PHS 101

GENERAL PHYSICS I

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Course Outline

PART A: MECHANICS

1. Units and Dimension
2. Rectilinear Motion
3. Newton's Laws
4. Friction
5. Work, Energy and Conservation of Energy
6. Gravitation
7. Elasticity, Young Modulus and Bulk Modulus

PART B: HEAT AND THERMODYNAMICS

1. Heat and Temperature
2. Elementary Thermodynamics
3. Elementary Kinetic Theory of Gases

CHAPTER ONE

1.0 UNITS AND DIMENSIONS

1.1 Units

In Physics, the value of any physical quantity must be expressed in terms of some standard or unit. For example, we might specify the distance between two posts in meters or in centimeters (cm) or in feet. Such units are necessary for us to compare measurements and also to distinguish between different physical quantities. All physical quantities can be expressed in terms of three fundamental quantities: mass, length and time. In the systeme International (SI) the base units for mass, length and time are the kilograms (kg), the meter (m) and the second (s). Kelvin is a base unit for temperature, the ampere (A) for electric current, and the candela (cd) for luminous intensity.

1.11 Derived Units

These are combinations of the fundamental or base units. For example, the unit of velocity is meter per seconds (ms^{-1}), for acceleration it is meter per seconds squared (ms^{-2}), for density it is kilogram per meter cubed (kgm^{-3}). The unit of force is given a special name Newton, $1N = kgms^{-2}$

1.2 Dimension

Each derived unit in mechanics can be reduced to factors of the base or fundamental units mass, length and time. Ignoring the unit system, that is, whether it is S.I or British, then the factor are called dimensions.

When referring to the dimension of a quantity x, we place it in square brackets: [x]. For example, an area A is the product of two lengths so its dimensions are

$$[A] = L^2$$

The dimensions of speed are $[v] = LT^{-1}$

The dimension of force $[F] = ma$

$$[F] = MLT^{-2}$$

An equation in Physics such as $X = Y + Z$ has meaning only if the dimensions of all the three quantities are identical. It makes no sense to add a distance to a speed. The equation must be dimensionally consistent.

Let us consider the equation

$$s = ½at^2$$

$$[s] = L$$

$$(at^2) = (LT^{-2})(T^2)$$

$$= L$$

$$L = L$$

Both sides have the same dimension L, so the equation is dimensionally consistent.

Dimensional analysis can be used to obtain the functional form of relations, or derived a formular.

Example

The period P of a simple pendulum is the time for one complete swing. How does P depend on the mass m of the bob, the length l of the string, and the acceleration due to gravity g?

Solution

Let us express the period P in terms of the other quantities as follows:

$$P = km^x l^y g^z$$

K is a constant, x, y, z are to be determined. Let us insert the dimensions of each quantity:

$$T = M^x L^y L^z T^{-2z}$$
$$= M^x L^{y+z} T^{-2z}$$

and equate the powers of each dimension on either side of the equation. Thus,

T: $1 = -2z$
M: $0 = x$
L: $0 = y + z$

$x = 0$, $z = -½$, $y = -z$, $y = +½$

Thus,

$$P = k\sqrt{\frac{l}{g}}$$

CHAPTER TWO

2.0 RECTILINEAR MOTION

This is the motion of an object in a straight line path, which is one dimensional translational motion but in two or three dimensions it becomes translational motion along paths that are not straight.

2.1 Frame of Reference

Any measurement of position, distance or speed must be made with respect to a frame of reference. For example, a person walks toward the front of a train at 5km/h. The train is moving 80km/h with respect to the ground, so the walking person's speed relative to the ground is 85km/h.

When specifying the motion of an object, it is important to specify not only the speed but also the direction of motion. Often we can specify a direction by using the cardinal points, North, East, South and West and by 'up' and 'down'. At times we draw a set of co-ordinates axes.

2.2 Displacement

This is the change in position of the object. That is, displacement is how far the object is from its starting point.

Let us consider a case of man walking 70m to the East and then turning around and walking back (West) a distance of 30m.

Total distance is 100m
But displacement is 70 – 30 = 40
$\Delta x = x_2 - x_1$

Exercise

An ant starts at x = 20cm on a piece of graph paper and walks along the x axis to x = -20cm. It then turns around and walks back to x = -10cm. What is the ant's displacement and total distance traveled?

2.3 Average Velocity

The velocity of a particle is the rate at which its position changes with time. The position of a particle in a particular reference frame is given by a position drawn from the origin of that frame to the particle. Let us consider a particle at point A at time t_1 and its position in the x-y plane is described by position vector r_1. Let the particle be at point B at a later time t_2 and its position is described by position r_2.
The displacement vector describing the change in position of the particle as it moves from A to B is $\Delta r = r_2 - r_1$ and the elapsed time for the motion between these points is $\Delta t = t_2 - t_1$. The average velocity for the particle during this interval is defined by

$$\bar{v} = \frac{\Delta r}{\Delta t} = \frac{displacement}{time}$$

2.31 Instantaneous Velocity

If the average velocity of a particle is measured for a number of different time intervals and it is not constant. Then this particle is said to move with variable velocity. So, we must seek to determine a velocity of the particle at any given instant of time, called the instantaneous velocity.

If Δr is the displacement in a small interval of time Δt, following the time t, the velocity at the time t is the limiting value approached by $\frac{\Delta r}{\Delta t}$ as both Δr and Δt approach zero. That is, if we let v represent the instantaneous velocity,

$$v = \lim_{\Delta t \to 0} \frac{\Delta r}{\Delta t}$$

In the notation of the calculus, the limiting value of $\frac{\Delta r}{\Delta t}$ as Δt approaches zero is written $\frac{dr}{dt}$ and is called the derivative of r with respect to t. We have then

$$v = \lim_{\Delta t \to 0} \frac{\Delta r}{\Delta t} = \frac{dr}{dt}$$

The magnitude v of the instantaneous velocity is called the speed and is simply the absolute value of v. That is,

$$v = |v| = \left|\frac{dr}{dt}\right|$$

2.4 Acceleration

The average acceleration for a finite time interval is defined as

$$\text{Average acceleration} = \frac{change\ in\ velocity}{time\ \ interval}$$

In one – dimension

$a_{av} = \frac{\Delta v}{\Delta t}$ It is measured in ms^{-2}

Example

What is the acceleration of a car that moves from rest to 90km/h in 15s?

$$a_{av} = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

$$= \frac{25}{15} = 1.6ms^{-2}$$

The instantaneous acceleration is defined as the derivative of v with respect to t.

$$a = \frac{dv}{dt}$$

Positive acceleration points in the direction of the +x axis, while negative acceleration points in the opposite direction. Negative acceleration does not mean a deceleration. The word 'deceleration' means only a slowing down; it tells us nothing about direction. Note when v and a have the same sign, the body speeds up; when they have opposite signs, the body slows down.

Example

A bird flies east at $10ms^{-1}$ for 100m. It then turns around and flies at $20ms^{-1}$ for 15s. Find its average speed and its average velocity.

Solution

In order to find the required quantities, we need the total time interval.
Let us consider the first part of the journey

$\Delta v_1 = 100ms^{-1}$
$\Delta x_1 = 100m$
$\Delta t_1 = ?$

$$\Delta v = \frac{\Delta x}{\Delta t}$$

$$\Delta t_1 = \frac{\Delta x}{\Delta v} = \frac{100}{10} = 10s$$

So, the first part of the journey took 10s.

$\Delta t_2 = 15s$ time for the second part of the journey

Total time interval $\Delta t = \Delta t_1 + \Delta t_2$
$\Delta t = 10 + 15 = 25s$

Distance traveled in the first part is $\Delta x_1 = 100m$
Distance traveled in the second part is Δx_2

$\Delta v_2 = 20ms^{-1}$
$\Delta t_2 = 15s$

$\Delta x_2 = \Delta v_2 \Delta t_2 = 20 \text{ x } 15 = 300m$

Total distance traveled Δx is

$\Delta x = \Delta x_1 + \Delta x_2 = 100 + 300 = 400m$

$\Delta x = 400m$

Average speed $= \frac{\Delta x}{\Delta t} = \frac{400}{25} = 16 ms^{-1}$

First of all, we find the net displacement. Let the net displacement be Δx

$\Delta x = \Delta x_1 + \Delta x_2 = 100 - 300 = -200$m

Average velocity $= \frac{\Delta x}{\Delta t} = \frac{-200}{25} = -8 ms^{-1}$

The negative sign means that average velocity is directed toward the west or it moves in the opposite direction.

2.5 Equation of Motion for Constant Acceleration

Acceleration = $\frac{change\ in\ velocity}{time\ interval}$

$$a = \frac{dv}{dt} = \frac{v_f - v_i}{t_f - t_i}$$

Let the initial values of position x_o and velocity v_0 be at t = 0 and the final values x and v, occur at a later time t.

Let us set $t_i = o$ and $t_f = t$, we have

$$a = \frac{v - v_o}{t - 0}$$

$$a = \frac{v - v_o}{t}$$

$v - v_o = at$

$v = v_o + at$ 1

We know that average velocity is

Average velocity = $\frac{change\ in\ displacement}{change\ in\ time}$

$$v_{av} = \frac{\Delta x}{\Delta t}$$

$$\Delta x = v_{av} \Delta t$$

$$v_{av} = \frac{1}{2}\left(v_i + v_f\right)$$

$$\Delta x = \frac{1}{2}\left(v_i + v_f\right)\Delta t$$

$$x - x_0 = \frac{1}{2}\left(v_0 + v\right)t$$

$$x = x_0 + \frac{1}{2}\left(v_0 + v\right)t$$

But $v = v_o + at$

$$x = x_0 + \frac{1}{2}\left(v_0 + v_0 + at\right)t$$

$$x = x_0 + \frac{1}{2}\left(2v_0 + at\right)t$$

$$x = x_0 + v_0 t + \frac{1}{2}at^2 \tag{2}$$

From equation 1

$$t = \frac{v - v_0}{a}$$

Put this into equation 2

$$x = x_0 + v_0\left(\frac{v - v_0}{a}\right) + \frac{1}{2}a\left(\frac{v - v_0}{a}\right)^2$$

$$x - x_0 = \left(\frac{v - v_0}{a}\right)\left(v_0 + \frac{a}{2}\left(\frac{v - v_0}{a}\right)\right)$$

$$x - x_0 = \left(\frac{v - v_0}{a}\right)\left(v_0 + \frac{v}{2} - \frac{v_0}{2}\right)$$

$$x - x_0 = \left(\frac{v - v_0}{a}\right)\left(\frac{1}{2}\left(\frac{v_0}{2} + v\right)\right)$$

$$2a(x - x_0) = (v - v_0)(v_0 + v)$$

$$2a(x - x_0) = v^2 - v_0^2$$

$$v^2 = v_0^2 + 2a(x - x_0) \qquad 3$$

Example

A car accelerates with constant acceleration from rest to $30ms^{-1}$ in 10s. It then continues at constant velocity. Find (a) its acceleration, (b) how far it travels while speeding up and (c) the distance it covers while its velocity changes from $10ms^{-1}$ to $20ms^{-1}$.

Solution

(a) $x_0 = 0$, Given: $v_0 = 0$, $v = 30ms^{-1}$, t = 10s. Unknown a = ?, x = ?

From equation 1, we have, $a = \dfrac{v - v_o}{t} = \dfrac{30}{10} = +3ms^{-2}$

(b) Given: $v_0 = 0$, $v = 30ms^{-1}$, t = 10s, $a = 3ms^{-2}$. Unknown x = ?

We use the equation $x = x_0 + \dfrac{1}{2}(v_0 + v)t$

$$x = 0 + \frac{1}{2}(0 + 30)10$$

$$x = 150m$$

(c) Given: $v_0 = 100ms_{-1}$, $v = 20ms_{-1}$, $a = 3ms_{-2}$. Unknown: x_0 = ?, x = ?, t = ?

To find x_0, we use

$\Delta x = x - x_0$

Using equation 3, we have

$$v^2 = v_0^2 + 2a(\Delta x)$$

$$20^2 = 10^2 + 2(3)(\Delta x)$$

$$\Delta x = 50m$$

2.6 Vertical Free Fall

Motion that occurs solely under the influence of gravity is called free-fall. This term applies as much to satellites orbiting the earth as to bodies moving vertically up or down.

In the absence of air resistance, all falling bodies have the same acceleration due to gravity, regardless of their sizes or shapes. The value of the acceleration due to gravity depends on both latitude and altitude. It is approximately 9.8ms^{-2} near the surface of the earth.

If we use the x-axis for horizontal motion and y-axis points upward, the acceleration due to gravity is a = -g. With a = -g, the equations of kinematics now read

$$v = v_0 - gt \qquad 1$$

$$y = y_0 + \frac{1}{2}(v_0 + v)t \qquad 2$$

$$y = y_0 + v_0 t - \frac{1}{2}gt^2 \qquad 3$$

$$v^2 = v_0^2 - 2g(y - y_0) \qquad 4$$

Exercise

A ball thrown up from the ground reaches a maximum height of 20m. Find

(a) its initial velocity
(b) the time taken to reach the highest point
(c) its velocity just before hitting the ground
(d) its displacement between 0.5 and 2.5s
(e) the time at which it is 15m above the ground

CHAPTER THREE

3.0 NEWTON'S LAWS

3.1 Newton's First Law of Motion

Every body continues in its state of rest or of uniform motion in a straight line unless it is compelled (or acted) to change that state by forces impressed upon it.

From this we obtain a property of bodies called Inertia. The inertia of a body is its tendency to resist any change in its state of motion.

3.11 Motion In A Plane or Two Dimensional Motion

In three dimensions the position vector r of a particle whose coordinates are (x, y, z) is $r = xi + yj + zk$

Let a particle moves from P at position r_1 to Q at position r_2, its displacement, that is, the change in position is $\Delta r = r_2 - r_1$

$$\Delta r = \Delta xi + \Delta yj + \Delta zk$$

$$r_2 = r_1 + \Delta r$$

In two dimension the position vector $r = xi + yj$

Average Velocity

$$v_{av} = \frac{\Delta r}{\Delta t}$$

Instantaneous Velocity

$$v = \lim_{\Delta t \to 0} \frac{\Delta r}{\Delta t}$$

$$v = \frac{dr}{dt}$$

$$v = v_x i + v_y j + v_z k \ , \quad \text{where } v_x = \frac{dx}{dt}, v_y = \frac{dy}{dt}, v_z = \frac{dz}{dt}$$

the direction of v is along the tangent to the path.

Instantaneous Acceleration

$$a = \frac{dv}{dt}$$

$$a = a_x i + a_y j + a_z k$$

$$a_x = \frac{dv_x}{dt}, a_y = \frac{dv_y}{dt}, a_z = \frac{dv_z}{dt}$$

3.12 Constant Acceleration

When a body moves with constant acceleration in two or three dimensions, the equations of motion are

$$v = v_0 + at$$

$$r = r_0 + \frac{1}{2}(v_0 + v)t$$

$$r = r_0 + v_0 t + \frac{1}{2}at^2$$

For Two – dimensional motion in the x-y plane, the x and y components of these equations are

$$v_x = v_{0x} + a_x t \qquad v_y = v_{0y} + a_y t$$

$$x = x_0 + \frac{1}{2}(v_{0x} + v_x)t \qquad y = y_0 + \frac{1}{2}(v_{0y} + v_y)t$$

$$x = x_0 + v_{0x}t + \frac{1}{2}a_x t^2 \qquad y = y_0 + v_{0y}t + \frac{1}{2}a_y t^2$$

$$v_x^2 = v_{0x}^2 - 2a_x(x - x_0) \qquad v_y^2 = v_{0y}^2 - 2a_y(y - y_0)$$

3.2 Projectile Motion

The equations of motion for projectiles near the earth's surface take the form

$$x = v_{0x}t$$

$$v_y = v_{0y} - gt$$

$$y = y_0 + v_{0y}t - \frac{1}{2}gt^2$$

$$v_y^2 = v_{0y}^2 - 2g(y - y_0)$$

Example

A ball is projected horizontally at $15ms^{-1}$ from a cliff of height 20m. Find
(a) its time of flight
(b) its horizontal range R

Solution

Given: $x_o = 0$, $y_o = 20m$, $v_{ox} = 15ms_{-1}$, $v_{oy} = 0ms^{-1}$

We know that $v = \frac{dx}{dt}$

$$x = v_{0x}t$$
$$x = 15t$$
$$y = 20 - 4.9t^2$$

(a) On landing, the vertical component of the ball is zero, that is, y = 0.

$$0 = 20 - 4.9t^2$$
$$t = \pm 2.02s$$
$$t = +2.02s$$

(b) $$x = v_{0x}t$$

Horizontal range R = horizontal distance x

$$R = v_{0x}t$$
$$R = 15x2.02$$
$$R = 30.3m$$

3.3 Newton's Second Law of Motion

Force is responsible for motion of any body. Force is either a pull or push. Force deform bodies, they expand springs, compress balloons, and bend beams. We have contact force and an action at a distance force.

$$F \propto \frac{dP}{dt}$$
$$F \propto m\frac{dv}{dt}$$
$$F = ma$$

In case of many forces acting on a body at a time, $\sum F = ma$

Example

A 1200kg car is stalled on an icy patch of road. Two ropes attached to it are used to exert forces F_1 = 800N at 35^oN of E and F_2 = 600N at 25^oS of E. What is the acceleration of the car?

Solution

Vector form of Newton's Second Law of Motion is $\sum F = F_1 + F_2 = ma$

The components of this equation are

$$\sum F_x = F_1 Cos\theta_1 + F_2 Cos\theta_2 = ma_x$$
$$\sum F_y = F_1 Sin\theta_1 - F_2 Sin\theta_2 = ma_y$$

$$a_x = \frac{F_1 Cos\theta_1 + F_2 Cos\theta_2}{m}$$
$$a_x = \frac{800x0.819 + 600x0.906}{1200}$$
$$a_x = 1.00ms^{-2}$$

$$a_y = \frac{800x0.574 - 600x0.423}{1200}$$
$$a_y = 0.17ms^{-2}$$

The resultant acceleration is a,

$$a = 1.00i + 0.17\,jms^{-2}$$

Newton's Law of Gravitation

It states that between any two point particles with masses m and M, separated by a distance r, there is an attractive force whose magnitude is given by

$$F = \frac{GmM}{r^2}$$

$$G = 6.67x10^{-11}\,Nm^2kg^{-2}$$

3.4 Newton's Third Law of Motion

This is the law of action and reaction.

The force exerted on A by B is equal and opposite to the force exerted on B by A.

Example

Two rail cars A and B with masses $m_A = 1.2 \times 10^4$ kg and $m_B = 8 \times 10^3$kg can roll freely on a horizontal track. A locomotive of mass 10^5kg exerts a force F_o on A that produces an acceleration of $2ms^{-2}$. Find (a) F_o and (b) the force exerted on A by B.

Solution

Rail Car A $\quad \sum F_x = F_o - F_{AB} = m_A a \qquad 1$

Rail Car B $\quad \sum F_x = F_{BA} = m_B a \qquad 2$

From equation 2, we have

$$F_{BA} = 8 \times 10^3 \times 2$$
$$= 1.6 \times 10^4 N$$

Since from Third law $F_{AB} = F_{BA}$

Equation 1 becomes

$$F_o - 1.6x10^4 = 1.2x10^4 x2$$
$$F_o = 4.0x10^4 N$$

CHAPTER FOUR

4.0 FRICTION

4.1 Laws of Friction

- Friction opposes motion
- Friction is independent of the area of contact
- Friction is independent of the speed
- Friction depends on the nature of the surfaces in contact

4.2 Static and Kinetic Friction

The force of static friction opposes the tendency of a block to move relative to the surface. If the block does not move, the force of static friction fs must be exactly equal to the applied force F. When F is increased, fs also increased and stay equal to F. when fs reached its maximum value after applying a large force, the block starts to slide in such case we have kinetic friction. As sliding commences, the frictional force rapidly falls at low speeds. At higher speeds, the force of kinetic friction fk either stays constant or decreases gradually as the speed increases.

The frictional force and the normal (reaction) force is related by

$F_k = \mu_k N$ --- Kinetic friction, where $\mu_k \equiv$ coefficient of kinetic friction

$F_s = \mu_s N$ --- Static friction, where $\mu_s \equiv$ coefficient of static friction

Example

A 5kg block is on a horizontal surface for which $\mu_s = 0.2$ and $\mu_k = 0.1$. It is pulled by a 10N force directed at 55^o above the horizontal. Find the force of friction on the block given that (a) it is at rest and (b) it is moving

Solution

a.

$$N = mg - F\sin 55^o$$
$$= 5 \times 10 - 10 \times 0.819$$
$$N = 41.8N$$

$$F_s = \mu_s N$$
$$= 0.2 \times 41.8$$
$$F_s = 8.36N$$

The horizontal component of the applied force is $10\cos 55^o = 5.74N$

$F_s > 5.74N$

So, the force of static friction required to keep the block at rest is just 5.74N

(b) $F_k = \mu_k N$

$= 0.1 \times 41.8$

$F_k = 4.$

CHAPTER FIVE

5.0 WORK, ENERGY AND POWER

5.1 Work

Work done = force x distance

For a body inclined at an angle θ, Work done $W = FsCos\theta$

5.11 In vector form

$$F = F_x i + F_y j + F_z k$$
$$s = \Delta xi + \Delta yj + \Delta zk$$
$$W = F_x \Delta x + F_y \Delta y + F_z \Delta z$$

Work is said to be done only when the point of application of the force moves through a distance.

5.12 Work done by Gravity

$W = mgh$
$W = mg(h_2 – h_1)$

The work done by the force of gravity depends only on the initial and final vertical coordinates, not on the path taken.

5.13 Integral Form of Work Done

The work done by a force Fx from an initial point A to final point B is given by

$$W_{A \to B} = \int_{x_A}^{x_B} F_x dx$$

5.2 Energy

$W = F\Delta x$

$W = ma\Delta x$

a is constant, so we can replace $a\Delta x$ by

$$v_f^2 = v_i^2 + 2a(\Delta x)$$

$$a\Delta x = \frac{v_f^2 - v_i^2}{2}$$

$$W = \frac{1}{2}m\left(v_f^2 - v_i^2\right)$$

$$W = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

The quantity $K = \frac{1}{2}mv^2$ is called the Kinetic energy.

W = mgh = F.x. This is the potential energy. This is the energy associated with the relative positions of two or more interacting particles.

5.3 Power

This is defined as the rate at which work is done

$$P_{av} = \frac{\Delta W}{\Delta t}$$

$$P_{inst.} = \frac{dW}{dt}$$

$$dW = F.ds$$

$$P = F.\frac{ds}{dt}$$

$$P = F.v$$

Power can also be defined as the rate of energy transfer from one body to another, or the rate at which energy is transferred from one form to another.

$$P = \frac{dE}{dt}$$

Example

A pump raises water from a well of depth 20m at a rate of $10kgs^{-1}$ and discharges it at $6ms^{-1}$. What is the power of the motor?

Solution

Total Work = $mgh + \frac{1}{2}mv^2$

$$P = \frac{dW}{dt} = \frac{d}{dt}(mgh) + \frac{1}{2}mv^2$$

$$P = \frac{dm}{dt}(gh) + \frac{v^2}{2}$$

$$P = 10(200 + 18)$$

$$P = 2180W$$

CHAPTER SIX

6.0 GRAVITATION

Newton's Law of Gravitation states that the force of attraction between two masses m_1 and m_2 separated by a distance r is proportional to the product of their masses and inversely proportional to the square of the distance of separation between them.

$$F = -\frac{Gm_1 m_2}{r^2}\bar{r}$$

$$F_{12} = -\frac{Gm_1 m_2}{r^2}\overline{r_{21}}$$

6.1 Gravitational Field Strength or Intensity

This is the gravitational force per unit mass F = mg, $g = \frac{F}{m}$

$$F = -\frac{GMm}{r^2}$$

$$g = -\frac{GMm}{mr^2}$$

$$g = -\frac{GM}{r^2}\bar{r}$$

The magnitude of the field strength at the surface of the earth is

$$g(R_E) = \frac{GM_E}{R_E^2}$$

6.2 Kepler's Laws of Planetary Motion

First Law – states that the planets move around the sun in elliptical orbits with the sun at one focus.

Second Law – states that the line joining the sun to a planet sweeps out equal areas in equal times.

Third Law – state that the square of the period of a planet is proportional to the cube of its mean distance from the sun

$$T^2 = kr^3$$

CHAPTER SEVEN

7.0 ELASTICITY, YOUNG'S MODULUS AND BULK MODULUS

7.1 Elastic Moduli

A force applied to an object can change its shape. In general, the response of a material to a given type of deforming force is characterized by an elastic modulus, which is defined as

$$\text{Elastic modulus} = \frac{stress(tensile)}{strain(tensile)}$$

(Tensile) Stress – This is a force per unit area and it measured in Nm^{-2}

(Tensile) Strain – This is a fractional change in a dimension or volume.

We shall discuss three elastic moduli; Young's modulus for solids, the shear modulus for solids and the bulk modulus for solids and fluids.

7.2 Young's Modulus

This is the measure of the resistance of a solid to a change in its length when a force is applied perpendicular to a face.

Let us consider a rod with an unstressed length lo and cross – sectional area A. Its length changes by Δl when it is subject to equal and opposite forces F along its axis and perpendicular to the end faces. These forces tend to stretch the rod.

Tensile stress on the rod is defined as

$$\text{Tensile stress} = \frac{F}{A}$$

$$\text{Tensile strain} = \frac{\Delta l}{l_o}$$

Young's modulus for the material of the rod is defined as the ratio

$$\text{Young's Modulus} = \frac{(Tensile)stress}{(Tensile)strain}$$

$$\gamma = \frac{F/A}{\Delta l/l_o}$$

7.3 Shear Modulus

The shear modulus of a solid indicates its resistance to a shearing force, which is a force applied tangentially to a surface.

Shear stress = $\dfrac{Tangential\ Force}{Area} = \dfrac{F_l}{A}$

Shear strain = $\dfrac{\Delta x}{h}$ where h is the separation between the top and the bottom surfaces.

The shear modulus S is defined as

$$S = \frac{shear\ stress}{shear\ strain}$$

$$S = \frac{F_l/A}{\Delta x/h}$$

7.4 Bulk Modulus

The bulk modulus of a solid or a fluid indicates its resistance to a change in volume. Let us consider a cube of some material, solid or fluid. All the faces experience the same force F normal to each face.

The pressure on the cube is normal force per unit area.

$$P = \frac{F}{A}$$

When the pressure on a body is increased, its volume decreases. The change in pressure ΔP is called the volume stress and the fractional change in volume $\Delta V/V$ is called the volume strain. The bulk modulus B of the material is defined as

Bulk Modulus = $\dfrac{Volume\ Stress}{Volume\ Strain}$

$$B = -\frac{\Delta P}{\Delta V/V}$$

$$K = \frac{1}{B} = compressibility$$

PART B

HEAT AND THERMODYNAMICS

CHAPTER ONE

TEMPERATURE AND HEAT
Temperature, with unit K (Kelvin), is a thermal phenomenon. It is that property of a system which determines whether or not it is in thermal equilibrium with other systems.
The most important characteristic in temperature is equalization; that is, equal degree of hotness between the bodies concerned. This is known as thermal equilibrium.
Meanwhile, heat is energy flow by conduction, convection or radiation from one body to another because of temperature difference between them.
The temperature of a body is a property of the body that determines how hot or cold the body is. It depends on the quantity of heat energy absorbed by the body and also the nature of the body and its mass.
Temperature is measured with a device known as thermometer,

Scales of Temperature
The thermodynamic scale is mostly used for scientific measurements. It has symbol T, and unit K (for Kelvin). It is defined using one fixed point, known as the triple point of water. This is the temperature where saturated water vapour, pure water and ice are all in equilibrium, at a temperature of 273.16 K. Hence, the Kelvin is $^1/_{273.16}$ of the thermodynamic temperature of triple point of water.
The Celsius scale is defined by $\theta = T - 273.15$. The two fixed points on this scale are the ice point $(0^o C)$ and the steam point$(100^o C)$, The ice point and the triple point differ by $0.01K$. The absolute zero, $0K = -273.15^o C$.
A temperature scale depends on the particular property on which it is based. In setting up a scale of temperature, we must:

(i) Choose a property that varies with temperature

(ii) Assume that this property varies uniformly with temperature.

Now, if we denote the property by F, then on the Celsius scale:

$$\frac{\theta}{100} = \frac{F_\theta - F_0}{F_{100} - F_0}$$

Where θ is the temperature to be measured, F_0 is its value at $0^o C$, F_θ is its value at $\theta^o C$ and F_{100} is its value at $100^o C$.

The Fahrenheit scale, mostly used in the U.S., employs a smaller degree than the Celsius scale and its zero is set to a different temperature value.
The relationship between the Celsius and the Fahrenheit scales is:

$$T_F = \frac{9}{5}T_C + 32$$

Therefore,

$$0^o C = 32^o F \quad and \quad 100^o C = 212^o F$$

Types of Thermometers

The following properties or instruments have all been used to measure temperature and are thus the basis of thermometers:

(i) Liquid – in – glass

(ii) Gas

(iii) Platinum resistance

(iv) Vapour pressure

(v) Optical pyrometer

(vi) Transistor

(vii) Thermistor

(viii) Strain

(ix) Bimetallic strip

(x) Liquid pressure

(xi) Thermocouple

The range of most common liquid-in-glass thermometers are:

1. Mercury –in-glass; $-39^oC\ to + 357^oC$
2. Pressurized mercury-in-glass: $-39^oC\ to + 500^oC$
3. Pressurized mercury-in-quartz: $-39^oC\ to + 800^oC$
4. Alcohol-in-glass: $-120^oC\ to + 60^oC$
5. Pentane –in-glass: $-200^0C\ to + 30^oC$

For gas thermometers:

1. Hydrogen: $-200^0C\ to + 500^oC$
2. Nitrogen: $+500^0C\ to + 1500^oC$
3. Helium: $-270^0C\ to + 1500^0C$

Thermocouple

If two dissimilar metals are joined together and the junctions between them maintained at different temperatures, then, an e.m.f will be generated across the junctions. This e.m.f. is proportional to the temperature difference as long as this is not too large.

The ranges of various pairs of wires and the e.m.f. generated for a temperature difference of 100^0C are given below:

Pair	Range	E.m.f Generated
Copper / Constantan	$0^0C\ to\ +300^0C$	$4.00mV$
Platinum / Platinum + rhodium	$0^0C\ to\ +1600^0C$	$0.65mV$
Iron / Constantan	$0^0C\ to\ +1090^0C$	$5.30mV$

It is very difficult to attain the absolute zero temperature (i.e. $-273K$) . However, one method used to reach very low temperatures – within 0.01^oC of absolute zero - is that of adiabatic demagnetization.
At very low temperatures, strange things happen. The viscosities of some liquids drop to virtually zero. This is known as super – fluidity. This enables some of these liquids to flow uphill! The resistance of a metal wire also falls to zero (Superconductivity) and in these conductions, current may flow in the conductors for ever with no energy input!

The Mechanical Equivalent of Heat
This is the classic experiment, first performed in 1847 by James Joule, which led to our modern view that mechanical work and heat are but different aspects of the same quantity: Energy. The experiment related the two concepts and provided a connection between Joule, defined in terms of mechanical variables (work, K.E., P.E., etc.) and the calorie, defined as the amount of heat that raises the temperature of one gram of water by one degree Celsius. Contemporary SI units do not distinguish between heat energy and mechanical energy, so that heat is also measured in Joules.
In this experiment, work is down by rubbing two metal cones, which raises the temperature of a known amount of water (along with the cones, stirrer, thermometer, etc.). The ratio of the mechanical work done (W) to the heat which has passed to the water (Q), determines the constant J, that is:

$$J = \frac{W}{Q}$$

Solved Examples

1. If a house thermostat is set to 70^oF , what is the temperature in Celsius scale?

Solution:

$T_F = \frac{9}{5}T_C + 32$

$\rightarrow \quad T_F - 32 = \frac{9}{5}T_C$

Therefore,

$T_C = \frac{5}{9}((T)_C - 32)$

$= \ 5/9\ 70 - 32)$

$= 23^oC$

2. At what temperature are the Fahrenheit and Celsius scales equal?

Solution:
When they are equal, $T_F = T_C = x$
Therefore,

$x = \frac{9}{5}x + 32$

$\rightarrow \quad x - \frac{9}{5}x = 32$

$x\left(1 - \frac{9}{5}\right) = 32$

Hence,

$x = -40^0C$

i.e. $-40^0C = -40^0F$

From the microscopic point of view, the temperature of a substance is related to the speed of the individual molecules which also give rise to pressure. Thus, a gas which has fast moving molecules will have a high temperature and pressure. Now, if we slow all the molecules to zero speed, the gas pressure will be zero, The temperature at which this happens is -273.15^0C .

CHAPTER TWO

ELEMENTARY THERMODYNAMICS

The zeroth Law

The zeroth law of thermodynamics states that if two bodies A and B are in thermal equilibrium with a third body C, then they are in equilibrium with each other.

That is; A is in thermal equilibrium with C

B is in thermal equilibrium with C

A is in thermal equilibrium with B

This law implies that C is the thermometer.

Heat and Work

When discussing work and energy for thermodynamic systems, it is useful to think about compressing a gas in a piston as shown in figure 1.

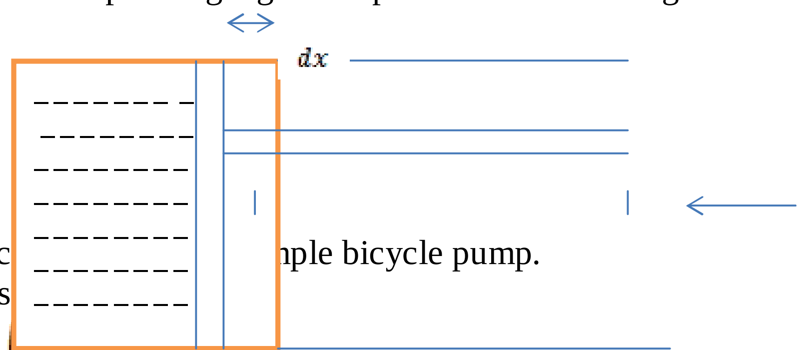

Figure 1

An exa... suc... ple bicycle pump.

Recall that work is

$$W = \int F \cdot dL$$

For the piston, all the motion occurs in on dimension so,

$$W = \int f.dx$$

Now, the pressure of a gas is defined as force divided area or:

$$P = \frac{F}{A} \rightarrow F = PA$$

Therefore, $dW = PAdx \; = PdV$

Where the volume is area multiplied by distance i.e. $dV = Adx$

Hence, when we compress the piston by a distance dx , the volume of the gas changes by $dV = Adx$, where A is the cross sectional area of the piston.

Writing $W = \int dW$ gives $W = \int_{V_i}^{V_f} PdV$

This is the work done by a gas of pressure P , changing its volume from $V_i \; to \; V_f$ or the work done on the gas.

The First Law of Thermodynamics

Let us first define the internal energy U , as the sum of the kinetic and potential energies of the atoms and or molecules of a system.

In an isolated system, there is no interaction between the contents of the system and the environment.

The first law states that:

$$\Delta Q = \Delta U + \Delta W \quad \text{(i.e. } Q = U + W \text{)}$$

Where ΔQ is the heat absorbed by the system.

ΔW is the work done by the system, and ΔU is the change in the internal energy. This law represents the application of conservation law to heat energy.

Another statement of the law is that it is impossible to construct a continuously operating machine that does work, without obtaining energy from an external source.

Therefore, $\Delta U = Q - W \;\; ie \;\; (dU = dQ - dW)$

The meaning of this law is that internal energy of a system can be changed by adding heat or doing work.

Special cases of the First Law of Thermodynamics

1. **Adiabatic Processes**:

   These are those processes that occur so rapidly that there is no transfer of heat between the system and its environment. Thus, $Q = 0$ and $\Delta U = -W$

   When a system expands under adiabatic conditions, W is positive, ΔU is negative and the internal energy decreases. When a system is compressed adiabatically, W is negative and internal energy increases.

The compression stroke in an internal combustion engine is an example of a process that is approximately adiabatic. The temperature rises as the air – fuel mixture in the cylinder is compressed. Similarly, the expansion of burned fuel during the power stroke is an approximate expansion with a drop in temperature.

2. Isochoric Processes:- Constant volume process

When the volume of a thermodynamic system is constant, it does no work on its surroundings. This implies that $W = \int P dV = 0$ and hence,

$\Delta U = \Delta Q$

This means that all the heat added to the system is used to raise its internal energy. An example of the process is heating a gas in a closed constant-volume container.

3. Isobaric Processes:

Isobaric means constant pressure. In general, none of the three quantities; $\Delta U, \Delta Q \text{ and } W$ in the first law is zero. But W is given as $W = P\Delta V$.

4. Isothermal Processes

In an isothermal process, the temperature remains constant. If the system is an ideal gas, then the internal energy must therefore also remain constant.

i.e.$\Delta U = 0$

Therefore, the first law becomes: $Q + W = 0$ (for isothermal process, and for an ideal gas)

If an amount of positive work is done on the gas, an equivalent amount of heat $Q = -W$ is released by the gas to the environment. None of the work done on the gas remains with the gas as stored internal energy.

5. Cyclical Processes

In a cyclical process, we carry out a sequence of operations that eventually restores the system to its initial state,

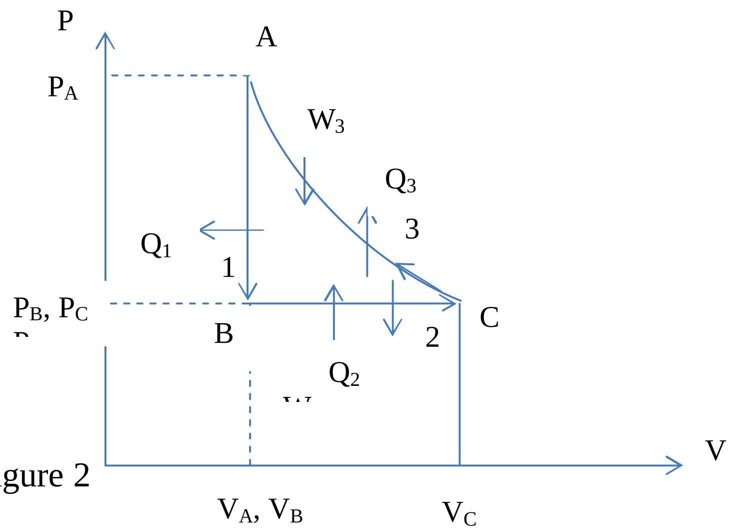

Figure 2

Consider figure 2 above. A gas undergoes a cyclical process starting at point A and consisting of (i) a constant volume process AB, (ii) a constant pressure processes BC, and (iii) an isothermal process CA.

Because the process starts and finishes at the point A, the internal energy change for the gas is zero. Thus, according to the first law: $Q + W = 0$

Where $Q \text{ and } W$ represent the totals for the cycle.

For any cycle that is done in a counter-clockwise direction, we must have $W > 0$, and thus $Q < 0$; while cycles performed in the clockwise direction have $W < 0 \text{ and } Q > 0$. Hence, $\Delta U = 0$ in one complete cycle.

6. Free Expansion

The internal energy of an ideal gas undergoing a free expansion remains constant, and because this depends only on the temperature, its temperature must similarly remain constant. Therefore, for free expansion,

$$\Delta U = 0$$

Then, $Q = W = 0$

CHAPTER THREE

ELEMENTARY KINETIC THEORY OF GASES

The kinetic theory of gases attempts to explain all the concepts of classical thermodynamics, such as temperature and pressure, in terms of a microscopic theory based on atoms and molecules. For instance, the temperature of a gas is related to the average K.E. of all molecules in the gas.

Avogadro's Number

One mole is the number of atoms in a 12 gram sample of C^{12}, and this number is determined from experiment to be 6.02×10^{23}. This is often called Avogadro's number. The number molecules must be the number of mole times the number of molecules per mole.

Thus we write Avogadro's number as; $N_A = 6.02 \times 10^{23}$ moles^{-1} and $N = nN_A$

Where N is the number of molecules and *n* is the number of moles.

Equation of State

This is the equation that specifies the exact relation between pressure P, volume V, and temperature T, for a substance. The equation of state for a gas is very different to the equation of state of a liquid.

Most gases obey a simple equation of state called the ideal gas law;

$$PV = nRT$$

Where P is the pressure, V is the volume, T is the temperature in Kelvin, n is the number of moles of the gas and R is the gas constant $= 8.31 J\, mol^{-1}K^{-1}$

Recall that the number of molecules is given by $n = nN_A$, where n = number of moles.

Thus $PV = nRT = \dfrac{N}{N_A}RT$

Let $k = \dfrac{R}{N_A} = \dfrac{8.31 mol^{-1}K^{-1}}{6.02 \times 10^{23} mol^{-1}} = 1.38 \times 10^{-23} JK^{-1}$

$$= 8.62 \times 10^{-5} eVK^{-1} \equiv \text{ Boltzmann's constant}$$

Where $eV = 1.6 \times 10^{-19} J$

Therefore, the ideal gas law is also written as $PV = NKT$

Where N is the total number of molecules.

The ideal gas law encompasses the properties or characteristics of a gas such as

1. If the volume V, is held constant, then the pressure P, increases as the temperature T, increases
2. If the pressure P is held constant, then as T increases P increases.
3. If the temperature T is held constant, then as P increases, V decreases.

Work done by an Ideal Gas

The equation of state can be represented on a graph of pressure P, versus volume V, often called a PV diagram. A PV diagram takes care of two of the three variables, the third variable T, represents different lines on the PV diagram.

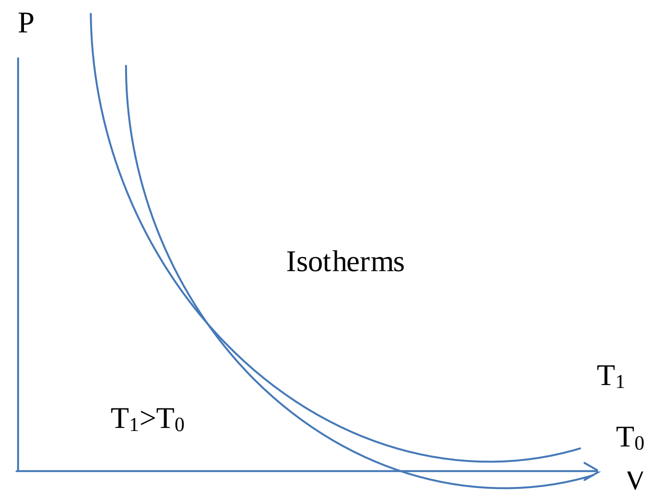

Figure 3

These difference lines are called isotherms (meaning – same temperature).

We may represent the work done, by a pressure-volume (PV) diagram, as shown in figure 4.

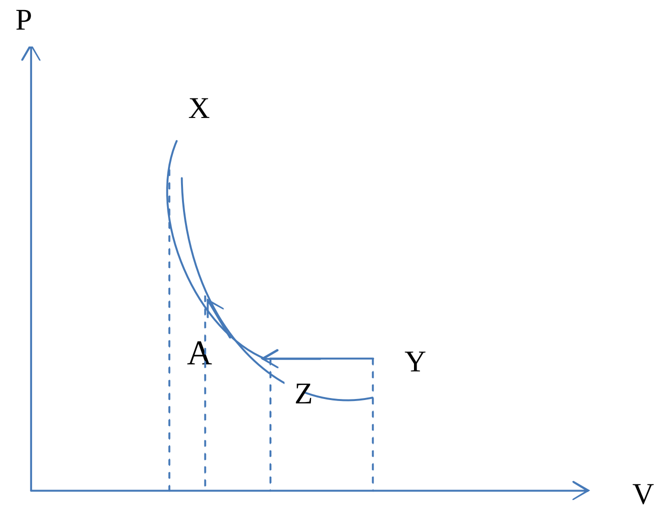

Figure 4

Consider a gas at X (volume V, and pressure P). Let the gas expand isothermally to Y and then let it be cooled to Z with no change in pressure. It is then compressed isothermally to A and finally compressed adiabatically to X.

The area, XYZA enclosed by these PV changes represents the work done by the gas.

Example

An ideal gas with a volume of $0.1\ m^3$ expands at a constant pressure of $1.5 \times 10^5\ Pa$ to triple its volume. Calculate the work done by the gas,

Solution

$Work\ done = P\Delta V$

Given that $P = 1.5 \times 10^5 Pa$

$$V_1 = 0.1m^3, V_2 = 3 \times 0.1m^3 = 0.3m^3$$

$$\Delta V = V_2 - V_1 = (0.3 - 0.1)m^3 = 0.2m^3$$