2. Temperature and the Zeroth Law of Thermodynamics

Thermodynamics is the branch of science which deals with the energy interactions. In order to find whether energy interactions are taking place or not some measurable mathematical parameters are needed. These parameters are called thermodynamic properties. Out of a number of thermodynamic properties discussed earlier the 'temperature' is one property.

One is well familiar with the qualitative statement of the state of a system such as cold, hot, too cold, too hot etc. based on the day to day experience. The degree of hotness or coldness is relative to the state of observer. For example, let us take an iron bar. Obviously the bar shall have an initial temperature equal to the room temperature. Now let us heat this metal bar. Observations at the molecular level show that upon heating the molecular activity inside the bar gets increased. This may be attributed to the more agitated state of molecules as energy is given to them in the form of heating of the bar. From the physiological sensations it can be felt that this has resulted in an increase in the degree of hotness of the bar. This qualitative indication of the relative hotness can be exactly defined by using a thermodynamic property known as temperature. If this hot bar is brought in contact with another bar at room temperature one can feel that after some time the two bars which were initially at high and low temperatures attain the same temperature which is lying between the two temperatures. It is indicative of the fact that there has been exchange of some entity between the two bars resulting in the attainment of final equilibrium temperature. This state of attainment of common equilibrium temperature is also termed as the state of **thermal equilibrium**. Thus, the temperature becomes a potential indicator of the energy interactions in the systems.

After the identification of 'Temperature' as a thermodynamic property for quantification of the energy interactions the big question was its estimation. Based on the relative degree of coldness/hotness concept it was concluded that the absolute value of temperature is difficult to be described. Hence it was mooted to make temperature estimations in reference to certain widely acceptable known thermal states of the substances. Temperature is thus the intensive parameter and requires reference states. These acceptable known thermal states are such as the boiling point of water commonly called steam point, freezing point of water commonly called ice point etc. These easily reproducible and universally acceptable states of the substance are known as reference states and the temperature values assigned to them are called reference temperatures. Since these reference points and reference temperatures maintain their constant value, therefore these are also called fixed points and fixed temperatures respectively.

The methodology adopted was to first develop a temperature measurement system which could show some change in its characteristics (property) due to heat interactions taking place with it. Such systems are called thermometers, the characteristics of property which shows change in its value is termed thermometric property and the substance which shows change in its thermometric property is called thermometric substance. Science that deals with the temperature and its measurement is called thermometry. For example in case of clinical thermometer the mercury in glass is the thermometric substance and since there is a change in the length of the mercury column due to the heat interactions taking place between the thermometer and the body whose temperature is to be measured, therefore the length is the thermometric property. Thus, the underlying principle of temperature measurement is to bring the thermometer in thermal equilibrium with the body whose temperature is to be measured, i.e. when there is no heat interaction or the state when two (thermometer and body) attain the same temperature. In this process it is to be noted that the thermometer is already calibrated using some standard reference points by bringing the thermometer in thermal equilibrium with reference states of the substance.

The zeroth law of thermodynamics states that if two bodies are in thermal equilibrium with a third body, then they are in thermal equilibrium with each other. It may seem silly that such an obvious fact is called one of the basic laws of thermodynamics. However, it cannot be concluded from the other laws of thermodynamics, and it serves as a basis for the validity of temperature measurement. By replacing the third body with a thermometer, the zeroth law can be restated as two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.

Temperature Scales

A number of temperature measuring scales came up from time to time. Different temperature scales have different names based on the names of persons who originated them and have different numerical values assigned to the reference states.

1. Celsius Scale or Centigrade Scale: Anders Celsius gave this Celsius or Centigrade scale using ice point of 0°C as the lower fixed point and steam point of 100ºC as upper fixed point for developing the scale. It is denoted by the letter C. Ice point refers to the temperature at which freezing of water takes place at standard atmospheric pressure. Steam point refers to the temperature of water at which its vaporization takes place at standard atmospheric pressure. The interval between the two fixed points was equally divided into 100 equal parts and each part represented 1ºC or 1 degree Celsius.

2. Fahrenheit Scale: Daniel Gabriel Fahrenheit gave another temperature scale known as Fahrenheit scale and has the lower fixed point as 32ºF and the upper fixed point as 212ºF. The interval between these two is equally divided into 180 parts. It is denoted by the letter F. Each part represents 1ºF. Fahrenheit Scale is related to Celsius scale as follows:

$$T_{\mathrm{F}} = \frac{9}{5} T_{\mathrm{C}} + 32$$

3. Kelvin Scale: Kelvin scale proposed by Lord Kelvin is very commonly used in thermodynamic analysis. It also defines the absolute zero temperature. Zero degree Kelvin or absolute zero temperature is taken as –273ºC. It is denoted by the letter K. It is related to Celsius scale as given below:

$T_K = T_C + 273$

4. Rankine Scale: Rankine scale was developed by William John Macquorn Rankine, a Scottish engineer. It is denoted by the letter R. It is related to Fahrenheit scale as given below:

$T_R = T_F + 460$

Heat

Heat is the energy transferred without transfer of mass across the boundary of the system due to the difference in temperature between the system and its surroundings. It is denoted (Q). If there is no temperature difference, then there is no heat transfer, thus heat is not a property. The unit of heat is Joule (J).

J = N.m

For one kilogram of the substance is the specific heat and denoted (q):

$$q = \frac{Q}{m} = \frac{\text{J}}{\text{kg}}$$

Specific Heat Capacity

The specific heat capacity of a substance is defined as the amount of heat which transfers into or out of a unit mass of the substance, while the temperature of the substance changes by one degree. Thus if:

C – Specific heat capacity of the substance.

m – Mass of the substance.

Q – Heat transfer.

T_1 – Initial temperature.

T_2 – Final temperature.

Then:

$$Q_{1-2} = m\ C\ \Delta T = m\ C\ (T_2 - T_1)$$

Specific heat capacity may vary with temperature. It should also be noted that when heat is transferred to the system, it will have a positive sign, and when it is transferred from the system, it will have a negative sign, (i.e. Q gained is positive and Q rejected is negative).

Example (2.1): An unknown metal weighing 0.9 kg at an initial temperature of 140°C is placed into an insulated container holding 3 kg of water at an initial temperature of 60°C. After thermal equilibrium the water rose to 65°C. Knowing that C_{water} = 4186 J/kg.°C, what is the specific heat capacity of the metal?

Solution:

The amount of heat lost by the metal equals the amount of heat gained by the water, thus:

$$Q_{Lost} = Q_{Gained}$$

$$-m_m C_m \Delta T_m = m_w C_w \Delta T_w$$

$$-0.9 \times C_m \times (65 - 140) = 3 \times 4186 \times (65 - 60)$$

$\boldsymbol{C_m = 930\ \mathrm{J/kg.°C}}$ **Ans.**

Example (2.2): A 10 g iron bar at 80°C is dropped into 70 g of water at 25°C. Knowing that C_{water} = 4.186 J/g.°C and C_{iron} = 0.47 J/g.°C, what is the final temperature after thermal equilibrium?

Solution:

The amount of heat lost by the iron bar equals the amount of heat gained by the water, thus:

$$Q_{Lost} = Q_{Gained}$$

$$-m_i C_i \Delta T_i = m_w C_w \Delta T_w$$

$$-10 \times 0.47 \times (T_f - 80) = 70 \times 4.186 \times (T_f - 25)$$

$\boldsymbol{T_f = 25.87\ °C}$ **Ans.**