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# UNIT 3 TEMPERATURE AND HEAT

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## 3.1 INTRODUCTION

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It has been pointed out earlier that there are only two types of interaction between systems. One of these, viz. work, has been discussed in the preceding unit. The other, viz., heat, is discussed in this unit. Heat is defined with reference to temperature difference; hence it is first necessary to know what is meant by temperature. The concept of temperature has additional physical significance, which will become apparent after the formulation of the first and second laws.

### Objectives

After studying this Unit, you should be able to

- \* understand the concept of thermal equilibrium,
- \* state and explain the significance of the Zeroth Law of Thermodynamics,
- \* recognize inequality of temperature,
- \* understand the fundamental concepts relating to the measurement of temperature,

- \* explain the principle of the ideal gas thermometer,
- \* define heat and understand the algebraic sign convention employed for heat,
- \* identify the three common modes of heat transfer,
- \* understand the term "adiabatic" as applied to processes and systems,
- \* understand the significance of heat transfer as a branch of mechanical engineering,
- \* recognize what heat is not, and
- \* explain the similarities and differences concerning work and heat.

### 3.2 THERMAL EQUILIBRIUM

The definition and measurement of temperature must be logically preceded by the concept of thermal equilibrium and the zeroth law.

To determine operationally whether two systems are in thermal equilibrium, they are placed together in contact and isolated from the surroundings. If one of them is hot and the other cold (in the sense in which we commonly use these words), then, after a certain period of time, the former feels less hot and the latter feels less cold. Simultaneously, changes in their physical properties, such as length, electrical resistance etc, occur. After a sufficiently long time (equivalent to the relaxation time) no further changes take place. The two systems are then said to be in thermal equilibrium; they are said to have the same temperature.

**Definition :** Two systems are equal in temperature if no change in any physical property occurs when they are brought into communication.

This definition must not be reversed. It does not imply that "when two systems are equal in temperature, no changes result from their communication". For instance, if an electric lamp and a battery are connected by means of an electrical conductor, then the lamp will light up; this is, of course, a work interaction.

Temperature is at the heart of the difference between work and heat ; hence the necessity to employ rigour in defining concepts relating to temperature. Two points are of significance with reference to the discussion on thermal equilibrium and equality of temperature:

- \* If the definition of temperature equality has to be given in such a manner as to apply equally well when it is reversed, the following condition should be added : "in the absence of any work interactions".
- \* The process of "communication" indicated in the definition is in fact "thermal" communication (excluding any "work interactions"). But this usage leads to circularity and hence is not employed until after temperature equality is defined.

### 3.3 THE ZEROTH LAW OF THERMODYNAMICS

Logically, this is an inductive conclusion based on observations or experiments with systems in thermal equilibrium. If the concept of temperature equality is applied to an experiment involving three systems,  $S_1$ ,  $S_2$  and  $S_3$ , an experimental law regarding temperature can be established.

Let the systems  $S_1$  and  $S_3$  be equal in temperature, as evidenced by the absence of any change in the physical properties of either system when they are brought into (thermal) contact. Similarly, let  $S_2$  and  $S_3$  be equal in temperature so that no change occurs when they are brought into contact. If now  $S_1$  and  $S_2$  are brought into contact, it is an empirical observation that no change occurs in their physical properties ; leading to the conclusion that  $S_1$  and  $S_2$  are equal in temperature.

This leads to the following formulation of the Zeroth Law of Thermodynamics :

**"Two systems which are equal in temperature to a third system are equal in temperature to each other".**

This law provides the basis for temperature measurement. It turns the thermometer into a useful instrument, by eliminating the need for bringing into physical contact each pair of systems whose temperatures we wish to compare.

To some, the zeroth law might appear to be so obvious as to be trivial, but, as will be shown now, it is not so. Let us consider three analogies:

- \* An amber rod A that has been rubbed with fur will attract a pith ball C. So will another amber rod B, but the two amber rods will not attract each other.
- \* The north pole of a magnet A will attract the south pole of a magnet B; so will the north pole of another magnet C. But the north poles of the magnets A and C will not attract each other.
- \* Now for an example from outside science : If Asha loves Bhaskar, and Chitra also loves Bhaskar, it does not mean that Asha and Chitra love each other; just the opposite!

Thus the zeroth law is not a mathematical proposition, but represents the essence of empirical information regarding temperature and thermal equilibrium.

Why is it called the zeroth law ? Because although this statement logically precedes the first and the second laws, it was not explicitly formulated until later. The British astrophysicist R.H.Fowler is credited with having given this name. It is interesting that an Indian physicist figures in this story. While reviewing the book entitled "Heat and Thermodynamics" by Meghnad Saha for a scientific journal in England, Fowler referred to this statement made in the book as the zeroth law, and the name stuck.

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### 3.4 INEQUALITY OF TEMPERATURE

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In a different type of situation, if system  $S_3$  is in thermal equilibrium with  $S_1$ , but when it is brought into contact with another system  $S_2$ , observable changes take place in  $S_3$ , (in the absence of any work interactions), then the temperatures of  $S_1$  and  $S_2$  are said to be unequal.

In order to facilitate the recognition of temperature inequality, the system  $S_3$  is so selected that changes in its physical characteristics can be easily observed. For example, in the commonly used mercury-in-glass thermometer, the thermometric property is the volumetric expansion of mercury relative to that of glass. In the above experiment, a difference in the length of the mercury column, when  $S_3$  contacts  $S_1$  and  $S_2$  in succession, means that  $S_1$  and  $S_2$  have unequal temperatures. On the other hand, if there had been no change in the length of the mercury column, this would mean that  $S_1$  and  $S_2$  have equal temperatures.

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### 3.5 MEASUREMENT OF TEMPERATURE

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Temperature is one of the most important thermodynamic properties, and its measurement and control are important in many applications in industry, R and D, commerce and home. The historical approach is presented here, while the more rigorous and modern concepts have to wait until after the Pure Substance is introduced and the Second Law is discussed.

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### 3.6 THERMOMETERS AND FIXED POINTS

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A thermometer is an instrument for measuring temperature. The zeroth law provides the basis for temperature measurement: The thermometer plays the role of  $S_3$  in the earlier discussion; it provides a quantitative measure of the inequality in temperature. For this purpose, it is possible to establish two standard systems whose conditions are easily reproducible. One of them is  $S_{ice}$  a system consisting of a mixture of ice and water at a pressure of one atmosphere; the second is  $S_{steam}$  consisting of water boiling at a pressure of one atmosphere. Let us employ a mercury-in-glass thermometer to measure temperature. The position of the meniscus of the mercury column, when it has attained thermal equilibrium with  $S_{ice}$  is marked and designated as the ice point; the position when thermal equilibrium is reached with  $S_{steam}$  is also marked and termed the steam point. The length of glass tube between these two marks, which are commonly called the fixed points, is then divided into a number of equal intervals.

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### 3.7 TEMPERATURE SCALES

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Temperature scales are defined by assigning numbers to the ice point, to the steam point, and to the number of divisions into which the interval is divided. The Celsius temperature scale has the ice point marked as 0, and the steam point marked as 100, with 100 equal sub-divisions. Now, if a thermometer  $S_3$  graduated in this manner, is brought into communication with system  $S_1$ , and the mercury rises to the sub-division marked 60, we say that the system  $S_1$  has a temperature of 60 degrees Celsius, written as  $60^\circ\text{C}$ . The size of each of the 100 sub- divisions defines the unit of temperature, the kelvin (K).

Another temperature scale which prevailed till recently (and still in vogue in North America) is the Fahrenheit scale, in which the ice point and the steam point are marked as 32 and 212, respectively, with 180 equal intermediate intervals. The size of the unit for this scale is the rankine(R). The relationship between the Celsius and Fahrenheit temperatures of a given body,  $t_C$  and  $t_F$ , is :

$$t_C = \frac{(t_F - 32)}{1.8} \quad \dots(3.1)$$

$$t_F = 1.8 t_C + 32 \quad \dots(3.2)$$

It is instructive to trace the history of the temperature scales. The common measure of temperature in terms of degrees Fahrenheit is a product of Sumerian or Babylonian influence; they made use of a sexagesimal system of measures for time and angles in terms of hours, minutes, seconds, and degrees. During the early part of the eighteenth century, the Danish astronomer Ole Romer chose the boiling point of water as his higher fixed point and the temperature of a mixture of ice, salt and water as the lower fixed point. Following the Babylonian tradition he adopted sixty divisions for his thermometer, so that his lowest and highest temperatures became 0 and 60, respectively. Romer noted that water froze at about 7.5 or 8 degrees, and that normal body temperature was approximately 22.5 degrees, on his thermometer.

In 1708 Gabriel Daniel Fahrenheit visited Romer in Copenhagen and this led him to adopt the same basic principles in his own work, with some minor changes. Fahrenheit chose the same lower fixed point but took the body temperature as his upper fixed point. He found Romer's scale to be too coarse, so he divided each of the 60 subdivisions into four parts. The freezing point of water thus became  $4 \times 8 = 32$ , and the body temperature  $4 \times 22.5 = 90$ .

Later he changed the scale slightly so that the normal body temperature would correspond to 96 instead of 90; on this modified scale he found that water boiled at 212 rather than at 240, thus resulting in 180 degrees between the freezing and boiling points of water. Fahrenheit thermometers were subsequently calibrated on the basis of the freezing and boiling points of water, so that Fahrenheit's original upper fixed point, viz., the body temperature, turned out to be only an incidental intermediate point at 98.6.

The origins of the thermometer scale with 100 subdivisions between the freezing and boiling points of water are not so clear. The first suggestion appears to have been made by Elvius of Sweden in 1710. The centigrade system is, however, credited to Anders Celsius, a Swedish astronomer, who employed the centesimal system in 1742. Celsius fixed the boiling point of water at 0 and the freezing point at 100. It is believed that he did this to avoid negative temperatures below the melting point of ice. (It is not known how he was going to tackle negative temperatures above the boiling point of water!). A few years later, one of his colleagues, Marten Stromer reversed the fixed points and produced the centesimal scale we use today. It is no longer referred to as the "centigrade" scale, but as the "Celsius" scale.

After discussing the second law of thermodynamics, the "absolute" scale of temperature will be introduced and its significance will be explained. This scale was proposed in 1851 by Lord Kelvin and is named after him; it locates the absolute zero of temperature at  $273.15^\circ\text{C}$  below the freezing point of water at atmospheric pressure. The absolute scale corresponding to the Fahrenheit temperatures is called the Rankine scale, and locates the absolute zero at  $491.67^\circ\text{F}$  below the freezing point of water.

As far as the number of fixed points is concerned, Guillaume Amontons, a French meteorologist, pointed out in 1701 that only one fixed point is really necessary. (Incidentally, he was also the first one to conceive of an absolute scale of temperature). This proposal was reinforced by Lord Kelvin, and again revived by W.F.Giauque of the University of California in 1939. It has been subsequently adopted by the International Union of Physics and Chemistry. The fixed point that is now adopted is the triple point of water, the combination of pressure and temperature at which all the three phases of water (solid, liquid and vapor) coexist in equilibrium. For water, the triple point temperature is assigned the value 273.16 K; this value is chosen to maintain the traditional difference of 100.00 K between the boiling point of water (373.15 K) and the melting point of ice (273.15 K).

### 3.8 EXTRAPOLATION BEYOND THE FIXED POINTS

How can we measure temperatures above and below those of the two fixed points? The uniform graduations between the fixed points may also be continued above and below the fixed points. If, for example, the mercury rises 40 divisions above the steam point mark of a Celsius thermometer, the temperature is then reckoned to be  $140^{\circ}\text{C}$ .

This manner of extrapolation is limited in practice by material properties: If the temperature falls too low, mercury freezes (at  $-38.9^{\circ}$ ), while at high temperatures glass becomes an unsuitable casing material. The strategies for overcoming these constraints include the use of different fluids and casing materials, or by using a different thermometric property.

Every thermometer has a thermometric property associated with it. The zeroth law ensures that the reading of the thermometer is the temperature of all systems in thermal equilibrium with it. The following properties are desirable in a thermometer :

sensitivity	:	an appreciable change in the thermometric property produced by a relatively small change in temperature.
accuracy	:	readings close to agreed-upon standards.
reproducibility	:	readings which can be duplicated consistently.
response	:	rapidly coming into thermal equilibrium with the system whose temperature is being measured.

Apart from volumetric expansion, some of the other thermometric properties in vogue are :

- \* electrical resistance of platinum wire
- \* potential difference between the junctions of dissimilar metals (the thermocouple)
- \* thermal (infra-red) or visible radiation (pyrometers).

For measuring temperatures below the freezing point of mercury, ethyl alcohol(ethanol) in glass can be used down to temperatures of  $-110^{\circ}\text{C}$ . However, such a change to new thermometric substances introduces a difficulty. An alcohol-in-glass thermometer and a mercury-in-glass thermometer, both measuring the temperature of the same system, give, in general, different readings, even though they were graduated with reference to the same standard systems. Figure 3.1 indicates this behaviour, the difference being shown magnified for illustration. Both the scales must agree at the fixed points, by definition. It is seen that these are, in fact, the only two points at which the two scales agree. In the example shown,

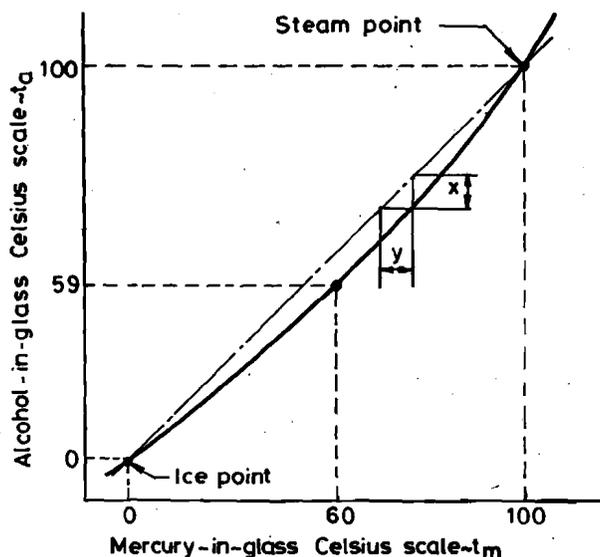


Figure 3.1 : Comparison of Temperature Scales

when  $t_m$  is  $60^{\circ}\text{C}$ ,  $t_a$  is  $59^{\circ}\text{C}$ . The question is : which thermometer is to be taken as correct?

The same problem arises also when other thermometric properties are employed over the same range. Except at the calibration points, these thermometers will not generally agree. The reason is that each of the thermometers depends on how each different physical

property - the volume of mercury, the electromotive force (emf) of a thermocouple, the electrical resistance of a wire, etc. - varies with temperature. There is no reason why all these physical properties of various real materials should be the same function of temperature; in fact, they are not.

### 3.9 THE ARBITRARINESS OF TEMPERATURE SCALES

It therefore appears that all temperature scales are arbitrary. Each step, from the selection of the thermometric substance and the casing material to the choice of the numbers for the fixed points, appears to be unrelated. The answer to the question : "which thermometer is correct" is that it is up to us to call one right and the other wrong. For example, in Figure 3.1, if the mercury-in-glass thermometer is taken as standard, then  $x$  is the "error" in the alcohol-in-glass reading. Similarly  $y$  is the "error" in the mercury-in-glass reading, if the alcohol-in-glass thermometer is taken as standard.

The other aspect about the arbitrariness of temperature scales is that the numbers on the scale are arbitrary. There is no special reason for the numbers given to the ice and steam points on the Celsius and Fahrenheit scales.

These features cause a serious problem since it means that any temperature measurement is a function of the thermometer used to measure it. In principle, any thermometer may be selected as the standard; however, it is desirable in practice for everyone to use the same standard. As a practical matter, in order to enable scientists and technologists to know exactly what each other means when a temperature is reported, an International Temperature Scale (ITS) has been established.

#### Example 3.1 :

The readings  $t_1$  and  $t_2$  of two Celsius thermometers agree at the ice point and at the steam point. They are related by the equation  $t_1 = A + Bt_2 + Ct_2^2$  between these two points, where A, B and C are constants. When both are immersed in an oil bath,  $t_1$  is  $51^\circ\text{C}$  while  $t_2$  is  $50^\circ\text{C}$ . Determine the value of  $t_1$  when  $t_2$  reads  $25^\circ\text{C}$ .

#### Solution :

At the ice point,  $t_1 = 0$ ,  $t_2 = 0$ ; hence  $A = 0$

At the steam point,  $100 = 100B + 10,000C$  ... (i)

When  $t_1 = 51$ ,  $t_2 = 50$ ;  $51 = 50B + 2500C$  ... (ii)

From (i) and (ii),

$$B = 1.04; C = -.4 \times 10^{-3}$$

Hence, when  $t_2 = 25^\circ\text{C}$ ,  $t_1 = 25.75^\circ\text{C}$  ANSWER

### 3.10 THE INTERNATIONAL TEMPERATURE SCALE (ITS)

The ITS is an internationally agreed practical standard scale. It is defined by specifying a number of fixed points (standard systems) together with a method of interpolating between them (standard thermometers). The ITS establishes a series of operational definitions for temperature in certain ranges.

Table 3.1 shows the basic fixed points which have been internationally adopted. (A few additional secondary fixed points have also been defined).

TABLE 3.1

Fixed points	Standard system at a pressure of 1 atm	Temperature	
		°C	°F
Oxygen-point	Oxygen boiling	-182.97	-297.35
Ice-point	Ice melting	0.00	32.00
Steam-point	Water boiling	100.00	212.00
Sulphur-point	Sulphur boiling	444.60	832.28
Silver-point	Silver melting	960.80	1761.40
Gold-point	Gold melting	1063.00	1945.40

The numbers assigned to the various fixed points of the ITS have been chosen in order that this scale should be consistent with the absolute temperature scale, which is independent of the properties of particular substances or systems.

In order to specify temperatures between the basic fixed points, an interpolation procedure is prescribed. The range of the scale is divided into four parts, and for each part a particular type of thermometer is specified as the indicator of the temperature. For example, between the ice-point and 660°C, the temperature  $t$  is deduced from the resistance  $R_t$  of a standard platinum resistance thermometer, through the equation :

$$R_t = R_0(1 + At + Bt^2) \quad \dots(3.3)$$

The constants  $R_0$ ,  $A$  and  $B$  of this equation are determined by calibrating the thermometer at the ice, steam and sulphur points. Different means of interpolation are specified for the other three portions of the scale. More information on the ITS is available from standard references such as the Handbook of Physics and Chemistry.

The establishment of the ITS makes it possible for scientists and technologists to agree on temperature measurements. Thus the practical problems created by the arbitrariness of temperature scales have been solved by the agreement on the ITS. The theoretical problems, however, still remain. Temperature still seems so arbitrary. It can be put on a sound basis only with the help of the second law.

A partial solution to the theoretical problem is provided by a type of thermometer which is independent of the physical properties of the substances or materials used in constructing the thermometer. It is the ideal gas thermometer. In addition, it gives readings which are quite identical with those on the absolute scale.

### 3.11 THE IDEAL GAS THERMOMETER

The ideal gas thermometer involves an extrapolation of results to zero pressure at which all gases behave as ideal gases. Figure 3.2 shows a gas thermometer. It consists essentially of a glass bulb connected to a U-tube containing a liquid such as, for example, mercury. A "permanent" gas (e.g. oxygen, nitrogen, hydrogen) is enclosed within the bulb and the connecting flexible tube by the mercury, the other limb of the U-tube being open to the atmosphere. During the experiments, the bulb is placed in contact with systems at different temperatures, and the level of the mercury can be adjusted to keep either the volume or the pressure of the gas constant.

Let us consider its operation as a constant-volume gas thermometer. In order to set up the temperature scale, we note the difference in the right-hand meniscus level (indicative of the gas pressure) at the two fixed points, maintaining the mercury level in the left-hand limb, and hence the gas volume, constant in each case. A gas thermometer Celsius scale is defined by assigning 0 and 100 to the ice and steam points, with 100 equal sub-divisions between them. This linear scale in gas pressure  $p$  may be expressed as follows :

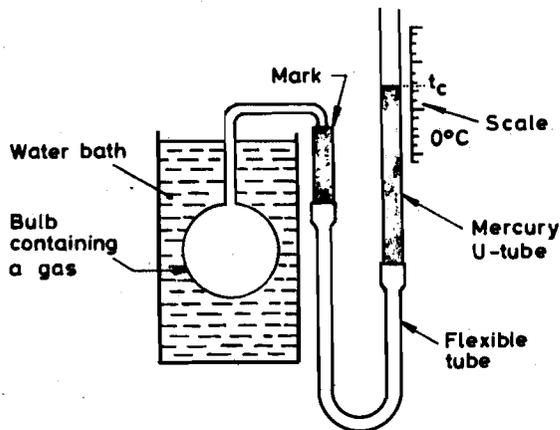


Figure 3.2 : Constant - Volume Gas Thermometer

$$p = p_i [1 + \alpha t] \quad \dots(3.4)$$

where  $p_i$  = the gas pressure at the ice point,  $0^\circ\text{C}$   
 $t$  = the "gas thermometer" Celsius temperature  
 $\alpha$  = a constant, equal to  $\frac{(p_s - p_i)}{100p_i}$   
 $p_s$  = the gas pressure at the steam point,  $100^\circ\text{C}$

A series of values of  $\alpha$  is obtained by performing the experiments employing equal volumes of the same gas at progressively lower gas pressures (i.e. smaller masses of gas). By plotting these values of  $\alpha$  against  $p_i$  in each experiment, and extrapolating the curve to zero pressure, a value of  $\alpha^*$  corresponding to zero pressure may be determined. In practice,  $\alpha$  varies little with pressure.

In a similar fashion, by the use of a number of different gases, a value of  $\alpha^*$  corresponding to zero pressure is obtained for each gas. The important experimental result is that these values of  $\alpha^*$  prove to be the same for every gas. The behaviour of gases at very low pressures corresponds to that of an ideal gas, and the value of  $\alpha^*$  so obtained by extrapolation defines the ideal-gas temperature scale.

The ideal gas Celsius scale is given by :

$$p = p_i [1 + \frac{1}{273.15} (t_c)] \quad \dots(3.5)$$

As can be seen from the above, the extrapolated value of  $\alpha^*$  corresponding to zero pressure is  $1/273.15$ . A corresponding equation, with the same value of  $\alpha^*$ , but with volume replacing pressure, is obtained using the constant-pressure gas thermometer.

It can be seen from equation 3.5. that when the pressure  $p$  is zero,  $t = -273.15^\circ\text{C}$  on the ideal gas Celsius scale.

In addition to providing us with a more satisfactory concept of temperature, the Kelvin (and Rankine) scales indicate a very important feature : Only positive absolute temperatures are defined. Negative Kelvin (or Rankine) temperatures do not exist. It is for this reason that these scales are called absolute. As a matter of fact the zero point on these scales is called the absolute zero to distinguish it from the zero points on the Celsius (and Fahrenheit) scales.

### SAQ 2

A constant volume gas thermometer containing helium gives readings of gas pressure ( $p$ ) of 1000 and 1366 mm Hg at the ice point and steam point, respectively.

- a) Express the gas thermometer Celsius temperature ( $t$ ) in terms of the gas pressure  $p$ .

- b) If the thermometer reads 1080 mm Hg, determine the corresponding temperature.

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## 3.12 A FINAL COMMENT ON TEMPERATURE MEASUREMENT

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Temperature is one of the most common and important thermodynamic properties measured by engineers. It is important to note that thermometers really measure only their own temperature! It is up to the engineer to ensure that the thermometer is at the same temperature as the system whose temperature is desired. The thermometer corresponds to system  $S_3$  in the zeroth law statement: If two systems (the unknown and the calibration standard) are equal in temperature to a third system (the thermometer), then they are equal in temperature to each other.

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## 3.13 HEAT

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We have defined equality of temperatures as the relation between two systems which exists when no change results from their communication. This suggests that when the temperatures are unequal, some change may result even when work interactions are absent. The interaction which invariably results from temperature differences is heat.

### 3.13.1 Definition of Heat

Heat is the interaction between systems which occurs by virtue of their temperature difference when they communicate.

This definition describes the procedure by which a heat interaction is recognised. It specifies two conditions which must be satisfied for a heat interaction between systems to occur:

- \* temperature difference
- \* communication.

The two conditions must be fulfilled simultaneously; the absence of either requirement will mean absence of heat.

In order to be useful, the definition of heat must be combined with a statement about how heat is to be measured. Looking back to how the measurement procedure for work was established, we defined a standard system (a specified amount of any substance) and a standard process which the system was caused to undergo by the interaction (a specified change of elevation in a standard gravitational field). The magnitude of the work interaction causing this process, i.e. the work, was then established as the unit of work, and was given a name, one newton metre.

Corresponding steps are needed in defining a measurement procedure for a heat interaction. The standard system is 1 kg of water at a temperature of 14.5°C and a pressure of 1 atm. The standard process involves putting this standard system into communication with a second system at a different temperature. A heat interaction occurs which causes the temperature of the standard system to rise to 15.5°C. The magnitude of the heat interaction in this operation is defined as one kilocalorie (1 kcal).

It is found experimentally that the second system mentioned above has to be at a temperature higher than 15.5°C. This is an illustration of the rule that a heat interaction tends to reduce the temperature difference which causes the interaction.

When a system  $H$  at a higher temperature communicates with a system  $L$  at a lower temperature, the heat interaction may be determined as follows: Imagine  $L$  to be replaced by a number of standard kilograms of water which rise in temperature from 14.5°C to 15.5°C as  $H$  performs the same process as when communicating with  $L$ . The number of kilograms is the required magnitude, in kcal. Of course, it is not necessary actually to carry

out this process. Physicists have devised many practical devices, in effect sub-standards, to serve day-to-day needs; but these are all calibrated in terms of the standard systems and process described.

### 3.13.2 The Direction of Heat Interaction

In defining a unit of heat, we described the standard process as involving a temperature rise of 1 kg of water. It is found experimentally that when, as a result of a heat interaction, the temperature of 1 kg of water falls from 15.5°C to 14.5°C, the magnitude of the heat interaction is again 1 kcal. In order to distinguish between these two cases, a directional language is used with a corresponding algebraic sign convention.

If, in a heat interaction between two systems  $H$  and  $L$ , system  $H$  is at the higher temperature, we say that a "heat transfer" has taken place from  $H$  to  $L$ . It must be noted that the words "transfer", "to", and "from" are metaphorical. They are universally employed because of their convenience, but there is really no substance "hotness" which is being transferred in the sense in which water can be poured from a container into a glass.

The "transfer" metaphor derives historically from the long-discredited caloric theory. The nature of heat as an interaction similar to work may perhaps be more logically conveyed if we use phrases such as "heat done on" a system or "heat done by" another. Unfortunately, these phrases conflict too much with common usage.

### 3.13.3 Algebraic Sign Convention

Heat interaction is commonly given the symbol  $Q$ , and is considered to be positive for a system if the system is at the lower temperature in comparison to its surroundings. This means that heat transfer to the system is positive, while heat transfer from the system is negative. A consequence of this convention is that if, in a given interaction, the heat for the system is positive, that for the surroundings is negative.

It will be noticed that this convention is just the opposite to that for work; as is illustrated in Figure 3.3, where the arrows express symbolically the "transfer" metaphor.

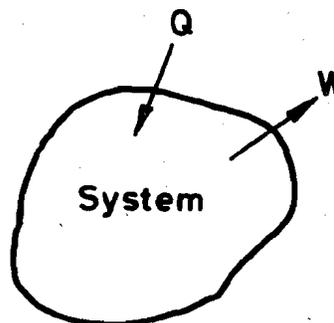


Figure 3.3 : Sign Convention for Heat and Work

There is a historical reason for these conventions. At the time the concepts of heat and work, and their inter-conversion, were first being studied, the principal application area was the operation of the steam engines which were necessary for pumping out the water from the coal mines, which incidentally provided the fuel for the steam engines. With efficiency defined as the ratio of output to input, the output being the work delivered by the steam engines, and the input being the heat transferred to the working fluid, it was necessary to employ the sign convention discussed here in order to come up with positive efficiency values.

Sometimes the directional language and the sign convention may appear simultaneously in phrases such as "the heat transfer to the system is negative", indicating that the direction of heat transfer is from the system to its surroundings.

#### PROBLEMS

State, giving reasons, whether the heat ( $Q$ ) and the work ( $W$ ) are positive or negative, or zero, in each of the following processes. The systems to be considered are indicated.

- (a) An electric current flows steadily through a system with hot reservoirs and cooling water.

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## 3.14 MODES OF HEAT TRANSFER

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We have seen above that two systems of different temperature must "communicate" if a heat interaction is to occur. We now briefly look at ways by which the communication may be effected.

### 3.14.1 Conduction

The simplest form of communication is by contact between the systems, either directly or across a separating layer. The heat interaction that occurs now is termed heat conduction. The rate ( $\text{W/m}^2$ ) of heat conduction is proportional to the prevailing temperature gradient ( $\text{K/m}$ ), and is given by Fourier's law:

$$q = -kA \nabla T \quad \dots(3.6)$$

where the proportionality constant  $k$  is termed the thermal conductivity ( $\text{W/m.K}$ ). It is a material property, generally large for metals, smaller for non-metallic solids and liquids, and smallest for gases.

### 3.14.2 Convection

If the conducting medium is a fluid in motion, the mode of heat transfer is called convection. The mechanism of heat convection may be explained with reference to a (double pipe) heat exchanger in which a flowing fluid is confined between a hot and a cold surface. Heat transfer from the hot surface to the fluid particles in contact with it occurs by conduction; causing the fluid temperature to rise. The warmed fluid, being in motion, subsequently comes into contact with the cold surface which is lower in temperature than the fluid, and heat transfer occurs by conduction from the fluid to the cold surface.

There are two types of convection:

- \* forced convection
- \* free (or natural) convection.

In forced convection, as described above, the fluid motion is "forced" by an external agency, such as a pump or compressor. In free or natural convection, the fluid motion arises as a result of density differences caused by temperature differences. The convection currents which may be discerned in the water contained in a vessel heated from below, or the vertical motion of hot gases in a candle flame, are examples of free convection.

### 3.14.3 Radiation

Even when the intervening space between two systems contains no matter or material, the systems are still in thermal communication. Electromagnetic radiation is transferred

between the surfaces, and it does not require any material communication. The radiative transfer from the sun to the earth is a familiar example. The rate of radiative heat transfer is much more sensitive to the temperatures of the surfaces than the rates of conduction and convection. It is often negligibly small at room temperature.

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### 3.15 THERMAL INSULATION

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In many applications, it is necessary to reduce the rate of heat transfer to small values. Examples are the familiar thermos or Dewar flasks, furnaces etc. The type of insulation employed depends upon the heat transfer mode which is dominant. Equation 3.6 provides the basis for minimizing the rate of conductive heat transfer : We need to separate the systems by thick layers of poorly-conducting or insulating materials; these are usually non-metallic solids containing pores filled with air, e.g. glass wool or mineral wool. If it is desired to reduce the rate of radiative heat transfer, then the exterior of the container should be a good reflecting surface.

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### 3.16 ADIABATIC PROCESSES AND ADIABATIC SYSTEMS

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These represent idealized situations in which the rate of heat transfer is essentially zero. As can be inferred from the preceding section, the magnitude of heat interaction between two systems may be considered to be negligibly small if they are separated by insulating materials, if the separation distance is large, or if the period of time under consideration is small. A process during which the heat interaction is zero is termed an adiabatic process, while a system isolated from its surroundings as regards heat transfer is called an adiabatic system. Thus, the term "adiabatic" means " $Q = 0$ ".

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### 3.17 "HEAT TRANSFER" AS A BRANCH OF MECHANICAL ENGINEERING

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There are several major types of engineering equipment employed in industrial practice which involve the application of heat transfer principles. They may be classified into two major classes, on the basis of the desired objective :

- \* equipment in which the heat transfer is to be maximized; as in all types of heat exchangers.
- \* equipment in which the heat transfer is to be minimized; as in all types of thermal insulation employed to prevent "heat leaks".

The principles of design and operation involve the determination of the rate of heat transfer, which is beyond the scope of thermodynamics. Heat transfer has developed into a separate branch of thermal engineering, and involves a combination of theory and experiment.

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### 3.18 WHAT HEAT IS NOT

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It is extremely instructive to discuss the following four features characterising what heat is not :

- \* Heat is not a fluid which passes from hot bodies to cold bodies, as was imagined during the 18th century. In the "caloric" theory postulated at that time, heat was considered to be a fluid, termed "caloric", and attempts were made to isolate it and weigh it. The temperature rise which occurs during metal-turning was explained to be the escape of the caloric as the material became sub-divided. The caloric theory was finally disproved by Count Rumford in 1798 by means of his famous Cannon-boring experiment.
- \* Heat transfer to a system does not always cause a temperature rise. For example, during phase changes such as melting and boiling, there is no temperature change accompanying the heat transfer.
- \* It is not only heat transfer which can cause a temperature rise. Work done on a system, as for example, stirring of the fluid in an insulated container, can result in a temperature rise.
- \* Heat is not a property of a system.

## 3.19 COMPARISON OF WORK AND HEAT

After having discussed both work and heat, it is possible to list the similarities and differences between them.

### 3.19.1 Similarities

- \* Both are energy transfers defined with reference to the system boundary.
- \* Both are transient; they exist only during the interaction.
- \* Neither of them is a property.
- \* Both are path-dependent.
- \* Both represent inexact differentials.

### 3.19.2 Differences

Table II illustrates the differences between work and heat. The second law establishes a more fundamental difference between work and heat, which will be discussed later.

Table 3.2 : Differences between Work and Heat

Work	Heat
Positive work defined in terms of the lifting of a weight being the sole effect during the interaction.	Defined as the interaction which occurs as a result of a temperature difference between two systems in thermal communication.
Can cause a temperature rise in an adiabatic system.	Being zero for an adiabatic system, cannot affect its temperature.
In the almost universally employed sign convention, work done by a system or transferred from a system, is considered to be positive.	In this sign convention, heat transferred to a system is considered to be positive.
There are as many types of work interactions as there are generalized forces, causing generalized displacements.	Three modes of heat transfer are recognised.
(Will be shown later that) complete conversion to other forms of work, or to heat, is possible	Complete conversion to work (in a cyclic process) is prohibited by the Second Law.

## 3.20 SUMMARY

This Unit describes the essential features concerning Temperature and Heat, which are closely inter-connected. The Zeroth Law of Thermodynamics provides the basis for temperature measurement, which involves thermometers, fixed points, and temperature scales.

Heat is an interaction between systems arising out of a temperature difference between them. There are essentially three modes of heat transfer, viz., conduction, convection and radiation. A comparison of heat and work lays the basis for introducing the First Law of Thermodynamics in the next Unit.

Two systems are equal in temperature if no change in any physical property occurs when they are brought into communication, in the absence of any work interactions.

Temperature is at the heart of the difference between work and heat.

The Zeroth Law of Thermodynamics states that "Two systems which are equal in temperature to a third system are equal in temperature to each other". This law provides the basis for temperature measurement.

A thermometer is an instrument for measuring temperature.

Temperature scales are defined by assigning numbers to the fixed points, and to the number of divisions into which the interval is divided. The Celsius temperature scale has the ice point marked as 0, and the steam point marked as 100, with 100 equal sub-divisions. The size of each of the 100 sub-divisions defines the unit of temperature, the kelvin (K). The

absolute temperature scale, proposed by Lord Kelvin in 1851, locates the absolute zero of temperature at 273.15°C below the ice point.

The International Union of Physics and Chemistry has now adopted a single fixed point, viz., the triple point of water, the combination of pressure and temperature at which all the three phases of water co-exist in equilibrium.

The properties desired in a thermometer are sensitivity, accuracy, reproducibility and response.

While all empirical temperature scales are arbitrary, the International Temperature Scale is an internationally agreed practical standard scale, which is defined by specifying a number of fixed points, together with a method of interpolating between them.

The ideal gas thermometer involves an extrapolation of results to zero pressure at which all gases behave as ideal gases. The ideal gas Celsius scale of a constant-volume ideal gas thermometer is given by :

$$p = p_i [1 + (1/273.15) t_c]$$

On the absolute temperature scale, only positive temperatures are defined. The zero point on this scale is called the absolute zero in order to distinguish it from the zero point on the Celsius scale.

Heat is the interaction between systems which occurs by virtue of their temperature difference when they communicate. Thus, two conditions must be satisfied for a heat interaction between systems to occur : temperature difference and communication.

In the commonly adopted sign convention, heat transfer to the system is positive, while heat transfer from the system is negative. Note that this convention is just the opposite to that for work.

There are essentially three modes of heat transfer :

- \* Conduction occurs by contact between the systems, either directly or across a separating layer.
- \* Convection occurs when the conducting medium is a fluid in motion.
- \* Radiation occurs even when the intervening space between two systems contains no matter or material.

In many applications, it is desirable to reduce the rate of heat transfer to negligible values ; this is the concern of thermal insulation.

A process during which the heat interaction is zero is termed an adiabatic process, while a system isolated from its surroundings as regards heat transfer is called an adiabatic system. Thus, the term "adiabatic" means  $Q = 0$ .

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### 3.21 KEY WORDS AND PHRASES

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Thermal Equilibrium	:	Two systems are in thermal equilibrium if no change in any physical property occurs when they are brought into communication.
Zeroth Law of Thermodynamics	:	Two systems which are equal in temperature to a third system are equal in temperature to each other.
Thermometer	:	An instrument for measuring temperature.
Heat	:	The interaction between systems which occurs by virtue of their temperature difference when they communicate.
Heat Conduction	:	Heat transfer by contact between systems, either directly or across a separating layer.
Forced Convection	:	Convection occurring when the fluid motion is forced by an external agency, such as a pump or compressor.
Free or Natural Convection	:	Convection occurring when the fluid motion arises as a result of density differences caused by temperature differences.
Heat Radiation	:	Heat transfer which occurs even when the intervening space between systems contains no matter or material.

- Adiabatic Process : A process during which the heat interaction is zero.
- Adiabatic System : A system isolated from its surroundings as regards heat transfer.

### 3.22 FURTHER READING

1. Holman, J.P., "THERMODYNAMICS", McGraw - Hill, 1974.
2. Natarajan, R., "THERMODYNAMIC ANALYSIS OF ENERGY SYSTEMS AND PROCESSES", Mechanical Engineering Monograph Series, IIT, Madras, 1984.

### 3.23 ANSWERS/SOLUTIONS TO SAQs

#### SAQ 1

$$T_k = t_c + 273.15; \text{ and } T_k = t_c$$

It is clear that this can not occur at positive values on the Celsius scale.

With negative values on the Celsius scale,

$$T_k = -t_c + 273.15; \text{ and } T_k = t_c$$

Hence, the numerical value is 136.575 ANSWER

#### SAQ 2

For a constant volume gas thermometer,

$$p = p_i [1 + \alpha t]$$

$$\text{where } \alpha = \frac{p_s - p_i}{100 p_i}$$

$$\text{Here } \alpha = \frac{(1366 - 1000)}{100 \times 1000} = 3.66 \times 10^{-3}$$

- a) Hence, for this constant volume thermometer,

$$p = p_i [1 + 3.66 \times 10^{-3} t] \text{ ANSWER}$$

- b)  $1080 = 1000 [1 + 3.66 \times 10^{-3} t]$

$$t = 21.86^\circ\text{C ANSWER}$$

#### SAQ 3

- a)  $Q < 0$ ; the resistor which becomes warm as a result of current flow, transfers heat to the surrounding water.  
 $W < 0$ ; electrical work is done on the resistor.
- b)  $Q = 0$ ; the container is insulated.  
 $W = 0$ ; there is no interaction at the container boundary.
- c)  $Q = 0$ ; the container of gas is insulated  
 $W > 0$ ; displacement work is done by the gas on the piston.
- d)  $Q = 0$ ; the container of liquid is insulated.  
 $W = 0$ ; rigid container; turbulence energy is converted to internal energy.
- e)  $Q < 0$ ; heat is transferred from the steam to the atmosphere.  
 $W = 0$ ; rigid container.
- f)  $Q = 0$ ; adiabatic process  
 $W = 0$ ; unresisted expansion.