ICT 1107: Physics

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ICT 1107: Physics

2. Heat and Thermodynamics

Principle of temperature measurements: platinum resistance thermometer, thermo-electric thermometer, pyrometer; Kinetic theory of gases: Maxwell's distribution of molecular speeds, mean free path, equipartition of energy, Brownian motion, Van der Waal's equation of state, review of the First Law of thermodynamics and its application, reversible and irreversible processes, Second Law of thermodynamics, Carnot cycle; Efficiency of heat engines, Carnot's Theorem, entropy and disorder, thermodynamic functions, Maxwell relations, Clausius-Clapeyron Equation, Gibbs Phase Rule, Third Law of thermodynamics.

8 Lectures

ICT 1107: Physics

Chapter 2

Heat and Thermodynamics

Thermometry

&

Temperature Measurements

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Chapter 2: Heat and Thermodynamics

The following Topics: Study by yourself

Principle of Temperature Measurements

Platinum Resistance Thermometer

Thermoelectric Thermometer

Thermometry

The branch of heat relating to the measurement of temperature of an object is called the thermometry.

Thermometer is an instrument used to measure the temperature of a body. The essential requisites of a thermometer are:

1. Construction
2. Calibration, and
3. Sensitiveness

Thermometers

A **thermometer** is a device that is used to measure the temperature of a system.

Thermometers are based on the principle that some physical property of a system changes as the system's temperature changes.

Thermometers

These properties include:

- The volume of a liquid
- The dimensions of a solid
- The pressure of a gas at a constant volume
- The volume of a gas at a constant pressure
- The electric resistance of a conductor
- The color of an object

A temperature scale can be established on the basis of any of these physical properties.

How the Thermometers Work?

Many thermometers work on the basis of expansion and contraction.

Expansion: An increase in volume of an object. Adding heat results to expand.

Contraction: A decrease in volume of an object. Take away/Removal of heat causes to contract.

Types of Thermometers

There are different types of thermometers:

1. Liquid thermometers (mercury, alcohol)
2. Gas thermometers (Constant pressure, constant volume)
3. Resistance thermometers (platinum resistance)
4. Thermoelectric thermometers **(details given later)**
5. Radiation thermometers (pyrometers)
6. Vapor pressure thermometers (helium vapor pressure thermometer)
7. Bimetallic thermometers (to measure temperatures at high altitudes)
8. Magnetic thermometers (for low temperature measuring)

Resistance Thermometers

A platinum resistance thermometer (PRT) is a piece of platinum wire which determines the temperature by measuring its electrical resistance. It is referred to as a temperature sensor. When manufactured carefully, these devices offer an excellent combination of sensitivity, range and reproducibility.

PRTs work in the following way. The electrical resistance of many metals (*e.g.*, copper, silver, aluminium, platinum) increases approximately linearly with absolute temperature and this feature makes them useful as temperature sensors. The resistance of a wire of the material is measured by passing a current through it and measuring the voltage across it with a suitable voltmeter.

Resistance Thermometer

Chapter 2: Heat & Thermodynamics

Platinum Resistance Thermometer

A platinum resistance thermometer consists of a pure platinum wire wound in a double spiral to avoid inductive effects. The wire is wound on a mica plate. The two ends of the platinum wire are connected to thick copper leads (for lower temperatures) and connected to the binding terminals B_1 B_2. For higher temperatures the leads are of platinum. C_1 and C_2 are the compensating leads exactly similar and of the same resistance as the leads used with the platinum wire. The platinum wire and the compensating leads are enclosed in a glazed porcelain tube. The tube is sealed and binding terminals are provided at the top. The leads pass through mica discs which offer the best insulation and also prevent convection currents (Fig. 1·6).

The resistance of a wire at t°C $= R_t$ and at 0°C $= R_0$. These resistances are connected by the relation

$$R_t = R_0\,(1+\alpha t+\beta t^2) \qquad \ldots(i)$$

Here α and β are constants. The values of α and β depend on the nature of the material used. To find the values of α and β, the resistance of the platinum wire is determined at three fixed points (*i*) melting point of ice, (*ii*) boiling point of water, (*iii*) boiling point of sulphur 444·6°C for high temperature measurement and (*iv*) boiling point of oxygen —182·5°C for low temperature measurement.

Using these values of resistance in equation (*i*)

$$R_{100} = R_0[1+\alpha\, 100+\beta 100^2] \quad \ldots(ii)$$

and

$$R_{444\cdot 6} = R_0[1+\alpha\, 444\cdot 6+\beta(444\cdot 6)^2] \quad \ldots(iii)$$

The values of α and β can be determined by solving the simultaneous equations (*ii*) and (*iii*).

From (*i*) $\quad R_t = R_0[1+\alpha t+\beta t^2]$

Neglecting βt^2 (because β is very small)

$$R_t = R_0\,[1+\alpha t] \qquad \ldots(iv)$$

and

$$R_{100} = R_0[1+\alpha\times 100]$$

$$\therefore \quad R_t - R_0 = R_0\,\alpha\,t \qquad \ldots(v)$$

$$R_{100} - R_0 = R_0\,\alpha.\,100 \qquad \ldots(vi)$$

Dividing (v) and (vi)

$$\frac{R_t - R_0}{R_{100} - R_0} = \frac{t}{100}$$

$$t = \left(\frac{R_t - R_0}{R_{100} - R_0}\right)\times 100 \qquad \ldots(vii)$$

Knowing the values of R_0, R_{100} and R_t, t can be calculated.

IR/Radiation Thermometers

IR thermometers are also known as ‘thermal radiation thermometers’ or ‘pyrometers’ or ‘radiation thermometers’ are non-contact thermometers, which measure the temperature of a body based on its emitted thermal radiation

Infrared thermometers are great for checking surface temperature, however, they do not measure the internal temperature of an object. Infrared thermometers are extremely fast, typically giving a reading in a fraction of a second, or the time it takes for the thermometer’s processor to perform its calculations.

Basic Principle of IR/Radiation Thermometers

Infrared thermometers measure temperature from a distance. This distance can range between miles or a fraction of an inch. Infrared thermometers are often used in circumstances where other sorts of thermometers are not practical. For example if an object is very fragile or dangerous to be near, an infrared thermometer is a good way to get a temperature from a safe distance. Infrared thermometers work based on a phenomenon called black body radiation.

Basic Principle of IR/Radiation Thermometers

Anything at a temperature above absolute zero has molecules inside of it moving around. The higher the temperature, the faster the molecules move. As they move, the molecules emit infrared radiation, a type of electromagnetic radiation below the visible spectrum of light. As they get hotter, they emit more infrared, and even start to emit visible light. That is why heated metal can glow red or even white. Infrared thermometers detect and measure this radiation. Infrared light works like visible light it can be focused, reflected or absorbed.

Basic Principle of IR/Radiation Thermometers

Infrared thermometers usually use a lens to focus infrared light from one object onto a detector called a thermopile. The thermopile absorbs the infrared radiation and turns it into heat. The more infrared energy, the hotter the thermopile gets. This heat is turned into electricity. The electricity is sent to a detector, which uses it to determine the temperature of whatever the thermometer is pointed at. The more electricity, the hotter the object is.

Radiation/IR Thermometers

Heat & Thermodynamics

Sample Questions (Self-Study)

1. Write short notes on the measurements of high and low temperatures.
2. State with reasons the type of thermometer which you consider most suitable for use at temperatures (a) -250°C (b) 700°C, and (c) 2000°C. Indicate briefly the methods of their use.
3. Describe a resistance thermometer. Explain how it is used to measure temperatures accurately. Discuss its advantages over a thermoelectric thermometer.

Heat & Thermodynamics

Sample Questions (Self-Study)

4. Describe a platinum resistance thermometer. How would you calibrate and use it for measuring temperature of an object. Mention its advantages.

5. Briefly state the principle underlying the working of a thermo-electric thermometer.

6. If the platinum temperature corresponding to 60°C on the gas scale is 60.25°C, what will be the temperature on the platinum scale corresponding t0 120°C on the gas scale?

Heat & Thermodynamics

Sample Questions (Self-Study)

7. If the platinum temperature corresponding to 60°C on the gas scale is 60.36°C, what will be the temperature on the platinum scale corresponding to 151.7°C on the gas scale?

Kinetic Theory of Gases

Kinetic Theory of Matter

According to Kinetic theory of matter, every substance (in the form of solid, liquid or gas) consists of a very large number of very small particles called the molecules. The molecules are the smallest particles of a substance that can exist in free state. The molecules possess the characteristic properties of the parent substance. The molecules are in a state of continuous motion with all possible velocities. The velocity of the molecules increases with rise in temperature.

Kinetic Theory of Matter

The energy possessed by the molecules can be of two forms, kinetic or potential. When the stop-cock of an evacuated flask is opened, air rushes in quickly to fill in the space. This shows that the molecules possess rapid motion and hence they possess kinetic energy. When a solid expands on heating, the molecules are pulled apart against the forces of intermolecular expansion. The amount of work done in separating the molecules to larger distances manifests itself as the potential energy of the molecules. Thus the amount of heat given to a solid substance increases the energy of the molecules and this increase in energy is partly kinetic and partly potential.

Thus, the kinetic theory of matter is based on the following three points : (*i*) matter is made up of molecules, (*ii*) molecules are in rapid motion, and (*iii*) molecules experience forces of attraction between one another.

Kinetic Theory of Gases

The continuous collision of the molecules of the gas with the walls of the containing vessel and their reflection from the walls results in the change of momentum of the molecules. According to Newton's second law of motion, the rate of change of momentum per unit area of the wall surface corresponds to the force exerted by the gas per unit area. The force per unit area measures the pressure of the gas.

Basic Postulates of the Kinetic Theory of Gases

1. The molecules in a gas are small and very far apart. Most of the volume which a gas occupies is empty space.

2. A gas consists of molecules in constant random motion.

3. Gas molecules influence each other only by collision; they exert no other forces on each other.

4. All collisions between gas molecules are perfectly elastic; all kinetic energy is conserved. (no loss in KE).

5. Molecules can collide with each other and with the walls of the container. Collisions with the walls account for the pressure of the gas.

6. The molecules exert no attractive or repulsive forces on one another except during the process of collision. Between collisions, they move in straight lines.

7. The gas is composed of small indivisible particles called molecules. The properties of the individual molecules are the same as that of the gas as a whole.

Heat & Thermodynamics

8. The distance between the molecules is large as compared to that of a solid or liquid and hence the forces of inter-molecular attraction are negligible.

9. The size of the molecules is infinitesimally small as compared to the average distance traversed by a molecule between any two consecutive collisions. The distance between any two consecutive collisions is called free path and the average distance is called the mean free path. The mean free path is dependent on the pressure of the gas. If the pressure is high the mean free path is less and if the pressure is low the mean free path is more.

10. The molecules are perfectly hard elastic spheres, and the whole of their energy is kinetic.

11. The time of impact is negligible in comparison with the taken to traverse the mean free path.

Sample Question

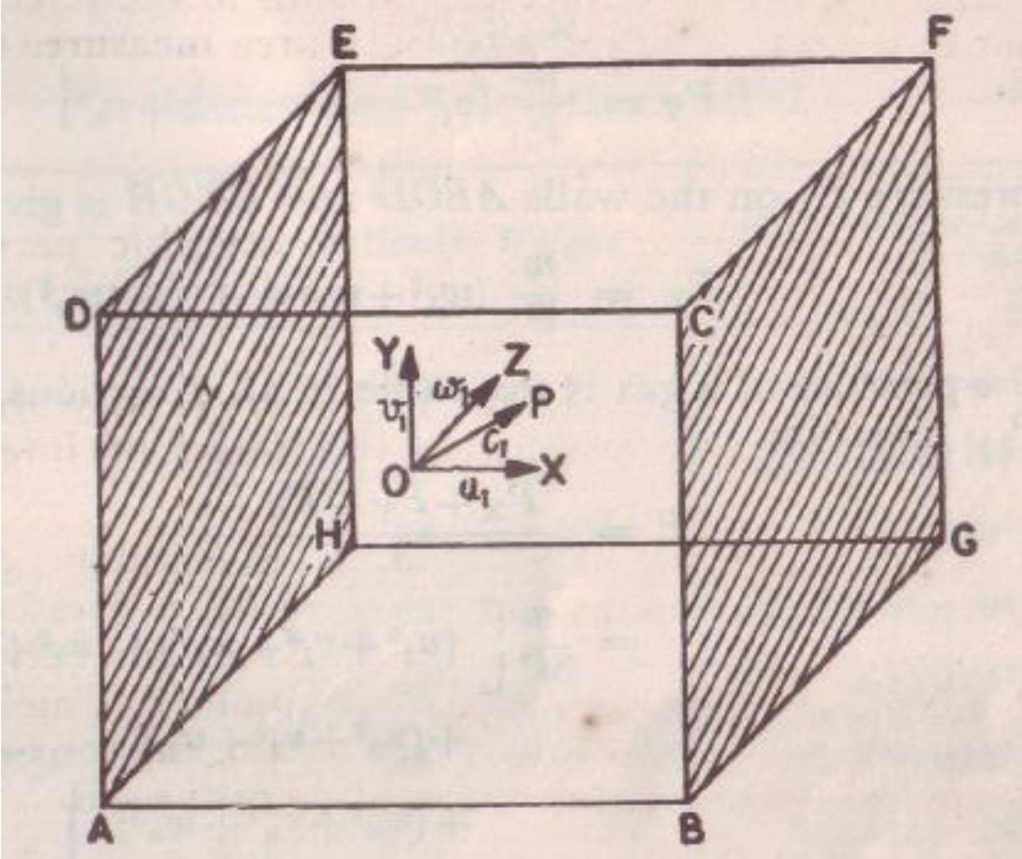
Q. Applying the kinetic theory of gases, the following expression for the pressure of a gas in terms of the properties of its molecules can be derived:

$$P = \frac{MC^2}{3V}$$

$$P = \frac{1}{3}\rho C^2$$

Answer

Expression for the Pressure of a Gas



Heat & Thermodynamics

Consider a cubical vessel *ABCDEFGH* of side l cm containing the gas. The volume of the vessel and hence that of the gas is l^3 cc. Let n and m represent the very large number of molecules present in the vessel and the mass of each molecule respectively.

Consider a molecule P moving in a random direction with a velocity C_1. The velocity can be resolved into three perpendicular components u_1, v_1 and w_1 along the X, Y and Z axes respectively. Therefore,

$$C_1^2 = u_1^2 + v_1^2 + w_1^2$$

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The component of the velocity with which the molecule P will strike the opposite face $BCFG$ is u_1 and the momentum of the molecule is mu_1. This molecule is reflected back with the same momentum mu_1 in an opposite direction and after traversing a distance l will strike the opposite face $ADEH$.

The change in momentum produced due to the impact is

$$mu_1-(-mu_1) = 2mu_1$$

As the velocity of the molecule is u_1, the time interval between two successive impacts on the wall $BCFG$ is

$$\frac{2l}{u_1} \text{ seconds}$$

$\therefore$ No. of impacts per second

$$= \frac{1}{\frac{2l}{u_1}}$$

$$= \frac{u_1}{2l}$$

Change in momentum produced in one second due to the impact of this molecule is

$$2mu_1 \times \frac{u_1}{2l} = \frac{mu_1^2}{l}$$

The force F_X due to the impact of all the n molecules in one second

$$= \frac{m}{l}\left[u_1^2 + u_2^2 + \ldots + u_n^2 \right]$$

Heat & Thermodynamics

Force per unit area on the wall $BCFG$ or $ADEH$ is equal to the pressure P_X

$$P_X = \frac{m}{l \times l^2}(u_1^2 + u_2^2 + u_3^2 + \ldots\ldots + u_n^2)$$

Similarly the pressure P_Y on the walls $CDEF$ and $ABGH$ is given by

$$P_Y = \frac{m}{l^3}(v_1^2 + v_2^2 + \ldots\ldots + v_n^2)$$

and the pressure P_Z on the walls $ABCD$ and $EFGH$ is given by

$$P_Z = \frac{m}{l^3}(w_1^2 + w_2^2 + \ldots\ldots + w_n^2)$$

Heat & Thermodynamics

As the pressure of a gas is the same in all directions, the mean pressure P is given by

$$P = \frac{P_X + P_Y + P_Z}{3}$$

$$= \frac{m}{3l^3}\Big[(u_1^2+v_1^2+w_1^2)+(u_2^2+v_2^2+w_2^2)+(u_3^2+v_3^2+w_3^2)+\ldots\ldots+(u_n^2+v_n^2+w_n^2)\Big]$$

$$= \frac{m}{3l^3}\Big[C_1^2+C_2^2+C_3^2+\ldots\ldots C_n^2\Big] \qquad \ldots(i)$$

But volume, $V = l^3$. Let C be the root-mean-square velocity of the molecules (R.M.S. velocity).

Then $$C^2 = \frac{C_1^2+C_2^2+C_3^2+\ldots\ldots C_n^2}{n}$$

or $$nC^2 = C_1^2+C_2^2+C_3^2+\ldots\ldots C_n^2$$

Substituting this value in equation (i), we get

$$P = \frac{m.nC^2}{3V} \qquad \ldots(ii)$$

Heat & Thermodynamics

But $M = mn$ where M is the mass of the gas of volume V, m is the mass of each molecule and n is the number of molecules in a volume V.

$$\therefore \quad P = \frac{MC^2}{3V}$$

or

$$P = \frac{1}{3} \rho C^2 \quad \ldots(iii)$$

$$\because \quad \frac{M}{V} = \rho \text{ the density of the gas.}$$

From equation (iii)

$$C^2 = \frac{3P}{\rho}$$

$$C = \sqrt{\frac{3P}{\rho}} \quad \ldots(iv)$$

Self Study

Kinetic Interpretation of Temperature

Self Study

Derivation of Gas Laws from Kinetic Theory of Gases

Sample Questions

1. Give the kinetic interpretation of temperature.

2. Applying the kinetic theory of gases derive the ideal gas equations.

Home Work

Solve a few problems related to the theory we have studied in this chapter

Thank You for Listening

Physics is hopefully simple but Physicists are not