Elements of Energy Systems (20IM3DCEES)

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Thermodynamics

- The branch of science that deals with energy levels and the transfer of energy between systems and between different states of matter

- **Thermodynamics** comes from the Greek words **therme** (Heat) and **dynamics** (Power).

  – Convert heat into power.

Engineering Thermodynamics

The **study of the science of thermodynamics** and the **usefulness** of this science in the design of each & every process, device or system **involving the effective utilization of energy and matter** for the benefit of mankind.

What is thermodynamics?

- The study of thermodynamics is concerned with energy is stored within a body and how energy transformations take place.

- **Approaches to study thermodynamics:**

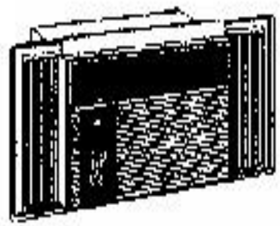
  - **Microscopic (Statistical thermodynamics)**
    - Study the behavior of each and every molecule and events occurring at their molecular level

  - **Macroscopic (Classical thermodynamics)**
    - Study the average effects of many molecule
    - These effects can be perceived by our senses and measured by instruments

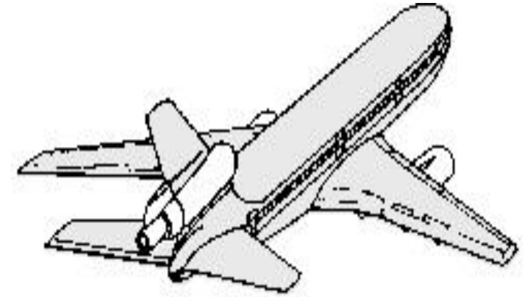
    Ex: Pressure, Temperature, etc

Applications of Thermodynamics

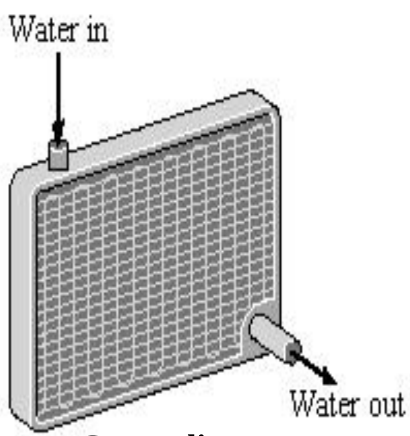
The human body



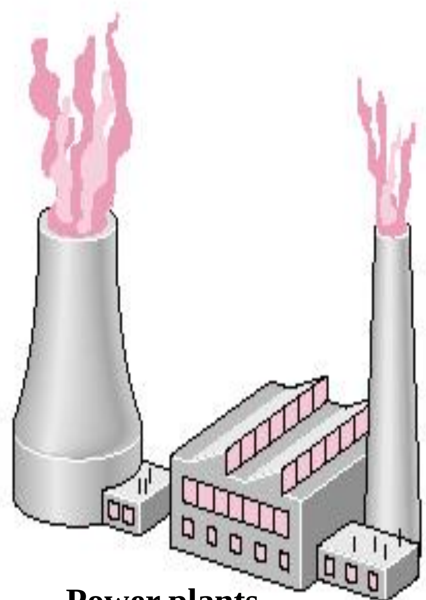
Air-conditioning systems



Airplanes



Car radiators



Power plants

Refrigeration systems

Thermodynamic System or System

Thermodynamic System

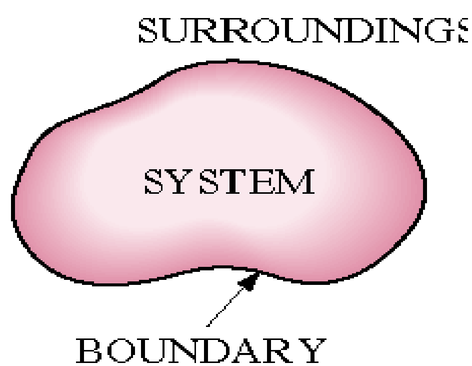
Quantity of matter or a region in space chosen for study

Surroundings

Physical space outside the system boundary

Boundary

Real or imaginary layer that separates the system from its surroundings



Types of Systems

1. Closed System

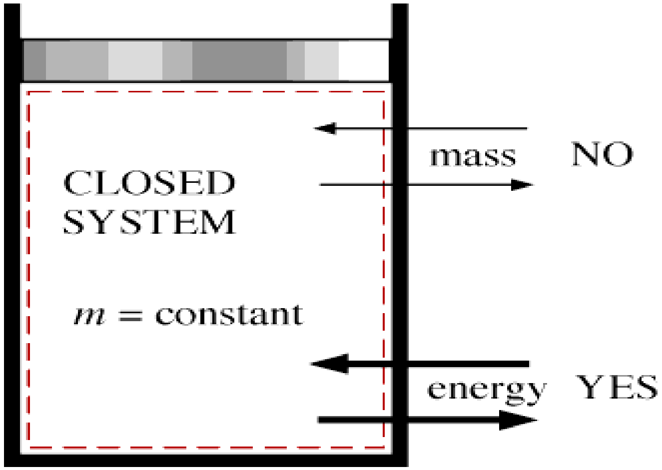
2. Open System

3. Isolated System

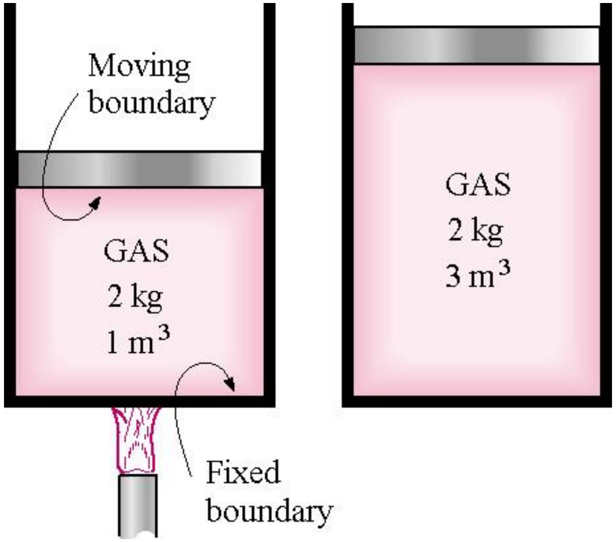
Closed System (Control Mass)

Energy, not mass, crosses closed-system boundaries

Closed Systems (fixed masses)

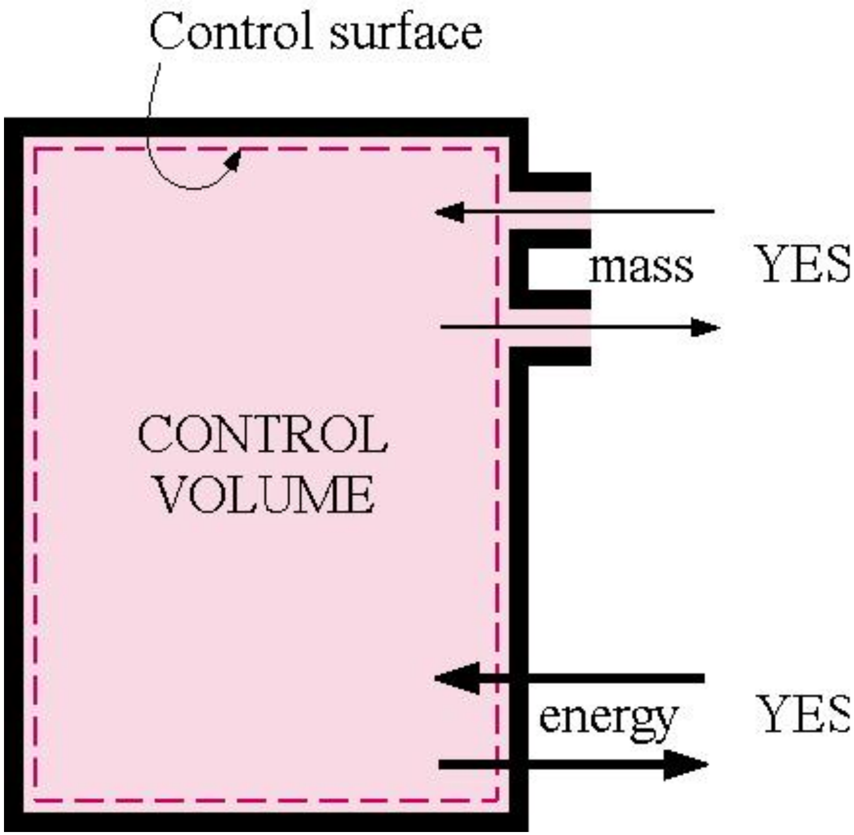


Closed System with Moving Boundary



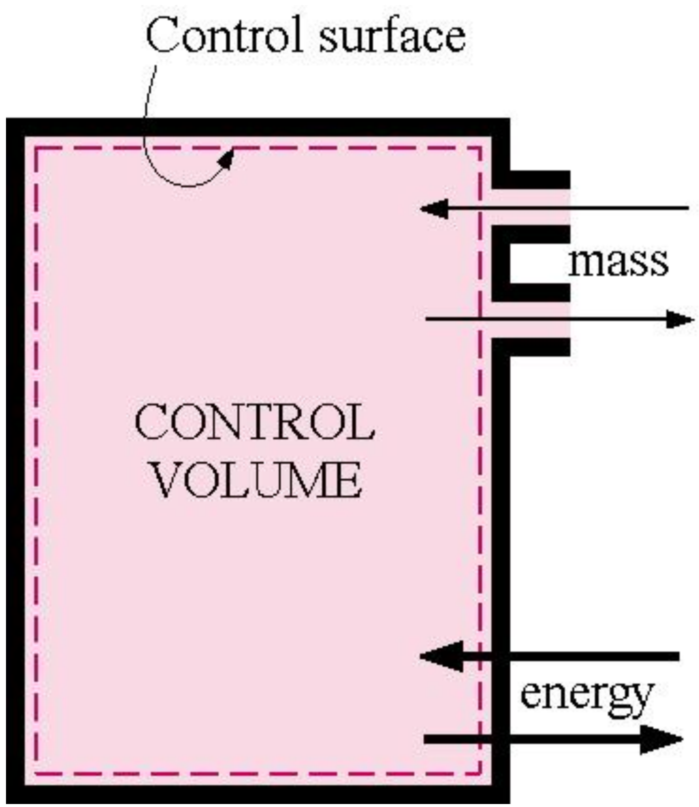
Open Systems (Control Volume)

Mass and Energy Cross Control Volume Boundaries



Isolated System

No Mass and Energy Cross the Control Volume Boundaries

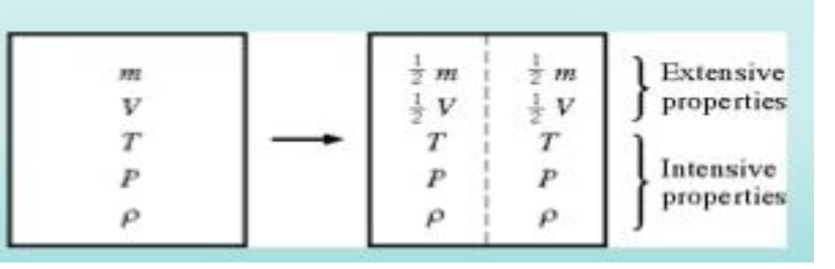


No

No

Properties of a system

Any characteristic of a system in equilibrium is called a property.



Types of properties

Extensive properties – depend on the size of the system

Examples: volume, mass, total energy

Intensive properties – independent of the size of the system

Examples: temperature, pressure, density

Extensive properties per unit mass are intensive properties

specific volume v = Volume/Mass = V/m

density ρ = Mass/Volume = m/V

State & Equilibrium

State: The condition of a system at any instant of time

State of a system:

System that is not undergoing any change

All properties of system are known & are not changing

If one property changes then the state of the system changes

Thermodynamic equilibrium:

"Equilibrium" - state of balance

A system is in equilibrium if it maintains thermal (uniform temperature), mechanical (uniform pressure), and chemical equilibrium

Adiabatic wall: Wall which is impermeable to the flow of heat

Diathermic wall: Wall which permits the flow of heat

Processes & Paths

Process:

When a system changes from one equilibrium state to another one

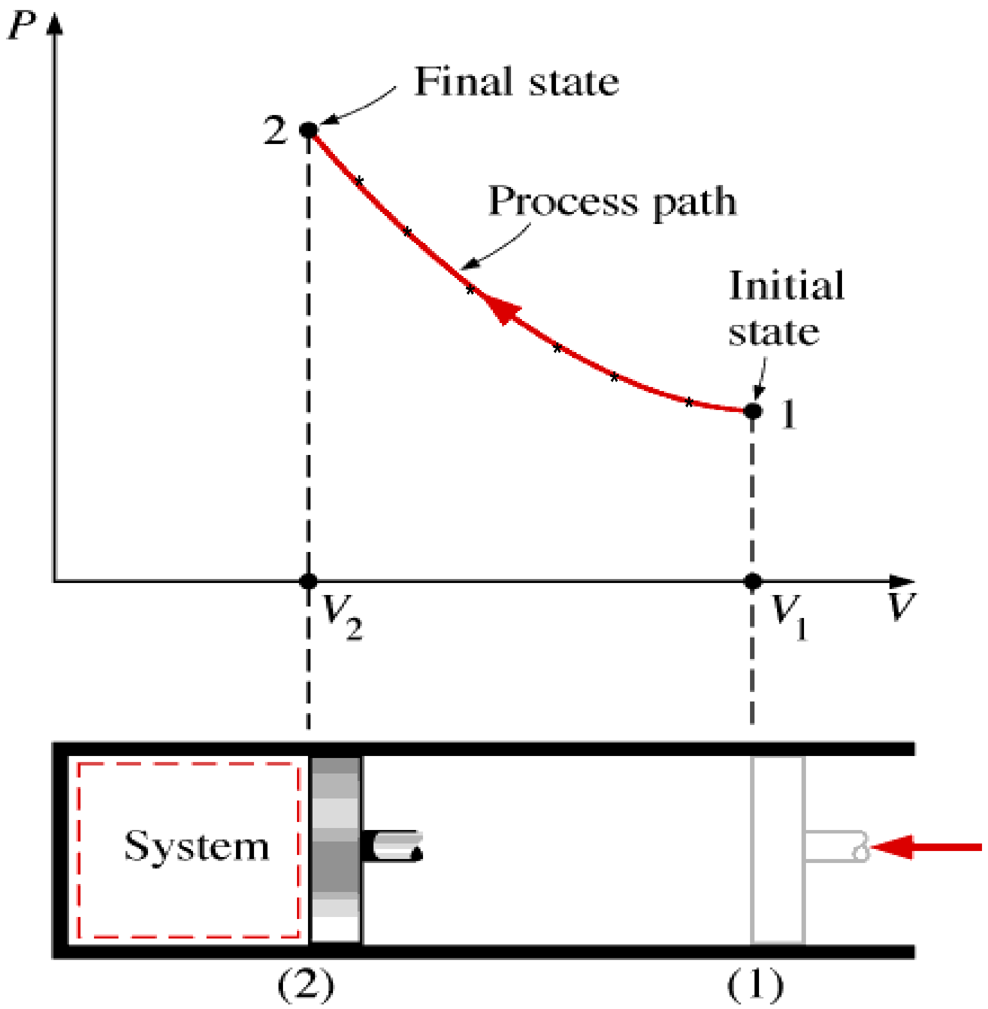
Some special processes:

- Isobaric process - constant pressure process
- Isothermal process - constant temperature process
- Isochoric process - constant volume process
- Isentropic process - constant entropy process

Path:

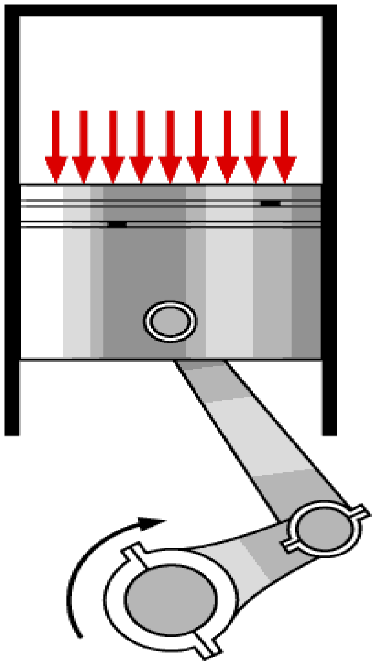
Series of states which a system passes through during a process

Compression Process



Quasi-Equilibrium Processes

- Slow process that allows the system to adjust itself internally
- Properties in point of the system do not change faster at other points
- Work-producing devices deliver the most work
- Work-consuming devices consume the least amount of work



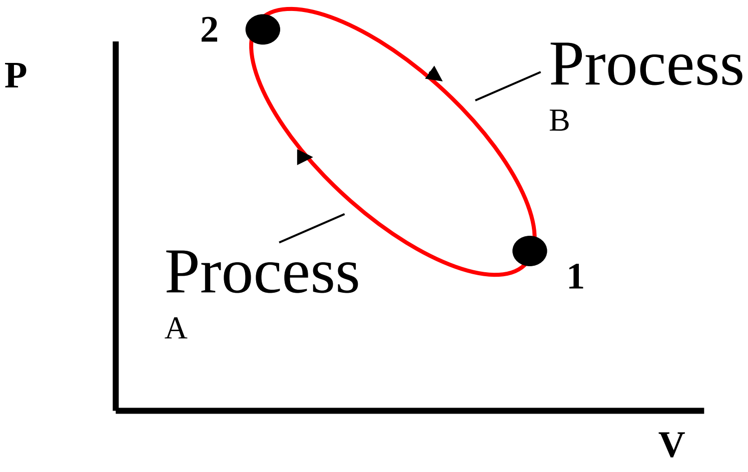
State & Cycles

State:

The thermodynamic state of a simple compressible substance is completely specified by two independent intensive properties.

Cycles:

A process (or a series of connected processes) with identical end states

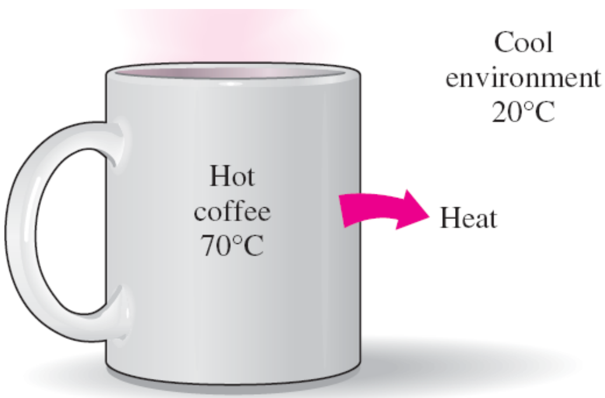


Temperature:

Measure of hotness or coldness

Express the level of temperature qualitatively (freezing cold, cold, warm, hot, and red hot)

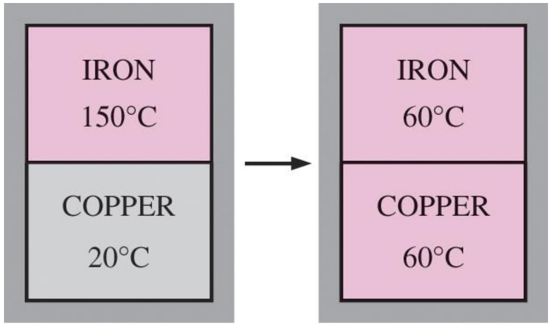
Can not assign numerical values to temperature based on our sensations

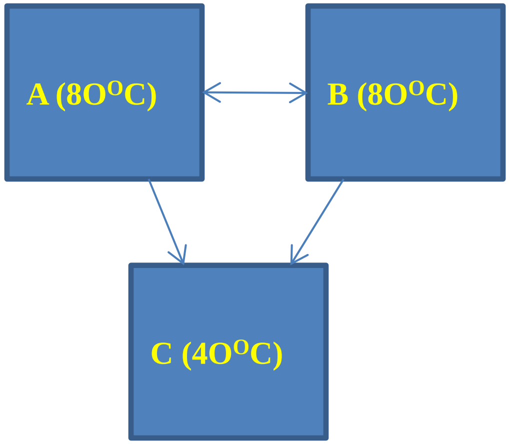


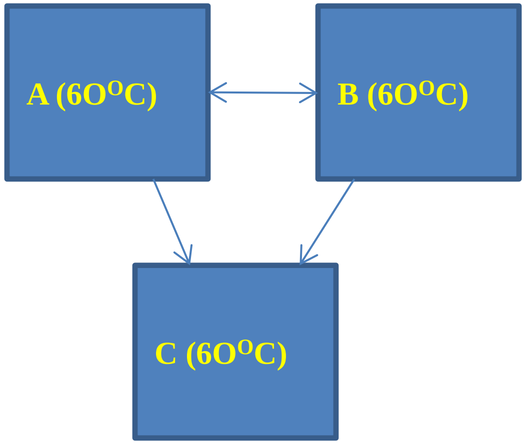
Heat flows in the direction of decreasing temperature

Zeroth Law Of Thermodynamics:

If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other







Temperature:

To obtain quantitative measure of temperature, a reference body is used

Physical characteristics of this body changes with temperature selected

The changes in the selected characteristics may be taken as an indication of change in temperature

Selected characteristic is called thermometric property

Reference body used in the determination of temp is called thermometer

Kinds of Thermometers:

1. Constant volume gas thermometer (pressure – thermometric property)

2. Constant pressure gas thermometer (volume – thermometric property)

3. Electrical resistance thermometer (resistance - thermometric property)

4. Thermocouple (thermal emf - thermometric property)

5. Mercury in glass thermometer (length – thermometric property)

Temperature Scale:

Kelvin scale: An absolute thermodynamic temperature scale whose unit of temperature is the kelvin (K)

Rankine scale: An absolute thermodynamic temperature scale with absolute zero that coincides with the absolute zero of the Kelvin scale

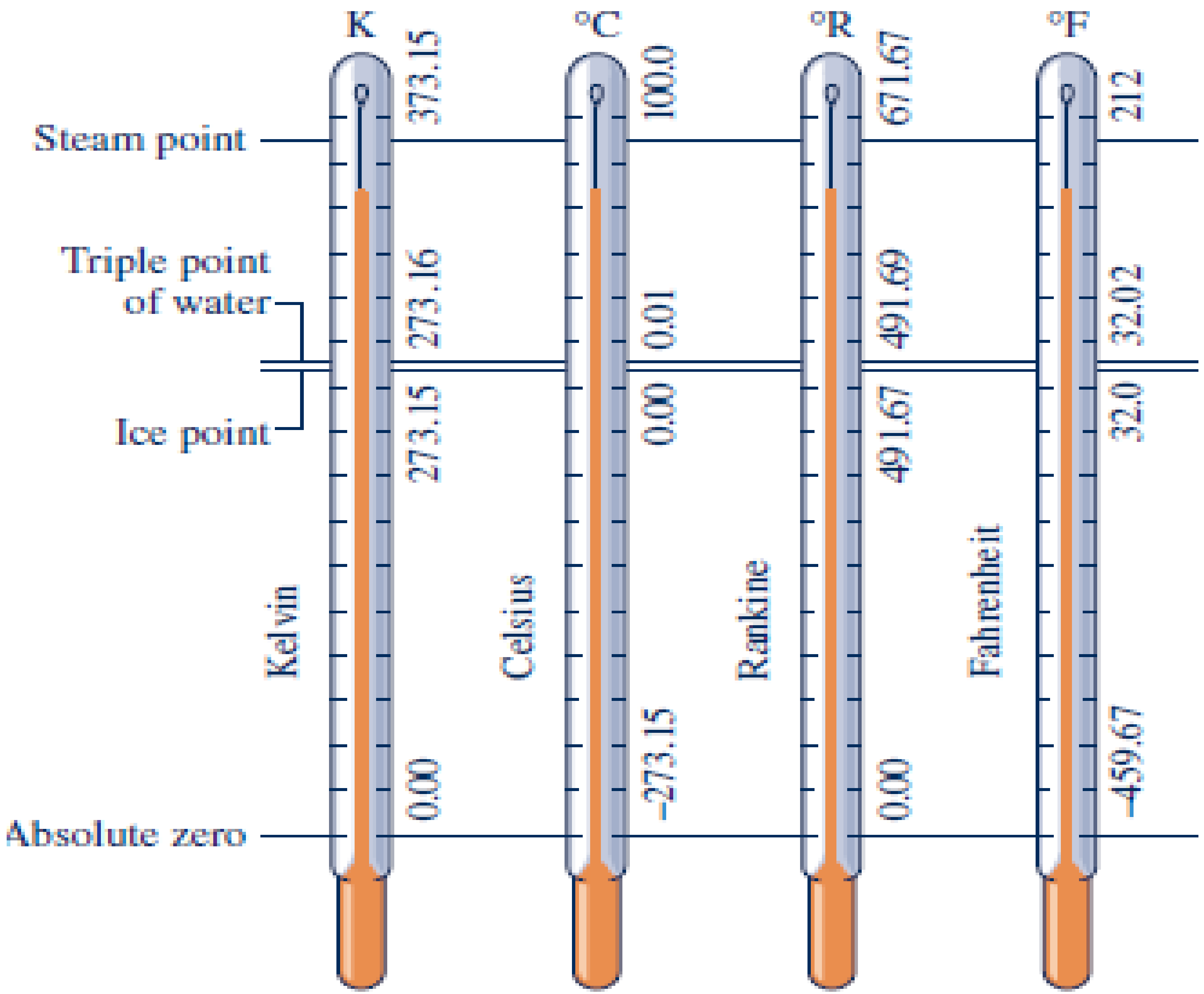
$T(^{o}\mathrm{R}) = 1.8T(\mathrm{K})$

Celsius scale (^{o}C):

$T(^{o}\mathrm{C}) = T(\mathrm{K}) - 273.15$

Fahrenheit scale (^{o}F):

$T(^{o}\mathrm{F}) = T(^{o}\mathrm{R}) - 459.67$



K
°C
°R
°F
373.15
100.0
671.67
212
Steam point
Triple point
of water
273.16
0.01
491.69
32.02
Ice point
273.15
0.00
491.67
32.0
Kelvin
Celsius
Rankine
Fahrenheit
0.00
–273.15
0.00
–459.67
Absolute zero

Relation between Celsius and Fahrenheit scale:

Let the temperature **'t'** be linear function of the property length **'x'** of the mercury column

$t = a\,x + b$ ……….. (1)

'a' and **'b'** are arbitrary constants

For Celsius Scale:

$t = 100^{o}C$ for steam and $t = 0^{o}C$ for ice

$100 = a\,x_s + b$ ……… (2)

$0 = a\,x_i + b$ ……… (3)

From equation (2) and (3) $100 = a\,(x_s - x_i)$

x_s and x_i - length corresponding to steam point and ice point

$a = 100 / (x_s – x_i)$ and $b = - a x_i$

Substitute the value of ‘a’ and ‘b’ in equation (1)

$t = [100 x /(x_s-x_i)] - [100 x_i /(x_s-x_i)]$

$t^oC = [100 (x-x_i) /(x_s-x_i)] = [(x-x_i) /(x_s-x_i)] * 100$ ……. (A)

For Fahrenheit Scale:

$t = a x + b$ ……….. (4)

$212 = a x_s + b$ ………. (5)

$32 = a x_i + b$ ………. (6)

From equation (5) and (6) $180 = a (x_s - x_i)$

$a = 180 / (x_s - x_i)$ and $b = 32 - a x_i$

Substitute a and b in equation (4)

$t = [180 x /(x_s-x_i)] + [32 - \{180 x_i /(x_s-x_i)\}]$

$t - 32 = [180 x /(x_s-x_i)] - [180 x_i /(x_s-x_i)] = [(x-x_i)/(x_s-x_i)] * 180$

$t^oF = [(x-x_i)/(x_s-x_i)] * 180 + 32$ …….. (B)

Equating (A) and (B)

$t^oC = t^oF$

$[(x-x_i) /(x_s-x_i)] * 100 = [(x-x_i)/(x_s-x_i)] * 180 + 32$

$$t^oF / t^oC = \{[(x-x_i)/(x_s-x_i)] * 180 + 32\} / \{[(x-x_i) /(x_s-x_i)] * 100\}$$

$$t^oF / t^oC = (180 / 100) + \{(32) / [((x-x_i) /(x_s-x_i)) * 100]\}$$

$$t^oF / t^oC = (9/5) + \{(32) / t^oC\}$$

$$\mathbf{t^oF = (9/5)\ t^oC + 32}$$

or

$$\mathbf{t^oC = (5/9)\ (t^oF - 32)}$$

Relate between any temperature scale

Steam point and ice point temperature for that scale

Measurement of Temperature – The reference points

Temperature of a system determines whether or not a system is in thermal equilibrium with other systems

Temperature measured by any temperature measuring device is same

If 'X' is the thermometric property, let us arbitrarily choose for the temperature common to the thermometer

All systems in thermal equilibrium

The linear function of X

$\theta(X) = aX$ a – constant

If X_1 corresponds to $\theta(X_1)$ then $\theta(X_1) = aX_1$

X_2 corresponds to $\theta (X_2) = a X_2$

$\theta (X_2) = [\theta (X_1) X_2] / X_1 = \theta (X_1) * [X_2 / X_1]$

Two temperatures on the linear X scale are the ratio of the corresponding X's

Method in use after 1954:

Since 1954 only one fixed point i.e **triple point** of water was used

Designating the triple point of water by $\boldsymbol{\theta_t}$

$\mathbf{X_t}$ is the thermometric property of the body

$\theta_t = a X_t$, $a = \theta_t / X_t = 273.16 / X_t$

$\theta = a X = X * (273.16 / X_t)$ $\theta = 273.16 * (X / X_t)$

Ideal Gas Temperature:

The bulb of a constant volume gas thermometer contains an amount of gas

The bulb is surrounded by water at its triple point

The pressure $\mathbf{P_t}$ is 1000 mm of Hg and keeping volume **V** is constant

Following procedure is conducted:

1. Surround the bulb with steam condensing at 1 atm, determine pressure P and calculate $\theta = 273.16 * (P / 1000)$

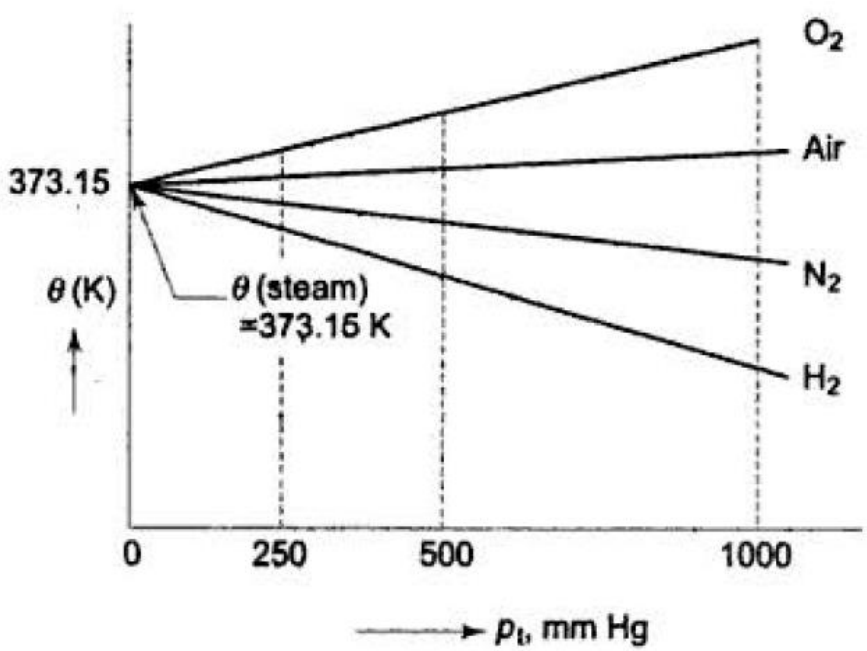
2. Remove some gas from the bulb when it is surrounded by water at its triple point

The pressure $\mathbf{P_t}$ is 500 mm of Hg, determine pressure P and calculate $\boldsymbol{\theta}$ for steam condensing at 1 atm, $\theta = 273.16 * (P/500)$

3. Continue reducing the amount of gas in the bulb so that $\mathbf{P_t}$ and **P** have smaller and smaller values (250 mm Hg, 100 mm Hg and so on)

At each value of '$\mathbf{P_t}$', calculate corresponding '$\boldsymbol{\theta}$'

4. Plot $\boldsymbol{\theta}$ versus $\mathbf{P_t}$ and extrapolate the curve to the axis where $\mathbf{P_t} = 0$



$$\lim_{P_t \to 0} \theta$$

The readings of a constant volume gas thermometer depends upon the nature of the gas

All gases indicate the same temperature as $\mathbf{P_t}$ is lowered and made to approach zero

Real gas used in the bulb behaves as a ideal gas as pressure approaches zero

Ideal gas temperature T

$$T = 273.16 \lim_{Pt \to 0} \frac{P}{P_t}$$

Mercury - Glass Thermometer:

Use liquids as the thermometric property

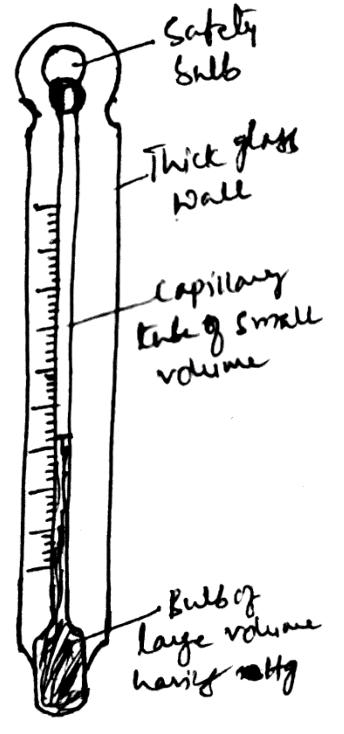
Change in the length of liquid level column in the capillary with heat interactions is the characteristics used for temperature measurement

Consists of a vertical tube with graduation marked on it to show the temperature

Mercury and alcohol are used liquids in the thermometers

One end is connected to thermometric bulb

Small quantity of Hg is filled in a capillary tube



Mercury has low specific heat and absorbs little heat from the body

When the bulb is brought in contact with a hot system, there will be change in volume of mercury

Results in rise or fall of mercury level in the capillary tube

The length of liquid column is used as a thermometric property and is a measure of temperature

Advantages:

1. Lower specific heat
2. Conveniently seen in the capillary tube
3. Good conductor of heat,
4. Doesn’t adhere to the wall of the tube
5. Uniform co-efficient of expansion

Gas Thermometers:

Gas thermometers are more sensitive and uses gaseous thermometric substances

Gas – Oxygen, Hydrogen, Helium etc.

High co-efficient of expansion and small change in temperature

1. Constant Volume Gas Thermometers

2. Constant Pressure Gas Thermometers

Constant Volume Gas Thermometer:

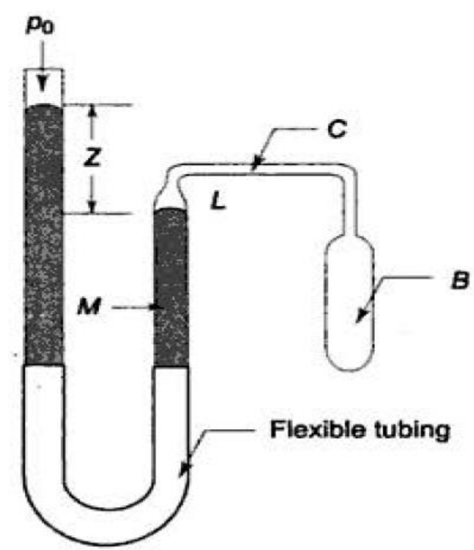
Consists of capillary tube (C) connects thermometer bulb with a U-tube manometer

Small amount of helium gas is contained in the bulb (B)

Left limb is kept open to atmosphere and mercury level on the right limb adjusted to touch the lip (L) of the capillary

pressure of the gas in the bulb is used as thermometric property

$P = P_{atm} + \rho_m h$



When the bulb is brought in contact with the system whose temperature is to be measured

It comes in thermal equilibrium with the system

Gas in the bulb heated and expanded and pushes the mercury column downward on the right limb

Mercury level in the left limb rises

The difference in mercury level ‘h’ is recorded and the pressure ‘P’ of the gas in the bulb is estimated

From ideal gas equation $\Delta T = (V/R)\,\Delta P$, $\Delta T \propto \Delta P$

$(T/T_{tp}) = (P/P_{tp})$ $T = 273.16 * (P/P_{tp})$

$$T = 273.16 \lim_{P_t \to 0} \frac{P}{P_t}$$

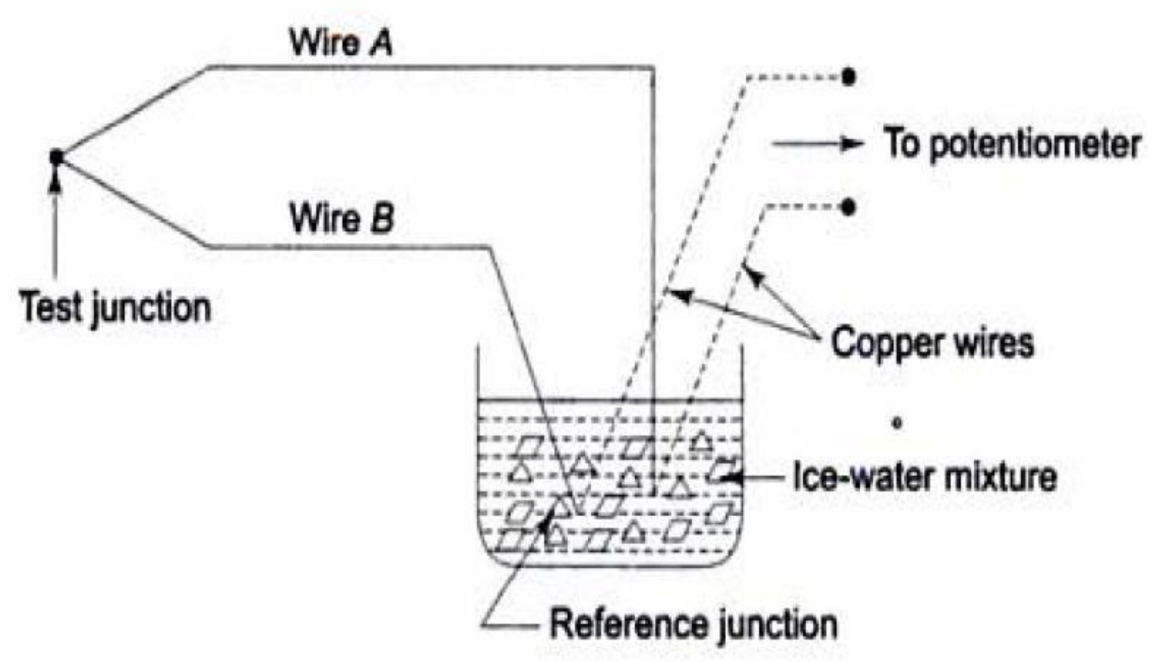
Thermocouple:

When two dissimilar wires are joined at their ends

Junctions are maintained at different temperatures, an emf is generated

By knowing the temperature at one junction, other junction temperature can be measured in terms of emf

$$T(E) = 273.16 * (E / E_{tp})$$



Electric Resistance Thermometer:

Platinum resistance thermometer was developed by Siemen in 1871

It works on the principle of Wheatstone bridge

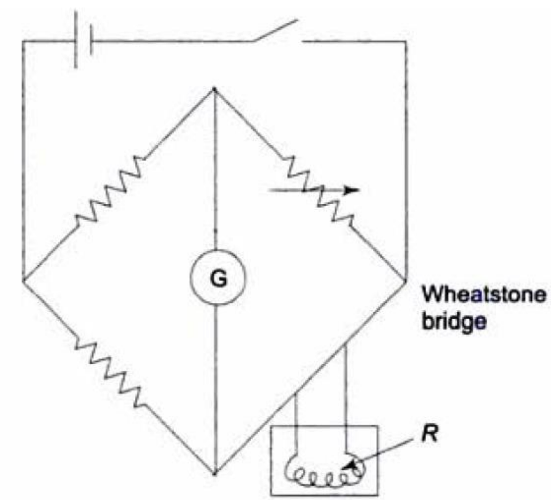
Temperature change causes change in resistance of a metal wire

Used for calibrating other thermometers

Measures temperature to a high degree of accuracy and more sensitive

$R = Ro\ [1+At+Bt^2]$

Ro – Platinum wire resistance
A & B – constants



Problems on Temperature Measurement

1. The steam and ice points of water for Newton scale are 400^{o}N and 100^{o}N respectively and correlate this with Celsius scale

Newton Scale:

$T^oN = AX + B$

For steam point, $400 = AXs + B$ …… (1)
For ice point, $100 = AXi + B$ …… (2)

From (1) and (2), $300 = A (Xs – Xi)$

$A = 300 / (Xs – Xi)$

$B = 100 – AXi = 100 - 300\ Xi / (Xs – Xi)$

$T^oN = AX + B = 300\ X / (Xs – Xi) + 100 - 300\ Xi / (Xs – Xi)$
$= [\{300\ (X – Xi) / (Xs – Xi)\} + 100]$

Celsius Scale:

$T^oC = AX + B$

For steam point, $100 = AX_s + B$ …… (3)

For ice point, $0 = AX_i + B$ ……. (4)

From (3) and (4), $100 = A (X_s – X_i)$

$A = 100 / (X_s – X_i)$

$B = - AX_i = - 100 X_i / (X_s – X_i)$

$T^oC = AX + B = [100 X / (X_s – X_i)] – [100 X_i / (X_s – X_i)]$

$= [\{100 (X – X_i)\} / (X_s – X_i)]$

$T^oN/ T^oC = [\{300(X – X_i)/(X_s – X_i)\} + 100] / [\{100(X – X_i)\}/(X_s – X_i)]$

$T^oN/ T^oC = (3) + \{(100) / [\{100 (X – X_i)\} / (X_s – X_i)]\}$

$T^oN/ T^oC = (3) + [(100) / (T^oC)]$

$T^oN = 3 T^oC + 100$

2. The temperature on a thermometric scale is defined in terms of a property 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 ice and steam point respectively which are 0^oC and 100^oC. Determine the temperature corresponding to a value of K = 2.42 on the thermometer

$T = a \ln K + b$

For steam point T = 100, $100 = a \ln 6.78 + b$

For ice point T = 0, $0 = a \ln 1.83 + b$

$100 = a \ln (6.78/1.83)$, $a = 76.39$

$b = - a \ln (1.83) = - 76.39 \ln (1.83) = - 46.13$

$T = a \ln K + b = 76.39 \ln (2.42) – 46.13 = 21.38^oC$

3. The temperature on a thermometric scale is defined in terms of a property by the relation $T = a \log_e P + b$ where a and b are constants. The values of K are found to be 1.86 and 6.81 at ice and steam point respectively which are 0^oC and 100^oC. Determine the temperature corresponding to a value of $P = 2.5$ on the thermometer