

CUET · PHYSICS · CLASS XI · CODE 322

# Mechanical Properties of Fluids

CUET unit: Mechanical Properties of Fluids

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 **Snapshot**

- Studies physical properties of liquids and gases (collectively "fluids") that flow and offer almost no resistance to shear stress, distinguishing them from solids.
- Builds the hydrostatics block: pressure as a scalar normal-force-per-area, variation with depth, Pascal's law, hydraulic machines, atmospheric pressure, barometers and manometers.
- Develops fluid dynamics for ideal fluids: streamline vs turbulent flow, equation of continuity ( $A_v = \text{constant}$ ), and Bernoulli's principle with its applications — Torricelli's law of efflux and dynamic lift (Magnus effect, aerofoil).
- Introduces viscosity (Newton's law of viscous flow, coefficient  $\eta$ ), Stokes' law and terminal velocity of a sphere falling through a viscous medium.
- Ends with surface tension as surface energy per unit area, angle of contact, excess pressure inside drops and bubbles, and capillary rise.

 **Detailed Notes****2.1 Core concepts**

- Fluids (liquids + gases) flow because they offer negligible resistance to shear stress — about a million times smaller than that of solids — but liquids are largely incompressible while gases are highly compressible (NCERT §9.1, p. 180).
- Pressure at a point in a fluid is defined in the limiting sense  $P = \lim (\Delta F / \Delta A)$  as  $\Delta A$  tends to 0; only the component of force normal to the area enters the numerator. Pressure is a scalar with dimensions  $[M L^{-1} T^{-2}]$  and SI unit pascal ( $\text{Pa} = \text{N m}^{-2}$ );  $1 \text{ atm} = 1.013 \times 10^5 \text{ Pa}$  (NCERT §9.2, p. 181).
- Density  $\rho = m/V$  is a positive scalar with SI unit  $\text{kg m}^{-3}$ ; relative density is the dimensionless ratio of a substance's density to that of water at  $4^\circ \text{C}$  ( $1.0 \times 10^3 \text{ kg m}^{-3}$ ) (NCERT §9.2, p. 181).
- Considering a right-angled prismatic element of fluid at rest, equilibrium together with geometry gives  $P_a = P_b = P_c$  — pressure exerted is the same in all directions at a point, confirming pressure is not a vector (NCERT §9.2.1, p. 182).
- For two points 1 and 2 separated vertically by height  $h$  in a fluid at rest, balancing the weight of the cylindrical element gives  $(P_2 - P_1) = \rho g h$ ; taking point 1 at the open surface yields the absolute pressure  $P = P_a + \rho g h$ , while  $P - P_a$  is the gauge pressure (NCERT §9.2.2, pp. 182–183).

- The hydrostatic paradox: vessels A, B and C of different shapes connected at the base fill to the same level on filling with water because the bottom pressure depends only on height of the fluid column, not on shape or base area (NCERT §9.2.2, p. 183).
- The atmospheric pressure at sea level equals the weight of an air column of unit area extending to the top of the atmosphere and is  $1.013 \times 10^5$  Pa (1 atm). Torricelli's mercury barometer gives  $P_a = \rho g h$ ; the mercury column at sea level is about 76 cm, so 1 mm of Hg = 1 torr = 133 Pa and 1 bar =  $10^5$  Pa (NCERT §9.2.3, pp. 183–184).
- An open-tube manometer is a U-tube containing a suitable liquid (oil for small, mercury for large pressure differences); it measures the gauge pressure  $P - P_a$  proportional to the difference of liquid heights (NCERT §9.2.3, p. 184).
- Pascal's law for transmission of fluid pressure: a change in pressure applied to an enclosed fluid is transmitted undiminished and equally in all directions to every point of the fluid and the walls. In a hydraulic lift the small piston of area  $A_1$  exerts force  $F_1$  producing pressure  $P = F_1/A_1$ ; the larger piston of area  $A_2$  then experiences force  $F_2 = (A_2/A_1) F_1$ , giving mechanical advantage  $A_2/A_1$ . The same principle is used in hydraulic brakes (NCERT §9.2.4, pp. 185–186).
- Steady (streamline) flow: at every fixed point, the velocity of each passing fluid particle is constant in time; the streamline is a curve whose tangent at any point gives the fluid velocity, and no two streamlines can cross (NCERT §9.3, pp. 186–187).
- Equation of continuity follows from conservation of mass:  $\rho_P A_P v_P = \rho_R A_R v_R = \rho_Q A_Q v_Q$ ; for an incompressible fluid this reduces to  $A v = \text{constant}$ , so velocity rises where the cross-section narrows (NCERT §9.3, p. 187).
- Beyond a critical speed, streamline flow loses steadiness and becomes turbulent — eddies and whirlpool-like white-water regions form (NCERT §9.3, p. 187).
- Bernoulli's principle: along a streamline of an ideal (non-viscous, incompressible, steady) flow,  $P + (1/2) \rho v^2 + \rho g h = \text{constant}$ . The derivation uses the work-energy theorem on an element pushed between two cross-sections at different heights (NCERT §9.4, pp. 187–188).
- Bernoulli's equation does NOT hold for viscous fluids, compressible fluids or non-steady/turbulent flows; for fluids at rest it reduces to  $P_1 + \rho g h_1 = P_2 + \rho g h_2$ , the hydrostatic relation (NCERT §9.4, p. 188).
- Torricelli's law of efflux: for a tank open to the atmosphere with a small hole at height  $y_1$  below the free surface (depth  $h = y_2 - y_1$ ), Bernoulli's equation gives speed of efflux  $v_1 = \sqrt{2 g h}$ , the same as that of a freely falling body; if a high pressure  $P$  drives the tank,  $v_1 = \sqrt{2 g h + 2(P - P_a)/\rho}$ , relevant to rocket propulsion (NCERT §9.4.1, pp. 188–189).
- Dynamic lift on a spinning ball (Magnus effect): a ball spinning while moving drags air with it, crowding streamlines on one side and rarifying them on the other; the

resulting pressure difference deflects the ball from a parabolic path (NCERT §9.4.2, pp. 189–190).

- Aerofoil lift on aircraft wings: the wing shape and orientation makes air flow faster above than below; the pressure difference  $\Delta P = (\rho/2)(v_2^2 - v_1^2)$  provides upward dynamic lift balancing the weight (NCERT §9.4.2, p. 190; Example 9.7).
- Viscosity is the internal friction between adjacent layers of a fluid in relative motion; experimentally the shear stress depends on rate of strain ( $v/l$ ), and the coefficient of viscosity  $\eta = \text{shear stress} / \text{strain rate}$ . SI unit is the poiseuille (PI) =  $\text{N s m}^{-2} = \text{Pa s}$ ; dimensions  $[\text{M L}^{-1} \text{T}^{-1}]$ . Viscosity of liquids decreases while that of gases increases with temperature (NCERT §9.5, pp. 190–191).
- Stokes' law: a sphere of radius  $a$  moving with velocity  $v$  through a fluid of viscosity  $\eta$  experiences a viscous drag  $F = 6 \pi \eta a v$  (NCERT §9.5.1, p. 192).
- A small sphere falling through a viscous fluid attains terminal velocity when (viscous drag + buoyant force) equals gravity; balancing gives  $6 \pi \eta a v_t = (4 \pi/3) a^3 (\rho - \sigma) g$ , so  $v_t = 2 a^2 (\rho - \sigma) g / (9 \eta)$ . Terminal velocity is proportional to square of radius and inversely to viscosity (NCERT §9.5.1, p. 192).
- Surface tension arises because molecules on the free surface have less negative potential energy than those in the bulk (about half), so increasing surface area requires work; consequently a liquid tends to minimise its free surface area (NCERT §9.6.1, p. 193).
- Stretching a film by distance  $d$  on parallel guides of length  $l$  increases area by  $2 d l$  (two surfaces); the work  $F d$  done equals the surface energy  $S (2 d l)$ , giving  $S = F / (2 l)$ . Surface tension is therefore both surface energy per unit area and force per unit length acting in the plane of the interface (NCERT §9.6.2, p. 194).
- Angle of contact  $\theta$  is measured between the tangent to the liquid surface at the line of contact and the solid surface, taken inside the liquid; equilibrium of interfacial tensions gives  $S_{la} \cos \theta + S_{sl} = S_{sa}$ .  $\theta$  is acute when  $S_{sl} < S_{la}$  (water on glass — wets), obtuse when  $S_{sl} > S_{la}$  (water on lotus leaf, mercury on glass — does not wet) (NCERT §9.6.3, pp. 195–196).
- Wetting agents (soaps, detergents) lower the angle of contact so liquids penetrate better; water-proofing agents raise it (NCERT §9.6.3, p. 196).
- Free drops and bubbles tend to be spherical because a sphere has the least surface area for given volume. Excess pressure inside a spherical liquid drop or cavity is  $(P_i - P_o) = 2 S_{la} / r$ ; for a soap bubble, with two interfaces, the excess pressure is  $(P_i - P_o) = 4 S_{la} / r$  (NCERT §9.6.4, pp. 196–197).
- Capillary rise: in a narrow tube of radius  $a$  with acute contact angle  $\theta$ , the concave meniscus produces an excess pressure  $2 S \cos \theta / a$ . Equating the hydrostatic head:  $h \rho g = 2 S \cos \theta / a$ , so  $h = 2 S \cos \theta / (\rho g a)$ . For mercury ( $\theta$  obtuse)  $\cos \theta$  is negative and the liquid is depressed in the capillary (NCERT §9.6.5, pp. 196–197).

## 2.2 Definitions to memorise

Term	Definition	Page
Pressure (P)	Normal component of force per unit area on a surface in a fluid; scalar; SI unit Pa = N m <sup>-2</sup>	181
Pascal (Pa)	SI unit of pressure equal to 1 N m <sup>-2</sup> ; 1 atm = 1.013 × 10 <sup>5</sup> Pa	181
Density (rho)	Mass per unit volume; SI unit kg m <sup>-3</sup> ; positive scalar	181
Relative density	Ratio of density of substance to density of water at 4 deg C; dimensionless	181
Gauge pressure	Excess of absolute pressure over atmospheric pressure, $P_g = P - P_a = \rho g h$	183
Pascal's law	Pressure applied to an enclosed fluid is transmitted undiminished and equally in all directions	185
Streamline	Curve whose tangent at every point is in the direction of fluid velocity at that point in steady flow	186
Equation of continuity	$A v = \text{constant}$ for an incompressible fluid in steady flow (conservation of mass)	187
Bernoulli's equation	$P + (1/2) \rho v^2 + \rho g h = \text{constant}$ along a streamline of an ideal fluid	188
Torricelli's law	Speed of efflux from a small open hole at depth h below the free surface, $v_1 = \sqrt{2 g h}$	189
Dynamic lift	Force on a body (wing, spinning ball) due to motion through a fluid; explained by Bernoulli	189
Magnus effect	Dynamic lift on a spinning body due to streamline asymmetry caused by rotation	189
Coefficient of viscosity (eta)	Ratio of shear stress to strain rate; SI unit poiseuille (PI) = Pa s; dimensions [M L <sup>-1</sup> T <sup>-1</sup> ]	191
Stokes' law	Viscous drag on a sphere of radius a moving with velocity v through a fluid: $F = 6 \pi \eta a v$	192
Terminal velocity	Constant velocity attained when net force is zero: $v_t = 2 a^2 (\rho - \sigma) g / (9 \eta)$	192
Surface tension (S)	Force per unit length in the plane of interface (or surface energy per unit area); units N m <sup>-1</sup>	194
Angle of contact (theta)	Angle between tangent to liquid surface at the contact line and the solid surface, measured inside the liquid	195
Excess pressure (drop)	$(P_i - P_o) = 2 S / r$ for a spherical liquid drop or cavity	197
Excess pressure (soap bubble)	$(P_i - P_o) = 4 S / r$ — two interfaces	197

Term	Definition	Page
Capillary rise (h)	$h = \frac{2 S \cos \theta}{\rho g a}$ for a narrow tube of radius a	197

## 2.3 Diagrams / processes to remember

- Fig. 9.1 — beaker with submerged object: fluid force is normal to every surface; idealised piston-spring pressure gauge (p. 181).
- Fig. 9.2 — right-angled prismatic fluid element used to prove that pressure at a point is the same in all directions (p. 182).
- Fig. 9.3 — vertical cylindrical column for deriving  $P_2 - P_1 = \rho g h$  (p. 183).
- Fig. 9.4 — three differently shaped vessels A, B, C filled to the same level — hydrostatic paradox (p. 183).
- Fig. 9.5 — (a) mercury barometer and (b) open-tube manometer (p. 184).
- Fig. 9.6 — (a) external pressure applied to a fluid is transmitted equally to all vertical tubes; (b) schematic of a hydraulic lift (pp. 185–186).
- Fig. 9.7 — streamlines: (a) trajectory of one fluid particle; (b) region of streamline flow showing planes P, R, Q (p. 186).
- Fig. 9.8 — (a) laminar streamlines; (b) jet on a flat plate showing turbulent flow (p. 187).
- Fig. 9.9 — flow of an ideal fluid in a pipe of varying cross-section for Bernoulli derivation (p. 188).
- Fig. 9.10 — Torricelli's law: tank with hole,  $v_1 = \sqrt{2 g h}$  (p. 189).
- Fig. 9.11 — (a) non-spinning sphere (symmetric streamlines, zero lift); (b) spinning sphere — Magnus effect; (c) aerofoil (p. 190).
- Fig. 9.12 — (a) liquid sandwiched between glass plates with top plate moving; (b) parabolic velocity profile in a tube (p. 191).
- Fig. 9.13 — block-and-pulley setup to measure coefficient of viscosity (p. 191).
- Fig. 9.14 — molecules in the bulk, at the surface, and balance of attractive/repulsive forces (p. 193).
- Fig. 9.15 — soap film on a sliding bar — derivation  $S = F/(2l)$  (p. 194).
- Fig. 9.16 — vertical glass plate balance for measuring surface tension (p. 195).
- Fig. 9.17 — water drop on lotus leaf (obtuse contact angle) vs spreading on clean plastic (acute) (p. 195).
- Fig. 9.18 — drop, cavity and bubble of radius r — excess pressure formulae (p. 196).
- Fig. 9.19 — capillary rise schematic with enlarged meniscus (p. 196).

## 2.4 Common confusions / NTA trap points

- Pressure is a scalar, even though it is "force per area" — only the normal component of force enters; vector-pressure options are NTA's favourite distractor.

- For a soap bubble use  $4 S / r$  (two interfaces), but for a liquid drop or an air cavity in a liquid use  $2 S / r$  — many students apply the wrong formula in numerical MCQs.
- Bernoulli's principle assumes incompressible, non-viscous, steady (streamline) flow. It does NOT apply to turbulent flow, compressible flow, or flow with significant viscous losses (e.g. rapids in a river).
- For a sphere falling through a viscous fluid, the terminal velocity is proportional to  $a^2$  (not  $a$ ) and inversely to  $\eta$  — questions deliberately swap the dependence.
- Viscosity behaves oppositely with temperature: liquids' viscosity decreases, gases' increases — a classic Assertion-Reason trap.
- For mercury in a capillary,  $\cos \theta$  is negative ( $\theta$  obtuse), so the formula  $h = \frac{2 S \cos \theta}{\rho g a}$  gives a depression — students often forget the sign.
- Hydrostatic pressure depends only on the vertical height of the column, not on the shape or base area of the container (hydrostatic paradox).

## Practice MCQs

## PYQ Alignment

This chapter is a high-yield CUET source — roughly 8–10 MCQs per year — with NTA favouring direct formula recall on hydrostatic pressure and Pascal's law, numericals on continuity, Bernoulli/Torricelli and capillary rise, and conceptual statement-based questions on validity conditions of Bernoulli's equation, behaviour of viscosity with temperature, and the angle-of-contact / wetting–non-wetting distinction.

### **CUET 2023–25 — Actual PYQs from this chapter**

No PYQs from this chapter appeared in CUET 2023, 2024 or 2025.