Thermodynamics
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Lecture 16
Methods of Temperature Measurement

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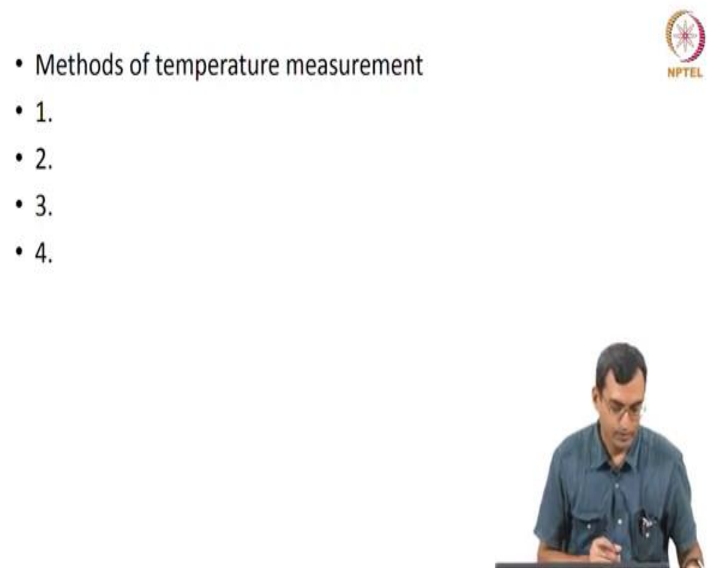

Let's look at some methods of temperature measurement. The commonly known device is a thermometer. Think of ways in which you can measure temperature of an object.

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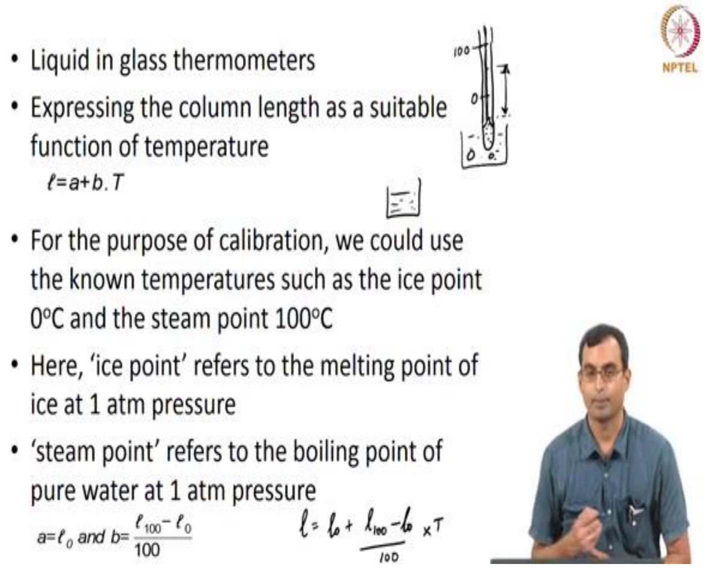

The most familiar device for temperature measurement is a liquid-in-glass thermometer. It is a hollow tube with a bulb-like structure at one of the ends. In that bulb-like structure, a liquid is kept which expands on receiving heat. If the bulb of the thermometer is brought into contact with some hot object whose temperature we want to measure, the liquid expands and travels a certain length of the tube and its length inside the tube gives temperature of the object. Let's see how it is done.

Here, we are trying to express the length of the liquid inside the tube as a function of temperature. Let's say it is $l = a + bT$, where l represents the length of the liquid inside the tube, T represents the temperature of the object, a and b are constants which need to be determined through calibration.

For finding a and b, we need to use fixed point temperatures such as ice and steam point of water at atmospheric condition. Ice point is 0 ℃ and the steam point is 100 ℃ (these are arbitrary values). Now, we put the thermometer in mixture of ice and water at 0 ℃ and let the thermometer attain thermal equilibrium with the mixture. The liquid inside the thermometer will rise to some height. We mark that as 0 ℃. Now, we put the thermocouple into boiling water at 100 ℃ and let the two attain the thermal equilibrium. The liquid inside the thermometer will rise to a new height. We mark this as 100 ℃. Since we know l and T at two different points, we can calculate a and b. In this way, we can measure temperature using liquid in glass thermometer assuming a linear relationship between l and T.

Let's call l corresponding to T= 0 ℃ as l_0 and l corresponding to T=100 ℃ as l_{100}. Then, a=l_0 and b=(l_{100}-l_0)/100. Hence, $l = l_0 + \frac{l_{100}-l_0}{100}T$. In this way, the temperature of the object can be calculated from the length of the liquid column inside the thermometer.

Assumptions made for such measurement are: (1) the cross-section of the thermometer tube is uniform, (2) thermometer liquid does not boil or freeze in the range of temperature to be measured, (3) the relationship between the liquid column length and temperature is linear.

For measuring temperature between 0 and 100 ℃, the above thermometer will work satisfactorily as the liquid used inside the thermometer does not boil or freeze in this range. What if we want to use this thermometer to measure temperature above 100 ℃? Then it may not give us correct reading.

The liquid inside the thermometer should have high boiling point and low melting point compared to the temperature to be measured. For measuring 100 ℃, we cannot use water inside the thermometer as it itself will start boiling at 100 ℃ giving wrong column length. Hence, commonly used liquids inside thermometers are gallium, mercury (liquid metals) which stay preferably in liquid phase at temperature to be measured. Gallium's melting point is around 30 ℃. Hence it should be used for measurement at higher temperature range.

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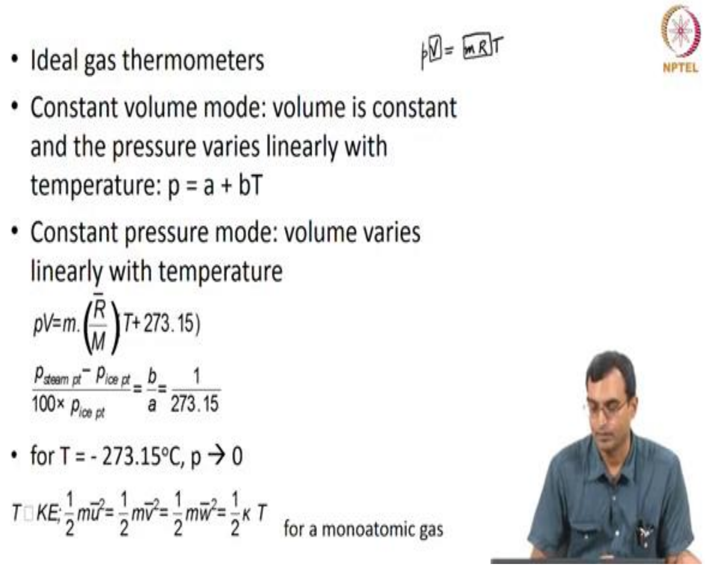

Another type of thermometer is ideal gas thermometer. We will look at the concept of ideal gas in a lot more detail in upcoming lectures. An ideal gas follows the following expression: $pV = mRT$, where p is the gas pressure, V is the gas volume, m is the gas mass, R is the specific gas constant and T is the gas temperature.

Fox a fixed mass of the ideal gas, if we somehow keep volume constant, then temperature depends only on pressure. Here, we find temperature by measuring the pressure of the gas (in liquid-in-glass thermometer, we find temperature by measuring the length of the liquid column). Pressure is a function of temperature, $p = a + bT$ (the expression is similar to the one in the case of liquid-in-glass thermometer). There are many devices to measure pressure (bourdon gauge, manometer). Hence, by keeping volume of the gas constant, putting the thermometer into different substances till thermal equilibrium is reached and measuring the corresponding pressure, and calibrating, we can measure the temperature of the substance.

Similarly, we can have constant pressure ideal gas thermometer. Here, the pressure of the gas is kept constant while its volume changes as a function of temperature. In this case, the expression $pV = mRT$ is written as $pV = m\left(\frac{\bar{R}}{M}\right)T + 273.15$, where $\bar{R}$ is universal gas constant and M is the molecular weight of the gas (we will learn more on this later in the course). As we did calibration in the case of liquid-in-glass thermometer by putting it into ice and water mixture at ice point and boiling water at steam point at atmospheric conditions and found the constants a and b, we can follow the similar procedure for constant pressure ideal gas thermometer and find the constants a and b from the following equation: $\frac{p_{steam\ point}-p_{ice\ point}}{100\ p_{ice\ point}} = \frac{b}{a} = \frac{1}{273.15}$ (we have 100 divisions on the scale here, hence there is 100 in the denominator). For very low temperatures, pressure also tends to 0. At such conditions, this thermometer is fairly reliable.

The temperature can be associated with kinetic energy of the molecules if we look at the molecular picture. Molecules move in all the three directions (x, y and z) and their corresponding kinetic energies can be expressed as $\frac{1}{2}m\bar{u}^2, \frac{1}{2}m\bar{v}^2, \frac{1}{2}m\bar{w}^2$ which can also be expressed in terms of Boltzmann constant and temperature as $\frac{1}{2}kT$ for a monoatomic gas, where k is Boltzmann constant. Molecules move fast at high temperatures and slow at low temperatures. Their kinetic energy is associated with temperature. A gas has pressure because the molecules collide (with each other as well as the walls of the container).

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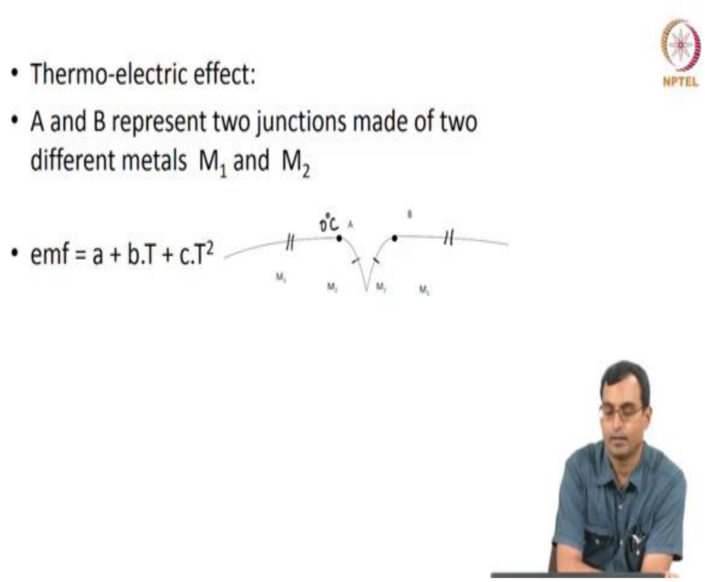

Figure. 1

There are thermometers based on thermoelectric effect. Consider wires of 2 metals M_1 and M_2. Connect them as shown in Fig. 1. It forms 2 junctions. If these two junctions are kept at different temperatures, voltage (emf) is generated which can be measured. This emf is a function of temperature which can be expressed as $emf = a + bT + cT^2$, where a, b and c are constants which can be found from calibration. In this case, as there are three constants, you will need 3 known temperatures to calculate them.

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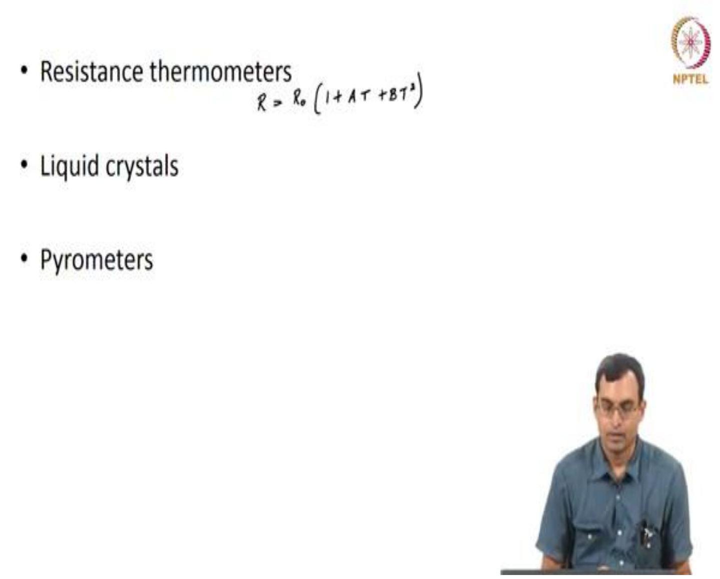

There are resistance thermometers. The resistance of a piece of wire changes with temperature. For most substances, it increases with temperature. Here, we can express resistance as a function of temperature. We keep the piece of wire in contact of the object whose temperature we want to measure, let the thermal equilibrium reach, and measure its resistance, which can be converted into temperature using the mathematical relation between resistance and temperature, for example, $R = R_0(1 + AT + BT^2)$, where A and B are constants.

There are liquid crystals which change color as temperature changes. Hence, these crystals can be painted onto some plate and the plate can brought into contact with the object whose temperature we want to measure, then the color change would indicate the temperature of the object.

For measuring high temperatures, we use pyrometers. These contain filaments whose color changes with change in temperature.

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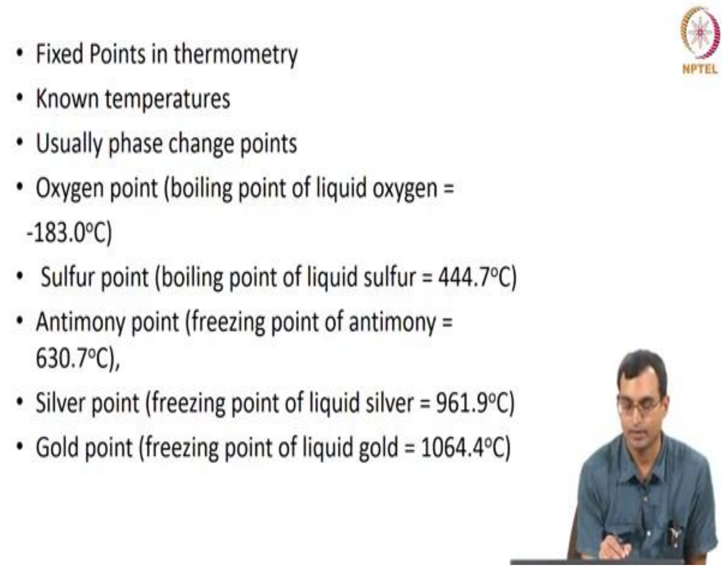

Figure 2.

In all the above methods of temperature measurement, we used some known temperatures for calibration. These are called fixed points in thermometry. These fixed points are usually phase change points (we will learn more on phase change later in the course) as these are easy to reproduce in different labs. Figure 2 mentions some of these fixed points, which are used for calibrating temperature measurement devices.