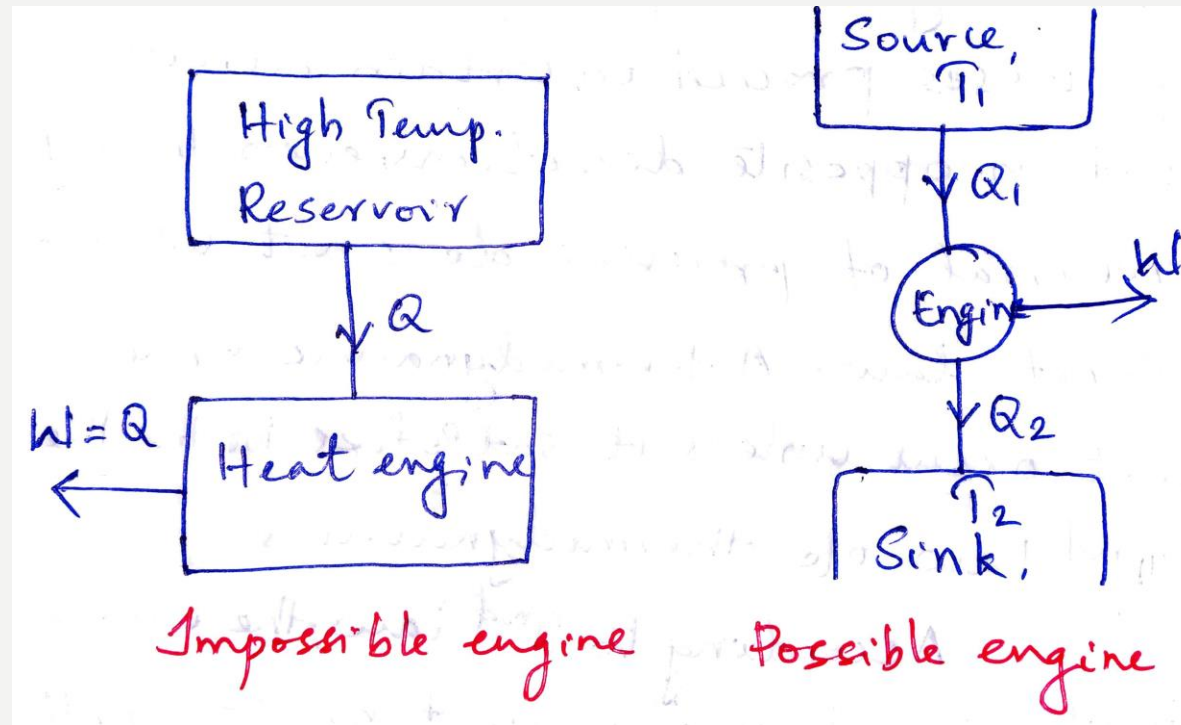
- Satisfying the first law of thermodynamics alone doesn't ensure that a thermodynamic process will take place.
- The second law of thermodynamics puts the restriction that processes proceed in certain directions and not in opposite directions, even though the reversal of processes doesn't violate the first law.
- A thermodynamic process will not occur unless it satisfies both the first and second law of thermodynamics.



- According to second law the whole of the heat transferred can't be converted into work and a part of the heat transferred must be rejected to the surroundings.
- The two common statements of second law of thermodynamics are,
  - 1) Kelvin Planck statement
  - 2) Clausius statement

# KELVIN PLANCK STATEMENT

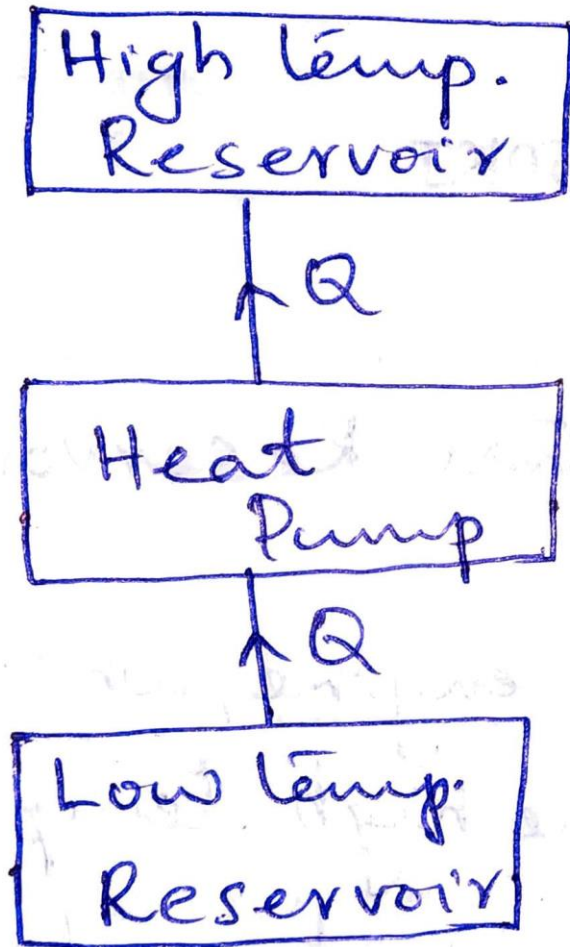
- It is impossible to construct an engine which operating in a cycle will produce no effect other than the exchange of heat from a single reservoir and produce an equal amount of work.
- In other words, **no actual heat engine working on a cyclic process can convert the whole of the heat supplied to it into mechanical work.**



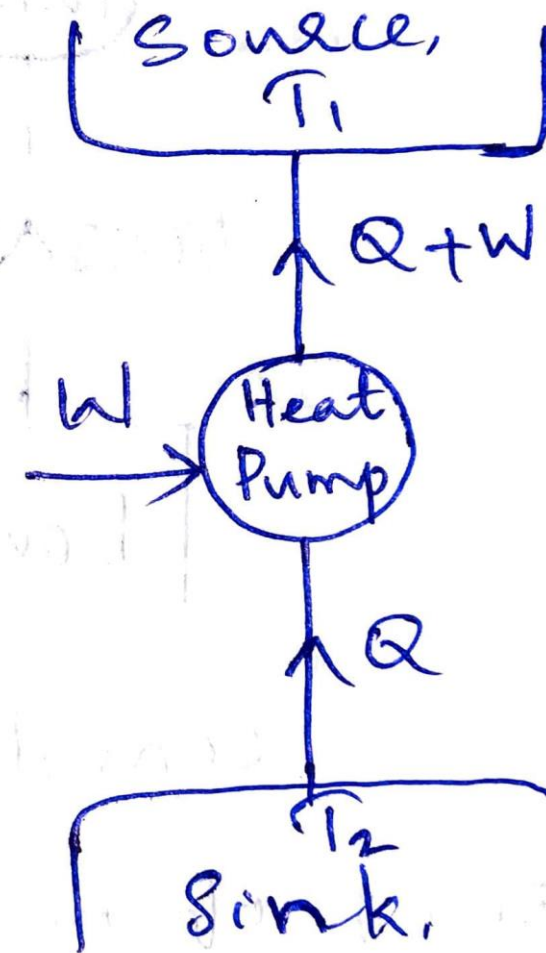
- It means that a part of the heat supplied to the heat engine must be rejected to the surroundings and only the remaining part is converted into work. Hence, the work done by a heat engine will be equal to the difference between heat supplied and heat rejected.

# CLAUSIUS STATEMENT

- ‘It is impossible for a self-acting machine working in a cyclic process, to transfer heat from a body at a lower temperature to a body at a higher temperature, without the aid of an external agency’.
- In other words, **heat cannot flow by itself from a cold body to a hot body without receiving external work.**



Impossible machine



Possible machine

# AVAILABLE ENERGY

- The part of heat (low grade energy) which is available for producing work (high grade energy) is known as available energy and the part of heat which is rejected to the surroundings is known as unavailable energy.

# IRREVERSIBILITY (I)

- A process which cannot be completely reversed without leaving a change either in the system or surroundings is called irreversible process.
- All actual process is irreversible.
- The concept of reversibility is partly hypothetical and hence irreversibility is a natural tendency.
- The workdone during irreversible process will be less than the workdone during a reversible process.

- The difference between workdone during reversible process and irreversible process is called **irreversibility** and is denoted by  $I$ .
- **Irreversibility,  $I = W_{rev} - W_{irr}$**
- Irreversibility is also known as **lost work or degradation**.



# ENTROPY

- First law of thermodynamics is a theorem of conservation of energy.
- It makes no distinction between various forms of energy and declares that all forms of energy are equivalent.
- According to second law of thermodynamics all forms of energy are not equivalent.

- Eg:- Work can be completely converted into heat, but according to Kelvin Planck statement heat cannot be completely converted into work.
- Work is considered as a high grade energy and heat as a low grade energy.
- The complete conversion of a low grade energy into high grade energy is impossible.
- When mechanical work is converted into heat, the energy is degraded.
- Entropy is defined as a measure of the degradation which energy experiences as a result of energy conversion.
- It is also defined as the measure of irreversibility associated with any process.

- The more the irreversibility the more will be the change in entropy.
- Entropy is a property which cannot be measured directly but change of entropy during any process can be calculated.
- A small change in entropy 'ds' is defined as the ratio of small amount of heat transfer 'dQ' to the absolute temperature T at which heat is transferred.
- $ds = \frac{dQ}{T}$
- During a process 1-2,  $\int_1^2 ds = \int_1^2 \frac{dQ}{T}$
- $S_2 - S_1 = \int_1^2 \frac{dQ}{T}$

# GAS LAWS

- A perfect or ideal gas is the gas which strictly obeys all the gas laws under the conditions of pressure and temperature.
- In reality there is no perfect gas exist in nature.
- Eg:- Air, Nitrogen, Hydrogen etc.

# BOYLE'S LAW

- It states that the absolute pressure of a perfect gas varies inversely as its volume when the temperature remains constant.

Or

- The volume of a perfect gas is inversely proportional to the absolute pressure when the temperature remains constant.

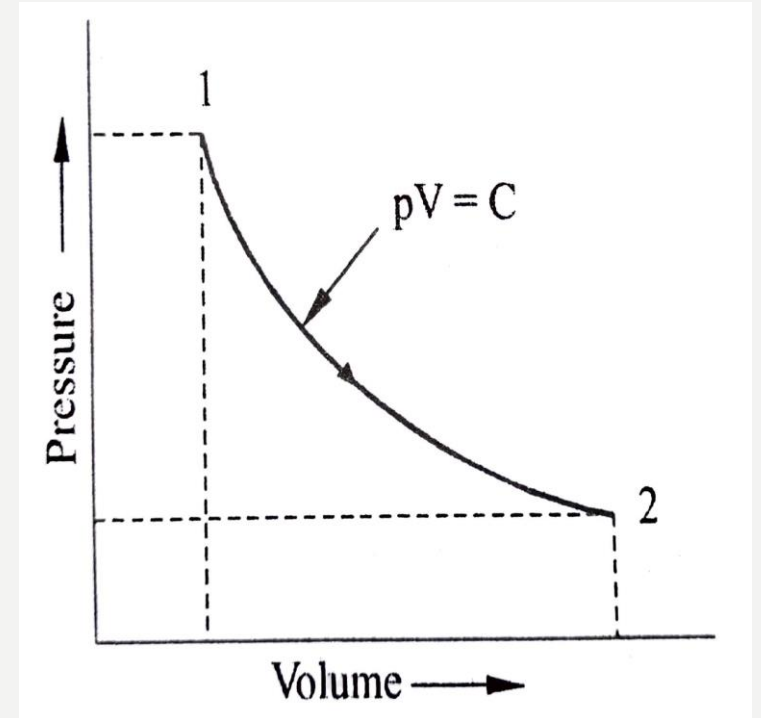
- $V \propto \frac{1}{P}$  at constant T

- Or

- $P \propto \frac{1}{V}$  at constant T

- $PV = \text{Constant, if } T = \text{Constant}$

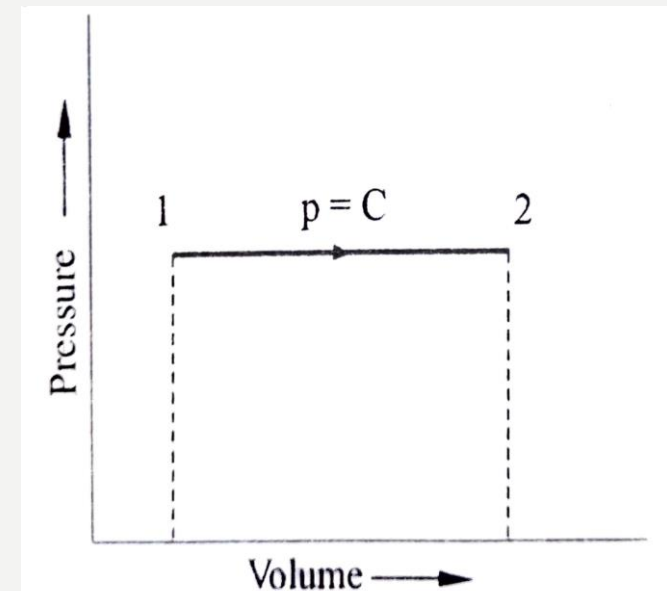
- The equation  $PV = \text{Constant}$ , represents a **rectangular hyperbola** as shown in figure.



- At state 1,  $P_1 V_1 = \text{Constant} \dots\dots\dots(1)$
- At state 2,  $P_2 V_2 = \text{Constant} \dots\dots\dots(2)$
- Equating (1) and (2),
- In general  $P_1 V_1 = P_2 V_2 = PV = \text{Constant}$

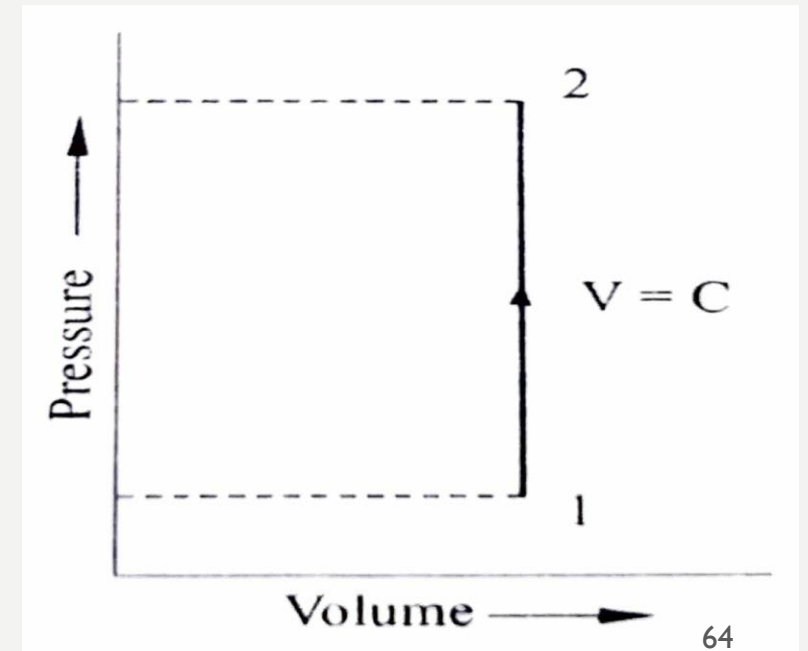
# CHARLE'S LAW

- It states that the volume of a given mass of a perfect gas is directly proportional to its absolute temperature, if the pressure remains constant.
- $V \propto T$  at constant P
- $\frac{V}{T} = \text{Constant}$ , at constant P
- The  $\frac{V}{T} = \text{Constant}$ , represents a horizontal line in the P-V diagram.
- At state 1,  $\frac{V_1}{T_1} = \text{Constant} \dots\dots\dots(1)$
- At state 2,  $\frac{V_2}{T_2} = \text{Constant} \dots\dots\dots(2)$
- Equating (1) and (2),
- $\frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V}{T} = \text{Constant}$



# GAY-LUSSAC'S LAW

- It states that the pressure exerted by a given mass of perfect gas varies directly as its absolute temperature, if the volume of the gas becomes constant.
- $P \propto T$ , at constant  $V$
- $\frac{P}{T} = \text{Constant}$ , at constant  $V$
- At state 1,  $\frac{P_1}{T_1} = \text{Constant} \dots\dots\dots(1)$
- At state 2,  $\frac{P_2}{T_2} = \text{Constant} \dots\dots\dots(2)$
- Equating (1) and (2),
- $\frac{P_1}{T_1} = \frac{P_2}{T_2} = \frac{P}{T} = \text{Constant}$





# AVOGADRO'S LAW

- This law states that equal volumes of all perfect gases under identical conditions of temperature and pressure contains equal number of molecules.

# JOULE'S LAW

- According to Joule's law the change in internal energy of a perfect gas is directly proportional to change in temperature and is independent of change in pressure and volume of the gas.
- $du \propto dT$
- $du = m C_v dT$
- $du = m C_v (T_2 - T_1)$

# REGNAULT'S LAW

- This law states that the two specific heats of a gas at constant pressure and that at constant volume remains constant with all the changes in temperature and pressure.

# CHARACTERISTIC GAS EQUATION

- The relationship between the three properties pressure, volume and temperature of a perfect gas is obtained by combining Boyle's law and Chale's law.
- Let a given mass of a perfect gas be expanded from state 1 to state 2.
- Let first part of expansion is from 1-1' be at constant temperature and the second part of expansion is from 1'-2 be at constant pressure.

- For first part of expansion applying Boyle's law,

- During process 1-1'

- $P_1 V_1 = P_1' V_1'$

- But  $P_1' = P_2$

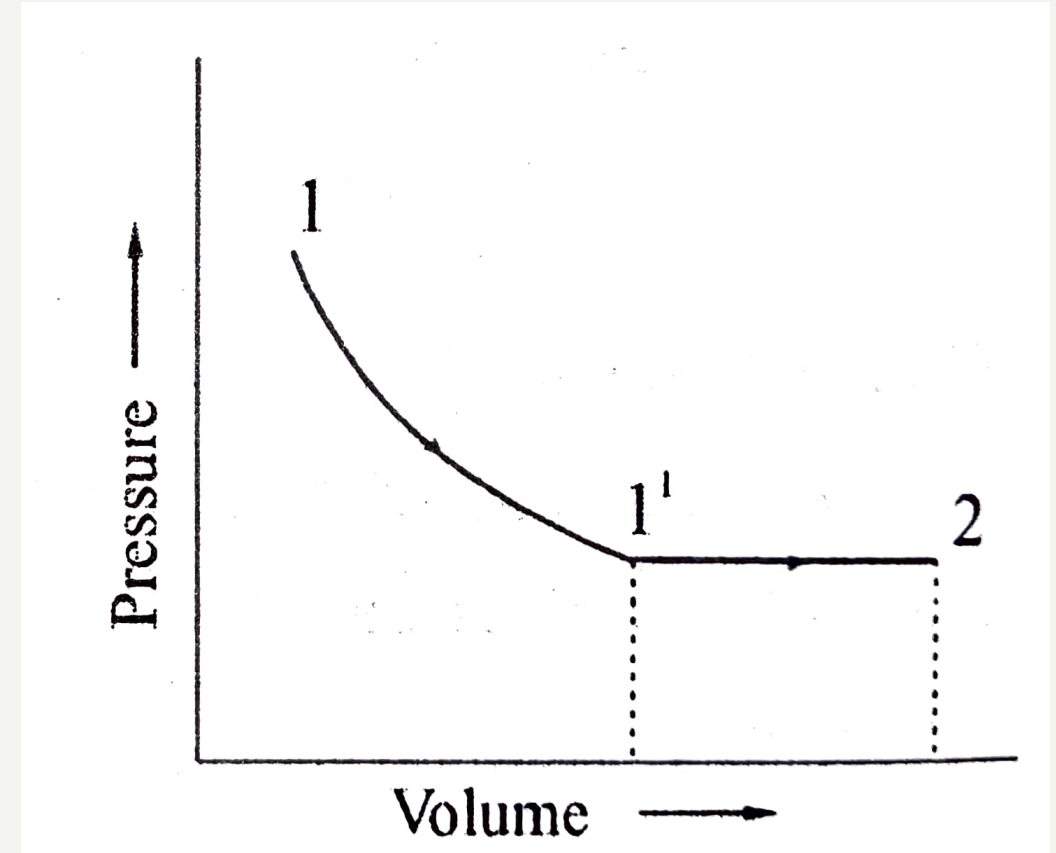
- $P_1 V_1 = P_2 V_1' \dots\dots(1)$

- For first part of expansion  
applying Chale's law,

- During process 1'-2

- $\frac{V_1'}{T_1'} = \frac{V_2}{T_2}$

- But  $T_1' = T_1$



- $\frac{V_1}{T_1} = \frac{V_2}{T_2}$
- $V_1 = T_1 \times \frac{V_2}{T_2} \dots\dots\dots(2)$
- Substitute eq. (2) in (1)
- $P_1 V_1 = P_2 \times T_1 \times \frac{V_2}{T_2}$
- $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{PV}{T} = \text{constant}$
- $\frac{PV}{T} = \text{constant}$
- $V = \text{constant} \times \frac{T}{P}$
- This constant depends on mass of the gas, properties of gas and temperature scale.

- $V = mR \times \frac{T}{P}$
- $PV = mRT$
- Here,  $m$  = mass of gas
- $R$  = constant
- The value of 'R' depends on the properties of gas and the temperature scale.
- This constant 'R' is called **characteristic gas constant**.
- The equation  $PV = mRT$  , is known as characteristic gas equation or equation of state of a perfect gas.

# UNIT OF CHARACTERISTIC GAS CONSTANT (R)

- $PV = mRT$
- $R = \frac{PV}{mT}$
- Substitute the units,
- $R = \frac{\frac{N}{m^2} \times m^3}{kg \times K}$
- $= \frac{Nm}{kgK}$
- $= \frac{J}{kgK}$
- For air, the value of  $R = 287 \frac{J}{kgK}$



# UNIVERSAL GAS CONSTANT

- The universal gas constant of a gas is the product of the characteristic gas constant and the molecular weight of the gas.
- It is denoted by  $R_u$ .
- $R_u = MR$
- Number of moles,  $n = \frac{m}{M}$
- I.e,  $M = \frac{m}{n}$
- $R_u = \frac{m}{n} \times R$

- $R = \frac{n R_u}{m} \dots\dots\dots (1)$
- We know,  $PV = mRT$
- $PV = m \times \frac{n R_u}{m} \times T$
- $PV = nR_u T$
- The value of  $R_u$  is same for all the gases and is equal to 8314 J/mol K
- ie,  $R_u = 8314 \text{ J/mol K}$

# RELATION BETWEEN SPECIFIC HEATS AND CHARACTERISTIC GAS CONSTANT

- Consider 'm' kg of gas being heated at constant pressure from state 1-2. For a stationary closed system undergoing a process 1-2,
- $$\Delta U = {}_1Q_2 - {}_1W_2 \dots \dots \dots (1)$$
- Change in internal energy,
- $$\Delta U = mC_v(T_2 - T_1) \dots \dots \dots (2)$$
- Heat supplied,
- $${}_1Q_2 = mC_p(T_2 - T_1) \dots \dots \dots (3)$$

- Workdone,  ${}_1W_2 = \int_1^2 P dv = P \int_1^2 dv$
- $= P[V_2 - V_1]$
- $= PV_2 - PV_1$
- ${}_1W_2 = P_2V_2 - P_1V_1$  (Since, pressure is constant)
- We know,  $PV = mRT$
- $P_1V_1 = mRT_1$
- $P_2V_2 = mRT_2$
- Substitute,
- ${}_1W_2 = mRT_2 - mRT_1$
- ${}_1W_2 = mR(T_2 - T_1) \dots \dots \dots (4)$

- Substitute equations (2), (3), (4) in equation (1)
- $mC_v(T_2 - T_1) = mC_p(T_2 - T_1) - mR(T_2 - T_1)$
- $C_v = C_p - R$
- $R = C_p - C_v$
- We know,  $\gamma = \frac{C_p}{C_v}$
- $C_p - C_v = R$
- $C_p(1 - \frac{C_v}{C_p}) = R$
- $C_p(1 - \frac{1}{\gamma}) = R$
- $C_p(\frac{\gamma - 1}{\gamma}) = R$
- $C_p = \frac{\gamma R}{\gamma - 1}$

- $C_p - C_v = R$

- $C_v \left( \frac{C_p}{C_v} - 1 \right) = R$

- $C_v (\gamma - 1) = R$

- $C_v = \frac{R}{\gamma - 1}$

**Q.1.** A vessel of capacity 5 m<sup>3</sup> contains 20 kg of an ideal gas having a molecular weight of 25. If the temperature of the gas is 15<sup>0</sup> C. Find its pressure.

- **Given data:**
- $V = 5 \text{ m}^3$
- $m = 20 \text{ kg}$
- $M = 25$
- $T = 15^0 \text{ C}$
- $= 15 + 273 = 288 \text{ K}$
- $P = ?$
- We know,  **$PV = mRT$**
- $R_u = MR$
- $8314 = 25 \times R$
- $R = 8314/25$
- $= 332.56 \text{ J/kgK}$
- **$PV = mRT$**
- $P \times 5 = 20 \times 332.56 \times 288$
- $= 1915545.6$
- $P = 1915545.6/5$
- $= 383109.12 \text{ N/m}^2$
- **$P = 3.83 \text{ bar}$**

**Q.2.** 0.01 kg of certain gas occupies a volume of 0.003 m<sup>3</sup> at a pressure of 7 bar and temperature of 131<sup>0</sup>C. Calculate the molecular weight of the gas. When the gas is allowed to expand until the pressure is 1 bar the final volume is 0.02 m<sup>3</sup>. Calculate the final temperature.

- **Given data:**

- $m = 0.01 \text{ kg}$

- $V_1 = 0.003 \text{ m}^3$

- $P_1 = 7 \text{ bar} = 7 \times 10^5 \text{ N/m}^2$

- $T_1 = 131^{\circ}\text{C} = 131 + 273 = 404 \text{ K}$

- $M = ?$

- $P_2 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$

- $V_2 = 0.02 \text{ m}^3$

- $T_2 = ?$

- $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

- $\frac{7 \times 10^5 \times 0.003}{404} = \frac{1 \times 10^5 \times 0.02}{T_2}$

- $T_2 = 384.76 \text{ K}$

- $= 384.76 - 273$

- $= 111.76^{\circ}\text{C}$



- We know,  $P_1 V_1 = mRT_1$
- $7 \times 10^5 \times 0.003 = 0.01 \times R \times 404$
- $R = 519.8 \text{ J/kgK}$
- $R_u = MR$
- $M = \frac{R_u}{R}$
- $= \frac{8314}{519.8}$
- $M = 15.99$

**Q.3.** 1 kg of an ideal gas is heated from 20°C to 100°C assuming  $R = 264 \text{ J/kgK}$  and  $\gamma = 1.18$  for the gases. Find (i) Specific heats (ii) Change in internal energy (iii) Change in enthalpy.

- **Given data:**

- $m = 1 \text{ kg}$

- $T_1 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$

- $T_2 = 100^\circ\text{C} = 100 + 273 = 373 \text{ K}$

- $R = 264 \text{ J/kgK}$

- $\gamma = 1.18$

- $C_p = ?$

- $C_v = ?$

- $\Delta U = ?$

- $\Delta H = ?$

- $C_p = \frac{\gamma R}{\gamma - 1}$

- $= \frac{1.18 \times 264}{1.18 - 1} = 1730.6 \text{ J/kgK}$

- $C_v = \frac{R}{\gamma - 1}$

- $= \frac{264}{1.18 - 1} = 1466.6 \text{ J/kgK}$

- $\Delta U = mC_v(T_2 - T_1)$

- $= 1 \times 1466.6 \times (373 - 293) = 117328 \text{ J}$

- $= 117.33 \text{ kJ}$

- $\Delta H = mC_p(T_2 - T_1)$

- $= 1 \times 1730.6 \times (373 - 293) = 138448 \text{ J}$

- $= 138.44 \text{ kJ}$

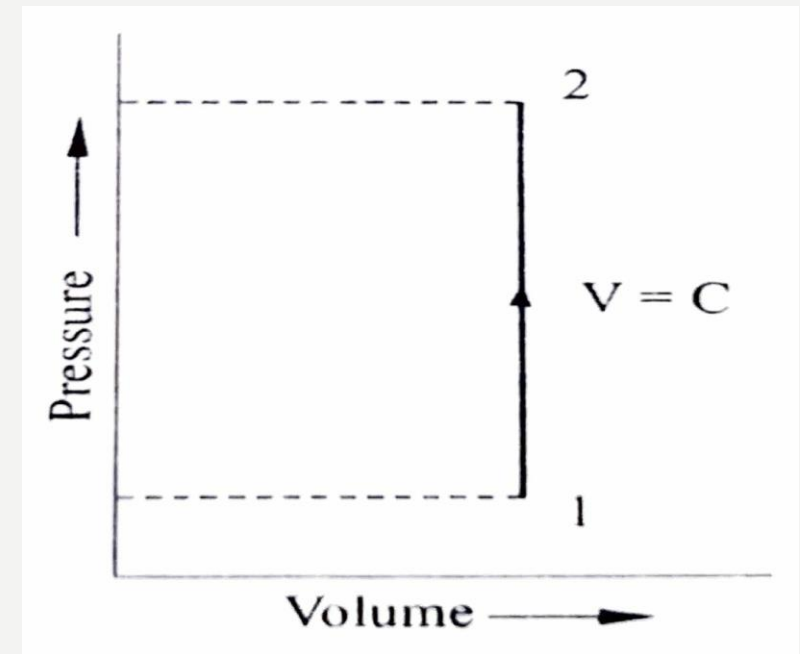
# **THERMODYNAMIC PROCESSES**

# CONSTANT VOLUME (ISOCHORIC) PROCESS

- Consider 'm' kg of a gas being heated in a cylinder at constant volume from an initial temperature  $T_1$  to final temperature  $T_2$

## 1) P-V-T Relationship

- For a perfect gas,  $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
- Since,  $V_1 = V_2 = V = \text{Constant}$
- $\frac{P_1}{T_1} = \frac{P_2}{T_2}$



## 2) Workdone

- ${}_1W_2 = \int_1^2 P dv$
- Since,  $V = \text{Constant}$ ,  $dV = 0$
- ${}_1W_2 = 0$

## 3) Change in internal energy

- $\Delta U = mC_v(T_2 - T_1)$

## 4) Heat supplied

- From first law of thermodynamics,  ${}_1Q_2 = {}_1W_2 + \Delta U$
- Since,  ${}_1W_2 = 0$
- ${}_1Q_2 = \Delta U$
- ${}_1Q_2 = mC_v(T_2 - T_1)$

**Q.1.** An insulated cylinder of capacity  $2.8 \text{ m}^3$  contains  $15 \text{ kg}$  of nitrogen. Paddle work is done on the gas till the pressure inside the gas increases from  $5 \text{ bar}$  to  $10 \text{ bar}$ . Determine (i) Change in internal energy (ii) Workdone (iii) Heat transfer, assume  $C_p = 1.04 \text{ kJ/kgK}$  and  $C_v = 0.7432 \text{ kJ/kgK}$ .

**Given data:**

- $V = V_1 = V_2 = 2.8 \text{ m}^3$
- $m = 15 \text{ kg}$
- $P_1 = 5 \text{ bar} = 5 \times 10^5 \text{ N/m}^2$
- $P_2 = 10 \text{ bar} = 10 \times 10^5 \text{ N/m}^2$
- $C_p = 1.04 \text{ kJ/kgK} = 1040 \text{ J/kgK}$
- $C_v = 0.7432 \text{ kJ/kgK} = 743.2 \text{ J/kgK}$
- $\Delta U = ?$
- ${}_1W_2 = ?$
- ${}_1Q_2 = ?$

i)  $\Delta U = mC_v(T_2 - T_1)$

- Find  $T_1$  and  $T_2$ , use

- $P_1 V_1 = mRT_1$

- $P_2 V_2 = mRT_2$

- $C_p - C_v = R$

- $1040 - 743.2 = R$

- $R = 296.8 \text{ J/kgK}$

- $P_1 V_1 = mRT_1$

- $5 \times 10^5 \times 2.8 = 15 \times 296.8 \times T_1$

- $T_1 = 314.47 \text{ K}$

- $P_2 V_2 = mRT_2$
- $10 \times 10^5 \times 2.8 = 15 \times 296.68 \times T_2$
- $T_2 = 628.93 \text{ K}$
- $\Delta U = mC_v(T_2 - T_1)$
- $= 15 \times 743.2 \times (628.93 - 314.47)$
- $= 3505600.08 \text{ J}$
- $\Delta U = 3505.6 \text{ kJ}$

ii) Note:

- Cases of  ${}_1W_2 \neq \int_1^2 P dv$

a) *Free expansion*

b) *Paddle work*

- *Given cylinder is an insulated cylinder, since heat transfer,  ${}_1Q_2 = 0$*

- ${}_1Q_2 = {}_1W_2 + \Delta U$

- ie,  ${}_1W_2 = -\Delta U$

- ${}_1W_2 = -3505.6 \text{ kJ}$

iii) *Given cylinder is an insulated cylinder, since heat transfer,*

- ${}_1Q_2 = 0$

**Q. 2.** A quantity of gas has a pressure of 350 kPa, when its volume is 0.03 m<sup>3</sup> and temperature is 35<sup>0</sup> C. If R = 0.29 kJ/kgK for this gas, determine the mass of the gas present. If the pressure is increased to 1 MPa while volume remains constant, find out new temperature. (April 2019 – 8 marks)

**Given data:**

- $P_1 = 350 \text{ kPa} = 350 \times 10^3 \text{ N/m}^2$
- $V = V_1 = V_2 = 0.03 \text{ m}^3$
- $T_1 = 35^\circ \text{C} = 35 + 273 = 308 \text{ K}$
- $R = 0.29 \text{ kJ/kgK} = 290 \text{ J/kgK}$
- $P_2 = 1 \text{ MPa} = 1 \times 10^6 \text{ N/m}^2$
- $m = ?$
- $T_2 = ?$
- We know,
- $P_1 V_1 = mRT_1$
- $350 \times 10^3 \times 0.03 = m \times 290 \times 308$
- $m = 0.1175 \text{ kg}$
- We know,  $\frac{P_1}{T_1} = \frac{P_2}{T_2}$
- $\frac{350 \times 10^3}{308} = \frac{1 \times 10^6}{T_2}$
- $T_2 = 880 \text{ K}$
- $T_2 = 880 - 273$
- $T_2 = 607^\circ \text{C}$



**Q.3.** A closed vessel contains 2 kg of CO<sub>2</sub> at a temperature 20° C and pressure 0.7 bar. Heat is supplied to the vessel till the pressure becomes 1.4 bar. Find (i) final temperature (ii) work done (iii) heat added ( $C_v = 0.657$  kJ/kgK) (April 2017- 7 marks)

**Given data:**

- Closed vessel = volume constant
- $m = 2$  kg
- $T_1 = 20^\circ \text{C} = 20 + 273 = 293$  K
- $P_1 = 0.7$  bar =  $0.7 \times 10^5$  N/m<sup>2</sup>
- $P_2 = 1.4$  bar =  $1.4 \times 10^5$  N/m<sup>2</sup>
- $C_v = 0.657$  kJ/kgK
- $T_2 = ?$
- ${}_1W_2 = ?$
- ${}_1Q_2 = ?$

(i) We know,  $\frac{P_1}{T_1} = \frac{P_2}{T_2}$

$$\bullet \frac{0.7 \times 10^5}{293} = \frac{1.4 \times 10^5}{T_2}$$

$$\bullet T_2 = 586 \text{ K}$$

$$\bullet = 586 - 273$$

$$\bullet T_2 = 313^\circ \text{C}$$

• (ii)  ${}_1W_2 = 0$  for constant volume process.

$$\bullet \text{ (iii) } {}_1Q_2 = mC_v(T_2 - T_1)$$

$$\bullet = 2 \times 0.657 (586 - 293)$$

$${}_1Q_2 = 385 \text{ kJ}$$

# CONSTANT PRESSURE (ISOBARIC) PROCESS

## 1) P-V-T Relationship

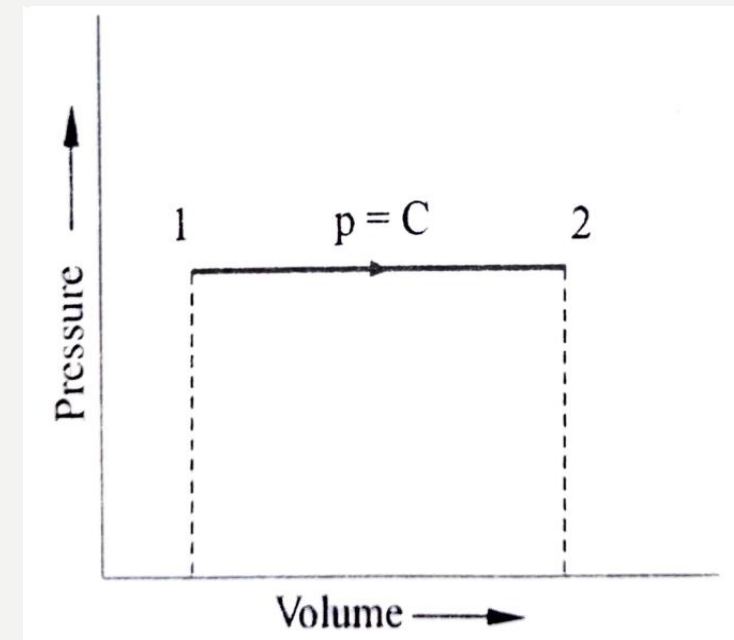
- For a perfect gas,  $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
- Since,  $P_1 = P_2 = P = \text{Constant}$
- $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

## 2) Workdone

- ${}_1W_2 = \int_1^2 P dv$
- $= P \int_1^2 dv$
- ${}_1W_2 = P[V_2 - V_1]$

## 3) Change in internal energy

- $\Delta U = mC_v(T_2 - T_1)$



#### 4) Heat supplied

- From first law of thermodynamics,
- ${}_1Q_2 = {}_1W_2 + \Delta U$
- ${}_1Q_2 = P[V_2 - V_1] + mC_v(T_2 - T_1)$
- $= P_2V_2 - P_1V_1 + mC_v(T_2 - T_1)$
- We know,  $P_1V_1 = mRT_1$  and  $P_2V_2 = mRT_2$
- ${}_1Q_2 = mRT_2 - mRT_1 + mC_v(T_2 - T_1)$
- $= mR(T_2 - T_1) + mC_v(T_2 - T_1)$
- $= m(T_2 - T_1)(R + C_v)$
- We know,  $C_p - C_v = R$ , from this,  $R + C_v = C_p$
- ${}_1Q_2 = m(T_2 - T_1) C_p$
- ${}_1Q_2 = mC_p(T_2 - T_1)$

**Q.1.** 5 m<sup>3</sup> of air at 0°C and a pressure of 3 bar is heated to 80°C at constant pressure.  
Find (i) Change in internal energy (ii) Workdone (iii) Heat transfer.

**Given data:**

- $V_1 = 5 \text{ m}^3$
- $T_1 = 0^\circ\text{C} = 273 \text{ K}$
- $P = P_1 = P_2 = 3 \text{ bar} = 3 \times 10^5 \text{ N/m}^2$
- $T_2 = 80^\circ\text{C} = 80 + 273 = 353 \text{ K}$
- For air,  $C_p = 1.005 \text{ kJ/kgK}$
- $C_v = 0.718 \text{ kJ/kgK}$
- $R = 287 \text{ J/kgK}$
- $\Delta U = ?$ ,  ${}_1W_2 = ?$ ,  ${}_1Q_2 = ?$
- *For a constant pressure process,*
- $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

- $\frac{5}{273} = \frac{V_2}{353}$

- $V_2 = 6.4 \text{ m}^3$

i)  $\Delta U = mC_v(T_2 - T_1)$

- To find the mass, use

- $P_1 V_1 = mRT_1$

- $3 \times 10^5 \times 5 = m \times 287 \times 273$

- $m = 19.14 \text{ kg}$

- $\Delta U = mC_v(T_2 - T_1)$

- $= 19.14 \times 0.718 \times (353 - 273)$

- $\Delta U = 1099.4 \text{ kJ}$

- ii)  ${}_1W_2 = P[V_2 - V_1]$
- $= 3 \times 10^5 [6.4 - 5]$
- $= 4.2 \times 10^5 \text{ J}$
- ${}_1W_2 = 420 \text{ kJ}$
- iii)  ${}_1Q_2 = mC_p(T_2 - T_1)$
- $= 19.14 \times 1.005 (353 - 273)$
- ${}_1Q_2 = 1538.8 \text{ kJ}$

**Q.2.** A gas having initial pressure, volume, temperature as 275 kN/m<sup>2</sup>, 0.09 m<sup>3</sup>, and 185<sup>0</sup> C respectively is compressed at constant pressure until its temperature is 15<sup>0</sup> C. Calculate the amount of heat transferred and workdone during the process. Take R = 290 J/kgK and C<sub>p</sub> = 1.005 kJ/kgK. (April 2019 – 8 marks)

**Given data:**

- $V_1 = 0.09 \text{ m}^3$
- $T_1 = 185^\circ \text{C} = 185 + 273 = 458 \text{ K}$
- $P = P_1 = P_2 = 275 \text{ kN/m}^2 = 275 \times 10^3 \text{ N/m}^2$
- $T_2 = 15^\circ \text{C} = 15 + 273 = 288 \text{ K}$
- For air,  $C_p = 1.005 \text{ kJ/kgK}$
- $R = 290 \text{ J/kgK}$
- ${}_1Q_2 = ?$
- ${}_1W_2 = ?$

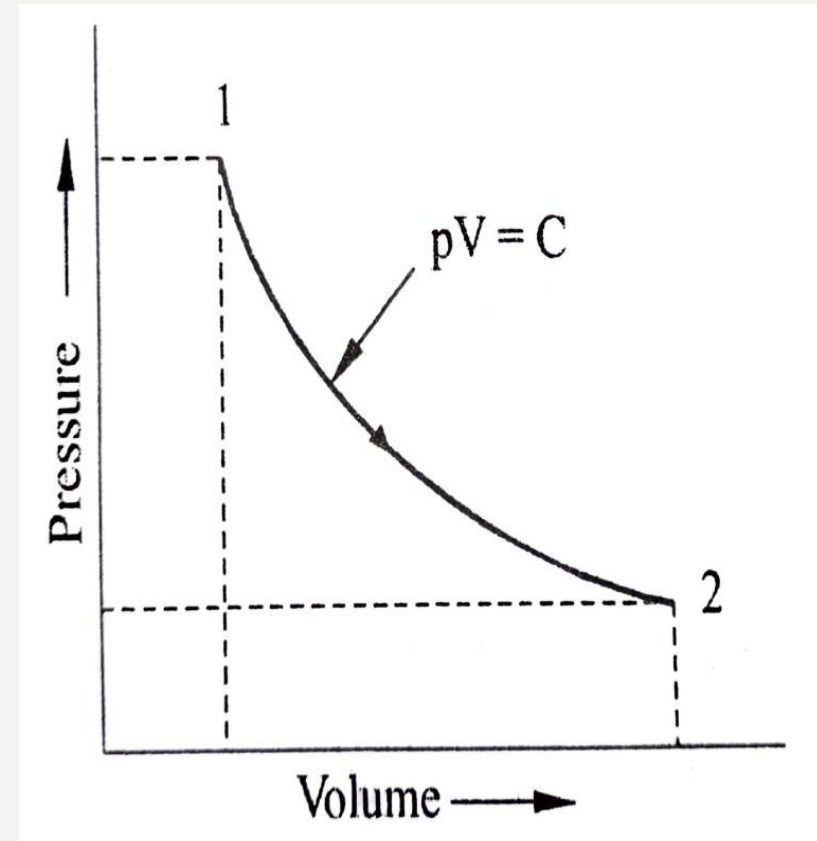
- i) Heat transferred,
- ${}_1Q_2 = mC_p(T_2 - T_1)$
- To find the mass, use
- $P_1 V_1 = mRT_1$
- $275 \times 10^3 \times 0.09 = m \times 290 \times 458$
- $m = 0.186 \text{ kg}$
- ${}_1Q_2 = mC_p(T_2 - T_1)$
- $= 0.186 \times 1.005 (288 - 458)$
- ${}_1Q_2 = - 31.78 \text{ kJ}$

- ii)  ${}_1W_2 = P[V_2 - V_1]$
- To find  $V_2$ ,
- *For a constant pressure process,*
- $\frac{V_1}{T_1} = \frac{V_2}{T_2}$
- $\frac{0.09}{458} = \frac{V_2}{288}$
- $V_2 = 0.056 \text{ m}^3$
- ${}_1W_2 = P[V_2 - V_1]$
- $= 275 \times 10^3 [0.056 - 0.09]$
- $= - 9350 \text{ J}$
- ${}_1W_2 = - 9.35 \text{ kJ}$

# CONSTANT TEMPERATURE (ISOTHERMAL) PROCESS

## 1) P-V-T Relationship

- For a perfect gas,  $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
- Since,  $T_1 = T_2 = T = \text{Constant}$
- $P_1 V_1 = P_2 V_2 = PV = \text{Constant}$





## 2) Workdone

- ${}_1W_2 = \int_1^2 P dv \dots\dots\dots (1)$
- $P_1 V_1 = PV = \text{Constant}$
- $P = \frac{P_1 V_1}{V} \dots\dots\dots (2)$
- Substitute (2) in (1)
- ${}_1W_2 = \int_1^2 \frac{P_1 V_1}{V} dv$
- $= P_1 V_1 \int_1^2 \frac{dV}{V}$
- $= P_1 V_1 (\ln V_2 - \ln V_1)$
- ${}_1W_2 = P_1 V_1 \ln \left( \frac{V_2}{V_1} \right)$
- Or,  $P_1 V_1 = P_2 V_2$
- $\frac{V_2}{V_1} = \frac{P_1}{P_2}$
- ${}_1W_2 = P_1 V_1 \ln \left( \frac{P_1}{P_2} \right)$

## 3) Change in internal energy

- $\Delta U = mC_v(T_2 - T_1)$
- $T_1 = T_2 = T = \text{Constant}$
- $\Delta U = 0$

## 4) Heat supplied

- From first law of thermodynamics,
- ${}_1Q_2 = {}_1W_2 + \Delta U$
- Since,  $\Delta U = 0$
- ${}_1Q_2 = {}_1W_2$
- ${}_1Q_2 = P_1 V_1 \ln \left( \frac{V_2}{V_1} \right)$
- ${}_1Q_2 = P_1 V_1 \ln \left( \frac{P_1}{P_2} \right)$

**Q.1.** Determine the volume of 2 kg of air at 30°C and under a pressure of 2 bar. What would be its volume after isothermal compression to a pressure of 4 bar. Calculate the workdone.

**Given data:**

- $m = 2 \text{ kg}$
- $T_1 = 30^\circ\text{C} = 30 + 273 = 303 \text{ K}$
- $P_1 = 2 \text{ bar} = 2 \times 10^5 \text{ N/m}^2$
- $P_2 = 4 \text{ bar} = 4 \times 10^5 \text{ N/m}^2$
- $V_1 = ?, V_2 = ?, {}_1W_2 = ?$
- We know,  $P_1 V_1 = mRT_1$
- For air,  $R = 287 \text{ J/kgK}$
- $P_1 V_1 = mRT_1$
- $2 \times 10^5 \times V_1 = 2 \times 287 \times 303$

- $V_1 = 0.869 \text{ m}^3$
- $P_1 V_1 = P_2 V_2$
- $2 \times 10^5 \times 0.869 = 4 \times 10^5 \times V_2$
- $V_2 = 0.4345 \text{ m}^3$
- ${}_1W_2 = P_1 V_1 \ln \left( \frac{V_2}{V_1} \right)$
- $= 2 \times 10^5 \times 0.869 \times \ln \left( \frac{0.4345}{0.869} \right)$
- $= - 119221.3 \text{ J}$
- ${}_1W_2 = - 119.22 \text{ kJ}$

**Q.2.** 1 kg of fluid is compressed reversibly according to a law  $PV = 0.2$ , where  $P$  is in bar and  $V$  is in  $\text{m}^3/\text{kg}$ . The final volume is  $(1/4)^{\text{th}}$  of the initial volume. Calculate the workdone on the fluid.

**Given data:**

- $m = 1 \text{ kg}$
- $PV = 0.2 \text{ bar m}^3/\text{kg}$
- $= 0.2 \times 10^5 \text{ N/m}^2 \times \text{m}^3/\text{kg}$
- $= 0.2 \times 10^5 \text{ Nm/kg}$
- $= 0.2 \times 10^5 \text{ J/kg}$
- $P_1 V_1 = P_2 V_2 = PV = 0.2 \times 10^5 \text{ J/kg}$
- $V_2 = \frac{1}{4} V_1$
- $\frac{V_2}{V_1} = \frac{1}{4}$
- ${}_1W_2 = P_1 V_1 \ln \left( \frac{V_2}{V_1} \right)$
- ${}_1W_2 = 0.2 \times 10^5 \times \ln \left( \frac{1}{4} \right)$
- $= - 27725.8 \text{ J}$
- ${}_1W_2 = - 27.725 \text{ kJ}$

**Q.3.** A quantity of air has a volume of  $0.4 \text{ m}^3$  at a pressure of 5 bar and a temperature of  $80^\circ \text{C}$ . It is expanded in a cylinder to a pressure of 1 bar. Determine the amount of workdone by the air during expansion. (April 2017 – 8 marks)

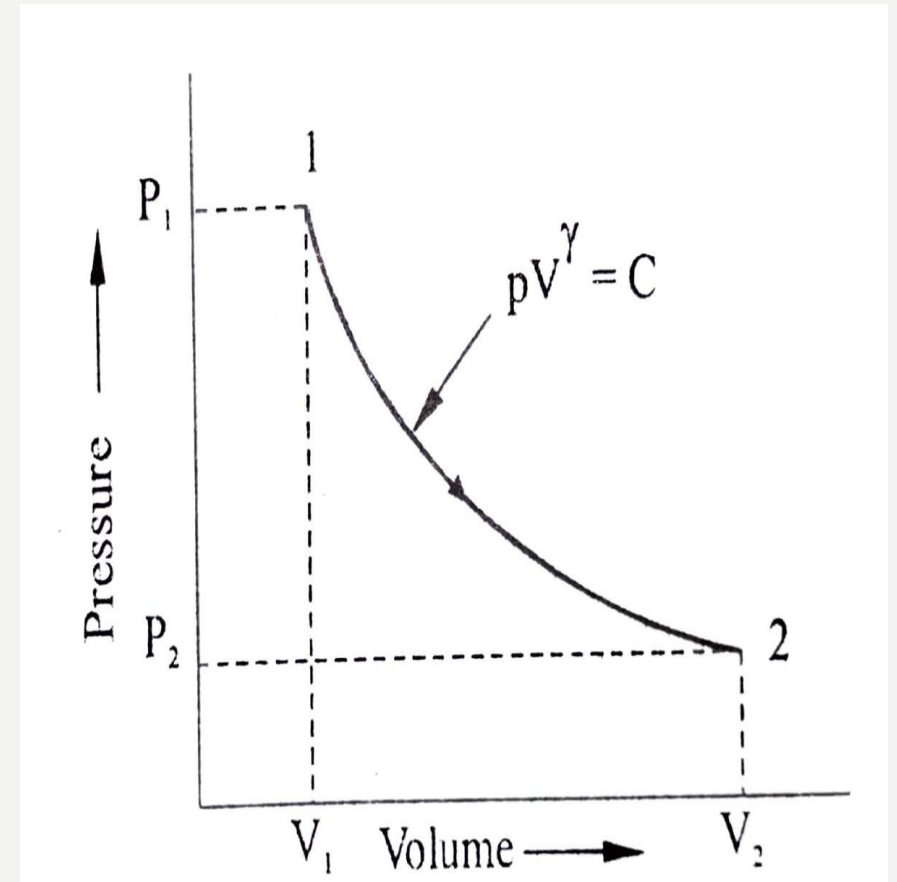
**Given data:**

- $V_1 = 0.4 \text{ m}^3$
- $P_1 = 5 \text{ bar} = 5 \times 10^5 \text{ N/m}^2$
- $T_1 = 80^\circ\text{C} = 80 + 273 = 353 \text{ K}$
- $P_2 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$
- For an isothermal process,
- $P_1 V_1 = P_2 V_2$
- $5 \times 10^5 \times 0.4 = 1 \times 10^5 \times V_2$
- $V_2 = 2 \text{ m}^3$

- Workdone,
- ${}_1W_2 = P_1 V_1 \ln \left( \frac{V_2}{V_1} \right)$
- ${}_1W_2 = 5 \times 10^5 \times 0.4 \times \ln \left( \frac{2}{0.4} \right)$
- $= 321887.58 \text{ J}$
- $= 321.88 \text{ kJ}$

# ADIABATIC PROCESS

- In an adiabatic process the gas neither receives nor rejects heat.
- In this process, the heat exchange,  $Q = 0$ , work is done by the gas at the expense of internal energy.
- According to first law of thermodynamics,
- ${}_1Q_2 = {}_1W_2 + \Delta U$
- For an adiabatic process,  ${}_1Q_2 = 0$



- ie,  ${}_1W_2 = -\Delta U \dots\dots\dots(1)$

- $\Delta U = mC_v(T_2 - T_1)$

- ${}_1W_2 = \int_1^2 Pdv$

- $\int_1^2 Pdv = -mC_v(T_2 - T_1)$

- Writing in differential form,

- $PdV = -mC_vdT \dots\dots\dots(2)$

- Consider  $PV = mRT$

- Differentiating,

- $PdV + VdP = mRdT$

- $mdT = \frac{PdV + VdP}{R} \dots\dots\dots(3)$

- Substitute (3) in (2)

- $PdV = -\left(\frac{PdV + VdP}{R}\right)C_v$

- $R \times PdV = -C_v(PdV + VdP)$

- We know,  $C_p - C_v = R$

- $(C_p - C_v) \times PdV = -C_v PdV - C_v VdP$

- $C_p PdV - C_v PdV = -C_v PdV - C_v VdP$

- $C_p PdV = -C_v VdP$

- $\frac{C_p}{C_v} \times \frac{dV}{V} = -\frac{dP}{P}$

- $\gamma \times \frac{dV}{V} + \frac{dP}{P} = 0$

- Integrating,
- $\gamma \times \ln V + \ln P = C_1$
- $\ln V^\gamma + \ln P = C_1$
- $\ln PV^\gamma = C_1$
- Taking exponential on both sides,
- $e^{\ln PV^\gamma} = e^{C_1}$
- $PV^\gamma = C$
- Since for an adiabatic process 1-2,
- $P_1V_1^\gamma = P_2V_2^\gamma = PV^\gamma = C$

## 1) P-V-T Relationship

### a) Relation between P & V

- For an adiabatic process,
- $P_1 V_1^\gamma = P_2 V_2^\gamma$
- $\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^\gamma \dots \dots \dots (1)$

### b) Relation between P & T

- From equation (1),  $\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}}$
- For a perfect gas,  $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
- $\frac{V_2}{V_1} = \frac{P_1}{P_2} \times \frac{T_2}{T_1}$
- $\frac{P_1}{P_2} \times \frac{T_2}{T_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}}$

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

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

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

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

$$\bullet \frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\frac{\gamma}{\gamma-1}} \dots \dots \dots (2)$$



### c) Relation between V & T

- Equating equation (1) and (2)

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

$$\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}} \dots \dots \dots (3)$$

### 2) Workdone

$${}_1W_2 = \int_1^2 P dv$$

- For an adiabatic process,

$$PV^\gamma = C$$

$$P = \frac{C}{V^\gamma}$$

$${}_1W_2 = \int_1^2 \frac{C}{V^\gamma} dv$$

$$= C \int_1^2 \frac{dV}{V^\gamma}$$

$$= C \int_1^2 V^{-\gamma} dV$$

$$\begin{aligned} &= C \left[ \frac{V^{-\gamma+1}}{-\gamma+1} \right]_1^2 \\ &= \frac{C}{1-\gamma} [V_2^{1-\gamma} - V_1^{1-\gamma}] \\ &= \frac{1}{1-\gamma} [C \times V_2^{1-\gamma} - C \times V_1^{1-\gamma}] \\ &= \frac{1}{1-\gamma} [P_2 V_2^\gamma \times V_2^{1-\gamma} - P_1 V_1^\gamma \times V_1^{1-\gamma}] \\ &= \frac{1}{1-\gamma} [P_2 V_2^{(\gamma+1-\gamma)} - P_1 V_1^{(\gamma+1-\gamma)}] \\ &= \frac{1}{1-\gamma} [P_2 V_2 - P_1 V_1] \\ &= \frac{-(P_1 V_1 - P_2 V_2)}{-(\gamma-1)} \end{aligned}$$

$${}_1W_2 = \frac{(P_1 V_1 - P_2 V_2)}{(\gamma-1)}$$

$${}_1W_2 = \frac{(mRT_1 - mRT_2)}{(\gamma-1)}$$

$${}_1W_2 = \frac{mR(T_1 - T_2)}{(\gamma-1)}$$

### 3) Change in internal energy

- $\Delta U = mC_v(T_2 - T_1)$
- According to first law of thermodynamics,
- ${}_1Q_2 = {}_1W_2 + \Delta U$
- For an adiabatic process,  ${}_1Q_2 = 0$
- $\Delta U = -{}_1W_2$
- $\Delta U = -\frac{mR(T_1 - T_2)}{(\gamma - 1)}$
- $\Delta U = \frac{mR(T_2 - T_1)}{(\gamma - 1)}$

### 4) Heat supplied

- For an adiabatic process, heat exchange = 0,
- ie,  ${}_1Q_2 = 0$

**Q.1.** 0.2 m<sup>3</sup> of gas at 1 bar and 100<sup>0</sup> C is compressed adiabatically to 0.05 m<sup>3</sup>. Determine (i) the mass of gas compressed (ii) final pressure and temperature of gas (iii) increase in internal energy. Take  $\gamma = 1.4$  and  $R = 295 \text{ J/kgK}$ .

**Given data:**

- $V_1 = 0.2 \text{ m}^3$
- $V_2 = 0.05 \text{ m}^3$
- $P_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$
- $T_1 = 100^\circ \text{C} = 100 + 273 = 373 \text{ K}$
- $\gamma = 1.4$
- $R = 295 \text{ J/kgK}$
- $m = ?, P_2 = ?, T_2 = ?, \Delta U = ?$

**(i)  $P_1 V_1 = mRT_1$**

- $1 \times 10^5 \times 0.2 = m \times 295 \times 373$
- $m = 0.1817 \text{ kg}$

**(ii)  $P_1 V_1^\gamma = P_2 V_2^\gamma$**

- $1 \times 10^5 \times (0.2)^{1.4} = P_2 (0.05)^{1.4}$
- $P_2 = 696440.4 \text{ N/m}^2$
- $P_2 = 6.96 \text{ bar}$

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

- From this,  $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$
- $T_1 = T_2 \left(\frac{V_2}{V_1}\right)^{\gamma-1}$
- $373 = T_2 \times \left(\frac{0.05}{0.2}\right)^{1.4-1}$
- $T_2 = 649.43 \text{ K}$
- $T_2 = 649.43 - 273 = 376.43^\circ \text{C}$

$$(iv) \Delta U = \frac{mR(T_2 - T_1)}{(\gamma - 1)}$$

- $$= \frac{0.1817 \times 295 (649.43 - 373)}{(1.4 - 1)}$$
- $$= 36989.13 \text{ J}$$
- $$= 36.99 \text{ kJ}$$

**Q.2.** 1kg gas expands adiabatically and its temperature is observed to fall from  $240^{\circ}\text{C}$  to  $115^{\circ}\text{C}$ , while the volume is doubled. The gas does 90 kJ of work during the process. Determine the value of  $C_p$  and  $C_v$ .

**Given data:**

- $m = 1\text{kg}$
- $T_1 = 240^{\circ}\text{C} = 240 + 273 = 513\text{ K}$
- $T_2 = 115^{\circ}\text{C} = 115 + 273 = 388\text{ K}$
- $V_2 = 2 V_1$
- $\frac{V_2}{V_1} = 2$
- ${}_1W_2 = 90\text{ kJ} = 90 \times 10^3\text{ J}$
- $C_v = ?$
- $C_p = ?$

• According to first law of thermodynamics,

$${}_1Q_2 = {}_1W_2 + \Delta U$$

• For an adiabatic process,  ${}_1Q_2 = 0$

$$\text{ie, } \Delta U = -{}_1W_2$$

$$\Delta U = mC_v(T_2 - T_1)$$

$$mC_v(T_2 - T_1) = -{}_1W_2$$

$$1 \times C_v \times (388 - 513) = -90 \times 10^3$$

$$C_v = 720\text{ J/kgK}$$

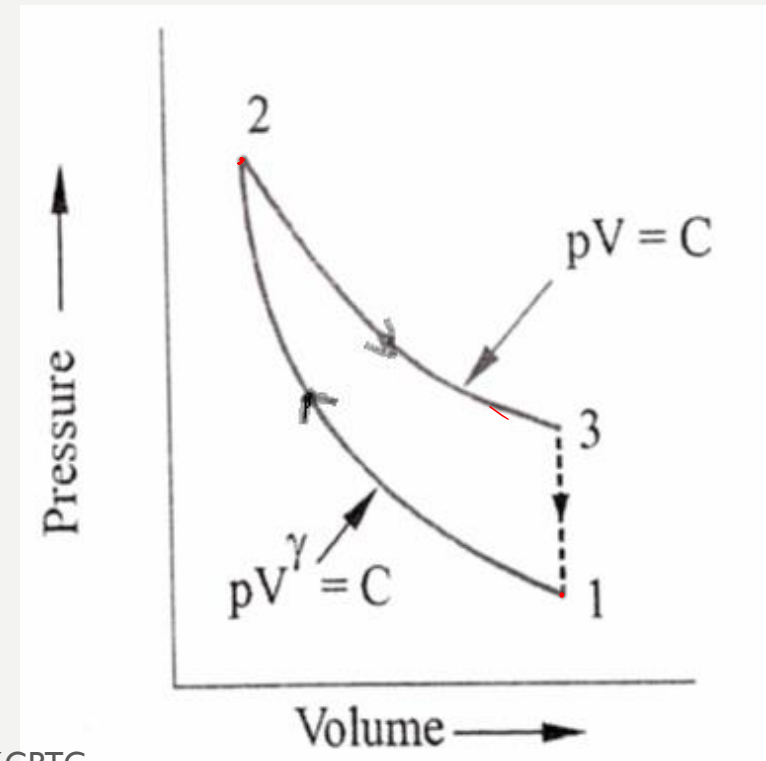
$$C_v = 0.72\text{ kJ/kgK}$$

- For an adiabatic process,  $\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^{\frac{1}{\gamma-1}}$
- From this,  $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$
- $\frac{513}{388} = (2)^{\gamma-1}$
- $1.322 = (2)^{\gamma-1}$
- $\ln 1.322 = \ln (2)^{\gamma-1}$
- $0.2791 = (\gamma - 1) \ln 2$
- $0.2791 = (\gamma - 1) \times 0.693$
- $(\gamma - 1) = 0.403$
- $\gamma = 1.4$
- $\gamma = \frac{C_p}{C_v}$
- $C_p = \gamma \times C_v = 1.4 \times 0.72 = 1.008 \text{ kJ/kgK}$

**Q.3.**  $3.5 \text{ m}^3$  of hydrogen gas at a pressure of  $100 \text{ kPa}$  and  $20^\circ \text{C}$  are compressed adiabatically to 4.5 times its original pressure. It is then expanded isothermally to its original volume. Determine the final pressure of the gas and the heat transferred. Also determine the quantity of heat that is to be exchanged to reduce the gas to its original pressure and volume. Take the specific heat at constant pressure for hydrogen as  $14.3 \text{ kJ/kgK}$ .

**Given data:**

- $V_1 = 3.5 \text{ m}^3 = V_3$
- $P_1 = 100 \text{ kPa} = 100 \times 10^3 \text{ N/m}^2$
- $= 10^5 \text{ N/m}^2$
- $T_1 = 20^\circ \text{C} = 20 + 273 = 293 \text{ K}$
- $T_2 = T_3$
- $P_2 = 4.5 P_1$
- $= 4.5 \times 10^5 \text{ N/m}^2$
- $C_p = 14.3 \text{ kJ/kgK} = 14.3 \times 10^3 \text{ J/kgK}$



- First find  $V_2$ ,  $T_2$  and  $P_3$
- For the process 1-2 (adiabatic)

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

- From this,  $\frac{V_2}{V_1} = \left[\frac{P_1}{P_2}\right]^{\frac{1}{\gamma}}$

- $\frac{V_2}{3.5} = \left[\frac{10^5}{4.5 \times 10^5}\right]^{\frac{1}{1.4}}$

- $V_2 = 1.2 \text{ m}^3$

- Also,  $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

- $\frac{10^5 \times 3.5}{293} = \frac{4.5 \times 10^5 \times 1.2}{T_2}$

- $T_2 = 452.05 \text{ K} = T_3$

- For the process 2-3 (isothermal)

- $P_2 V_2 = P_3 V_3$

- $4.5 \times 10^5 \times 1.2 = P_3 \times 3.5$

- $P_3 = 154285.7 \text{ N/m}^2$

- To find the heat transferred

- For process 1-2 (adiabatic)

- ${}_1Q_2 = 0$

- For process 2-3 (isothermal expansion)

- ${}_2Q_3 = P_2 V_2 \ln\left(\frac{V_3}{V_2}\right)$

- $= 4.5 \times 10^5 \times 1.2 \times \ln\left(\frac{3.5}{1.2}\right)$

- $= 578038.36 \text{ J}$

- ${}_2Q_3 = 578.04 \text{ kJ}$

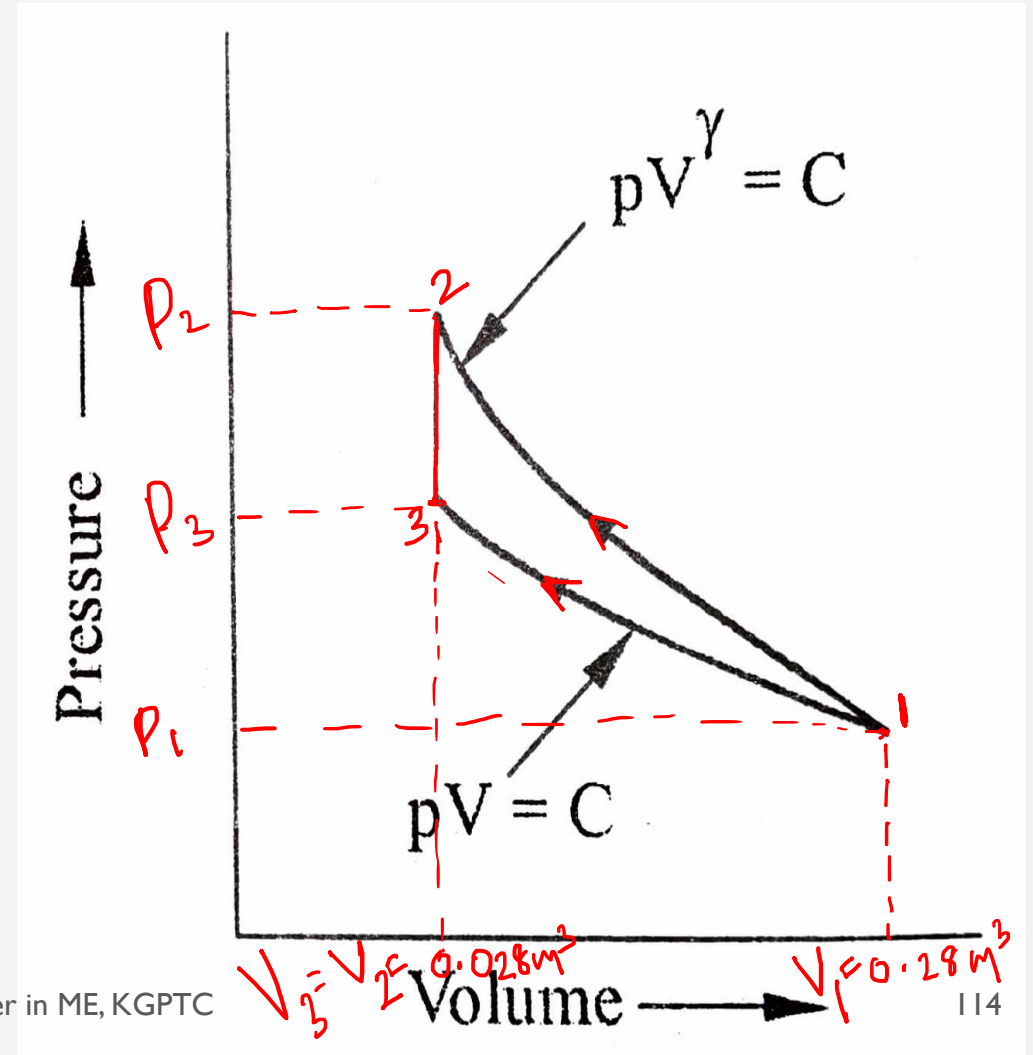


- For process 3-1 (isochoric)
- ${}_3Q_1 = {}_3W_1 + \Delta U$
- We know workdone during constant volume process,  ${}_3W_1 = 0$
- ${}_3Q_1 = \Delta U$
- $\Delta U = mC_v(T_1 - T_3)$
- ${}_3Q_1 = mC_v(T_1 - T_3)$
- Find 'm' and  $C_v$
- $P_1V_1 = mRT_1$
- Find R
- $R = \frac{R_u}{M}$
- Molecular weight of hydrogen,  $M = 2$
- $R = \frac{8314}{2}$
- $R = 4157 \text{ J/kgK}$
- $P_1V_1 = mRT_1$
- $10^5 \times 3.5 = m \times 4157 \times 293$
- $m = 0.28 \text{ kg}$
- $C_p - C_v = R$
- $14.3 \times 10^3 - C_v = 4157$
- $C_v = 10143 \text{ J/kgK}$
- $= 10.14 \text{ kJ/kgK}$
- ${}_3Q_1 = mC_v(T_1 - T_3)$
- $= 0.28 \times 10143 \times (293 - 452.05)$
- $= - 451708.36 \text{ J}$
- ${}_3Q_1 = - 451.71 \text{ kJ}$

**Q.4.** Find the difference between the workdone in compressing  $0.28 \text{ m}^3$  of air at a pressure of  $1.4 \text{ bar}$  to a volume of  $0.028 \text{ m}^3$  when the compression is adiabatic and isothermal.

**Given data:**

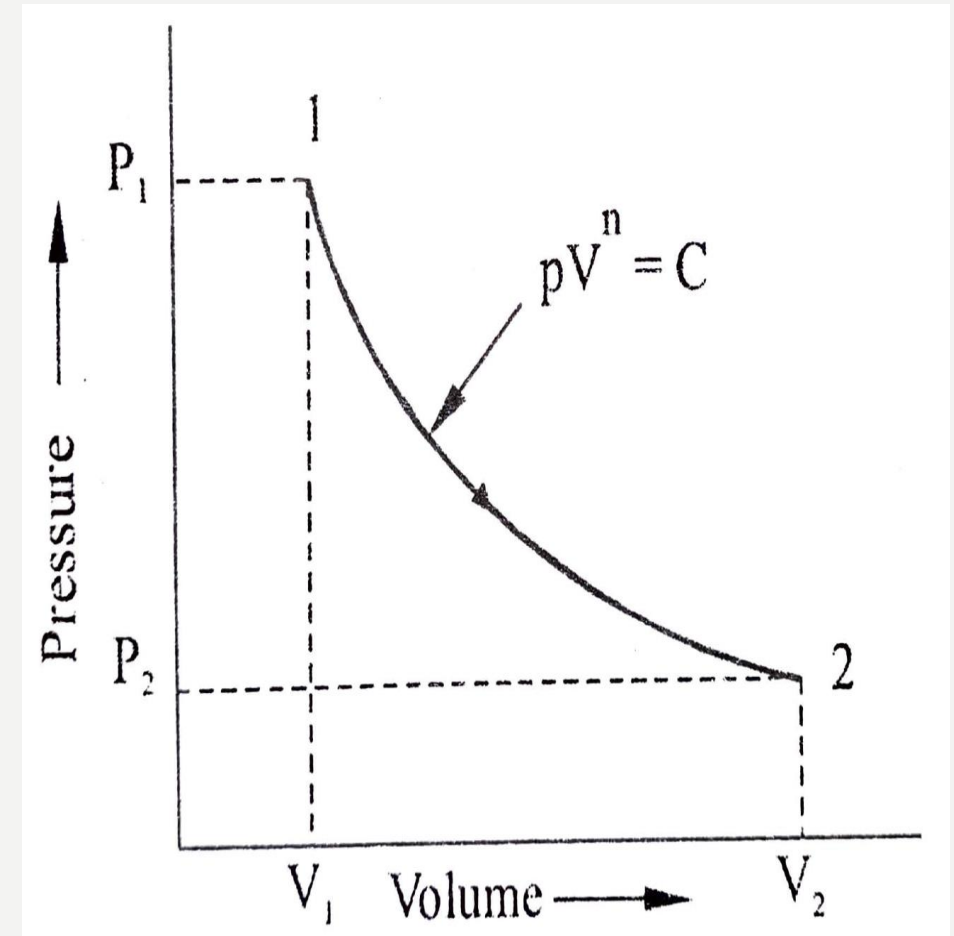
- $V_1 = 0.28 \text{ m}^3$
- $P_1 = 1.4 \text{ bar} = 1.4 \times 10^5 \text{ N/m}^2$
- $V_2 = 0.028 \text{ m}^3 = V_3$
- For the adiabatic process 1-2,
- $P_1 V_1^\gamma = P_2 V_2^\gamma$
- For air,  $\gamma = 1.4$
- $1.4 \times 10^5 \times 0.28^{1.4} = P_2 \times 0.028^{1.4}$
- $P_2 = 35.16 \times 10^5 \text{ N/m}^2$
- $= 35.16 \text{ bar}$



- Workdone during adiabatic process 1-2,
- ${}_1W_2 = \frac{(P_1V_1 - P_2V_2)}{(\gamma - 1)}$
- $= \frac{(1.4 \times 10^5 \times 0.28 - 35.16 \times 10^5 \times 0.028)}{(1.4 - 1)}$
- ${}_1W_2 = -148120 \text{ J}$
- Workdone during isothermal process 1-3,
- ${}_1W_3 = P_1V_1 \ln \left( \frac{V_3}{V_1} \right)$
- $= 1.4 \times 10^5 \times 0.28 \times \ln \left( \frac{0.028}{0.28} \right)$
- ${}_1W_3 = -90261.33 \text{ J}$
- Difference between workdone =  $148120 - 90261.33$
- $= 57858.67 \text{ J}$

# POLYTROPIC PROCESS

- In this process both volume and pressure changes in a certain specified manner.
- It follows the law,
- $PV^n = C$
- $n$  = polytropic index of expansion or compression.



## 1) P-V-T Relationship

### a) Relation between P & V

- For an adiabatic process,
- $P_1 V_1^n = P_2 V_2^n$
- $\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n \dots \dots \dots (1)$

### b) Relation between P & T

- From equation (1),  $\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$
- For a perfect gas,  $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
- $\frac{V_2}{V_1} = \frac{P_1}{P_2} \times \frac{T_2}{T_1}$
- $\frac{P_1}{P_2} \times \frac{T_2}{T_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$

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

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

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

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

$$\bullet \frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\frac{n}{n-1}} \dots \dots \dots (2)$$

### c) Relation between V & T

- Equating equation (1) and (2)

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

- $\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^{\frac{1}{n-1}} \dots \dots \dots (3)$

### 2) Workdone

- ${}_1W_2 = \int_1^2 P dv$

- For an adiabatic process,

- $PV^n = C$

- $P = \frac{C}{V^n}$

- ${}_1W_2 = \int_1^2 \frac{C}{V^n} dv$

- $= C \int_1^2 \frac{dV}{V^n}$

- $= C \int_1^2 V^{-n} dV$

- $= C \left[ \frac{V^{-n+1}}{-n+1} \right]_1^2$

- $= \frac{C}{1-n} [V_2^{1-n} - V_1^{1-n}]$

- $= \frac{1}{1-n} [C \times V_2^{1-n} - C \times V_1^{1-n}]$

- $= \frac{1}{1-n} [P_2 V_2^n \times V_2^{1-n} - P_1 V_1^n \times V_1^{1-n}]$

- $= \frac{1}{1-n} [P_2 V_2^{(n+1-n)} - P_1 V_1^{(n+1-n)}]$

- $= \frac{1}{1-n} [P_2 V_2 - P_1 V_1]$

- $= \frac{-(P_1 V_1 - P_2 V_2)}{-(n-1)}$

- ${}_1W_2 = \frac{(P_1 V_1 - P_2 V_2)}{(n-1)}$

- ${}_1W_2 = \frac{(mRT_1 - mRT_2)}{(n-1)}$

- ${}_1W_2 = \frac{mR(T_1 - T_2)}{(n-1)}$

### 3) Change in internal energy

- $\Delta U = mC_v(T_2 - T_1)$

### 4) Heat supplied

- According to first law of thermodynamics,

- ${}_1Q_2 = {}_1W_2 + \Delta U$

- ${}_1Q_2 = \frac{mR(T_1 - T_2)}{(n-1)} + mC_v(T_2 - T_1)$

- $= m(T_1 - T_2) \left[ \frac{R}{(n-1)} - C_v \right]$

- We know,  $C_v = \frac{R}{\gamma-1}$

- ${}_1Q_2 = m(T_1 - T_2) \left[ \frac{R}{(n-1)} - \frac{R}{(\gamma-1)} \right]$

- ${}_1Q_2 = mR(T_1 - T_2) \left[ \frac{(\gamma-1) - (n-1)}{(n-1)(\gamma-1)} \right]$

- $= mR(T_1 - T_2) \left[ \frac{\gamma-1-n+1}{(n-1)(\gamma-1)} \right]$

- $= mR(T_1 - T_2) \left[ \frac{\gamma-n}{(n-1)(\gamma-1)} \right]$

- ${}_1Q_2 = \frac{\gamma-n}{(\gamma-1)} \times \frac{mR(T_1 - T_2)}{(n-1)}$

- ${}_1Q_2 = \frac{\gamma-n}{(\gamma-1)} \times {}_1W_2$

- *Expression for polytropic index*

- For a polytropic process,

- $P_1 V_1^n = P_2 V_2^n$

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

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

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



**Q.1.** 1 kg of air at a pressure of 6 bar and a temperature of 40<sup>0</sup> C expands to a pressure of 1 bar according to the law  $PV^{1.3} = \text{Constant}$ . Determine (i) change in internal energy (ii) workdone (iii) heat supplied. Assume  $R = 287 \text{ J/kgK}$  and  $C_v = 0.718 \text{ kJ/kgK}$ .

**Given data:**

- $m = 1 \text{ kg}$
- $P_1 = 6 \text{ bar} = 6 \times 10^5 \text{ N/m}^2$
- $T_1 = 40^0 \text{ C} = 40 + 273 = 313 \text{ K}$
- $P_2 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$
- $PV^{1.3} = \text{Constant}$
- $n = 1.3$
- $R = 287 \text{ J/kgK}$
- $C_v = 0.718 \text{ kJ/kgK} = 718 \text{ J/kgK}$
- $\Delta U = ?$
- ${}_1W_2 = ?$
- ${}_1Q_2 = ?$
- For a polytropic process,
- $\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\frac{n}{n-1}}$
- From the above equation,
- $\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}}$
- $\frac{313}{T_2} = \left(\frac{6 \times 10^5}{1 \times 10^5}\right)^{\frac{1.3-1}{1.3}}$
- $T_2 = 207 \text{ K}$
- $P_1 V_1 = mRT_1$
- $6 \times 10^5 \times V_1 = 1 \times 287 \times 313$
- $V_1 = 0.1497 \text{ m}^3$

- For a polytropic process,

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

- From this,  $\frac{V_2}{V_1} = \left[\frac{P_1}{P_2}\right]^{\frac{1}{n}}$

- $\frac{V_2}{0.1497} = \left[\frac{6 \times 10^5}{1 \times 10^5}\right]^{\frac{1}{1.3}}$

- $V_2 = 0.594 \text{ m}^3$

(i)  $\Delta U = mC_v(T_2 - T_1)$

- $= 1 \times 718 (207 - 313)$

- $= - 76108 \text{ J}$

- $= - 76.11 \text{ kJ}$

(ii)  ${}_1W_2 = \frac{mR(T_1 - T_2)}{(n-1)}$

- $= \frac{1 \times 287(313 - 207)}{(1.3 - 1)}$

- $= 101406.6 \text{ J}$

- ${}_1W_2 = 101.41 \text{ kJ}$

(iii)  ${}_1Q_2 = \frac{\gamma - n}{(\gamma - 1)} \times {}_1W_2$

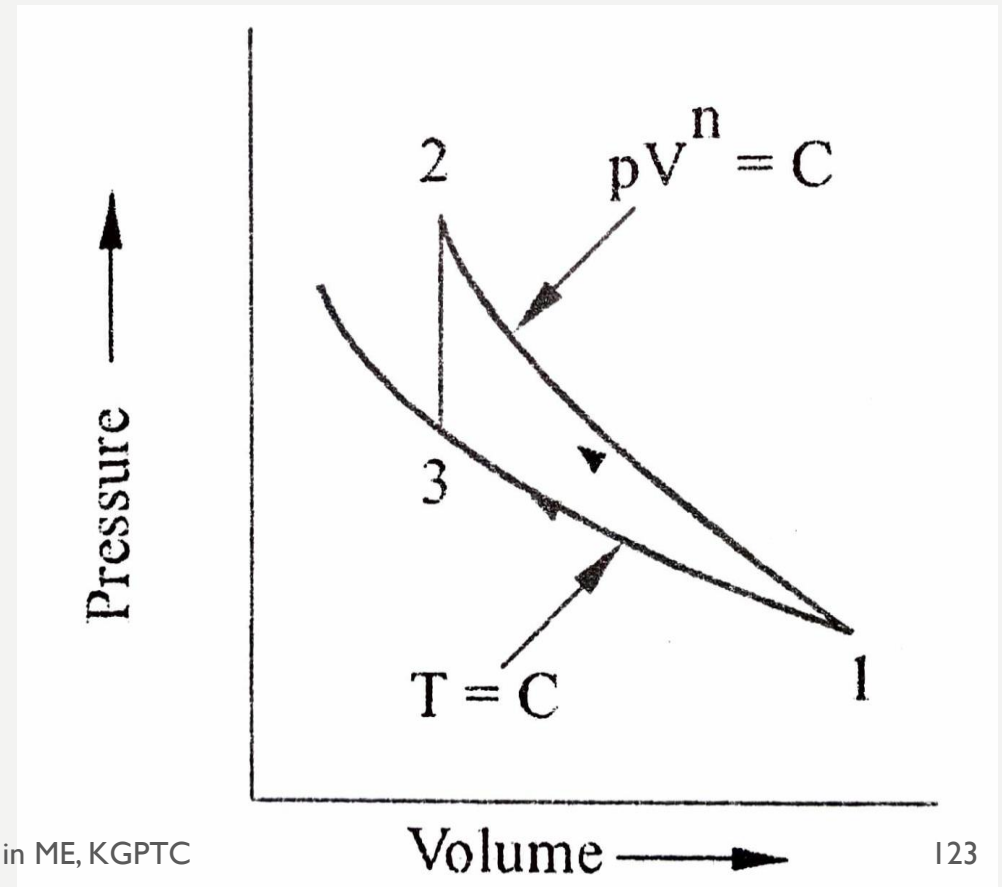
- $= \frac{1.4 - 1.3}{(1.4 - 1)} \times 101.41$

- ${}_1Q_2 = 25.35 \text{ kJ}$

**Q.2.** A certain quantity of air has a volume of  $0.028 \text{ m}^3$  at a pressure of  $1.25 \text{ bar}$  and  $25^\circ \text{ C}$ . It is compressed to a volume of  $0.0042 \text{ m}^3$  according to the law  $PV^{1.3} = \text{Constant}$ . Determine the final temperature and workdone during compression. Also determine the reduction in pressure at a constant volume required to bring the air back to its original temperature. (Oct 2018 – 8 marks)

**Given data:**

- $V_1 = 0.028 \text{ m}^3$
- $P_1 = 1.25 \text{ bar} = 1.25 \times 10^5 \text{ N/m}^2$
- $T_1 = 25^\circ \text{ C} = 25 + 273 = 298 \text{ K}$
- $V_2 = 0.0042 \text{ m}^3 = V_3$
- $PV^{1.3} = \text{Constant}$
- $n = 1.3$
- $T_2 = ?$ ,  ${}_1W_2 = ?$ ,  $P_2 - P_3 = ?$



- For a polytropic process 1-2

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

- From this,  $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n-1}$

- $\frac{298}{T_2} = \left(\frac{0.0042}{0.028}\right)^{1.3-1}$

- $T_2 = 526.49 \text{ K}$

- $= 526.49 - 273$

- $T_2 = 253.49^\circ \text{ C}$

- For a polytropic process 1-2

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

- $\frac{1.25 \times 10^5}{P_2} = \left(\frac{0.0042}{0.028}\right)^{1.3}$

- $P_2 = 1472283.26 \text{ N/m}^2$

- $P_2 = 14.72 \text{ bar}$

- For the process 1-3 (isothermal)

- $P_1 V_1 = P_3 V_3$

- $1.25 \times 10^5 \times 0.028 = P_3 \times 0.0042$

- $P_3 = 833333 \text{ N/m}^2$

- $P_3 = 8.33 \text{ bar}$

- Workdone,  $_1W_2 = \frac{(P_1 V_1 - P_2 V_2)}{(n-1)}$

- $= \frac{(1.25 \times 10^5 \times 0.028 - 14.72 \times 10^5 \times 0.0042)}{(1.3-1)}$

- $= - 8941.3 \text{ J}$

- $_1W_2 = - 8.941 \text{ kJ}$

- Reduction in pressure,  $P_2 - P_3 = 14.72 - 8.33$

$$P_2 - P_3 = 6.39 \text{ bar}$$

**Q.3.** Some amount of gas is compressed according to the law  $PV^{1.37} = C$ . Before compression, the pressure and temperature are 1 bar and 316 K respectively. The compression ratio is 13.5. Find (i) pressure at the end of compression. (ii) temperature at the end of compression. (iii) workdone per kg during compression. Take  $R = 289 \text{ J/kgK}$ . (October 2017 – 8 marks)

**Given data:**

- $PV^{1.37} = C$
- $n = 1.37$
- $P_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$
- $T_1 = 316 \text{ K}$
- Compression ratio,  $\frac{V_1}{V_2} = 13.5$
- $R = 289 \text{ J/kgK}$
- $P_2 = ?, T_2 = ?, {}_1W_2 = ?$
- For a polytropic process,
- $\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n$
- $\frac{1 \times 10^5}{P_2} = \left(\frac{1}{13.5}\right)^{1.37}$
- $P_2 = 3536366.459 \text{ N/m}^2$
- $P_2 = 35.36 \text{ bar}$

- For a polytropic process 1-2,

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

- From this,  $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n-1}$

- $\frac{316}{T_2} = \left(\frac{1}{13.5}\right)^{1.37-1}$

- $T_2 = 827.77 \text{ K}$

- $= 827.77 - 273$

- $T_2 = 554.77^\circ \text{ C}$

- Workdone,  ${}_1W_2 = \frac{mR(T_1 - T_2)}{(n-1)}$

- Workdone/kg,  $m = 1 \text{ kg}$

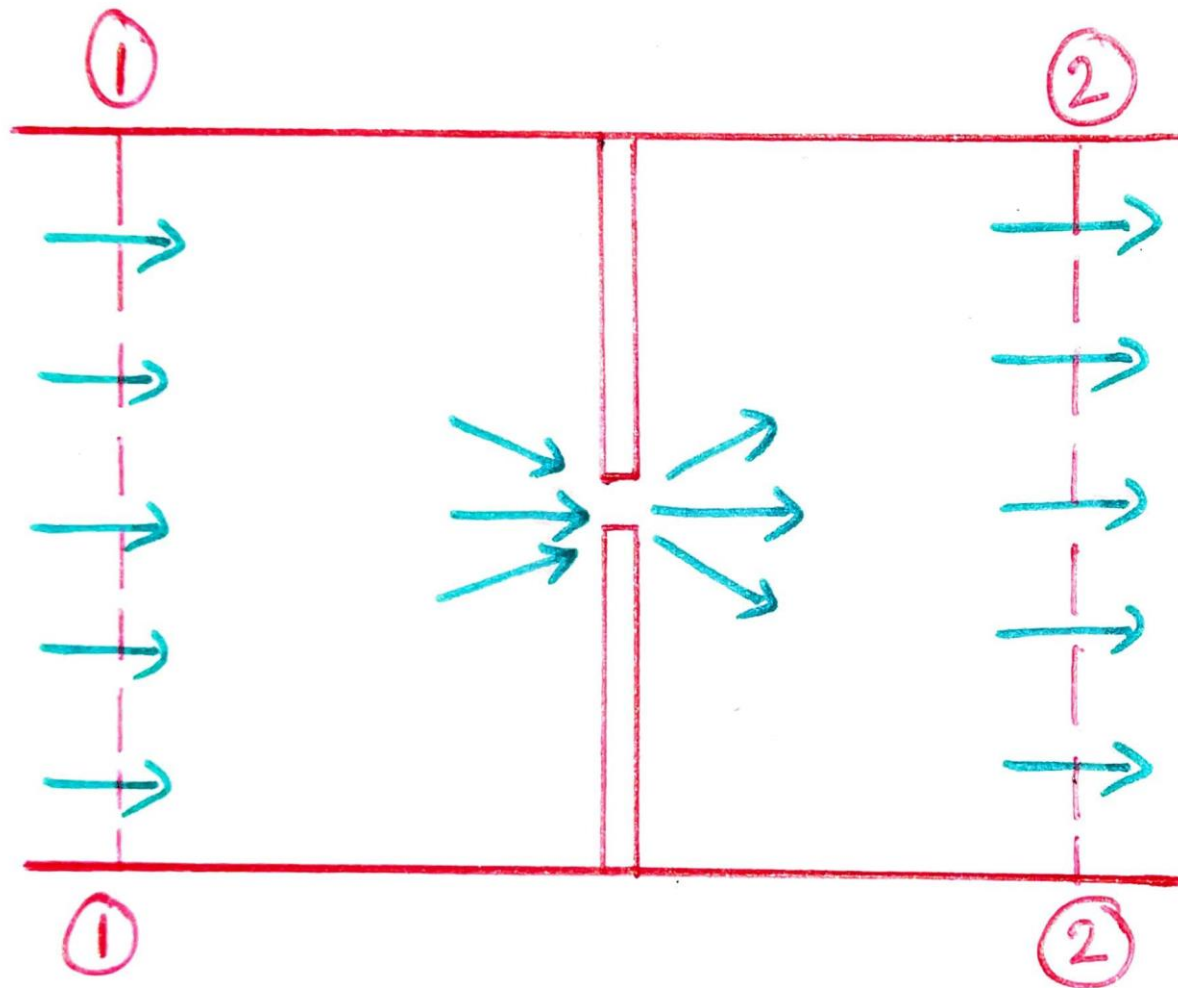
- Workdone/kg,  $= \frac{1 \times 289 (316 - 827.77)}{(1.37 - 1)}$

- $= - 399733.86 \text{ J}$

- ${}_1W_2 = - 399.73 \text{ kJ}$

# THROTTLING PROCESS

- A throttling process is one in which a gas expands through a minute aperture such as a narrow throat, slightly opened valve or leaking valve etc.
- Leak of a gas through a crack in a pipe is a good example for throttling process.
- Due to fall in pressure the gas should come out with large velocity.
- But due to the frictional resistance between the gas and the valve there is no considerable change in velocity and converts the kinetic energy into heat, which warms up the gas to its initial temperature.



$$W=0, Q=0$$



- It is an irreversible process in which the pressure of gas decreases without performing external work.
- During this process, no heat is supplied or rejected.
- ie,  $W = 0$
- $Q = 0$
- Also the enthalpy does not change during throttling process.
- Ie, throttling process is often referred as isenthalpic process.
- ie,  $h_1 = h_2$