Applied Physics 1

Viscosity, Terminal Velocity and Stoke's Law

1. Viscosity

Viscosity is the property of a fluid (liquid or gas) by virtue of which it opposes the relative motion between its adjacent layers. It may be understood as a kind of internal friction that exists within a moving fluid, arising from the interaction between molecules in layers that move at different velocities relative to one another.

When a fluid flows, different layers of the fluid generally move with different velocities — for example, the layer of fluid in contact with a stationary solid surface tends to remain at rest, while layers farther away move progressively faster. Viscosity is the property that resists this relative sliding motion between adjacent layers, causing faster-moving layers to be slowed down and slower-moving layers to be dragged along, tending to bring the entire fluid to a common, uniform motion.

Fluids such as honey, glycerine, and heavy engine oil, which flow slowly and resist relative motion strongly, are said to be highly viscous, while fluids such as water and petrol, which flow easily, are said to have low viscosity.

2. Coefficient of Viscosity

The coefficient of viscosity (η, pronounced “eta”) is a quantitative measure of the viscosity of a fluid, representing the magnitude of the internal frictional force acting between adjacent layers of the fluid per unit area, for a given velocity gradient (rate of change of velocity with distance) between the layers.

A fluid with a higher coefficient of viscosity offers greater resistance to flow and to the relative motion of its layers, while a fluid with a lower coefficient of viscosity flows more freely.

The units of coefficient of viscosity in different systems are given below:

System	Unit of Coefficient of Viscosity	Relation
SI	pascal-second (Pa·s) or N·s/m^2	1 Pa·s = 1 kg/(m·s)
CGS	poise	1 poise = 1 dyne·s/cm^2
Relation between units	—	1 Pa·s = 10 poise

The coefficient of viscosity is an important property in engineering and industrial applications, influencing the design of lubrication systems, pipeline flow, hydraulic machinery, and the selection of oils and fluids for specific mechanical applications.

3. Terminal Velocity

When a small solid body, such as a spherical ball, falls freely through a viscous fluid (such as a liquid or air), it experiences three forces acting on it: its own weight acting downward, the upward buoyant force (upthrust) due to the fluid, and an upward viscous drag force due to the viscosity of the fluid, which increases as the velocity of the falling body increases.

Initially, when the body starts falling from rest, its velocity is low, and the viscous drag force is small, so the net downward force accelerates the body. As the velocity of the body increases, the viscous drag force acting upward also increases. Eventually, a stage is reached at which the upward viscous force and the buoyant force together exactly balance the downward weight of the body, so that the net force on the body becomes zero.

At this stage, the body no longer accelerates and continues to fall with a constant velocity, called the terminal velocity. Terminal velocity is therefore defined as the maximum constant velocity attained by a body falling freely through a viscous fluid, at which the net force acting on it becomes zero.

4. Stoke's Law

Stoke's law gives an expression for the viscous drag force experienced by a small spherical body moving slowly through a viscous fluid. According to Stoke's law, the viscous force F acting on a small sphere of radius r, moving with velocity v through a fluid of coefficient of viscosity η, is given by:

- $F = 6 \pi \eta r v$

This formula shows that the viscous drag force on a small sphere moving through a fluid is directly proportional to the coefficient of viscosity of the fluid, the radius of the sphere, and its velocity. As the velocity of the falling sphere increases, this viscous force increases proportionally, until it eventually balances the net downward force, allowing the sphere to reach its terminal velocity, as described above.

Using Stoke's law together with the condition for terminal velocity (where the net force on the sphere becomes zero, that is, weight = viscous force + buoyant force), it can be shown that the terminal velocity of a small sphere falling through a viscous fluid is directly proportional to the square of the radius of the sphere and inversely proportional to the coefficient of viscosity of the fluid. This is why larger spherical bodies (of the same material) fall through a given viscous fluid with a greater terminal velocity than smaller ones, and why bodies fall more slowly through highly viscous fluids than through fluids of low viscosity.

5. Effect of Temperature on Viscosity

The viscosity of a fluid is significantly affected by its temperature, although the nature of this effect is different for liquids and gases:

State of Matter	Effect of Increasing Temperature on Viscosity
Liquids	Viscosity decreases with an increase in temperature, since increased thermal energy weakens the cohesive forces between molecules, allowing them to slide past one another more easily.
Gases	Viscosity increases with an increase in temperature, since viscosity in gases arises mainly from the exchange of momentum between molecules due to their random motion, which increases with temperature.

This difference in behaviour between liquids and gases arises from the different physical origins of viscosity in the two states of matter: in liquids, viscosity is dominated by intermolecular cohesive forces, which weaken as temperature rises, whereas in gases, viscosity arises mainly from the transfer of momentum between molecules through random collisions, which becomes more frequent and effective as temperature rises.

This temperature dependence of viscosity has important practical consequences. For example, engine lubricating oils are specially formulated to maintain a suitable viscosity over a range of operating temperatures, ensuring effective lubrication whether an engine is cold at start-up or hot during continuous operation.

6. Multiple Choice Questions (MCQs)

Answer the following questions by selecting the most appropriate option.

1. Viscosity is best described as a property of a fluid that represents:

A) Its resistance to compression
B) Its internal friction, or resistance to relative motion between its layers
C) Its surface tension
D) Its density

2. The SI unit of coefficient of viscosity is:

A) Poise
B) Pascal-second (Pa·s)
C) Newton
D) Joule-second

3. The CGS unit of coefficient of viscosity is:

A) Pascal-second
B) Poise
C) Stokes
D) Newton-second

4. The relation between the SI unit and the CGS unit of viscosity is:

A) 1 Pa·s = 1 poise
B) 1 Pa·s = 10 poise
C) 1 Pa·s = 100 poise
D) 1 Pa·s = 0.1 poise

5. Terminal velocity of a body falling through a viscous fluid is the constant velocity attained when:

A) The net force on the body becomes zero
B) The body is still accelerating
C) The viscous force becomes zero
D) Gravity stops acting on the body

6. According to Stoke's law, the viscous force on a small sphere moving through a fluid is given by:

A) $F = 6\pi\eta rv$
B) $F = 4\pi\eta rv$
C) $F = 6\pi\eta r^2v$
D) $F = 6\pi\eta v/r$

7. In Stoke's law, the symbol η represents:

A) Density of the sphere
B) Coefficient of viscosity of the fluid
C) Radius of the sphere
D) Terminal velocity

8. According to Stoke's law, the viscous force on a sphere is directly proportional to:

A) The square of its radius
B) Its radius and its velocity
C) Its mass only
D) The square of its velocity

9. As a sphere falls through a viscous fluid, the viscous force acting on it:

A) Decreases as velocity increases

B) Increases as velocity increases
C) Remains constant throughout
D) Is independent of velocity

10. The terminal velocity of a small sphere falling through a viscous fluid is directly proportional to:

A) The radius of the sphere
B) The square of the radius of the sphere
C) The coefficient of viscosity
D) The inverse of the radius

11. As the temperature of a liquid increases, its viscosity generally:

A) Increases
B) Decreases
C) Remains unchanged
D) Becomes infinite

12. As the temperature of a gas increases, its viscosity generally:

A) Increases
B) Decreases
C) Remains unchanged
D) Becomes zero

13. Viscosity of a liquid decreases with rising temperature mainly because:

A) The molecules move slower
B) The cohesive forces between molecules weaken as thermal energy increases
C) The density of the liquid increases
D) The liquid becomes more viscous

14. Which of the following is an everyday example demonstrating viscosity?

A) Honey flowing much more slowly than water
B) A stone floating on water
C) A ball bouncing on the ground
D) Water boiling at 100°C

15. The rise of viscosity in gases with temperature is mainly attributed to:

A) Increased cohesive forces between gas molecules
B) Increased momentum exchange between molecules due to greater random motion
C) Decreased molecular motion
D) Decreased pressure

Answer Key

1. B) Its internal friction, or resistance to relative motion between its layers | 2. B) Pascal-second (Pa·s) | 3. B) Poise | 4. B) 1 Pa·s = 10 poise | 5. A) The net force on the body

becomes zero | 6. A) $F = 6\pi\eta rv$ | 7. B) Coefficient of viscosity of the fluid | 8. B) Its radius and its velocity | 9. B) Increases as velocity increases | 10. B) The square of the radius of the sphere | 11. B) Decreases | 12. A) Increases | 13. B) The cohesive forces between molecules weaken as thermal energy increases | 14. A) Honey flowing much more slowly than water | 15. B) Increased momentum exchange between molecules due to greater random motion

7. Broad / Long Answer Questions

1. Define viscosity. Explain the concept of internal friction between layers of a fluid in motion.

2. Define coefficient of viscosity. State its SI and CGS units, and the relation between them.

3. Define terminal velocity. Explain the physical conditions under which a body falling through a viscous fluid attains terminal velocity.

4. State Stoke's law and write its formula, explaining each term used in it.

5. Explain, using Stoke's law and the concept of terminal velocity, why a small sphere falling through a viscous liquid eventually stops accelerating and moves with a constant velocity.

6. Explain why the terminal velocity of a falling sphere depends on the square of its radius, based on the formula derived from Stoke's law and the force balance on the sphere.

7. Explain the effect of temperature on the viscosity of liquids, and give the physical reason for this behaviour.

8. Explain the effect of temperature on the viscosity of gases, and explain why this behaviour is opposite to that observed in liquids.

9. Explain, with a suitable example, how the difference in viscosity between two liquids (such as water and honey) affects their rate of flow.

10. Explain why raindrops falling from a great height do not accelerate indefinitely but instead reach the ground with a fairly constant (terminal) velocity, relating your answer to viscosity and Stoke's law.