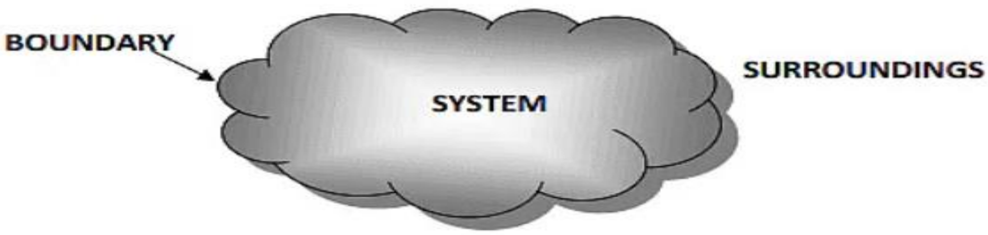
THERMODYNAMICS

Module 1: Introduction and basic concepts of thermodynamics

Content: Systems and control volume, properties of a system, state and equilibrium, quasi-static equilibrium, processes and cycles, forms of energy, pressure, work and heat transfer, temperature and the Zeroth law of thermodynamics.

Thermodynamics is a science of energy transfer and its effect on the properties of a system. It describes state and changes in state of physical systems.

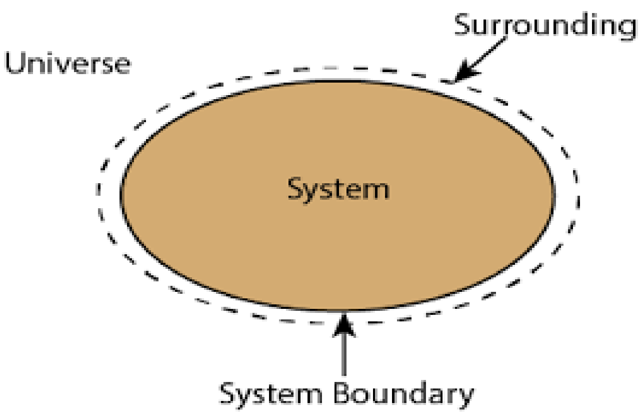
System: A thermodynamic system is defined as a quantity of matter or a region in space which is selected for the study.



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

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

Universe: A system and its surroundings together constitute the universe. Everything is contained in the universe, so everything occurring whether energy transfer or transformation or losses remains inside the universe.



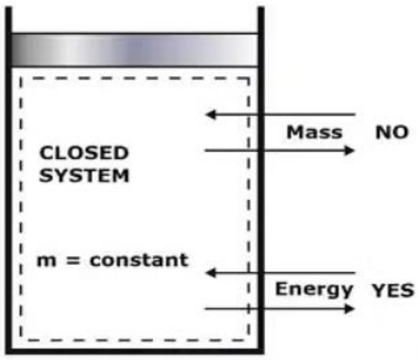
TYPES OF THERMODYNAMIC SYSTEM

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

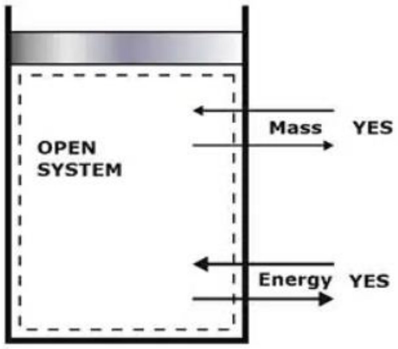
Closed System: A system in which the transfer of energy but not mass can take place across the boundary is called closed system. The mass inside the closed system remains constant.

Example- Tea in the kettle, automobile engine with the valve closed etc.



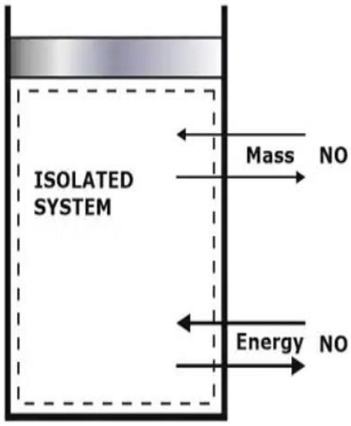
Open system: A system in which the transfer of both mass and energy takes place is called an open system. This system is also known as control volume.

Example - air compressor, boiler, pump, IC engine with the valve open, etc.
The majority of engineering devices come under this category.



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

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 flak is an isolated system.



CONTROL VOLUME

- It's 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- It's 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.

Examples:

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.

Macroscopic v/s Microscopic Approach

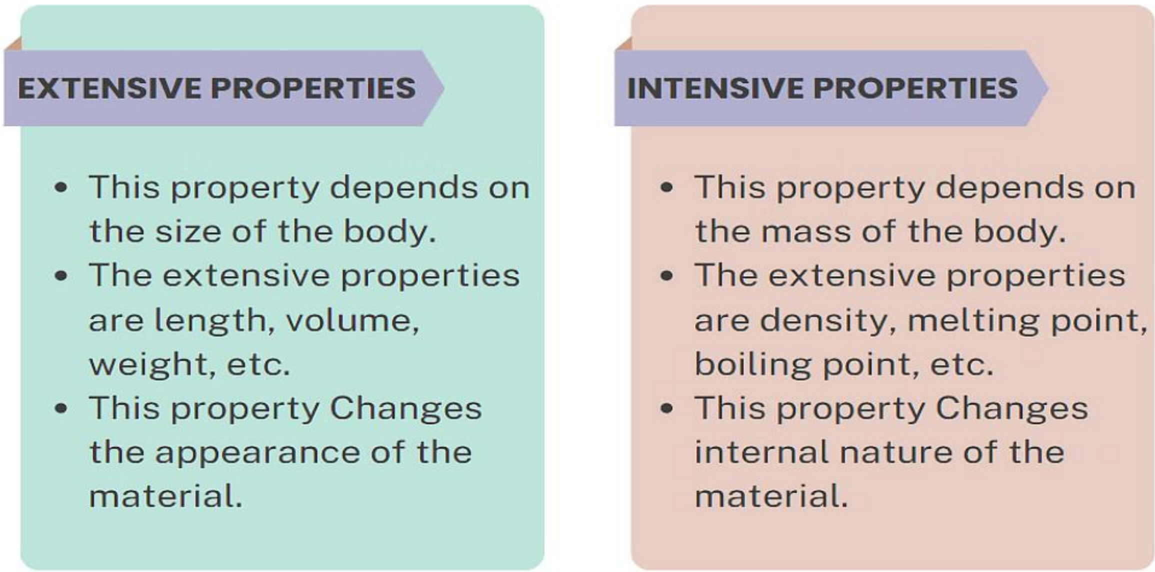
Macroscopic Approach – When a certain quantity of matter is considered, without getting into molecular level, such systems are called Isolated systems (also called as classical approaches). Every property will be the average of that property of each molecule passing through that space.

Example: Measuring the pressure of a gas in a cylinder using a pressure gauge.

Microscopic Approach - When the study is made on a molecular level as the matter is composed of a large number of molecules, such approach is called a microscopic approach. The behaviour of the gas is determined by considering the behaviour of each molecule.
Example: Using kinetic theory to determine the pressure of a gas by analyzing the motion of molecules.

Note: The **concept of continuum** assumes that a material is continuous and homogeneous, with no gaps or voids, even at a microscopic level. This means the properties of the material (like density, pressure, temperature) are uniformly distributed and can be described by continuous functions of space and time.

Extensive Properties v/s Intensive Properties



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.

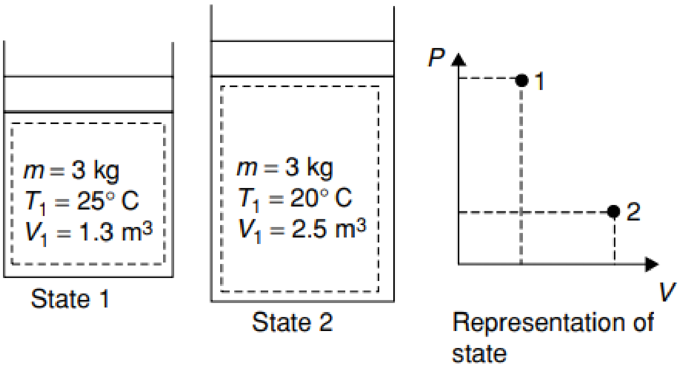
A thermodynamic system will be in a state of thermodynamic equilibrium if the system is the state of Mechanical equilibrium, Chemical equilibrium and Thermal equilibrium.

- **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, PROCESS & CYCLE

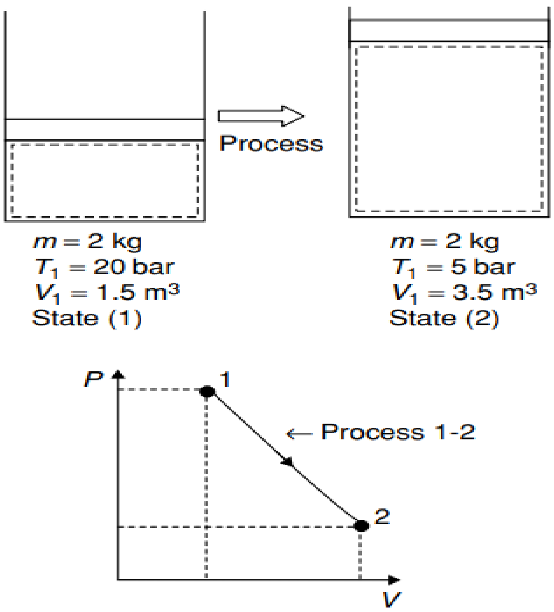
State: The thermodynamic state of a system is defined by specifying values of a set of measurable properties sufficient to determine all other properties.

Example: The state of an electric battery requires the specification of the amount of electric charge it contains.



Process and Cycle

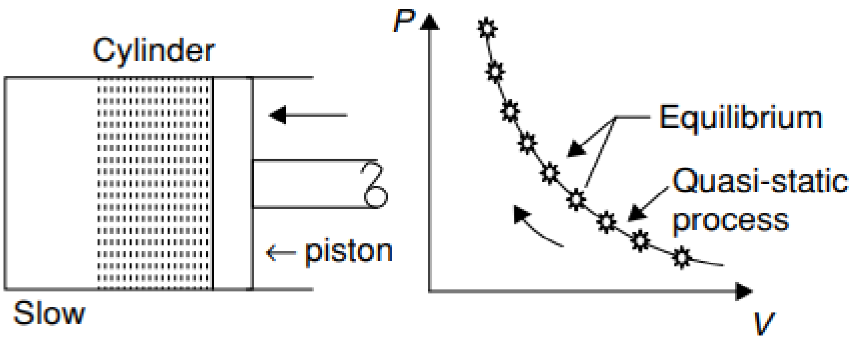
When an interaction between systems and surrounding takes place, the properties of that particular system changes from one equilibrium condition (state 1) to another equilibrium condition (state 2). This change in property of the system is termed as 'process' and the series of the equilibrium condition (state) which the systems is going through is termed as 'path'. Example: Let a system, changes its state from (1) to state 2, as shown in figure



Quasi-equilibrium (Quasi-static) Process

If a process is followed by succession of equilibrium states, it is known as Quasti-static process.

Example: Let us consider a very slow compression process in which equilibrium is attained at any intermediate state.

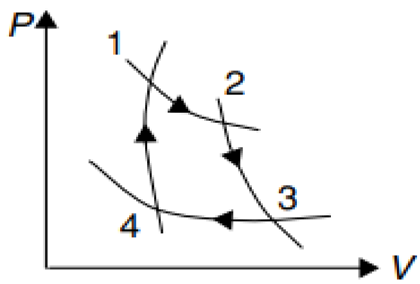


Important

- A Quasistatic process is also called reversible process.
- Reversible process can be represented by continuous line.

Thermodynamic Cycle

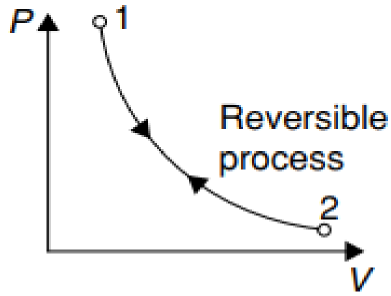
A series of processes can be put together such that the system returns to initial state. This series of processes is called a thermodynamic cycle.



In the above diagram 1 – 2, 2 – 3, 3 – 4, 4 – 1 represent processes and 1 – 2 – 3 – 4 represents a thermodynamic cycle.

Reversible Process

A process is said to be reversible process if when reversed in direction follows the same path as that of the forward path without leaving any effect on system and surroundings.



Example:

1. Frictionless relative motion.
2. Extension and compression of spring.
3. Frictionless adiabatic expansion or compression.
4. Polytrophic expansion or compression of a fluid.
5. Isothermal expansion or compression.
6. Electrolysis

Irreversible Process

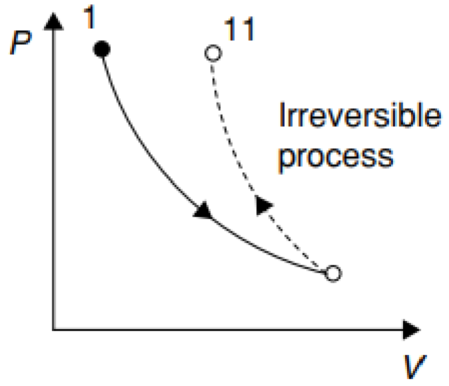
A process which is not reversible is an irreversible process. Friction is the main cause of irreversibility.

Or

A process is irreversible if a system passes through a sequence of non-equilibrium states.

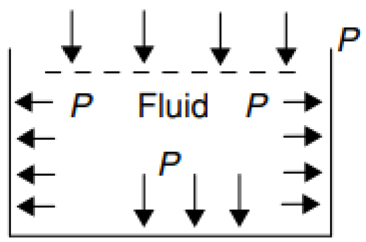
Example:

1. 1.Fluid flow with friction
2. Combustion of air and fuel
3. Diffusion of gases.
4. Throttling
5. Free expansion
6. Heat transfer



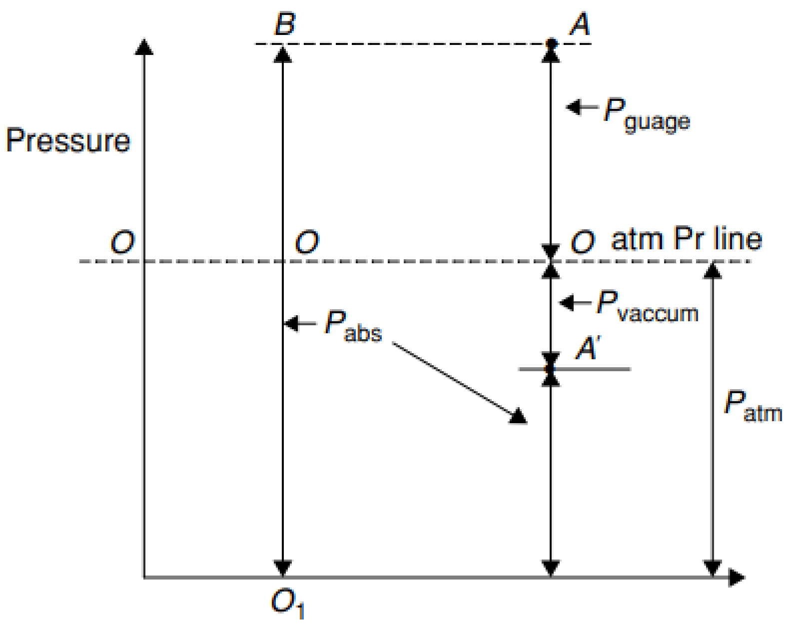
PRESSURE

Force per unit area exerted by fluid normal to the surface is called pressure.



Various Forms of Pressure

1. **Atmospheric Pressure (Patm):** Normal pressure measured by barometer in the atmosphere is called atmospheric pressure.



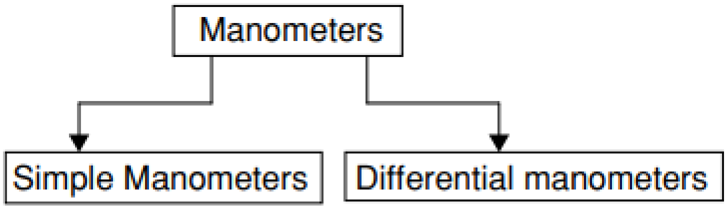
2. **Gauge Pressure (P gauge):** Pressure measured with respect to atmospheric pressure is called gauge pressure.

- Gauge pressure may be positive or negative.
- If the pressure lies above atmospheric pressure (i.e., at point A shown in figure) is called gauge pressure which is positive.
- If the pressure lies below atmospheric pressure (i.e., at point A′ as shown in figure) is called vacuum pressure which is negative.

3. **Absolute Pressure (Pabs):** The pressure measure with respect to absolute zero pressure is called absolute pressure.

$$\boxed{P_{\text{abs}} = P_{\text{atm}} + P_{\text{gauge}}}$$

Manometers: It is an instrument used to measure the pressure.



- Simple manometers measures pressure at single point.
- Differential manometers measure the difference in pressure between two points.

Problem: A 30 m high vertical column of a fluid of density 1878 kg/m3 exists in a place where g = 9.65 m/s2. What is the pressure at the base of the column.

Solution:

p = zρg

= 30 × 1878 × 9.65 Pa

= 543.681 kPa

Energy Transfer

A closed system and its surroundings can interact in two ways.

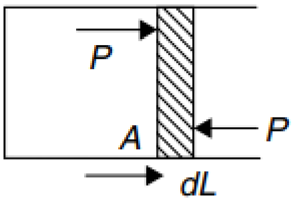
1. By work transfer
2. By heat transfer

These are called as energy interactions and these bring about changes in the properties of the system.

Work Transfer

In mechanics, work is defined as the product of force (F) and the distance (dL) moved in the direction of force.

$$\boxed{dW = F \cdot dL}$$



Consider a piston-cylinder mechanism which is shown above. A pressure 'P' of the gas inside the cylinder is acting on a cross-sectional area 'A'. Then the force acting on the piston is PA. This force is balanced by an external opposing force. If the piston is allowed to move a distance 'dL' under these conditions such that opposing force is balanced by the gas pressure, then infinitesimal work done by the gas is given by

$$\begin{aligned} dW &= FdL \\ &= PA\, dL \\ &= pdV \end{aligned}$$

If there are two states 1 and 2, then the total work done is given by

$$\boxed{W = \int_1^2 PdV}$$

for non-flow process.

Problem: **The piston of an oil engine, of area 0.0045 m2, moves downwards 75 mm, drawing in 0.00028 m3 of fresh air from the atmosphere. The pressure in the cylinder is uniform during the process at 80 kPa, while the atmospheric pressure is 101.325 kPa, the difference being due to the flow resistance in the induction pipe and the inlet valve. Estimate the displacement work done by the air finally in the cylinder.**

Solution:

(Ans. 27 J)

Volume of piston stroke

$= 0.0045 \times 0.075 m^3$

$= 0.0003375 m^3$

$\therefore \quad \Delta V = 0.0003375 \ m^3$

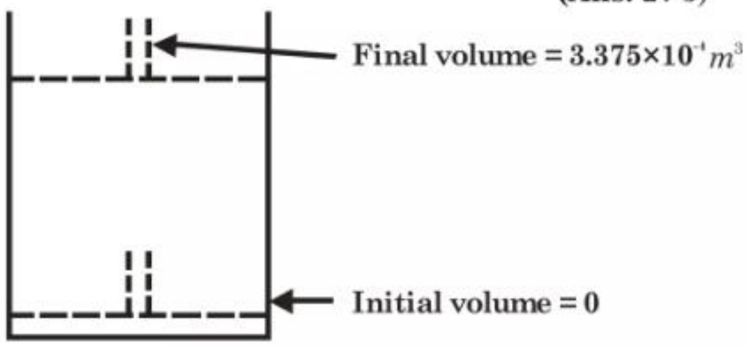
as pressure is constant

$= 80$ kPa

So work done $= p\Delta V$

$= 80 \times 0.0003375$ kJ

$= 0.027$ kJ $= 27$ J



Problem: **An engine cylinder has a piston of area 0.12 m3 and contains gas at a pressure of 1.5 MPa. The gas expands according to a process which is represented by a straight line on a pressure-volume diagram. The final pressure is 0.15 MPa. Calculate the work done by the gas on the piston if the stroke is 0.30 m.**

Solution:

(Ans. 29.7 kJ)

Initial pressure $(p_1) = 1.5$ MPa

Final volume $(V_1) = 0.12 m^2 \times 0.3 m$

$= 0.036 \ m^3$

Final pressure $(p_2) = 0.15$ MPa

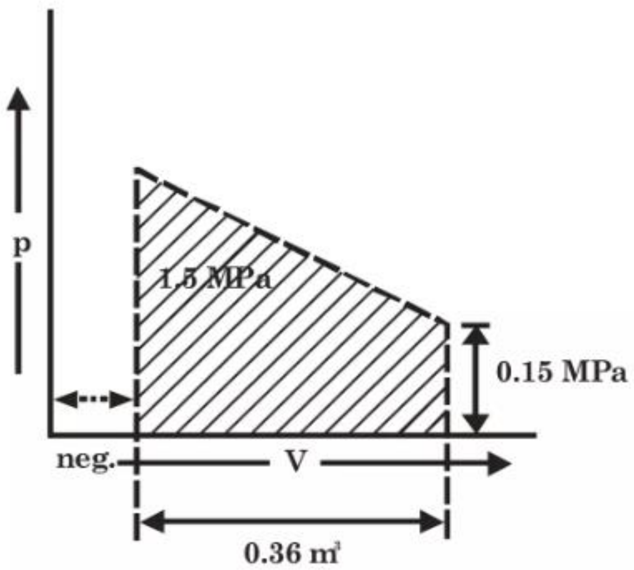
As initial pressure too high so the volume is neglected.

Work done = Area of pV diagram

$$= \frac{1}{2}(p_1 + p_2) \times V$$

$$= \frac{1}{2}(1.5 + 0.15) \times 0.036 \times 10^3 \ \text{kJ}$$

$$= 29.7 \ \text{kJ}$$



Problem: A mass of gas is compressed in a quasi-static process from 80 kPa, 0.1 m3 to 0.4 MPa, 0.03 m3. Assuming that the pressure and volume are related by pvn = constant, find the work done by the gas system.

Solution:

$$\text{Given initial pressure}(p_1) = 80\text{kPa}$$
$$\text{Initial volume}(V_1) = 0.1 \text{ m}^3$$

$$\text{Final pressure } (p_2) = 0.4 \text{ MPa} = 400 \text{ kPa}$$
$$\text{Final volume}(V_2) = 0.03 \text{ m}^3$$
$$\text{As p-V relation } pV^n = C$$
$$\therefore \quad p_1 V_1^n = p_2 V_2^n$$
taking $\log_e$ both side
$$\ln p_1 + n \ln V_1 = \ln p_2 + n \ln V_2$$
$$\text{or} \quad n[\ln V_1 - \ln V_2] = \ln p_2 - \ln p_1$$
$$\text{or} \quad n \ln\left(\frac{V_1}{V_2}\right) = \ln\left(\frac{p_2}{p_1}\right)$$
$$\text{or} \quad n = \frac{\ln\left(p_2/p_1\right)}{\ln\left(V_1/V_2\right)} = \frac{\ln\left(\frac{400}{80}\right)}{\ln\left(\frac{0.1}{0.03}\right)} = \frac{1.60944}{1.20397} \approx 1.3367 \approx 1.34$$
$$\therefore \quad \text{Work done}(W) = \frac{p_1 V_1 - p_2 V_2}{n-1}$$
$$= \frac{80 \times 0.1 - 400 \times 0.03}{1.34 - 1} = -11.764 \text{ kJ}$$

Problem: A mass of 1.5 kg of air is compressed in a quasi-static process from 0.1 MPa to 0.7 MPa for which pv = constant. The initial density of air is 1.16 kg/m3. Find the work done by the piston to compress the air.

Solution:

(Ans. 251.62 kJ)

For quasi-static process

Work done $= \int pdV$ [given $pV = C$

$= p_1V_1 \int_{V_1}^{V_2} \frac{dV}{V}$ $\therefore \quad p_1V_1 = pV = p_2V_2 = C$

$= p_1V_1 \ln\left(\frac{V_2}{V_1}\right)$ $\therefore \quad p = \frac{p_1V_1}{V}$

$= p_1V_1 \ln\left(\frac{p_1}{p_2}\right)$ $\therefore \quad \frac{p_1}{p_2} = \frac{V_2}{V_1}$

$= 0.1 \times 1.2931 \times \ln\left|\frac{0.1}{0.7}\right| \text{MJ}$ given $p_1 = 0.1$ MPa

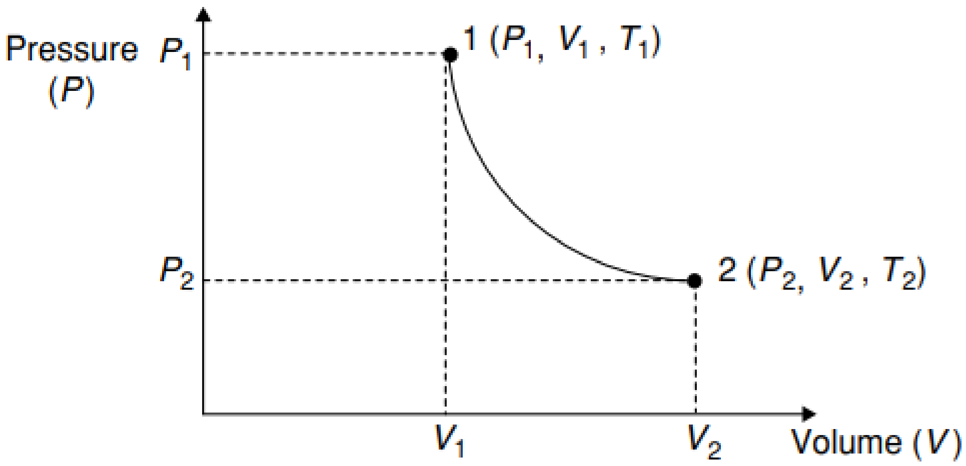
$= 251.63$ kJ $\quad V_1 = \frac{m_1}{\rho_1} = \frac{1.5}{1.16} \text{ m}^3$

$p_2 = 0.7$ MPa

Point and Path functions:

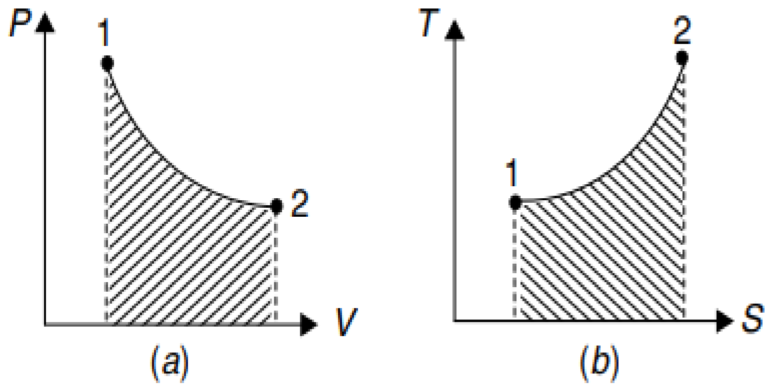
Point function does not depend on the history (or path) of the system. It only depends on the state of the system.

Examples: 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: work and heat.



(a) Area under P–V diagram = work transfer,

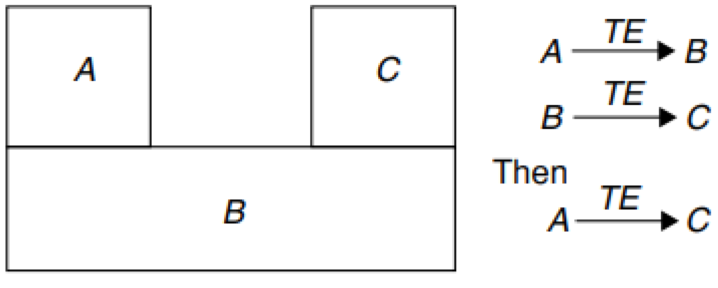
(b) Area under T–S diagram = heat transfer

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 defined in order to evaluate path functions.

Zeroth Law of Thermodynamics:

When a body A is in thermal equilibrium with body B and body B is in thermal equilibrium with body C separately, then A and C are in thermal equilibrium.



$$\frac{C}{5} = \frac{F - 32}{9}$$

Thermometry: The art of measurement of temperature is called thermometry.

Thermometric Property: The property which helps to determine the temperature is known as thermometric property.

Example: Pressure, volume, resistance, voltage, wavelength …etc

Problem: The temperature t on a thermometric scale is defined in terms of a property K by the relation t = a ln K + b Where a and b are constants. The values of K are found to be 1.83 and 6.78 at the ice point and the steam point, the temperatures of which are assigned the numbers 0 and 100 respectively. Determine the temperature corresponding to a reading of K equal to 2.42 on the thermometer.

Solution:

$t = a \ln x + b$

$0 = a \times \ln 1.83 + b$ … (i)

$100 = a \times \ln 6.78 + b$ … (ii)

Equation {(ii) – (i)} gives

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$$a \cdot \ln \cdot \left(\frac{6.78}{1.83}\right) = 100$$

$$\begin{aligned} a &= 76.35 \\ b &= -a \times \ln 1.83 \\ &= -46.143 \\ t &= 76.35 \ln k - 46.143 \\ t^* &= 76.35 \times \ln 2.42 - 46.143 \\ &= 21.33°C \end{aligned}$$

Problem: A new scale N of temperature is divided in such a way that the freezing point of ice is 100°N and the boiling point is 400°N. What is the temperature reading on this new scale when the temperature is 150°C? At what temperature both the Celsius and the new temperature scale reading would be the same?

Solution:

$$\frac{150-0}{100-0} = \frac{N-100}{400-100}$$

or $N = 550^{\circ} N$

let N= C for x°

then $\frac{C-0}{100-0} = \frac{N-100}{400-100}$

or $\frac{x}{100} = \frac{x-100}{300}$

or $x = \frac{x-100}{3}$

or $3x = x - 100$

or $2x = -100$

or $x = -50^{\circ} C$