TOPIC 1 Brownian Motion

SQ 13.1.1 What is thermal physics?

Definition

Thermal physics is an area which includes the knowledge of statistical mechanics and the kinetic theory of gases.

SQ 13.1.2 Give some applications of the kinetic theory of gases in daily life.

Applications

The kinetic theory of gases is applied in automobile engines, turbines, pumps, air conditioners, the preparation of food and the environment.

SQ 13.1.3 Define Brownian motion.

Definition

Brownian motion is the random and irregular motion of molecules in a gas.

SQ 13.1.4 Who observed Brownian motion and how?

Answer

In 1827 Robert Brown, a botanist, observed under a microscope that tiny plant pollen grains suspended in water moved randomly. These particles were identified as dust particles.

SQ 13.1.5 Why does a molecule in a gas follow a zig-zag path?

Reason

A molecule changes its path after collision with another molecule. When it keeps colliding with other molecules, it follows a random or zig-zag motion.

Effect

Collision transfers or exchanges the momentum and energy between the molecules.

SQ 13.1.6 What does Brownian motion represent?

Answer

Brownian motion describes randomness and chaos, therefore it represents one of the simple models of randomness.

SQ 13.1.7 Why do lighter particles show more vigorous Brownian motion?

Reason

For a given impulse, lighter or smaller-mass particles gain a large change in velocity, so they show more vigorous Brownian motion.

SQ 13.1.8 How does viscosity affect Brownian motion?

Answer

The speed of the particles is inversely proportional to the viscosity of the fluid. Low viscosity of the fluid results in faster Brownian movement.

SQ 13.1.9 Define viscosity.

Definition

Viscosity describes the magnitude of the internal friction in a fluid. It represents the resistance to flow of the fluid.

SQ 13.1.10 What is the effect of Brownian motion on the particles of a fluid?

Answer

Brownian motion causes the particles of a fluid to be in constant motion.

SQ 13.1.11 Who explained Brownian motion theoretically and who verified it?

Answer

Albert Einstein explained the pollen movement in a liquid assisted by the molecules in 1905. In 1908 the French physicist J. Perrin experimentally verified Einstein’s explanation, which earned him the 1926 Nobel Prize in physics.

SQ 13.1.12 Explain how a drop of ink in a beaker of water will behave.

Answer

The ink particles will be struck randomly by the water molecules and will spread out through the water in a random zig-zag manner. This is an example of Brownian motion.

TOPIC 2 Kinetic Theory of Gases

SQ 13.2.1 What does the kinetic theory of gases describe?

Answer

The kinetic theory of gases describes the molecular composition of the gas and their motion. In this theory the gas pressure arises due to particles interacting with each other and with the walls of the container.

SQ 13.2.2 Which properties does the kinetic theory define?

Properties

It defines properties such as temperature, volume and pressure, as well as transport properties such as viscosity, thermal conductivity and diffusivity.

SQ 13.2.3 State the first assumption of the kinetic molecular theory.

Assumption

Gases consist of a very large number of tiny spherical particles that are far apart from one another compared to their sizes.

SQ 13.2.4 State the assumption about the motion of gas particles.

Assumption

Gas particles are in constant rapid motion in random directions.

SQ 13.2.5 **State the assumption about collisions in the kinetic theory.**

Assumption
Collisions between gas particles and the container walls are perfectly elastic.

SQ 13.2.6 **State the assumption about forces between gas particles.**

Assumption
There are no forces of attraction or repulsion between gas particles until the particles perform collisions with each other.

SQ 13.2.7 **On what does the average kinetic energy of gas particles depend?**

Answer
The average kinetic energy of gas particles is dependent upon the temperature of the gas.

SQ 13.2.8 **Why is the volume of gas molecules negligible?**

Answer
A small cube of air can have as many as 10^{20} molecules, yet the volume of the gas molecules is negligible compared to the volume of the empty spaces between them.

SQ 13.2.9 **Define mean free path.**

Definition
The mean free path is the average distance a moving particle covers before it undergoes a collision that significantly alters its direction.

TOPIC 3 Pressure in a Gas

SQ 13.3.1 **What does the kinetic theory allow us to derive?**

Answer
We can use the kinetic theory of gases to derive an equation which relates the macroscopic properties of a gas, that is pressure and volume, to the microscopic properties of its molecules, that is mass and speed.

SQ 13.3.2 **What assumption is made about the single molecule in the derivation?**

Assumption
It is assumed that a single molecule of mass m moving with speed v is inside a cube-like box of each side L. It moves back and forth, colliding at regular intervals with the walls.

SQ 13.3.3 **Why do gas molecules exert force on the container walls?**

Reason
When gas molecules strike the walls, they exert a force on them due to the change in momentum during each collision.

SQ 13.3.4 **Define the pressure of a gas.**

Definition
The pressure of a gas is defined as the force exerted per unit area of the container walls as a result of the collisions of gas molecules.

SQ 13.3.5 **Why is no energy lost during collisions?**

Reason
Since the collisions are perfectly elastic, no energy is lost, and the average kinetic energy of the molecules is directly proportional to the absolute temperature of the gas.

SQ 13.3.6 **How does an increase in temperature raise the pressure?**

Explanation
An increase in temperature increases the speed of the molecules, leading to more collisions with the walls, and consequently a higher pressure.

SQ 13.3.7 **Write the ideal gas law and name its quantities.**

Formula
$PV = nRT$
Here P is pressure, n is the number of moles, R is the general gas constant and T is the temperature of the gas.

SQ 13.3.8 **Write the relation between R, Boltzmann constant and Avogadro number.**

Formula
$R = N_A k_B$
Values
$k_B = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$
and
$N_A = 6.02 \times 10^{23}\,\mathrm{mol^{-1}}$

SQ 13.3.9 **Write the gas law in terms of the number of particles.**

Formula
$PV = Nk_BT$
Here N is the number of particles of the gas.

SQ 13.3.10 **Find the change in momentum when a molecule strikes a wall elastically.**

Derivation
The molecule with velocity v_x rebounds elastically with velocity $-v_x$, so its momentum changes from mv_x to $-mv_x$.
Result
$\Delta p = -2mv_x$

SQ 13.3.11 **What distance does a molecule travel between two consecutive collisions with the same wall?**

Answer
The molecule travels a distance $2L$ between consecutive collisions with the same wall of the cube.
Formula
$$\Delta t = \frac{2L}{v_x}$$

SQ 13.3.12 **Which law is used to find the average force on the wall?**

Answer
The average force is found using Newton's second law of motion, since force is equal to the rate of change of momentum.

SQ 13.3.13 **Write the pressure exerted on the wall by one molecule.**

Formula

$$P = \frac{mv_x^2}{L^3} = \frac{mv_x^2}{V}$$

SQ 13.3.14 **How is the total pressure of all the molecules obtained?**

Method

We add up the contributions of all the molecules that strike the wall, allowing for the possibility that they all have different speeds, and divide the total force by the area of the wall.

Formula

$$P = \frac{m}{V}(v_{1x}^2 + v_{2x}^2 + v_{3x}^2 + \dots)$$

SQ 13.3.15 **Why do we square the velocities before averaging?**

Reason

The velocity striking the wall is v_x and after striking it is $-v_x$, which would result in an average velocity of zero. In order to avoid this zero, we take the square of the velocities before averaging.

SQ 13.3.16 **Define root mean square velocity.**

Definition

If we take the square root of the average of the squares of the velocities, it is known as the root mean square velocity.

Formula

$$v_{rms} = \sqrt{\langle v^2 \rangle}$$

SQ 13.3.17 **How is the mean-square speed shared among the three axes?**

Answer

Since the molecules are moving randomly in all directions, the mean-square speed is shared equally among the three axes.

Formula

$$\langle v_x^2 \rangle = \frac{1}{3}\langle v^2 \rangle$$

SQ 13.3.18 **Write the pressure of a gas in terms of the mean-square speed.**

Formula

$$P = \frac{1}{3}\frac{Nm\langle v^2 \rangle}{V}$$

SQ 13.3.19 **Write the pressure of a gas in terms of its density.**

Derivation

Since the total mass is

$$M = mN$$

and the density is

$$\rho = \frac{M}{V}$$

Formula

$$P = \frac{1}{3}\rho\langle v^2 \rangle$$

SQ 13.3.20 **Write the expression for rms speed in terms of pressure and density.**

Formula

$$v_{rms} = \sqrt{\frac{3P}{\rho}}$$

SQ 13.3.21 **An ideal gas has ρ = 4.5 kg m⁻³ at P = 9.3 × 10⁵ Pa. Find the rms speed.**

Solution

Using

$$v_{rms} = \sqrt{\frac{3P}{\rho}}$$

Calculation

$$v_{rms} = \sqrt{\frac{3 \times 9.3 \times 10^5}{4.5}}$$

Result

$$v_{rms} \approx 7.9 \times 10^2\,\mathrm{m\,s^{-1}}$$

SQ 13.3.22 **Find the rms speed of oxygen and nitrogen molecules at 25 °C.**

Data

The mass of O_2 is 5.3×10^{-26} kg and that of N_2 is 4.6×10^{-26} kg, with

$$T = 298\,\mathrm{K}$$

Result

The rms speed of oxygen is about $482\,\mathrm{m\,s^{-1}}$ and that of nitrogen is $515\,\mathrm{m\,s^{-1}}$.

SQ 13.3.23 **How does the speed of air molecules compare with the speed of sound?**

Answer

The speed of air molecules is much greater than the speed of sound, which is about $340\,\mathrm{m\,s^{-1}}$.

SQ 13.3.24 **What is the effect on pressure if the density of a gas is doubled?**

Answer

Since

$$P = \frac{1}{3}\rho\langle v^2 \rangle$$

the pressure is directly proportional to density. Therefore doubling the density doubles the pressure.

TOPIC 4 Average Translational Kinetic Energy of a Gas

SQ 13.4.1 **Show that pressure is proportional to average translational kinetic energy.**

Derivation

The pressure can be written as

$$P = \frac{2}{3}\frac{N}{V}\left(\frac{1}{2}m\langle v^2 \rangle\right).$$

Result

This shows that pressure is directly proportional to the average translational kinetic energy of the molecules of a gas.

SQ 13.4.2 **Write the expression for average translational kinetic energy of a gas molecule.**

Formula

$$\langle KE_T \rangle = \frac{3}{2}k_B T$$

SQ 13.4.3 **Show that temperature is a direct measure of average translational kinetic energy.**

Explanation
The average translational kinetic energy of the molecules in a gas is given by a simple constant times the temperature.
Conclusion
Therefore the temperature of a gas is a direct measure of the average translational kinetic energy of its molecules.

SQ 13.4.4 **Write the rms speed in terms of temperature and molar mass.**

Formula
$v_{rms} = \sqrt{\frac{3RT}{M}}$
Here M is the molar mass of the gas.

SQ 13.4.5 **Calculate the value of k(B)T for an air molecule at 300 K.**

Solution
$k_BT = (1.38 \times 10^{-23})(300)$
Result
$k_BT = 4.14 \times 10^{-21}\,\mathrm{J}$

SQ 13.4.6 **Why is the electron volt used instead of the joule at molecular scale?**

Reason
The energy k_BT is a very small quantity in joules, so the electron volt is used instead.
Definition
The electron volt is the kinetic energy of an electron accelerated through a potential difference of one volt, and
$1\,\mathrm{eV} = 1.6 \times 10^{-19}\,\mathrm{J}$

SQ 13.4.7 **Write the value of k(B)T at room temperature in electron volts.**

Solution
Boltzmann constant is $8.62 \times 10^{-5}\,\mathrm{eV\,K^{-1}}$, so
$k_BT = (8.62 \times 10^{-5})(300)$.
Result
$k_BT = 0.026\,\mathrm{eV}$

SQ 13.4.8 **Explain popcorn as a daily life example of the kinetic theory.**

Explanation
When a popcorn kernel is heated, the moisture trapped inside becomes steam. The pressure in the kernel increases and it ruptures the corn cover, releasing the gelatinous starch which becomes solid after cooling.

SQ 13.4.9 **Explain tyre pressure as a daily life example of the kinetic theory.**

Explanation
When air is pumped into a tyre, the number of air molecules increases which raises the air pressure inside. More molecules result in frequent molecular collisions with the tyre walls due to the limited volume.
Result
The pressure gives the tyre its hardness and bears the car's weight without deflating.

SQ 13.4.10 **What is the effect on gas molecules when a gas in a container is heated?**

Answer
Heating increases the average kinetic energy and hence the speed of the molecules. This leads to more frequent and more forceful collisions with the walls, so the pressure increases.

TOPIC 5 Kinetic Theory and Statistical Physics

SQ 13.5.1 **Why is statistical physics needed for gases?**

Reason
The kinetic theory determines the pressure of an ideal gas using the gas laws and the random motion of molecules. For a large number of molecules we use statistical physics.

SQ 13.5.2 **Define statistical physics.**

Definition
Statistical physics is the branch of physics that uses probability theory. Accordingly, atoms and molecules of a system may exist in different energy states due to their different speeds.

SQ 13.5.3 **What did Boltzmann derive?**

Answer
Boltzmann derived the Boltzmann kinetic equation. This equation describes the dynamic processes in gases having a large number of molecules.

SQ 13.5.4 **State the Boltzmann distribution law.**

Statement
The probability of finding molecules in a particular energy state varies exponentially as the negative of the energy divided by k_BT.
Result
Therefore more particles reside in lower energy states than in higher ones.

SQ 13.5.5 **What do N_1 and N_2 represent in the Boltzmann distribution?**

Answer
N_1 and N_2 are the populations of the lower and higher energy states, and
$\Delta E = E_2 - E_1$
is the energy difference between these states.

SQ 13.5.6 **What is the relation between number density and pressure?**

Answer
The number density is directly proportional to the pressure.

SQ 13.5.7 **What happens to a molecule during billions of collisions in a container?**

Answer
Each collision changes the speed of the molecule and thereby its kinetic energy. However, kinetic theory concludes that the average kinetic energy at temperature T remains $\frac{3}{2}k_BT$.

SQ 13.5.8 **What is Boltzmann constant effectively?**

Answer

Boltzmann constant k_B is effectively the gas constant per molecule.

SQ 13.5.9 **What did Maxwell derive and when was it confirmed?**

Answer

In 1860 James Clerk Maxwell derived an expression that describes the distribution of molecular speeds within a system at thermal equilibrium. About 60 years later, experiments were performed to confirm Maxwell's predictions.

TOPIC 6 Stellar Evolution

SQ 13.6.1 **How does the kinetic theory help in astrophysics?**

Answer

The kinetic theory of gases, when extended to astrophysical systems like stars and galaxies, helps us understand the evolution of stars in a galaxy or gas atoms in a stellar atmosphere.

SQ 13.6.2 **What is stellar evolution?**

Definition

Stellar evolution deals with the changes in a star over time. A star can have a lifetime ranging from a few million years to trillions of years, and this depends on the mass of the star.

SQ 13.6.3 **How are stars formed?**

Answer

All stars are formed from clouds of gas and dust which are often called nebulae or molecular clouds. This is also called a proto-star.

SQ 13.6.4 **What happens as a molecular cloud contracts?**

Answer

As the cloud contracts, its density and temperature increase due to the rise in kinetic energy of the particles. After millions of years these proto-stars can become a star, having achieved a state of equilibrium.

SQ 13.6.5 **How does the rms velocity of gases change in a forming star?**

Answer

The rms velocity of gases in a star increases with the rise of density. This in turn increases the average kinetic energy, and finally the temperature increases with time.

SQ 13.6.6 **When is a stable star formed?**

Condition

A stable star is formed when the inward gravitational force is exactly balanced by the outward pressure.

SQ 13.6.7 **Write the hydrostatic equation and state what it ensures.**

Formula

$$\frac{dP}{dr} = -\frac{GM_r\rho_r}{r^2}$$

Purpose

This equation ensures that the star neither collapses under gravity nor expands indefinitely.

SQ 13.6.8 **What does the negative sign in the hydrostatic equation indicate?**

Answer

The negative sign indicates that the pressure decreases outward, while gravity pulls inward.

SQ 13.6.9 **What are the two possibilities if pressure and gravity are not balanced?**

Possibilities

The gravitational force may be greater than the internal pressure, in which case the star contracts.
The gravitational force may be less than the internal pressure, in which case the star expands.

SQ 13.6.10 **What happens when the temperature in a star's core rises sufficiently?**

Answer

Nuclear fusion is initiated, allowing hydrogen nuclei to combine and form helium. This process releases an immense amount of energy, which sustains the star and powers it for the majority of its lifetime.

SQ 13.6.11 **Why does a star begin to expand?**

Reason

The continuous energy production not only maintains equilibrium against gravitational collapse but also leads to a gradual increase in internal temperature, so the star begins to expand.

SQ 13.6.12 **What is a red giant?**

Answer

With further increases in temperature and changes in core composition, a star may expand significantly to become a red giant. Stars possessing at least about half the mass of the Sun can then initiate helium fusion in their cores.

SQ 13.6.13 **Up to which element does fusion continue in massive stars?**

Answer

In more massive stars the process continues with the fusion of even heavier elements in successive stages, forming increasingly complex nuclei up to iron.

SQ 13.6.14 **What is the fate of low and intermediate mass stars?**

Answer

In low and intermediate mass stars the core contracts into a dense white dwarf, while the outer layers are expelled into space, forming a planetary nebula.

SQ 13.6.15 **What is the fate of stars about ten times more massive than the Sun?**

Answer

They undergo a dramatic supernova explosion. During this event the inert iron core collapses under gravity, leading to the formation of dense remnants such as neutron stars or black holes.

SQ 13.6.16 **Why do red dwarf stars follow a slower evolutionary path?**

Reason
Red dwarf stars have low mass and highly efficient fuel consumption. The universe is not yet old enough for any red dwarf to have completed its life cycle.

SQ 13.6.17 **What do theoretical models predict for red dwarfs?**

Answer
These stars will gradually become hotter and more luminous over time, before eventually exhausting their hydrogen fuel and evolving into low mass white dwarfs.

SQ 13.6.18 **What are neutron stars?**

Definition
Neutron stars are among the densest known objects in the universe, second only to black holes. Due to their extremely high density, matter inside them behaves like a degenerate gas.

SQ 13.6.19 **Describe the role of pressure in a neutron star.**

Answer
In a neutron star the inward gravitational force is balanced by the outward neutron degeneracy pressure. This pressure prevents the star from collapsing further into a black hole.

SQ 13.6.20 **How many neutron stars may exist in the Milky Way?**

Answer
According to estimates by NASA, there may be up to a billion neutron stars in the Milky Way galaxy.

SQ 13.6.21 **What are pulsars?**

Definition
Many of the neutron stars observed so far are relatively young and rotate rapidly, emitting beams of radiation. These are known as pulsars.

SQ 13.6.22 **How is pulsar radiation produced?**

Answer
Scientists believe that pulsar radiation is produced when strong magnetic fields channel matter toward the magnetic poles of neutron stars.

SQ 13.6.23 **Why does the magnetic field intensify when a star collapses?**

Reason
When a star collapses to form a neutron star, not only is its mass compressed but its magnetic field is also greatly intensified. Magnetic field lines become stronger as they are squeezed closer together during the collapse.

SQ 13.6.24 **How dense is a neutron star?**

Answer
A neutron star is so dense that one teaspoon of its material would have a mass over 5.5×10^{12} kg. The entire mass of the Earth at neutron star density would fit into a sphere 305 m in diameter.

SQ 13.6.25 **How and when was the Sun formed?**

Answer
The Sun was formed about 4.6 billion years ago from a huge cloud of gas and dust called a solar nebula. Due to gravitational contraction the temperature at the centre increased and a protostar was formed.

SQ 13.6.26 **Name the life stages of the Sun.**

Stages
The life stages of the Sun are nebula, protostar, main sequence, red giant, planetary nebula and white dwarf.

SQ 13.6.27 **In which stage is the Sun at present?**

Answer
At present the Sun is in the main sequence stage, where it is producing heat and light by converting hydrogen into helium.

SQ 13.6.28 **Why is the Sun important in thermal physics?**

Answer
The Sun is important because it is a natural source of enormous heat energy, and it transfers this energy mainly by radiation.

SQ 13.6.29 **Define a parsec.**

Definition
A parsec is a unit of distance used by astronomers as an alternative to the light-year.

Value
One parsec is approximately 3.26 light years, or almost 31 trillion kilometres.

SQ 13.6.30 **A star has mass 2×10^{30} kg and radius 7×10^{8} m. Its internal pressure is 1.0×10^{14} Pa. Is it stable?**

Solution
The gravitational pressure comes out to be nearly 1.1×10^{14} Pa, so $P_g \approx P_{internal}$.

Result
As both pressures are nearly equal, the star is in stable equilibrium.

SQ 13.6.31 **A star has mass 4×10^{30} kg, radius 5×10^{8} m and internal pressure 1×10^{14} Pa. What is its fate?**

Solution
Here the gravitational pressure is greater than the internal pressure.

Result
Gravity is stronger, therefore the star will contract and may eventually collapse into a neutron star or a black hole.

SQ 13.6.32 **A star has mass 1×10^{30} kg, radius 1×10^{9} m and internal pressure 5×10^{14} Pa. Determine its state.**

Solution
Here the internal pressure is greater than the gravitational pressure.

Result
Internal pressure dominates, therefore the star will expand and may evolve into a red giant.