8 Thermometry

Thermal physics, the branch of physics that deals with the changes in the properties of system that occur when work is done on (or by) them and heat energy is added to (or taken form) them.

The water in the shower or bathtub feels hot or cold or warm. The weather outside is *chilly* or *steamy*. We certainly have a good feel for how one temperature is qualitatively different than another temperature. We may not always agree on whether the room temperature is too hot or too cold or just right.

The temperature of a body may be defined as its thermal condition, considered with reference to its power of communicating heat to or receiving heat from other bodies. This definition gives no direction as to how the temperature of a body is to be measured numerically.

In order to measure temperature we may select one of the effects produced by an accession of heat in a particular instrument, and estimate the range of temperature through which that instrument is raised or lowered when placed in contact with the body whose temperature is to be measured by measuring the amount of the effect produced.

This is the method practically adopted. The instrument which is so used is called a thermometer, and the branch of the science of heat which treats of the application of such instruments is called thermometry.

A thermometer is calibrated by typical process involves using the freezing point and the boiling point of pure water. Water is known to freeze at 0°C and to boil at 100°C at an atmospheric pressure of 1 atm. By placing a thermometer in mixture of ice water and allowing the thermometer liquid to reach a stable height, the 0° mark can be placed; Similarly, by placing the thermometer in boiling water and allowing the liquid level to reach a stable height, the 100° mark can be placed upon the thermometer.

With these two markings placed upon the thermometer, 100 equally spaced divisions can be placed between them to represent the 1° marks for which it has been calibrated.

Note

Today, there are a variety of types of thermometers. The type that most of us are familiar with from science class is the type that consists of a liquid encased in a narrow glass column. Older thermometers of this type used liquid mercury. In response to our understanding of the health concerns associated with mercury exposure, these types of thermometers usually use some type of liquid alcohol. These liquid thermometers are based on the principle of thermal expansion. When a substance gets hotter, it expands to a greater volume. Nearly all substances exhibit this behaviour of thermal expansion. It is the basis of the design and operation of thermometers.

Temperature Scales

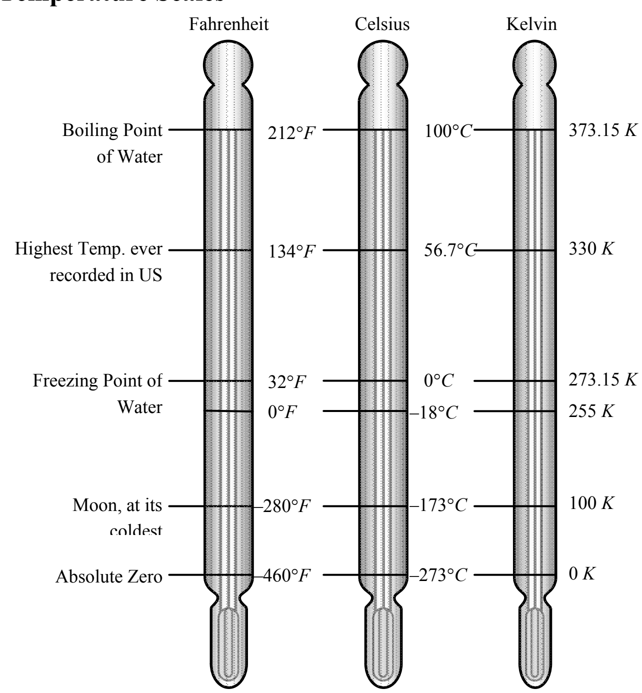

Figure: 8.1

Thermometry

If X is temperature dependent property of substance varying linearly with temperature, then

$$\text{Temperature } t = \frac{X_t - X_0}{X_{100} - X_0} \times 100°C$$

Relation of change of reading of one thermometer to another is:

$$\frac{C-1}{100} = \frac{F-32}{180} = \frac{K-273}{100} = \frac{R-0}{80} = \frac{R_n - 492}{180}$$

Table: 8.1 Different temperature scales

Name of the scale	Symbol for each degree	Lower fixed point (LFP)	Upper fixed point (UEP)	Number of divisions on the scale
Celsius °C	$°C$	$°C$	$100°C$	100
Fahrenheit	$°F$	$32°F$	$212°F$	180
Reaumur	$°R$	$0°R$	$80°R$	80
Rankine	$°Ra$	460 Ra	627 Ra	212
Kelvin	K	273.15 K	373.15 K	100

Gas Thermometers: In this thermometer a gas, assumed ideal, is used at constant volume. This gas is filled at high temperature and low pressure. $t = \dfrac{P_t - P_0}{P_{100} - P_0} \times 100°C$

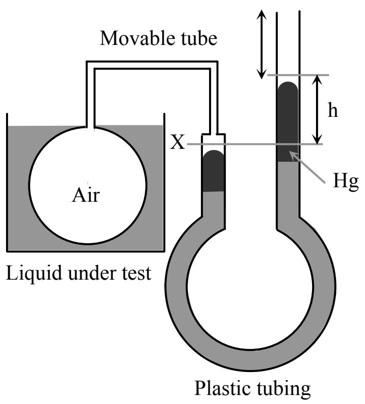

Figure: 8.2

Vapour Pressure Thermometer: $\log P = a + bt - \dfrac{C}{T}$

Table: 8.2

S No.	Thermometers	Temperature Ranges of Different
1	Mercury Thermometer	$-30°C$ to $357°C$
2	Gas Thermometer	$-268°C$ to $1500°C$
3	Thermocouple Thermometer	$-200°C$ to $-1200°C$
4	Thermocouple Thermometer	$-200°C$ to $-1600°C$
5	Radiation Pyrometer	Form 800°C to no upper limit.
6	Disappearing Filament Pyrometer	$600°C$ to $2700°C$
7	Vapour Pressure thermometer	0.71 K to 122 K
8	Magnetic Thermometer	Near absolute zero

Heat

- The form of energy which is exchanged among various bodies or system on account of temperature difference is defined as heat.
  We can change the temperature of a body by giving heat (temperature rises) or by removing heat (temperature falls) from body.
- The amount of heat (Q) is given to a body depends upon it's mass (m), change in it's temperature $(\Delta\theta° = \Delta\theta)$ and nature of material *i.e.* $Q = m.c.\Delta\theta$; where, c = specific heat of material.
- Heat is a scalar quantity. It's units are *joule*, *erg*, *cal*, *kcal etc*. The calorie (cal) is defined as the amount of heat required to raise the temperature of 1 gm of water from 14.5°C to 15.5°C.
  Also 1 $kcal$ = 1000 cal = 4186 J
  and 1 cal = 4.18 J

British Thermal Unit (BTU): One BTU is the quantity of heat required to raise the temperature of one pound $(1 lb)$ of water from 63°F to 64°F.

1 $BTU = 778\, ft.\, lb = 252\, cal = 1055\, J$

- In solids thermal energy is present in the form of kinetic energy, in liquids, in the form of translator energy of molecules. In gas it is due to the random motion of molecules.
- Heat always flows from a body of higher temperature to lower temperature till their temperature becomes equal (Thermal equilibrium).
- The heat required for a given temperature increase depends only on how many atoms the sample contains, not on the mass of an individual atom.

Specific Heat: When a body is heated it's temperature rises (except during a change in phase).

- **Gram specific heat:** The amount of heat energy required to raise the temperature of unit mass of a body through 1°C (or K) is called specific heat of the material of the body.
  If Q heat changes the temperature of mass m by $\Delta\theta$ then specific heat $c = \dfrac{Q}{m\Delta\theta}$
- **Units:** *Calorie*/*gm* × °C (practical), J/kg × K (S.I.) Dimension: $[L^2T^{-2}\theta^{-1}]$
- For an infinitesimal temperature change $d\theta$ and corresponding quantity of heat dQ.
  Specific heat $c = \dfrac{1}{m} \cdot \dfrac{dQ}{d\theta}$
- Molar specific heat: Molar specific heat of a substance is defined as the amount of heat required to raise the temperature of 1 gram mole of the substance through a unit degree it is represented by (capital) C.
  Molar specific heat
  (3) $= M \times$ Gram specific heat
  (3) (M = Molecular mass of substance)

$$C = M\frac{Q}{m\Delta\theta} = \frac{1}{\mu}\frac{Q}{\Delta\theta} \left(\text{where, Number of moles } \mu = \frac{m}{M}\right)$$

Units: calorie/mole × °C (practical); J/mole × kelvin (S.I.)

Dimension: $[ML^2T^{-2}\theta^{-1}]$

- Specific heat of ice : In C.G.S.

$$c_{\text{ice}} = 0.5\frac{cal}{gm\times°C}$$

In S.I. $c_{\text{ice}} = 500\frac{cal}{kg\times°C} = 2100\frac{Joule}{kg\times°C}$.

Specific Heat of Liquid (Water)

- Among all known solids and liquids specific heat of water is maximum *i.e.* water takes more time to heat and more time to cool *w.r.t.* other solids and liquids.
- It is observed that by increasing temperature, initially specific heat of water goes on decreasing, becomes minimum at 37°C and then it start increasing. Specific heat of water is –

  $\frac{1cal}{gm\times°C} = 1000\frac{cal}{kg\times°C} = 4200\frac{J}{kg\times°C}$ (This value is obtained between the temperature 14.5°C to 15.5°C).
- Relative humidity $= \frac{m}{M}\times100\% = \frac{p}{P}\times100\%$

Latent heat: The amount of heat required to change the state of the mass m of the substance is written as: $Q = mL$, where L is the latent heat. Latent heat is also called as Heat of Transformation. Its unit is *cal/gm* or *J/kg* and Dimension: $[L^2T^{-2}]$

Latent heat of fusion: The latent heat of fusion is the heat energy required to change 1 *kg* of the material in its solid state at its melting point to 1 *kg* of the material in its liquid state. It is also the amount of heat energy released when at melting point 1 *kg* of liquid changes to 1 *kg* of solid. For water at its normal freezing temperature or melting point (0°C), the latent heat of fusion (or latent heat of ice) is

$$L_F = L_{\text{ice}} \approx 80\,cal/gm \approx 60\,kJ/mol \approx 336\,kilo\ joule/kg$$

- **Latent heat of vaporisation:** The latent heat of vapourisation is the heat energy required to change 1 *kg* of the material in its liquid state at its boiling point to 1 *kg* of the material in its gaseous state. It is also the amount of heat energy released when 1 *kg* of vapour changes into 1 *kg* of liquid. For water at its normal boiling point or condensation temperature (100°C), the latent heat of vapourisation (latent heat of steam) is

$$L_V = L_{\text{steam}} \approx 540\,cal/gm$$
$$\approx 40.8\,kJ/mol \approx 2260\,kilo\ joule/kg$$

- Latent heat of vapourisation is more than the latent heat of fusion. This is because when a substance gets converted from liquid to vapour, there is a large increase in volume. Hence more amount of heat is required.

Anomalous Expansion of Water

- Generally matter expands on heating and contracts on cooling. In case of water, it expands on heating if its temperature is greater than 4°C. In the range 0°C to 4°C, water contracts on heating and expands on cooling, i.e., γ is negative. At 4°C, density of water is maximum while its specific volume is minimum. This behaviour of water in the range from 0°C to 4°C is called anomalous expansion.

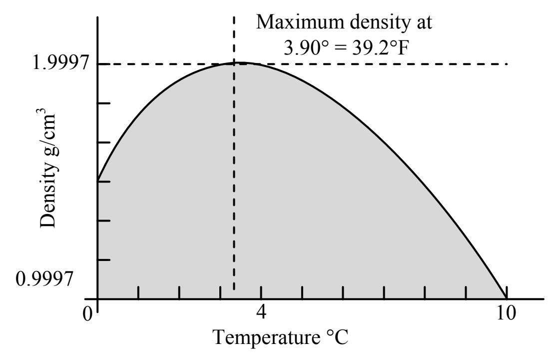

Figure: 8.3

- The anomalous behaviour of water arises due to the fact that water has three types of molecules, viz., H_2O $(H_2O)_2$ and $(H_2O)_3$ having different volume per unit mass and at different temperatures their properties in water are different.

Thermal Resistance

The thermal resistance of a body is a measure of its opposition to the flow of heat through it. It is defined as the ratio of temperature difference to the heat current (= rate of flow of heat). Unit of thermal resistance is °C × sec/cal or K × sec/k-calorie.

Now, temperature difference $= (\theta_1 \sim \theta_2)$

Heat current, $H = \frac{Q}{t}$

$$\therefore \quad R_{Th} = \frac{\theta_1 \sim \theta_2}{H} = \frac{\theta_1 \sim \theta_2}{(Q/t)}$$

$$= \frac{\theta_1 \sim \theta_2}{KA(\theta_1 \sim \theta_2)/d} = \frac{d}{KA}$$

Table: 8.3 Temperature of mixture in different cases

Condition	**Temperature of mixture**
If bodies are of same material *i.e.* $c_1 = c_2$	$\theta_{mix} = \frac{m_1\theta_1 + m_2\theta_2}{m_1 + m_2}$
If bodies are of same mass $m_1 = m_2$	$\theta_{mix} = \frac{\theta_1 c_1 + \theta_2 c_2}{c_1 + c_2}$
If $m_1 = m_2$ and $c_1 = c_2$	$\theta_{mix} = \frac{\theta_1 + \theta_2}{2}$

- **Evaporation:** Vaporisation occurring from the free surface of a liquid is called evaporation. Evaporation is the escape of molecules from the surface of a liquid. This process takes place at all temperatures and increases with the increase of temperature. Evaporation leads to cooling because the faster molecules escape and, therefore, the average kinetic energy of the molecules of the liquid (and hence the temperature) decreases.

Melting (or fusion)/freezing (or solidification):

The phase change of solid to liquid is called melting or fusion. The reverse phenomenon is called freezing or solidification.

- When pressure is applied on ice, it melts. As soon as the pressure is removed, it freezes again. This phenomenon is called **regelation**.

- **Vaporisation/liquefaction (condensation):** The phase change from liquid to vapour is called vaporisation. The reverse transition is called liquefaction or condensation.
- **Sublimation:** Sublimation is the conversion of a solid directly into vapours. Sublimation takes place when boiling point is less than the melting point. A block of ice sublimates into vapours on the surface of moon because of very low pressure on its surface. Heat required to change unit mass of solid directly into vapours at a given temperature is called heat of sublimation at that temperature.

- **Hoar frost:** Direct conversion of vapours into solid is called hoar frost. This process is just reverse of the process of sublimation, *e.g.*, formation of snow by freezing of clouds.

- **Vapour pressure:** When the space above a liquid is closed, it soon becomes saturated with vapour and a dynamic equilibrium is established. The pressure exerted by this vapour is called Saturated Vapour Pressure (S.V.P.) whose value depends only on the temperature – it is independent of any external pressure. If the volume of the space is reduced, some vapour liquefies, but the pressure is unchanged.

- A saturated vapour does not obey the gas law whereas the unsaturated vapour obeys them fairly well. However, a vapour differs from a gas in that the former can be liquefied by pressure alone, whereas the latter cannot be liquefied unless it is first cooled.

- **Boiling:** As the temperature of a liquid is increased, the rate of evaporation also increases. A stage is reached when bubbles of vapour start forming in the body of the liquid which rise to the surface and escape. A liquid boils at a temperature at which the S.V.P. is equal to the external pressure. It is a fast process. The boiling point changes on mixing impurities.

- **Dew point:** It is that temperature at which the mass of water vapour present in a given volume of air is just sufficient to saturate it, *i.e.* the temperature at which the actual vapour pressure becomes equal to the saturated vapuor pressure.

- **Humidity:** Atmospheric air always contains some water vapour. The mass of water vapour per unit volume is called absolute humidity. The ratio of the mass of water vapour (m) actually present in a given volume of air to the mass of water vapour (M) required to saturate the same volume at the same temperature is called the relative humidity (R.H.). Generally, it is expressed as a percentage, *i.e.*,

$$\text{R.H.}(\%) = \frac{m}{M} \times 100(\%)$$

Relative humidity may also be defined as the ratio of the actual vapour pressure (p) of water at the same temperature,

i.e. $\text{R.H.}(\%) = \frac{p}{P} \times 100(\%)$

Thus R.H. may also be defined as

$$\text{R.H.}(\%) = \frac{\text{S.V.P. at dew point}}{\text{S.V. P. at given temperature}} \times 100$$

Multiple Choice Questions

1. The temperature of the sun is measured with
   a. Platinum thermometer
   b. Gas thermometer
   c. Pyrometer
   d. Vapour pressure thermometer

2. Maximum density of H_2O is at the temperature
   a. $32°F$ **b.** $39.2°F$ **c.** $42°F$ **d.** $4°F$

3. The study of physical phenomenon at low temperatures (below liquid nitrogen temperature) is called
   a. Refrigeration **b.** Radiation
   c. Cryogenics **d.** Pyrometry

4. The absolute zero is the temperature at which
   a. Water freezes
   b. All substances exist in solid state
   c. Molecular motion ceases
   d. None of the above

5. Absolute zero (0 K) is that temperature at which
   a. Matter ceases to exist
   b. Ice melts and water freezes
   c. Volume and pressure of a gas becomes zero
   d. None of these

6. On which of the following scales of temperature, the temperature is never negative
   a. Celsius **b.** Fahrenheit
   c. Reaumur **d.** Kelvin

7. The temperature on Celsius scale is $25°C$. What is the corresponding temperature on the Fahrenheit scale
   a. $40°F$ **b.** $77°F$ **c.** $50°F$ **d.** $45°F$

8. The temperature of a body on Kelvin scale is found to be x K. When it is measured by Fahrenheit thermometer, it is found to be $x°F$, then the value of x is:
   a. 40 **b.** 313 **c.** 574.25 **d.** 301.25

9. A centigrade and a Fahrenheit thermometer are dipped in boiling water. The water temperature is lowered until the Fahrenheit thermometer registers 140°. What is the fall in temperature as registered by the Centigrade thermometer
   a. 30° **b.** 40° **c.** 60° **d.** 80°

10. At what temperature the centigrade (Celsius) and Fahrenheit, readings are the same
    a. – 40° **b.** + 40° **c.** 36.6° **d.** – 37°

11. Mercury thermometers can be used to measure temperatures upto
    a. $100°C$ **b.** $212°C$ **c.** $360°C$ **d.** $500°C$

12. Mercury boils at $367°C$. However, mercury thermometers are made such that they can measure temperature up to $500°C$. This is done by
    a. Maintaining vacuum above mercury column in the stem of the thermometer
    b. Filling nitrogen gas at high pressure above the mercury column
    c. Filling nitrogen gas at low pressure above the mercury level
    d. Filling oxygen gas at high pressure above the mercury column

13. A device used to measure very high temperature is:
    a. Pyrometer **b.** Thermometer
    c. Bolometer **d.** Calorimeter

14. The absolute zero temperature in Fahrenheit scale is
    a. $-273°F$ **b.** $-32°F$ **c.** $-460°F$ **d.** $-132°F$

15. If temperature of an object is $140°F$, then its temperature in centigrade is:
    a. $105°C$ **b.** $32°C$ **c.** $140°C$ **d.** $60°C$

16. When a rod is heated but prevented from expanding, the stress developed is independent of
    a. Material of the rod **b.** Rise in temperature
    c. Length of rod **d.** None of above

17. Expansion during heating
    a. Occurs only in solids
    b. Increases the weight of a material
    c. Decreases the density of a material
    d. Occurs at the same rate for all liquids and solids

18. In cold countries, water pipes sometimes burst, because
    a. Pipe contracts
    b. Water expands on freezing
    c. When water freezes, pressure increases
    d. When water freezes, it takes heat from pipes

19. A quantity of heat required to change the unit mass of a solid substance, from solid state to liquid state, while the temperature remains constant, is known as:
    a. Latent heat **b.** Sublimation
    c. Hoar frost **d.** Latent heat of fusion

20. The latent heat of vaporisation of a substance is always
    a. Greater than its latent heat of fusion
    b. Greater than its latent heat of sublimation
    c. Equal to its latent heat of sublimation
    d. Less than its latent heat of fusion

ANSWERS

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
c	b	c	c	c	d	b	c	c	a
11.	**12.**	**13.**	**14.**	**15.**	**16.**	**17.**	**18.**	**19.**	**20.**
c	b	a	c	d	c	c	b	d	a

SOLUTIONS

1. **(c)** Pyrometer can measure temperature from $800°C$ to $6000°C$. Hence temperature of sun is measured with pyrometer.

2. **(b)** Maximum density of water is at $4°C$

Also $\frac{C}{5}=\frac{F-32}{9}$

$\Rightarrow \frac{4}{5}=\frac{F-32}{9}$

$\Rightarrow F=39.2°F$

3. **(c)** Production and measurement of temperature close to 0° K is done in cryogenics.

4. **(c)** At absolute zero (*i.e.* 0 *K*) v_{rms} becomes zero.

5. **(c)** We know that $P=P_0(1+\gamma t)$

and $V=V_0(1+\gamma t)$

and $\gamma=(1/273)/°C$ for $t=-273°C$,

We have $P=0$ and $V=0$

Hence, at absolute zero,
the volume and pressure of the gas become zero.

6. **(d)** Zero Kelvin $=-273°C$ (absolute temperature).

As no matter can attain this temperature, hence temperature can never be negative on Kelvin scale.

7. **(b)** $\frac{C}{5}=\frac{F-32}{9}$

$\Rightarrow \frac{25}{5}=\frac{F-32}{9} \Rightarrow F=7\dot{7}°F$

8. **(c)** $\frac{F-32}{9}=\frac{K=273}{5}$

$\Rightarrow \frac{x-32}{9}=\frac{x-273}{5}$

$\Rightarrow \quad x=574.25$

9. **(c)** $\frac{C}{5}=\frac{F-32}{9}$

$\Rightarrow \frac{C}{5}=\frac{(140-32)}{9} \Rightarrow C=60°$

10. **(a)** $\frac{C}{5}=\frac{F-32}{9}$

$\Rightarrow \frac{t}{5}=\frac{t-32}{9} \Rightarrow t=-40°$

11. **(c)** The boiling point of mercury is $400°C$. Therefore, the mercury thermometer can be used to measure the temperature upto $360°C$.

12. **(b)** By filling nitrogen gas at high pressure, the boiling point of mercury is increased which extend the range upto $500°C$.

13. **(a)** Pyrometer is used to measure very high temperature.

14. **(c)** $\frac{F-32}{9}=\frac{K-273}{5}$

$\Rightarrow \frac{F-32}{9}=\frac{0-273}{5}$

$\Rightarrow F=-459.4°F \approx -460°F$

15. **(d)** $\frac{C}{5}=\frac{F-32}{9}$

$\Rightarrow \frac{C}{5}=\frac{140-32}{9}$

$\Rightarrow C=60°C$

16. **(c)** Stress $=Y\alpha\Delta\theta$, hence it is independent of length.

17. **(c)** Solids, liquids and gases all expand on being heated as result density (= mass/volume) decreases.

18. **(b)** In anomalous expansion, water contracts on heating and expands on cooling in the range $0°C$ to $4°C$. Therefore water pipes sometimes burst, in cold countries.

20. **(a)** The latent heat of vaporisation is always greater than latent heat of fusion because in liquid to vapour phase change there is a large increase in volume. Hence more heat is required as compared to solid to liquid phase change.

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