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COLLEGE OF BASIC AND APPLIED SCIENCES
DEPARMENT OF MATHEMATICS AND PHYSICAL SCIENCES

Course Code: PHY 111 **Course Title:** GENERAL PHYSICS I

Lecture Notes B2 – Heat Measurement

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Content:

Introduction

This topic introduces the measurement of heat. Some of the major concepts crucial to the measurement of heat which will be discussed here are: heat capacity, specific heat capacity, method of mixture, specific latent heat of fusion and vapourization. In addition, you will also learn about the three basic effects of heat - expansion, change in temperature and change in state, and how they are associated with the measurement of heat. The word heat is sometimes used to refer to the process by which energy is transferred between objects because of a difference in their temperatures.

Concept of Heat Energy

Energy is the capacity of matter to perform work as a result of its motion or position in relation to forces acting on it. Energy exists in various forms: mechanical, thermal, chemical, radiant, atomic, etc. The unit of energy is Joule (J) which is also the unit of measuring mechanical energy and electrical energy. We also have larger units such as kilo-joule (KJ) and mega-joule (MJ). Therefore, thermal energy is the energy derived from heat.

Heat is the energy transferred between objects because of a difference in their temperatures. Heat and temperature are not the same but they are closely related. What is temperature? Temperature is the degree of coldness or hotness of a body. It is measured objectively and quantitatively by suing the thermometer.

In physics, the study of heat measurement is known as Calorimetry. Heat can be transferred in various ways such as conduction, convection and radiation. The nature of substance plays an important role in the study of thermal phenomena. For example, a large iron tank and an aluminum kettle have a different heat capacity. It depends on their respective masses and on the metal need.

Heat Capacity

The heat capacity (H) of a body, is the quantity heat (Q) in joules required to change its temperature by one degree (Celsius or one Kelvin).

Let t_1°C be the initial temperature of the body and t_2°C be the final temperature when Q joules of heat has been supplied.

$$H = \frac{Q\ (J)}{\Delta\,\theta\ ℃}$$

Where, $\Delta\theta = (t_2 - t_1)$

$$H = \frac{Q\ (J)}{(t_2 - t_1)\ ℃} \qquad (1)$$

Thus the unit of heat (thermal) capacity is $\mathrm{JK^{-1}}$ or $\mathrm{J\ ℃^{-1}}$

The values of H for different bodies are not the same. They vary from one body to another.

Example 1

A metal container of heat capacity $500\ \mathrm{J\ ℃^{-1}}$ is heated from 15℃ to 65℃. Calculate the total quantity of heat required?

Solution

$$H = \frac{Q\ (J)}{(t_2 - t_1)\ ℃}$$

$$\therefore\quad Q = H\,(t_2 - t_1) = 500\ \mathrm{J\ ℃^{-1}} \times (65 - 15)℃$$

$$= 500 \times 50$$

$$= 25000\ \mathrm{J}$$

$$Q = 25\ \mathrm{KJ}$$

Specific Heat Capacity

The specific heat capacity of a substance is therefore defined as the amount of heat Q (in joules) required to raise the temperature of 1kg mass of substance through unit degree (1℃ or 1 K).

The unit of C is J/kg ℃ or $\mathrm{JKg^{-1}℃^{-1}}$or $\mathrm{JKg^{-1}K^{-1}}$.

If there are different masses of a substance m_1, m_2 and m_3, it will be observed that to raise their temperatures through 1℃ each, they will require different quantities of heat energy Q_1, Q_2 and Q_3.

$$Q \propto m \qquad (2)$$

$$Q \propto \Delta\theta \qquad (3)$$

Combining equations (2) and (3), we obtain

$$Q \propto m\Delta\theta$$

Or $$Q = Cm\Delta\theta \qquad (4)$$

Where C is a constant of proportionality known as the specific heat capacity of the substance

$$\therefore \quad C = \frac{Q}{m\Delta\theta}$$

The value of C differs from one substance to another.

Table 1: Specific Heat Capacity for Some Substances

Substance	Specific heat capacity in $JKg^{-1}°C^{-1}$
Iron	460
Copper	387
Lead	128
Aluminum	899
Gold	129
Mercury	138
Water	4200

Example 2

How much heat is needed to raise 10 g of water from 30°C to boiling point?
(Specific heat capacity of water = 4200 $JKg^{-1}°C^{-1}$)

Solution

$Q = mC\Delta\theta = mC(t_2 - t_1)$ = 0.01 Kg × 4200 J/kg °C × (100 – 30) °C

Q = 2940 J

= 2.94 KJ

Calorimetry

Calorimetry an experimental procedure used to measure the energy transferred from one substance to another as heat. This is an approach to determining a substance's specific heat capacity. Devices that are used for making this measurement are called calorimeters. A calorimeter also contains both a thermometer to measure the final temperature of substances at thermal equilibrium and a stirrer to ensure the uniform mixture of energy throughout the water. This procedure is termed method of mixture.

Method of Mixtures

The method of mixtures works on the principle of conservation of heat energy.

This principle states that ***"the heat lost by a hot body is equal to the heat gained by the cold body in any system provided there is no heat exchange between the substances involved and their surrounding"***

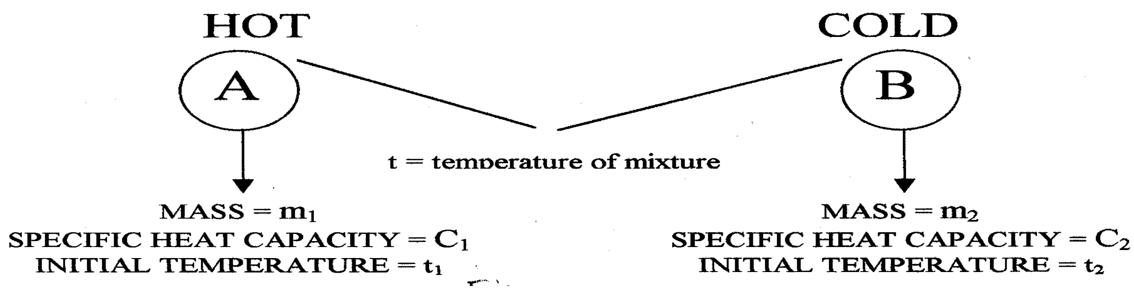

Fig. 1

If body A is the hot body at temperature t_1 and B is the cold body at temperature t_2, A and B are then mixed up to give a final temperature of mixture t.

1. The hot body has lost some heat to the cold body B.
   Let Q_1 be the amount of heat lost
   $Q_1 = m_1C_1\Delta\theta_1$
   $\therefore \quad Q_1 = m_1C_1(t_1 - \text{t})$ (i)

2. The cold body B has gained some heat.
   Let Q_2 be the amount of heat gained.
   $\therefore \quad Q_2 = m_2C_2\Delta\theta_2$
   $Q_2 = m_2C_2(\text{t} - t_2)$ (ii)

Using the principle of conservation of heat energy, which says that

Heat lost = Heat gained

$\therefore \quad Q_1 = Q_2$

$\therefore \quad m_1C_1\Delta\theta_1 = m_2C_2\Delta\theta_2$

$\therefore \quad m_1C_1(t_1 - \text{t}) = m_2C_2(\text{t} - t_2)$ (5)

Example 3

A 2.0 kg mass of brass is heated to 75°C and then dropped gently into 1.5 kg of water at 18°C. If the equilibrium temperature is 25°C, find the specific heat capacity of brass.

Method of Mixtures Involving Calorimeter

Here we have the hot body A at a higher temperature than the liquid contained in the calorimeter. Thus, the liquid and the calorimeter are considered as the cold body gaining heat from the hot body.

Heat lost by hot body, A = Q_1

$Q_1 = m_1C_1\Delta\theta_1 = m_1C_1(t_1 - \text{t})$ (iii)

Heat gained by cold liquid (B) = Q_2

$Q_2 = m_2C_2\Delta\theta_2 = m_2C_2(\text{t} - t_2)$ (iv)

Heat gained by cold calorimeter C = Q_3.

$$Q_3 = m_3 C_3 \Delta\theta_3 = m_3 C_3 (t - t_3) \qquad \text{(v)}$$

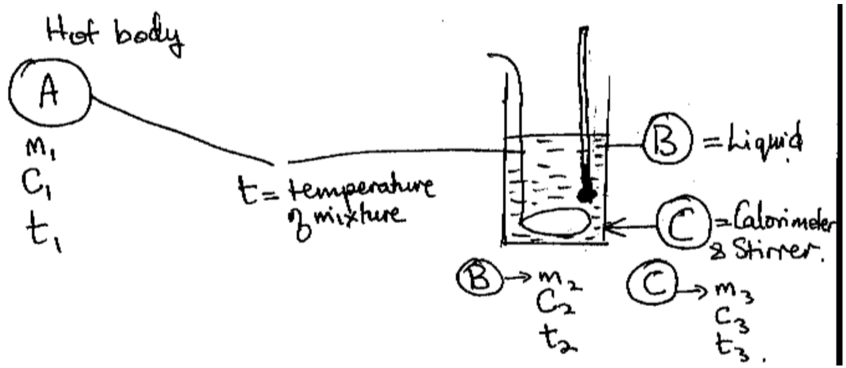

Fig. 2

Note that the liquid (B) and calorimeter (C) are both gaining heat. Therefore their changes in temperature will be the same.

$$\therefore \quad \Delta Q_2 = \Delta Q_3$$

$$\therefore \quad (t - t_2) = (t - t_3)$$

By applying the principle of conversation of heat energy, we have

Heat lost = Heat gained

$$\mathbf{Q_1} = \mathbf{Q_2} + \mathbf{Q_3} \qquad \text{(vi)}$$

$$\therefore \quad m_1 C_1 (t - t_1) = m_2 C_2 (t - t_2) + m_3 C_3 (t - t_2) \qquad (6)$$

Or $$m_1 C_1 (t - t_1) = m_2 C_2 (t - t_2) + H\,(t - t_2) \qquad (7)$$

Example 4

A calorimeter contains 0.50 Kg of water at 22°C. When 0.70 Kg hot water at 85°C is poured in, the temperature of the mixture is found to be 52°C. What is the heat capacity of the calorimeter? Specific heat capacity of water = 4200 $Jkg^{-1}{}^{o}C^{-1}$

Latent Heat

Latent heat is the energy per unit mass that is transferred during a phase change (or change of state) of a substance.

There are two kinds of latent heat – the one at the melting point and the other at the boiling point.

i. **Latent heat of fusion** is defined as the heat required to melt a whole mass of solid at melting point to liquid at the same temperature.

ii. **Latent heat of vapourization** is defined as the heat required to convert a whole mass of liquid at boiling point to vapour at the same temperature. It is expressed in joules per kilogram (Jkg^{-1}).

To understand the concept of Latent heat, let us consider the effect of heat on a solid ice-block as it is heated from say -10°C to the boiling point 100°C. The graph of the process involved is a plot of temperature against time shown below.

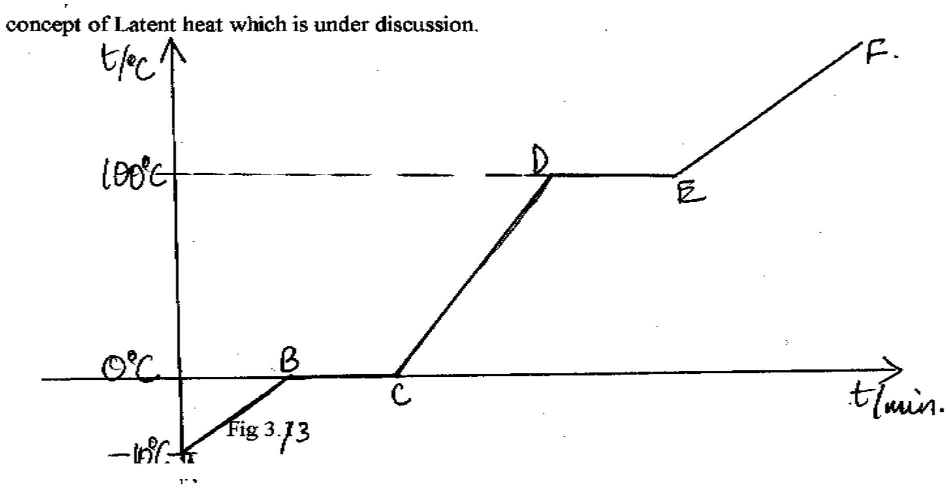

Fig. 3

ıbsorption of heat

The amount of heat supplied, $Q_1 = m_1 C_1 \Delta\theta_1$ (i)

Where m_1 = mass of ice, C_1 = Specific heat capacity of solid ice

$\Delta\theta_1$ = the change in temperature from -10°C to 0°C

$\Delta\theta_1$ = (0 – (-10))°C = 10°C

$\therefore$ Q_1 = $m_1 C_1$ x 10 J

ii. BC shows no increase in temperature with respect to time. At this stage the solid ice is seen to change its state from ice to water (i.e. form solid to liquid). This takes place as 0°C – the melting/freezing point of water. The process is called melting. The reverse process of melting is freezing.

BC corresponds to the absorption of heat energy without any change in temperature. The energy appears latent that is, hidden since there is no change in temperature.

Amount of heat supplied to BC, $Q_2 = mL_f$ (ii)

Where, m = mass of ice and L_f = Specific latent heat of fusion for ice = 3.3 x 10^5 JKg^{-1}

iii. CD indicates an increase in temperature with respect to time.

CD = Q_3 = the quantity of heat supplied to change its temperature from its melting point to 100°C, the boiling point.

$$Q_3 = m_2 C_2 \Delta\theta_2 \quad \text{(iii)}$$

m = mass of the liquid converted from solid ice

C_2 = specific heat capacity of water, and

$\Delta\theta_2$ = change in temperature from 0°C to 100°C.

iv. DE indicates no increase in temperature as the water is being heated. This happens at another fixed temperature of 100°C which is the boiling point of water. The liquid water changes its state from water to steam (gas). The process is called **vapourization.** The reverse process of vapourization is condensation.
DE shows that there is an increase in heat energy while the temperature does not change. DE therefore corresponds to the change in state from liquid to vapour. The heat energy appears latent, meaning that it's hidden, since there was no change in temperature.

The quantity of heat supplied is Q_4.

$$Q_4 = mL_V \qquad \text{(iv)}$$

Where, m = mass of water and

L_V = specific latent heat of vapourization at its boiling point.

L_V for water = 2.4×10^6 J/Kg at 100°C and external pressure of 760mmHg.

Hence, the total heat energy required to change the mass m of ice at -10°C to vapour at 100°C is Q where

$$Q = Q_1 + Q_2 + Q_3 + Q_4$$

$$Q = m_1C_1\Delta\theta_1 + mL_f + m_2C_2\Delta\theta_2 + mL_V \qquad (8)$$

v. EF shows that there is an increase in temperature of steam with respect to time.

Specific latent heat

i. **Specific latent heat of fusion, L_f** is defined as the amount of heat required to change 1kg of mass of solid at its melting point to liquid at the same temperature.
Latent heat of fusion for ice = 3.3×10^5 J/Kg

ii. **The specific latent heat of vaporization**, L_V of a liquid is the quantity of heat required to change 1kg of a liquid at its boiling point to vapour at the same temperature.

Example 5

How much heat is needed to melt 2 kg of ice and then to raise the temperature of the resulting water to 60°C? (Specific latent heat of fusion for ice = 3.3×10^5 J/Kg)

Solution

$$\text{SOLID} \xrightarrow{0^\circ C} \text{WATER} \xrightarrow{60^\circ C} \text{STEAM}$$

Quantity of heat used in melting the ice, Q_1 = mL_f

= $2\,Kg \times 3.3 \times 10^5$ J/Kg

= 6.6×10^5 J

Q_2 = Quantity of heat needed to raise water at 0°C to 60°C

= $m_1C_1\Delta\theta_1$

= $2\text{ Kg} \times 4200\text{ JKg}^{-1}\,°\text{C}^{-1} \times 60°\text{C}$ = 5.04×10^5 J

Total amount of heat required is

$Q = Q_1 + Q_2$

$= 6.6 \times 10^5$ J $+ 5.04 \times 10^5$ J

$= 11.64 \times 10^5$ J

Example 6

How much heat is released when 120 g of steam at 100℃ cool to water at 25℃?
(Specific latent heat of vapourization of water = 2.3×10^6 J/Kg).

Solution

Q_1 = Heat released when steam condenses to water at 100℃

$Q_1 = mL_V = 1.2\, kg \times 2.3 \times 10^6$ J/Kg

$Q_1 = 2.27 \times 10^6$ J

Q_2 = Heat given out by steam when it cools from 100℃ to 25℃

$Q_2 = mC\Delta\theta$

$Q_2 = 1.2$ Kg $\times$ 4200 J/Kg℃ $\times$ (100 – 25)℃

$= 3.78 \times 10^5$ J

Total heat released, Q = $Q_1 + Q_2$

$Q = 2.27 \times 10^6$ J $+ 3.78 \times 10^5$ J $= 2.65 \times 10^6$ J

Assessment Questions

1. Differentiate between the concepts of temperature and heat
2. What is heat capacity?
3. Define specific heat capacity.
4. List the methods of determining the specific heat capacity of a substance.
5. Define latent heat
6. Define specific latent heats of vapourization and fusion.

Assignment

1. An aluminum of mass 300 g is immersed in boiling water and then dropped into 100 g alcohol at 27℃. If the final mixture is 45℃, calculate the specific heat capacity of the alcohol. (Specific heat capacity of iron and water are 800 $JKg^{-1}K^{-1}$ and 4200 $JKg^{-1}K^{-1}$ respectively).
2. A 0.225 kg sample of tin initially at 97.5°C is dropped into 0.115 kg of water. The initial temperature of the water is 10.0°C. If the specific heat capacity of tin is 230 J/kg °C, what is the final equilibrium temperature of the tin-water mixture?

3. A copper calorimeter of mass 120 g contains 80 g of water at $20℃$. If 250 g of a metal at $100℃$ dropped into the water raises the temperature of the mixture to $32℃$. Calculate the specific heat capacity of the metal. (Specific heat capacity of copper = $400\ \mathrm{JKg^{-1}K^{-1}}$).
4. Calculate the mass of ice is required to cool 60 g of water from $53℃$ to $18℃$.
5. How much heat must be added to 5 Kg of copper to raise its temperature from $30℃$ to $90℃$? Take specific heat capacity of copper as $391\ \mathrm{JKg^{-1}K^{-1}}$.

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