1.4 THERMOMETERS

1.4.1 Thermometric Property

The temperature of a system in a thermodynamic equilibrium can be measured by bringing the given system in equilibrium with a reference system, called the thermometric substance, whose temperature has been calibrated somehow. The reference system used for measuring a temperature is called a thermometer. But the question is how to find systems with known temperature readings. This is akin to the chicken and egg problem, you need temperature to establish a state of thermal equilibrium, and a state of thermal equilibrium is necessary to define a temperature.

To break this cycle, we introduce another measurable property such as volume or pressure that varies with temperature. Any property X that varies with temperature t will suffice. The property X chosen for this purpose is called the thermometric property and the function $t(X)$ determines the temperature scale. Some of the thermometric properties used are listed in Table 1.1. By assuming that the temperature varies linearly with property X we can write the temperature t corresponding to the property X by the following type of relation.

$$t(X) = aX, \tag{1.3}$$

where a is a constant of proportionality to be fixed by choosing a reference condition of matter to which we arbitrarily assign a values of t corresponding to the measured value of the property$X$ in that condition. This is also called calibrating a thermometer. I will now describe a method of calibration of thermometer based on triple point of water that has been agreed upon internationally.

Table 1.1: Thermometers and thermometric properties

Thermometer Type	Thermometric Property	Example thermometric material
Gas (Constant Volume)	Pressure	Hydrogen gas
Liquid (Constant Pressure)	Volume	Liquid mercury
Electric Resistor	Resistance	Platinum wire
Thermocouple	Thermoelectric EMF	Chromel (Ni-Cr alloy)/ Constantan (Cu-Ni alloy))
Paramagnetic material	Magnetic susceptibility	Cerrous magnesium nitrate
Blackbody radiation	Intensity	No thermometric material needed

1.4.2 Calibration Using The Triple Point of Water

Since 1954 the triple point of water, a state in which a mixture of ice, liquid water and vapor coexist in equilibrium, has been chosen as the standard reference which is arbitrarily assigned a value of 273.16 K. This fixes the value of constant a in Eq. 1.3 in terms of the assigned value of the temperature of triple point and the value of X at $X = X_{TP}$ of the thermometric property when the thermometer is in equilibrium at the triple point of water.

$$273.16\ K = aX_{TP} \tag{1.4}$$

Eliminating a from Eqs. 1.3 and 1.4, we are able to immediately determine temperature t when the value of the thermometric property X is known.

$$t(X) = \left(\frac{273.16\ K}{X_{TP}}\right) X \tag{1.5}$$

A good question is: suppose you follow this procedure for different thermometer, e.g. a gas thermometer, a resistance thermometer and a thermocouple, will you get the same readings in them? The answer is a resounding no, if the unknown temperature is not near the triple point of water. The temperature of an unknown will be different even for two gas thermometer that are somehow different, either having different size bulbs or different amount of gas. When you use formula given in Eq. 1.5 for different thermometer you get different values for the temperature of the same thermal bath. To solve this problem, we need a standard thermometer to calibrate other thermometer and not obtain multiple values for the temperature of the same system. The constant volume gas thermometer provides a procedure for obtaining a unique temperature independent of the thermometric material as we will see below, and therefore it is used as a standard thermometer.

1.4.3 Constant Volume Gas Thermometer

A constant volume gas Thermometer is a Thermometer that uses a gas as the Thermometric medium and its pressure as the property X. It consists of a bulb B of a gas that connects to a reservoir R of mercury and a manometer M as shown in Fig. 1.8.

When the gas bulb is immersed in a thermal bath, the pressure of the volume of the gas changes changing the mercury level from the indicial point C in arm M. By moving the reservoir R up or down the mercury level in arm M can be brought to the reference

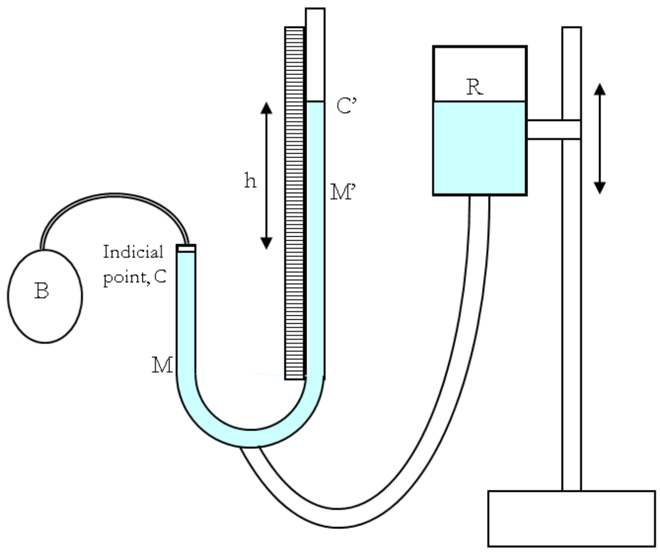

Figure 1.8: Constant volume gas Thermometer.

point C. Movement of reservoir also changes the level C' in arm M'. The difference h in the level C' and C is measured when the bulb is immersed in the unknown temperature t. From the difference in heights we can determine the absolute pressure p in the bulb.

$$p = p_0 + \rho g h$$

where p_0 is the atmospheric pressure since the tube on the M' side is open to the atmosphere. The temperature of the unknown is determined from the absolute pressure reading by equating the ratio of the absolute pressures to the ratio of temperatures expressed in Kelvin scale.

$$T = \frac{p}{p_{TP}} T_{TP} \tag{1.6}$$

where p_{TP} is the absolute pressure when the bulb is immersed in water at triple point ($T_{TP} = 273.16\ K$).

Experiments with gas Thermometer have shown that there are minor differences in temperature readings for different gases placed in the bulb as shown in Fig. 1.9. Furthermore, even these minor differences can disappear when the pressure in the bulb is reduced by using less gas.

The graphs of different gases show that a unique temperature cannot be assigned to an unknown thermal state for a non-zero pressure since the temperature value assigned depends on the Thermometric gas. For instance, if you draw a vertical line at p=100 kPa in Fig. 1.9, you will find that there are three different values of the temperature for the same sample if you use He, Ar and N_2 in the bulb as you can see by drawing a vertical line for p = 100 kPa. You can

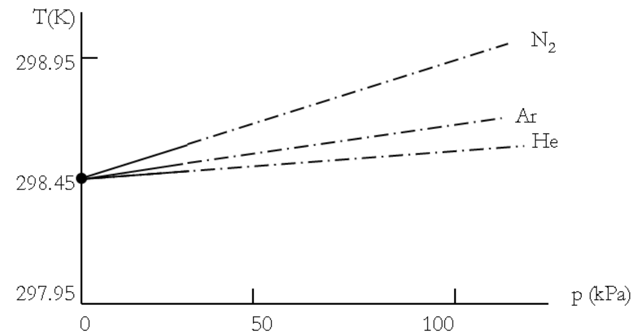

Figure 1.9: Temperature for the same bath for constant gas Thermometer utilizing different gases at different pressures. The differences in the readings decrease as pressure in the bulb is reduced.

also see in Fig. 1.9 that the extrapolations of the graphs for different gases meet at one point, giving a unique reading of the temperature independent of the nature of gas in the bulb. This procedure defines an **Absolute scale of temperature** also called the **Kelvin scale**.

1.4.4 Calibration With Two Fixed Points

A Thermometer is sometimes calibrated to operate over a small range of temperatures by picking two reproducible thermal conditions of known temperatures. Readily available thermal conditions are the conditions that exist in which a material can coexist between two different material phases, such as solid and liquid, or three different phases simultaneously, such as the triple point. These conditions are also called fixed points. Some of the fixed points of common use are shown in Fig. 1.10.

The procedure for extrapolating between two nearby fixed points are based on the assumption of the linear dependence of the change in the Thermometric property ΔX on the change in temperature ΔT. Let X_1 and X_2 be the value of the property X at reference reproducible baths with temperature t_1 and t_2. If the temperature range between the baths is not too great it is reasonable to assume that the property X will vary linearly with temperature (t) between the two temperatures t_1 and t_2, and can be extended on either side of t_1 and t_2. Then the linear relation shown in Fig. 1.11 will have the following analytic relation.

$$X(t) = X_1 + \left(\frac{X_2 - X_1}{t_2 - t_1}\right)(t - t_1) \qquad (1.7)$$

Unfortunately, most properties do not vary linearly with temperature over a large range, and therefore, we need many reference baths to

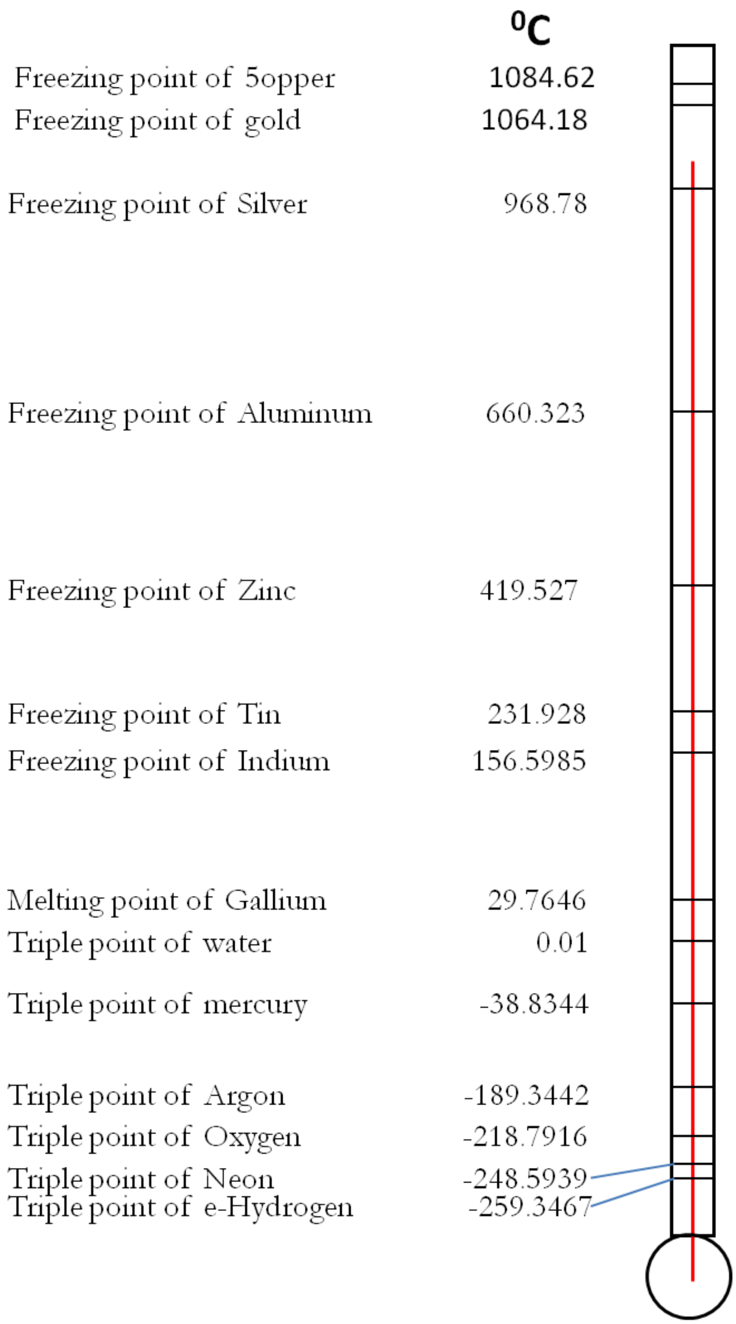

Figure 1.10: Important fixed points of ITS-90 temperature scale. Melting and freezing points measured at a pressure of 101,325 Pa.

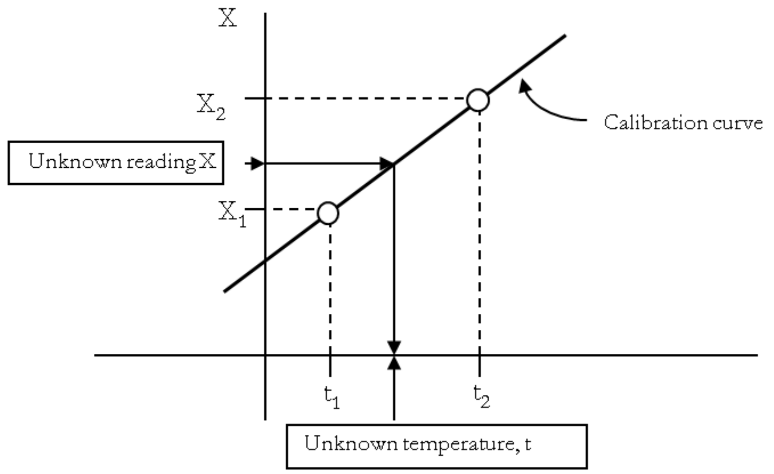

Figure 1.11: Interpolating temperature between fixed points 1 and 2.

recalibrate, and use different Thermometer in different ranges. One makes sure that, in the overlap regions, all Thermometer that are workable in those temperatures produce identical readings.