

Module 1 Measurement of Temperature and Gas Laws

This module is designed to help you to:

- use the zeroth law of thermodynamics for measurement of temperature;
- introduce various scales of temperature and their correlation;
- describe different types of thermometers and the specific purposes for which they are used;
- explain the significance of triple point of water;
- justify the need of a standard thermometer;
- express the ideal gas equation in its various forms;
- differentiate between a real gas and an ideal gas.

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11.1.10 Summary

11.1.1 Introduction

In this unit we shall learn about measurement of temperature, the different types of thermometers used for its measurement and the need for a standard thermometer. We shall also learn about the triple point of water, the ideal gas equation and the absolute scale of temperature. We shall also differentiate between an ideal gas and a real gas.

A clear definition of temperature came through the ‘zeroth law of thermodynamics’ and is based on the concept of ‘thermal equilibrium’. Thermal equilibrium of two systems is characterised by zero net heat flow between them.

The zeroth law of thermodynamics states that “when two systems, A and B, are separately in thermal equilibrium with a third system C, the two systems A and B, are also in thermal equilibrium with each other”.

This law thus implies that a number of systems, in thermal equilibrium with one another, can be regarded as having some property which has the same value for all of them. This property is referred to as temperature. It needs to be emphasised that heat is not the energy possessed by a (given) system. Heat is the energy in transit (or being exchanged) with another system when the two systems are in thermal contact with one another. It is wrong to use the term work in a body. Likewise, it is equally incorrect to say heat in a body. The SI unit of heat is joule (J).

11.1.2 Measurement of temperature

Any device used for the measurement of temperature is known as a thermometer. Thermometers use some physical parameter (called thermometric property) that changes with temperature. Different thermometers make use of different physical parameters (thermometric property).

A temperature scale is defined in terms of two standard fixed points, related to the thermometric property used. The two standard points chosen are assigned different values on different temperature scales. The difference is divided into a suitable number of equal parts to define the size of the unit and to express the temperature of any system on the chosen scale.

11.1.3 Scales of temperature and their correlation

Thermometers are calibrated so that a numerical value may be assigned to the given temperature of a given system. Fig 11.1.1 explains the procedure.

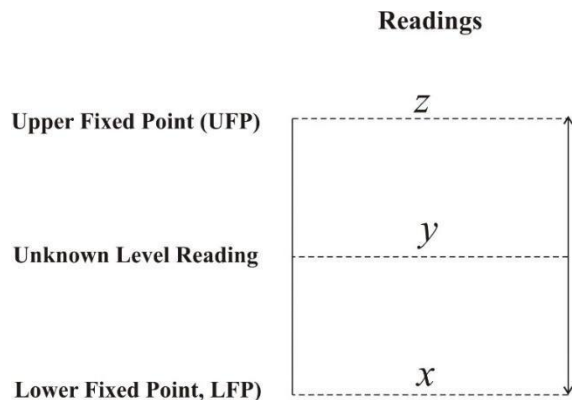


Fig. 11.1.1: Calibration of thermometer

Let us now assign appropriate temperature y to a system on a particular temperature scale.

Assuming a linear variation of the thermometric property used with temperature, we have

$$\frac{y-x}{z-x} = \frac{(\text{Temperature on the scale chosen}-\text{LFP})}{(\text{UFP}-\text{LFP})} = \text{constant}$$

x , y , z represent the values of the thermometric property chosen, at the lower fixed point, the Temperature on the scale chosen and the upper fixed point respectively.

The values assigned to the LFP and the UFP, in some commonly used temperature scales, are given in Table 11.1.1.

Table 11.1.1 LFP and the UFP of Celsius, Fahrenheit and Reaumur scales

	Celsius (°C)	Fahrenheit (°F)	Reaumur (°R)
(UFP, z)	100° C	212° F	80° R
(Unknown, y)	°C	°F	°R
(LFP, x)	0° C	32° F	0° R

$$\frac{y-x}{z-x} = \frac{(c-0)}{(100-0)} = \frac{(F-32)}{(212-32)} = \frac{(R-0)}{(80-0)} = \text{constant}$$

$$\text{Or, } \frac{y-x}{z-x} = \frac{(C)}{100} = \frac{(F-32)}{180} = \frac{(R)}{80} = \text{constant}$$

$$\text{Or, } \frac{y-x}{z-x} = \frac{(C)}{5} = \frac{(F-32)}{9} = \frac{(R)}{4} = \text{constant}$$

The temperatures on the three scales are related as

$$\frac{C}{5} = \frac{F-32}{9} = \frac{R}{4}$$

We can now use these relations for conversion of temperature difference values for one scale to the corresponding temperature difference values on another scale as shown in Table 11.1.2.

Table 11.1.2

	Celsius	Fahrenheit
(UFP)	100 °C	212 °F
(Unknown)	C ₂	F ₂
(Unknown)	C ₁	F ₁
(LFP)	0 °C	32 °F

$$\frac{(C_2-0)}{5} = \frac{F_2-32}{9} \text{ and } \frac{(C_1-0)}{5} = \frac{F_1-32}{9}$$

$$\frac{(C_2-C_1)}{5} = \frac{(F_2-F_1)}{9}$$

$$\text{Or, } \frac{\Delta C}{5} = \frac{\Delta F}{9}$$

Similarly, we have

$$\frac{\Delta C}{5} = \frac{\Delta F}{9} = \frac{\Delta R}{4} = \frac{\Delta K}{5}$$

It is interesting to note here that a unit difference of temperature, on the Celsius scale is equal to a unit difference of temperature on the Kelvin scale.



Let Us Reflect

Q.11.1.1 The temperature of a system(x^0) measured on Celsius scale is half its value on the Fahrenheit scale.

The value of x is

- (A) 320
- (B) 160
- (C) 80
- (D) -40

Q.11.1.2 On a new temperature scale, the interval between the lower fixed point (ice-point) and the upper fixed point (steam-point) is divided into 150 equal parts. The temperature of a system is 50°C . The corresponding temperature on the new scale is

- (A) 33.3
- (B) 50
- (C) 66.7
- (D) 75

Q.11.1.3 The ice-point and the steam-point on a scale are marked as -10 and 130 respectively. The temperature of a system on this scale is 60. The corresponding value on Celsius scale is

- (A) 40
- (B) 50
- (C) 60
- (D) 65



Answers

A.11.1.1 (B)

A.11.1.2 (D)

A.11.1.3 (B) $\{(60 + 10)/c\} = \{(130 + 10)\}/100;$

$$2c = 100, c = 50$$

11.1.4 Different types of thermometers and their need

Table 11.1.3 shows details of different types of thermometers used for measurement of temperatures.

Table 11.1.3: *Thermometric parameters in different thermometers*

Thermometric substance	Thermometric parameter	Type of Thermometer
Gas	Pressure (P)	Constant volume gas thermometer $P \propto T$
Gas	Volume (V)	Constant pressure gas thermometer $V \propto T$
Liquid	Volume (We use $L \propto V$)	Liquid thermometer $L \propto T$
Pure metal	Resistance (R)	Resistance thermometer

		$R_t = R_0(1 + at + bt^2)$
Dissimilar Metals	Thermo emf (E)	Thermoelectric thermometer ($E = at + bt^2$)
Paramagnetic Salt	Magnetic susceptibility (χ)	Susceptibility thermometer ($= \frac{c}{T}$)
Black body	Emissive power (e_λ)	Radiation pyrometer ($e_\lambda = \sigma T^4$)

Different types of thermometers are chosen for different applications depending on

- (i) the temperature range,
- (ii) the accuracy desired and
- (iii) the ease, convenience and economy associated with different thermometers.

The fixed points play a very crucial role in determining the temperature of a system. So, it is imperative to define a fundamental fixed point in thermometry. For this purpose, we shall discuss the triple point of water.

11.1.5 Triple point of water

The ice point (0°C) and the steam point (100°C) are very sensitive to atmospheric pressure, presence of impurities in the liquid, nature of the glass used to hold the liquid in addition to other factors. It is therefore, invariably difficult to reproduce identical values of these fixed points. To overcome this difficulty, it was decided that the triple point of water - the temperature at which all the three phases, that is - ice, water and water vapour co-exist in equilibrium, be taken as the fixed point. The triple point of water is a very good choice for a 'fixed point' because the three phases of water (ice, water and vapour) coexist only at very precise and well-defined values of temperature and pressure. The temperature at the triple point was assigned the numerical value 273.16 and the unit is called kelvin (symbol K).

The triple point is the fundamental fixed point in thermometry. On the Celsius scale, it is known as the ice-point and its value is taken as 0°C . This temperature on the Fahrenheit scale is taken as 32°F and 0°R on the Reaumur scale.

The temperature values on the Kelvin scale T (K) and the Celsius scale t ($^{\circ}\text{C}$) are related as

$$t (^{\circ}\text{C}) = T (\text{K}) - 273.16$$

Here K stands for Kelvin, the unit of temperature on the Kelvin scale (also known as absolute scale of temperature). It follows that a temperature of -273.16 , on the Celsius scale would correspond to the zero of the Kelvin scale. This temperature (0 K) is also known as the absolute zero of temperature and is the lower limit of temperature.

11.1.6 Need for a standard thermometer

The temperature scale of each thermometer is conveniently defined by assuming a linear variation with temperature of the thermometric property used. The nature of variation (with temperature) of different physical properties of different systems or devices would not be quite the same. Hence, except at the two fixed points (which are assigned the same values for all thermometers) the temperature value assigned to an unknown set up by different thermometers would not be the same. There is, therefore, a need for calibrating different thermometers in terms of one of them, taken as the standard (or reference) thermometer.

Table 11.1.4 gives the values of temperature ranges and the standard thermometer relevant to each range as per the International Temperature Scale 1990 (ITS-90).

Table 11.1.4: *Temperature range of some thermometers*

Sr. No.	Temperature Range	Thermometer
1.	0.65K to 5K	Saturation vapour pressure thermometer using ^3He from 0.65 K to 3.2 K ^4He from 2.1768 K to 5 K
2.	3.0 K to 24.5561 K	^3He or ^4He constant volume gas thermometer
3.	13.8033 K to 1234.93 K	Platinum resistance thermometer
4.	>1234.93 K	Optical pyrometer

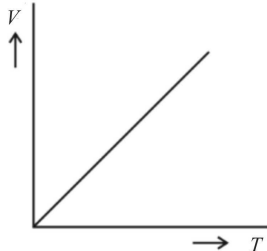
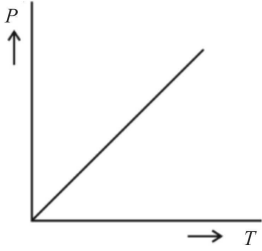
The choice of the gases mentioned for different temperature ranges is guided by the fact that it is a very close approximation to an ideal gas for the temperature range considered.

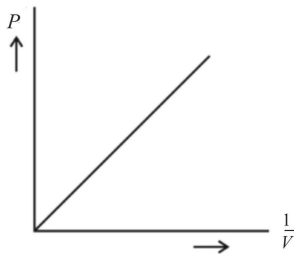
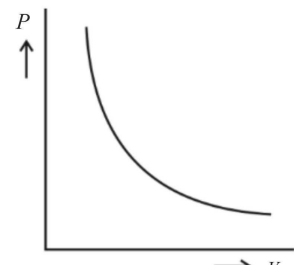
11.1.7 Ideal gas equation and absolute temperature

A thermometer that uses an ideal gas gives the same value of temperature regardless of the gas used in it. The variables that describe the behaviour of a given quantity (mass) of gas are pressure, volume and temperature (P , V and T). Here, T (K) = t (°C) + 273.16, t is the temperature in °C.

A gas is ideal or perfect if it fulfils all the conditions spelt out in the postulates of the kinetic theory of gases, i.e.

- (i) its molecules are point masses occupying no finite volume
- (ii) its molecules have no mutual attraction or repulsion.

Ideal gas laws	
(a)	Charles Law Pressure remaining constant, the volume of a given mass of an ideal gas (perfect gas) varies directly as its absolute temperature (Fig. 11.1.2). $V \propto T$ or $\frac{V}{T} = \text{constant}$ or, $\frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V_3}{T_3} = \dots = \text{constant}$ (for constant pressure)  Fig. 11.1.2
(b)	Gay-Lussac's law Volume remaining constant, the pressure exerted by a given mass of an ideal gas varies directly as its absolute temperature (Fig. 11.1.3). $P \propto T$ or, $\frac{P}{T} = \text{constant}$ or $\frac{P_1}{T_1} = \frac{P_2}{T_2} = \frac{P_3}{T_3} = \dots = \text{constant}$ (for constant volume)  Fig. 11.1.3

(c)	Boyle's law Temperature remaining constant, the pressure exerted by a given mass of an ideal gas varies inversely as its volume (Fig. 11.1.4). $P \propto 1/V$ or, $PV = \text{constant}$ or $P_1V_1 = P_2V_2 = P_3V_3 = \dots \text{constant}$ (for constant temperature)	 Fig. 11.1.4
(d)	Ideal Gas Equation The above laws lead us to the result, $\frac{PV}{T} = \text{constant.}$ Hence, $\frac{P_0V_0}{T_0} = \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = \dots \text{constant } (R)$ where R is known as the universal gas constant corresponding to a mass of gas that equals one gram-molecule. Fig.11.1.5 is P versus V curve, when temperature is constant. The same holds for Boyle's law also.	 Fig. 11.1.5

Values of universal gas constant R

- We know that one mole of an ideal gas at STP, i.e., at 1 atmospheric pressure, and 273.16 K, occupies 22.4 litre. So, $P_0 = 10^5 \text{ N/m}^2$; $V_0 = 22.4 \text{ litre} = 22400 \times 10^{-6} \text{ m}^3$;

$$T_0 = 273.16 \text{ K}$$

$$\therefore R = \frac{P_0 V_0}{T_0} = \frac{10^5 \times 22400 \times 10^{-6}}{273.15} = 8.31 \text{ J mole}^{-1} \text{K}^{-1}$$
- $$R = \frac{8.31}{4.2} \text{ calorie mole}^{-1} \text{K}^{-1}$$

$$= 1.99 \text{ calorie mole}^{-1} \text{K}^{-1}$$

- For, $P_0 = 1 \text{ atm}$; $V_0 = 22.4 \text{ litre}$; $T_0 = 273.16 \text{ K}$

$$R = \frac{P_0 V_0}{T_0} = \frac{1 \times 22.4}{273.15} = 0.082 \text{ litre-atm mol}^{-1} \text{ K}^{-1}$$

11.1.8 Different forms of gas equation

- (i) For n moles of an ideal gas

$$PV = nRT, \text{ where } R \text{ is the molar gas constant.}$$

- (ii) For 1 mole of gas

$$PV = RT$$

- (iii) For a mass m of a gas

$$n = \frac{m}{M} \quad \text{where } M \text{ is molecular weight}$$

$$\text{Hence, } PV = \frac{m}{M} RT = m R_{\text{specific}} T \quad \text{where } R_{\text{specific}} = \frac{R}{M} = \text{Specific gas constant}$$

- (iv) For N molecules of a gas

$$N = \frac{m}{\mu}, \text{ where } \mu = \text{mass of one molecule and}$$

$$M = \mu N_A \text{ where } N_A = \text{Avogadro number} = 6.023 \times 10^{23} \text{ molecules/mole}$$

$$\text{Thus, } PV = \frac{m}{\mu} \cdot \frac{R}{N_A} \cdot T = NkT \text{ when } k = \frac{R}{N} = \text{Boltzmann constant}$$

$$\text{Boltzmann constant, } k = 1.38 \times 10^{-23} \text{ JK}^{-1}$$

The relation $PV \propto T$ allows a gas to be used to measure temperature.

At constant volume, $P \propto T$.

Therefore, in a constant volume gas thermometer, temperature is read in terms of pressure.

A graph of pressure versus temperature is a straight line as shown in Fig 11.1.6.

An extrapolation of the graph shows that $P = 0$ when temperature(t) equals -273.15°C

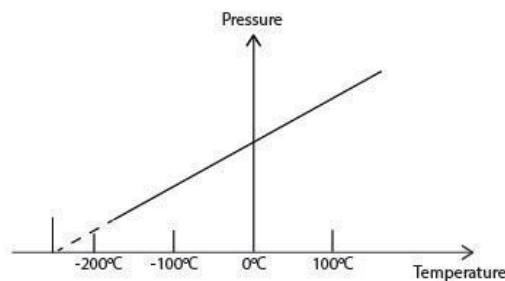


Fig. 11.1.6: *Extrapolation of P - T graph*

11.1.9 Difference between an ideal gas and a real gas

The values of the pressure, volume and temperature for real gases deviate from those predicted by the ideal gas laws. The deviation increases as the temperature is lowered and the pressure is increased. The relationship between P and T is linear over a large temperature range and it appears that the pressure becomes zero with decreasing temperature if the gas continues to behave as an ideal gas. The absolute minimum temperature for an ideal gas therefore can be inferred by extrapolating the straight line to the temperature - axis, as shown in Fig 11.1.6.

This temperature is found to be -273.16°C and is designated as the absolute zero of temperature.

An ideal gas is considered to be composed of point masses - a particle so small that the volume of that particle is negligible. However, real gas atoms/molecules do have a finite volume.

For an ideal gas, the collisions between gas particles are considered to be perfectly elastic. There are no attractive or repulsive forces between the particles. Therefore, no loss of energy during the collisions. For a real gas, collisions are not perfectly elastic as intermolecular forces are present.



Let Us Reflect

Q.11.1.4 A certain gas thermometer uses variation of pressure of the gas to measure temperature. The thermometer is based on

- (A) Boyle's law
- (B) Gay-Lussac's law
- (C) Charle's law
- (D) Avogadro law.

Q.11.1.5 Half mole of oxygen at a pressure of 10^5 Nm^{-2} and temperature T has the same volume as one mole of hydrogen at a pressure of $0.8 \times 10^5 \text{ Nm}^{-2}$. The value of T is

- (A) 275 K
- (B) 375 K
- (C) 600 K
- (D) 750 K

Q.11.1.6 I and II are P versus $\frac{1}{V}$ graphs of an ideal gas for (mass; m_1 ; temperature T_1) and (mass; m_2 ; temperature T_2) respectively as shown in Fig. 11.1.7.

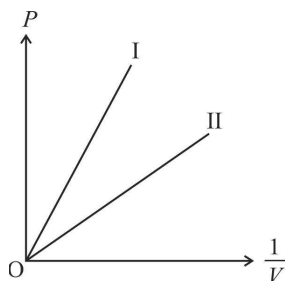


Fig. 11.1.7: P - $1/V$ of an ideal gas

We have

- (A) $T_1 > T_2$
- (B) $m_1 > m_2$
- (C) $m_1 T_1 = m_2 T_2$
- (D) $m_1 T_2 > m_2 T_1$



Answers

A.11.1.4 (B)

A.11.1.5 (D)

A.11.1.6 (D)



11.1.10 Summary

- The concept of temperature is based on the zeroth law of thermodynamics according to which the two systems in thermal equilibrium with a third system are also in thermal equilibrium with each other.
- Thermometer is a device used for measuring temperature. The measurement of temperature with a thermometer is done using a thermometric parameter of a substance that changes with temperature.
- Different temperature scales are used to design different thermometers. The temperature scales are based on two fixed points(ice point and steam point) that are assigned some arbitrary values of temperature.
- A standard thermometer facilitates comparing temperatures measured with different temperature scales.
- The relation between the pressure (P), volume (V) and temperature (T) of an ideal gas is expressed by the ideal gas equation $PV = nRT$.
- The zero of the absolute temperature scale corresponds to $-273.16\text{ }^{\circ}\text{C}$.
- The temperature at which solid, liquid and gaseous phase of water co-exist is known as the triple point of water. The triple point of water being a unique temperature is preferred as a fixed point in thermometry.
- An ideal gas is assumed to be consisting of perfectly elastic particles occupying zero volume and having no interacting forces between them. However, the particles in a real gas interact with each other and occupy a finite volume. This accounts for the deviation of the behaviour of a real gas from the ideal gas equation.

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