Mechanical Measurements

Module 2:

Formally we start the study of “Mechanical Measurements” now! Module 2 will consider the measurement of field quantities like temperature, pressure and fluid velocity. First topic to be covered is “Thermometry” or the Science and Art of “Temperature Measurement”

Sub Module 2.1

Thermometry or the science and art of temperature measurement

Preliminaries

Temperature along with pressure is an important parameter that governs many physical phenomena. Hence the measurement of temperature is a very important activity in the laboratory as well as in industry. The lowest temperature that is encountered is very close to 0 K and the highest temperature that may be measured is about 100000 K. This represents a very large range and cannot be covered by a single measuring instrument. Hence temperature sensors are based on many different principles and the study of these is the material of this sub module.

We take recourse to thermodynamics to provide a definition for temperature of a system. Thermodynamics is the studies of systems in equilibrium and temperature is an important intensive property of such systems. Temperature is defined via the so called zeroth law of thermodynamics. A system is said to be in equilibrium if its properties remain invariant. Consider a certain volume of an ideal gas at a specified pressure. When the sate of this volume of gas is disturbed it will eventually equilibrate in a new state that is described by two new values of volume and pressure. Even though we may not be able to describe the system as it is undergoing a change we may certainly describe the two end states as equilibrium states. Imagine two such systems that may interact through a wall that allows changes to take place in each of them. The change will manifest as changes in pressure and/or volume. If, however, there are no observable changes in pressure and volume of each one of them when they are allowed to interact as mentioned above, the two systems are said to be in equilibrium with each other and are assigned the *same temperature*. The numerical value that is assigned will have to follow some rule or convention as we shall see later.

The zeroth law of thermodynamics states that is a system C is in equilibrium separately with two thermodynamic systems A and B then A and B are also in equilibrium with each other. At once we may conclude that systems A and B are at the same temperature! Thermometry thus consists of using a thermometer (system C) to determine whether or not two systems (A and B in the above) are at the same temperature.

Principle of a thermometer

Principle of any thermometer may be explained using the facts indicated in Figure 1. Consider a system whose state is fixed by two properties – coordinates – **X and Y**. It is observed that several pairs of values of X, Y will be in equilibrium with a second system of **fixed temperature (or a fixed state)**. These multiplicity of sates must all be characterized by the *same* temperature and hence represent an *isotherm*.

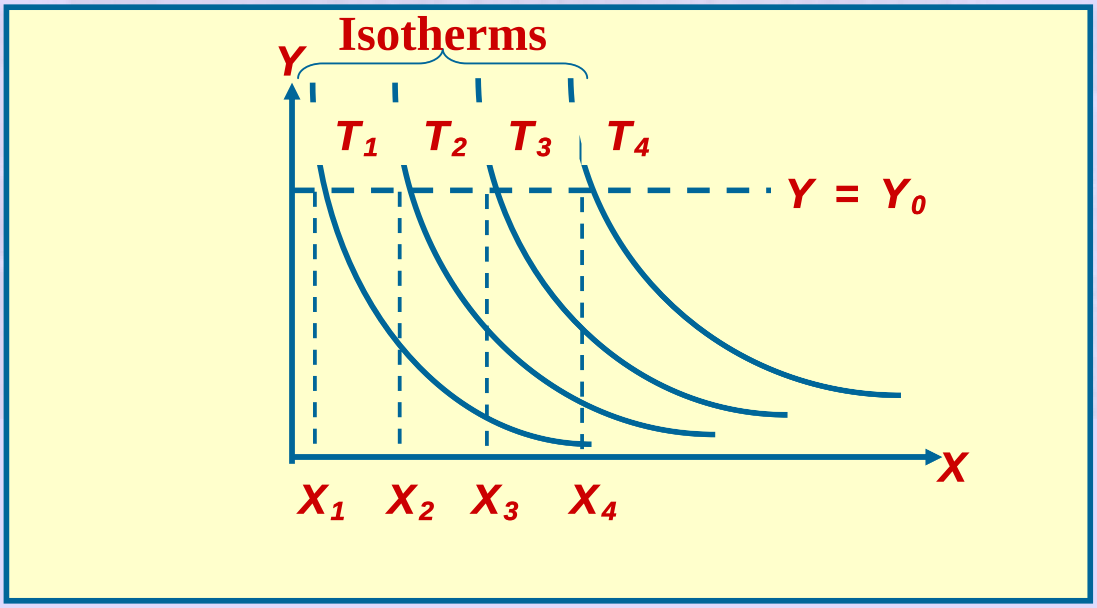

Figure 1 Principle of thermometry explained

Assume that one of the coordinates of the system (Y) is fixed at a value equal to Y_0. Then there is only one sate that will correspond to any given isotherm. If the system is allowed to equilibrate with a system characterized by different isotherms, the property X will change as indicated by the points of intersection X_1, X_2 and so on. These will then correspond to the respective temperatures T_1, T_2 and so on. We refer to **X** as the **thermometric property** and the system as a thermometer.

Thermometer	Thermometric property	Symbol
Gas at constant volume	Pressure	P
Electric resistance under constant tension	Electrical resistance	R
Thermocouple	Thermal electromotive force	E
Saturated vapor of a pure substance	Pressure	P
Blackbody radiation	Spectral emissive power	
Acoustic thermometer	Speed of sound	a

Table 1 Thermometers and thermometric properties

Table 1 shows several thermometers that are actually used in practice. The thermometric property as well as the symbol that is used to indicate it is also shown in the table.

Constant volume gas thermometer

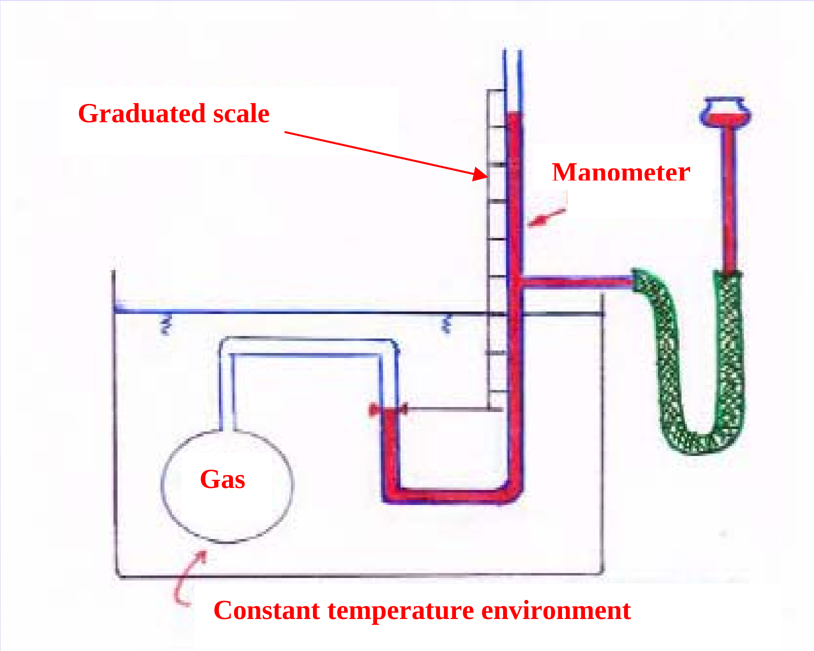

Figure 2 Schematic of a constant volume gas thermometer

We look at the constant volume gas thermometer in some detail now. Schematic of such a thermometer is shown in Figure 2. It consists of a certain volume of a gas contained in a rigid vessel. The vessel is connected to a U tube manometer with a side tube and height adjustable reservoir as shown. The volume is kept constant by making the meniscus in the left limb of the U tube always stay at the mark mad3e on the left limb of the U tube. The right limb has a graduated scale attached to it as shown. The gas containing vessel is immersed in a constant temperature environment. The graduated scale helps in determining the pressure of the confined gas in terms of the manometer head.

The following experiment may be performed. Choose the pressure of the gas to have a definite value when the constant temperature environment corresponds to standard fixed state such as the triple point of water (or the ice point at one atmosphere pressure). Now move the thermometer into an environment at the steam point (boiling point of water at one atmosphere). The pressure of the gas has to be adjusted to a higher value than it was earlier by adjusting the height of the reservoir suitably so as to make the meniscus in the left limb of the U tube stay at the mark. The above experiment may be repeated by taking less and less gas to start with by making the pressure at the triple point of water to have a smaller and smaller value (the vessel volume is the same in all the cases). The experiment may also be repeated with *different* gases in the vessel. The result of such an experiment gives a plot as shown in Figure 3.

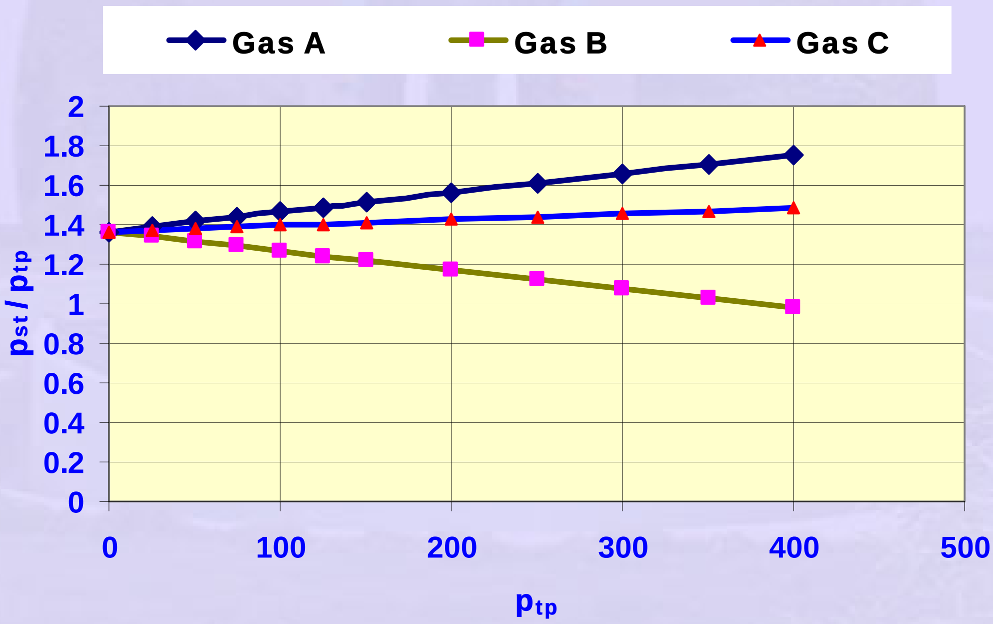

Figure 3 Gas thermometer characteristics

The ratio of the pressure of the gas corresponding to the steam point to that at the triple point of water tends to a unique number as $P_{tp} \to 0$ (the intercept on the pressure ratio axis) independent of the particular gas that has been used. This ratio has been determined very accurately and is given by $\frac{P_{st}}{P_{tp}} \rightarrow 1.366049 as\ P_{tp} \rightarrow 0$. The gas thermometer temperature scale is defined based on this unique ratio and by assigning a numerical value of $T_{tp} = 273.16\ \text{k or } 0.01^{\circ} c$. The defining relation is

$$\frac{T_{st}}{T_{tp}} = \frac{P_{st}}{P_{tp}}\ as\ P_{tp} \rightarrow 0 \quad (1)$$

This last value is referred to as the **single fixed point for thermometry or the primary fixed point**. At this temperature ice, liquid water and water vapor all coexist, if in addition, the pressure is maintained at 4.58 mm Mercury column or 610.65 Pa. The ice point is at 273.15 K or 0°C and was used in early times as the primary fixed point in thermometry. In ordinary laboratory practice the ice point is easier to achieve and hence is commonly used.

Equation 1 may be generalized to define the constant volume gas thermometer temperature scale as

$$\frac{T}{T_{tp}} = \frac{P}{P_{tp}}\ as\ P_{tp} \rightarrow 0 \quad (2)$$

Thus the temperature ratio and pressure ratios are the same in the case of a constant volume gas thermometer. The latter is *measured* while the former is *inferred*. The message thus is clear! A measurable property that varies systematically with temperature is used to infer the temperature! The measured property is termed the thermometric property.

Example 1

- *In determining the melting point of a certain alloy with a gas thermometer, an investigator finds the following values of the pressure p when the pressure p_{tp} at the triple point of water has the indicated value.*

p_{tp}	100	200	300	400
p	233.4	471.6	714.7	962.9

- *If the triple point of water is taken as 273.16 K, what is the melting point of the alloy?*

o *In order to determine the melting point we need the limiting value of the ratio* $\frac{p}{p_{tp}}$ *as* $p_{tp} \to 0$. *This value is obtained by extrapolation. The ratios are calculated and are given by the following table.*

p	100	200	300	400
$\frac{p}{p_{tp}}$	2.334	2.358	2.382	2.407
Difference		0.024	0.024	0.025

o *Since the common differences are constant we may extrapolate linearly to get*

$$\lim_{p_{tp}\to 0} \frac{p}{p_{tp}} = 2.334 - 0.024 = 2.31$$

o *The melting point of the alloy on the gas scale is then given by:*

$$T_{mp} = T_{tp} \times \lim_{p_{tp}\to 0} \frac{p}{p_{tp}} = 273.16 \times 2.31 = 630.99 \text{ K} \approx 631\text{K}$$

Practical thermometry

We have mentioned earlier that the range of temperatures encountered in practice is very wide. It has not been possible to device a single thermometer capable of measuring over the entire range. Since all thermometers must be pegged with respect to the single fixed point viz. the temperature at the triple point of water it is necessary to assign temperature values to as many reproducible states as possible using the constant volume gas thermometer. Subsequently these may be used to calibrate other thermometers that may be used to cover the range of temperatures encountered in practical thermometry. These ideas are central to the introduction of International Temperature Scale 1990 (or ITS90, for short). The following is a brief description of ITS90.

Specification of ranges and corresponding thermometers according to ITS 90

- **Between 0.65 K and 5.0 K T_{90} is defined in terms of the vapor-pressure temperature relations 3He and 4He.**

- **Between 3.0 K and the triple point of neon (24.5561 K) T_{90} is defined by means of a helium gas thermometer calibrated at three experimentally realizable temperatures having assigned numerical values (defining fixed points) and using specified interpolation procedures.**

- **Between the triple point of equilibrium hydrogen (13.8033 K) and the freezing point of silver (961.78 ºC) T90 is defined by means of platinum resistance thermometers calibrated at specified sets of defining fixed points and using specified interpolation procedures**

- **Above the freezing point of silver (961.78ºC) T_{90} is defined in terms of a defining fixed point and the Planck radiation law.**

It is noted that the above uses several “secondary fixed points” to define the temperature scale. These are shown in Table 2.

Table 2 Secondary fixed points used in ITS90

Equilibrium state	T_{90} K	T_{90} °C	Equilibrium state	T_{90} K	T_{90} °C
Triple point of H_2	13.8033	-259.3467	Triple point of Hg	234.3156	-38.8344
Boiling point of H_2 at 250 mm Hg	17	-256.15	Triple point of H_2O	273.16	0.01
Boiling point of H_2 at 1 atmosphere	20.3	-252.85	Melting point of Ga	302.9146	29.7646
Triple Point of Ne	24.5561	-248.5939	Freezing point of In	429.7483	156.5985
Triple point of O_2	54.3584	-218.7916	Freezing point of Sn	505.078	961.928
Triple Point of Ar	83.8058	-189.3442	Freezing point of Al	933.473	660.323
			Freezing point of Ag	1234.93	961.78

Even though the ITS90 specifies only a small number of thermometers, in practice we make use of many types of thermometers. These are discussed in detail below.

How do we make a thermometer?

Properties that vary systematically with temperature may be used as the basis of a thermometer. Several are listed here.

Thermoelectric thermometer

- Based on thermoelectricity - Thermocouple thermometers using two wires of different materials

Electric resistance

- Resistance thermometer using metallic materials like Platinum, Copper, Nickel etc.
- Thermistors consisting of semiconductor materials like Manganese-Nickel-cobalt oxide mixed with proper binders

Thermal expansion

- Bimetallic thermometers
- Liquid in glass thermometer using mercury or other liquids
- Pressure thermometer

Pyrometry and spectroscopic methods

- Radiation thermometry using a pyrometer
- Special methods like spectroscopic methods, laser based methods, interferometry etc.