Chapter 5: Fluid Mechanics (Enriched Draft with Integration)

5.1 Introduction

Fluid mechanics is the study of the behavior of fluids (liquids, gases, and plasmas) and the forces acting on them. Unlike solids, fluids can flow and change shape under the least applied force. Fluid mechanics is a foundational subject in engineering because it explains the behavior of systems involving water, air, oil, and other fluids in motion or at rest.

Applications span across civil engineering (dams, pipelines), mechanical engineering (pumps, turbines), aerospace (aircraft design, rocket propulsion), environmental engineering (water distribution, pollution control), and even biomedical sciences (blood flow in arteries).

Fluid mechanics is broadly divided into:

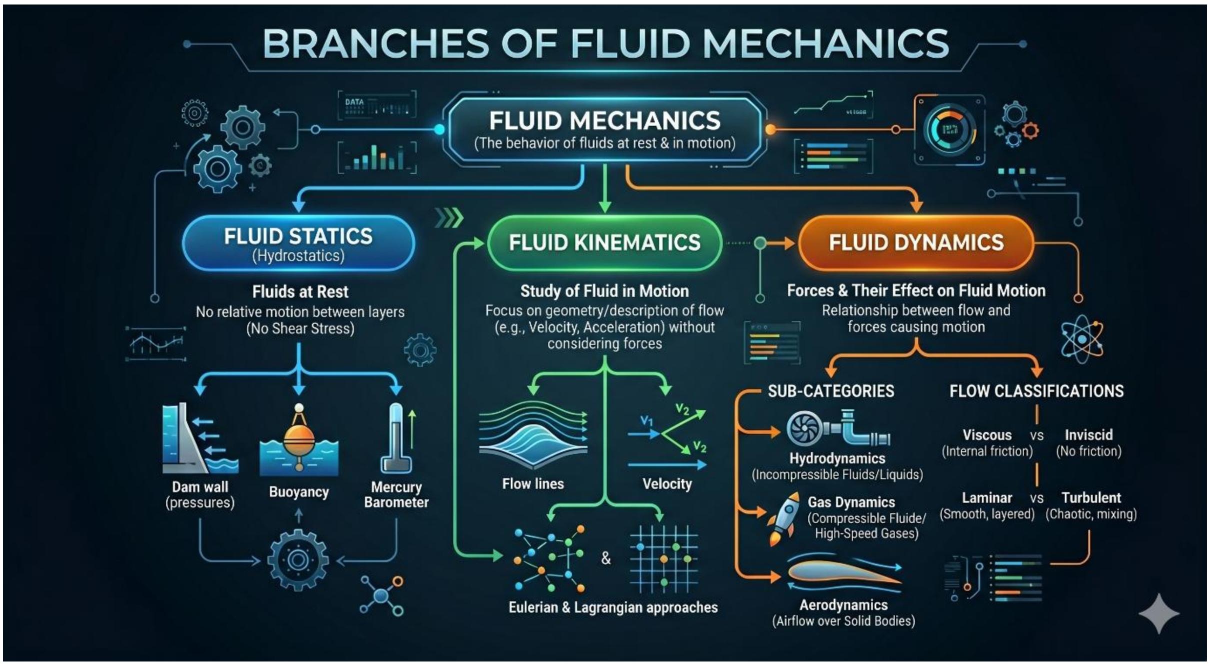

Figure 5.1: Branches of fluid mechanics

- **Fluid statics** – fluids at rest.
- **Fluid kinematics** – fluids in motion without considering forces.
- **Fluid dynamics** – fluids in motion under the influence of forces.

5.2 Properties of Fluids

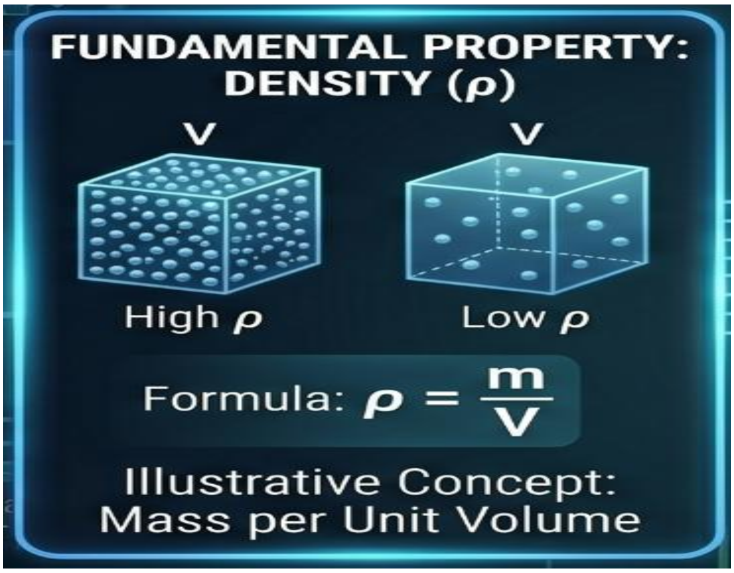

Figure 5.2: illustrative concept for density

1. **Density (ρ)**

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

where *m* is mass and *V* is volume.

- SI unit: **kg/m³**
- Water at room temperature: ~1000 kg/m³.
- Air at room temperature: ~1.225 kg/m³.

Application: Density determines buoyancy, fuel consumption in vehicles, and the lift of balloons/airships.

2. **Pressure (P)**

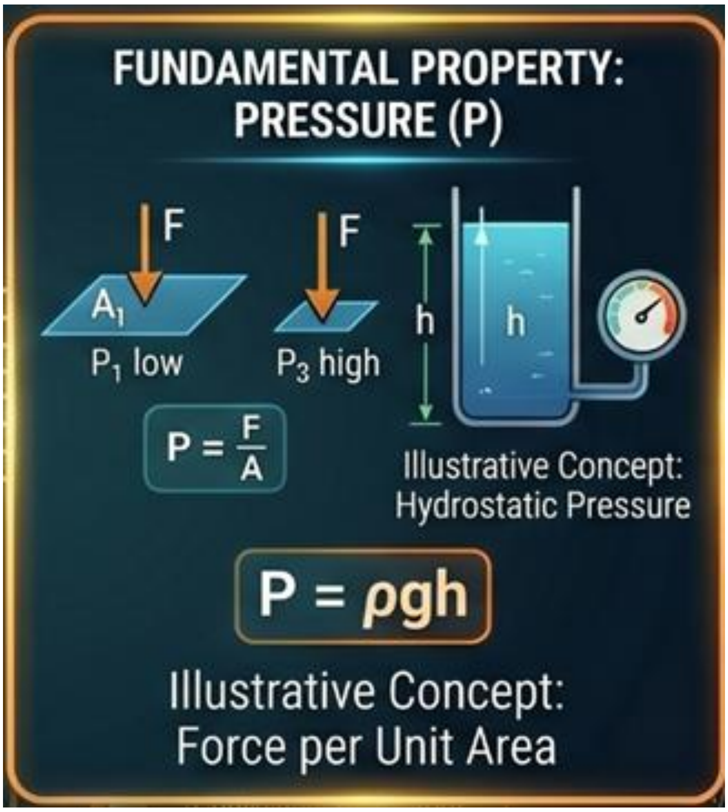

Figure 5.3: Illustrative concept for pressure

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

where *F* is the perpendicular force applied on area *A*.

- SI unit: **Pascal (Pa) = N/m²**

Hydrostatic pressure in a fluid column:

$$P = \rho g h$$

where *h* is depth in fluid, *ρ* is fluid density, and *g* is gravitational acceleration.

Example: Calculate the pressure of water at a depth of 5 m below the surface.

P=1000×9.81×5=49,050 Pa≈0.49 atm.

5.3 Fluid Statics

Pascal's Principle

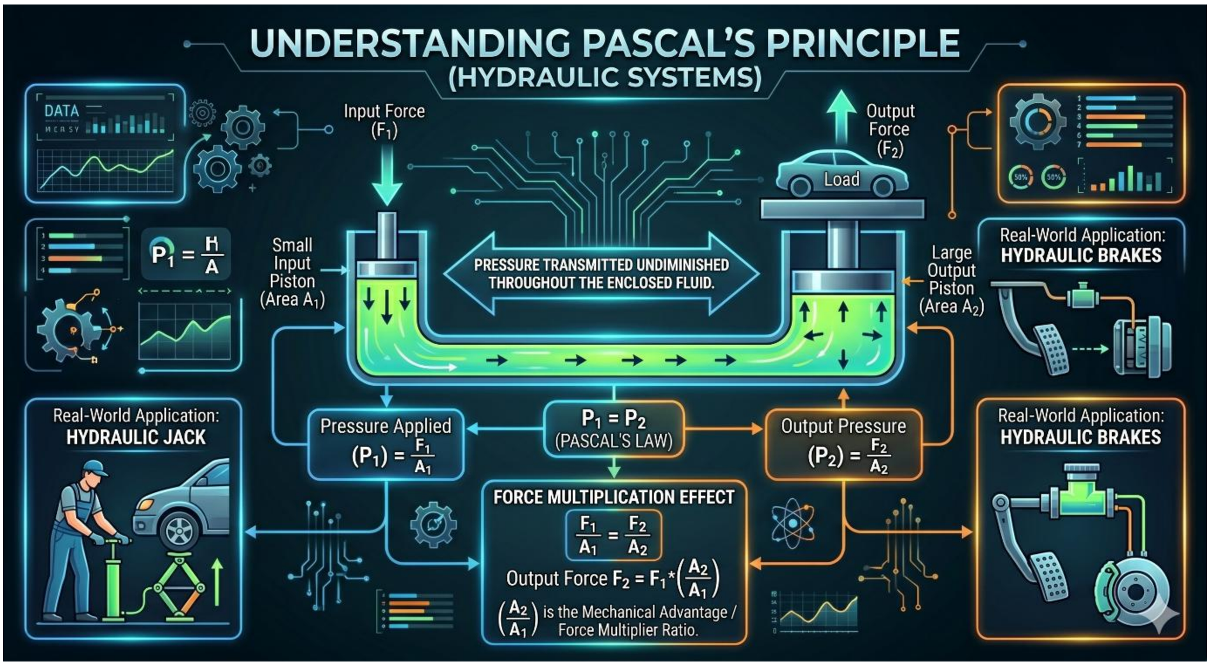

Figure 5.4: Summary Pascal's Principle

A change in pressure applied at any point in an enclosed fluid is transmitted equally in all directions.

Equal Pressure Transmission: The diagram shows that when pressure (P_1) is applied to the small input piston, that pressure is transmitted *undiminished* throughout the fluid to the larger output piston ($P_1 = P_2$).

Force Multiplication: Although the pressure is equal, the output force (F_2) is multiplied because the output piston has a much larger surface area (A_2). This is what allows a small input force to lift a heavy load, like a car.

Application: Hydraulic lifts and brakes in vehicles.

Archimedes' Principle

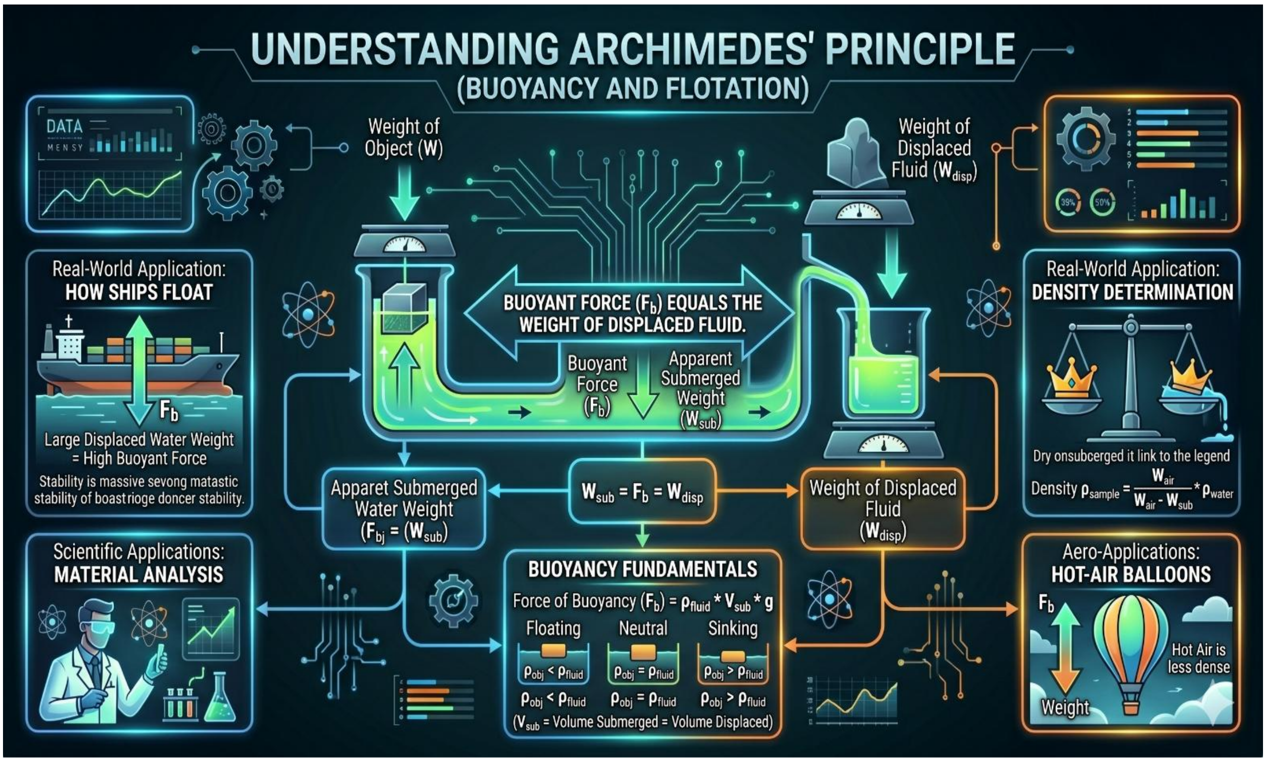

Figure 5.5: Illustration of Archimedes' Principle

A body wholly or partially submerged in a fluid experiences an upward buoyant force equal to the weight of the fluid displaced.

$$F_b = \rho_{fluid} g V_{displaced}$$

Where:

- F_b= buoyant force (N)
- ρ_{fluid} = density of the fluid (kg/m³)
- g = acceleration due to gravity (9.81 m/s²)
- $V_{displaced}$ = volume of fluid displaced (m³)

Key Insights

1. **Floating Objects:** If the buoyant force equals the object's weight, it floats.
2. **Sinking Objects:** If the buoyant force is less than the object's weight, it sinks.

3. **Neutral Buoyancy:** When buoyant force equals weight but object is fully submerged (e.g., submarines adjusting ballast).

Worked Example: 1 Floating

A wooden block of mass 1 kg and volume 0.002 m³ is placed in water. Will it float?

- Weight of block:

$W = mg = 1 \times 9.81 = 9.81\, N$

- Maximum buoyant force (if fully submerged):

$$F_b = \rho_{water} g V = 1000 \times 9.81 \times 0.002 = 19.62 N$$

Since F_b>W, the block floats, but only part of it remains submerged until F_b=W

Fraction submerged:

$$\frac{V_{sub}}{V} = \frac{W}{F_b} = \frac{9.81}{19.62} = 0.5$$

So, **half of the block's volume is underwater**.

Worked Example 2 – Sinking

A steel ball of volume 0.001 m³ and mass 7.8 kg is placed in water.

- Weight:

$$W = 7.8 \times 9.81 = 76.52\, N$$

Buoyant force (fully submerged):

$$F_b = 1000 \times 9.81 \times 0.001 = 9.81\, N$$

Since $W > F_b$, the steel ball sinks.

Engineering and Real-Life Applications

- **Shipbuilding:** Despite steel being denser than water, ships float because their large hull encloses air, lowering the *average density*.
- **Submarines:** Adjust buoyancy by pumping water in/out of ballast tanks to sink or rise.

- **Hydrometers:** Instruments that float at different levels depending on liquid density (used in alcohol or battery testing).
- **Hot Air Balloons:** Air inside is heated → less dense than surrounding air → buoyant force makes balloon rise.
- **Dams & Reservoirs:** Engineers calculate buoyant forces acting on gates or submerged structures.

Quick Thought Experiment

If you drop a heavy stone in water while in a boat:

- When in the boat, it adds to the boat's total weight → boat sinks deeper → **more water displaced**.
- When thrown overboard, the stone sinks → it displaces only its volume, which is less than the volume displaced by the boat when carrying it.
- So the water level actually **falls** when the stone is thrown out.

5.4 Fluid Dynamics

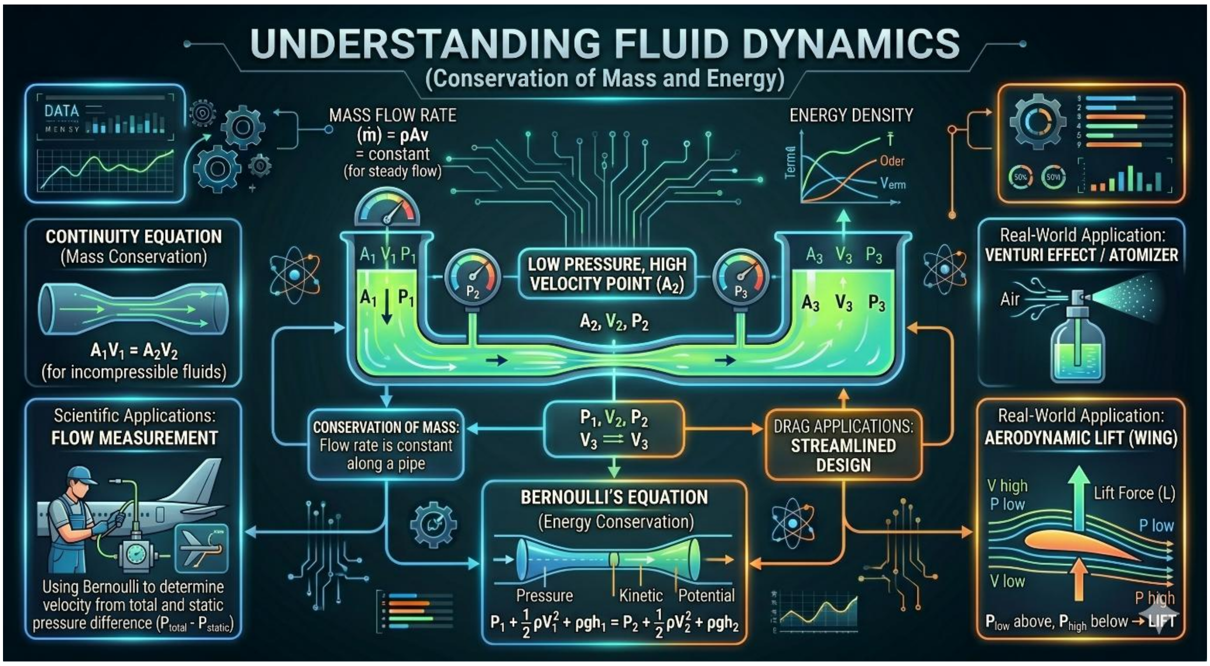

Figure 5.6: Illustration of Fluid Dynamics concept

Equation of Continuity

For an incompressible, non-viscous fluid:

$$A_1 v_1 = A_2 v_2$$

where A = cross-sectional area, v = velocity.

Application: Explains why water speeds up in a narrow hose nozzle.

Bernoulli's Principle

For steady flow of an incompressible, non-viscous fluid:

$$P + \frac{1}{2}\rho v^2 + \rho g h = constant$$

- P: fluid pressure
- ρv^2: dynamic pressure (kinetic energy per volume)
- $\rho g h$: hydrostatic pressure (potential energy per volume)

Energy Conversions in Bernoulli's Principle

Bernoulli's principle can be seen as a statement of the **conservation of mechanical energy in a fluid system**. It shows how energy shifts between three forms:

1. **Pressure Energy** → work done by fluid pressure
2. **Kinetic Energy** → energy due to motion $\frac{1}{2}\rho v^2$
3. **Potential Energy** → gravitational energy $\rho g h$

As a fluid flows:

- If velocity increases (narrow pipe), kinetic energy rises and pressure energy falls.
- If fluid rises in height, potential energy increases while pressure or velocity decreases.

- If pressure is high, it can be converted into velocity or lift.

Examples of Conversion:

- **Aircraft Wing:** Fast-moving air above wing → higher kinetic energy, lower pressure → lift is generated.
- **Venturi Effect (Carburettor/Sprays):** Narrow pipe → velocity increases, pressure drops → suction pulls in fuel or liquid.

5.5 Worked Example

Problem: A water pipe narrows from 0.05 m² to 0.01 m². If the velocity in the wide section is 2 m/s, find the velocity in the narrow section.

Solution:
From continuity equation,

$$A_1 v_1 = A_2 v_2$$

$0.05 \times 2 = 0.01 \times v_2$

$$v^2 = \frac{0.1}{0.01} = 10\, m/s$$

So, the velocity increases fivefold in the narrow section.

5.6 Real-Life Applications of Fluid Mechanics

- **Civil Engineering:** Design of dams, irrigation canals, and storm drains.
- **Mechanical Engineering:** Pumps, turbines, lubrication systems.
- **Aerospace:** Aerofoil lift, jet propulsion.
- **Environmental Engineering:** Pollution dispersion in rivers and atmosphere.
- **Biomedical Engineering:** Blood flow modelling, artificial heart valves.

Exercises

1. Calculate the difference in blood pressure (in atmosphere) between the heart and the foot in a person of height 2.00 m and the height from the heart to the head is 0.40 m and the density of blood is $1.06 \times 10^3 kg/m$.
2. The U-shape in Fig 1 contains two liquids in static equilibrium: water of density $998\ kg/m^3$ and an unknown liquid with unknown density. Find the density of the unknown liquid if h=155 mm and l=135 mm.

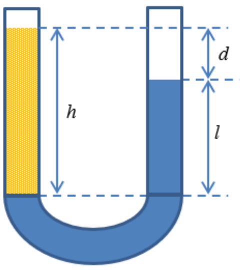

Figure 1

3. Your friend asks you to determine whether the ring that she recently bought is made of pure gold. (The density of gold is $1.93 \times 10^4\ \ kg/m^3$.) Using a thread of negligible mass and volume, you tie the ring to a very accurate spring balance and determine that in air it weighs $6.40 \times\ 10^{-3}\ \ N$. You then fully immerse the ring in a beaker full of water and find that its apparent weight is $6.00\ \ \times 10^{-3}\ N$. Determine if the ring is made of pure gold.
4. A 60.0-kg woman wearing high-heeled stilettos is invited into a home in which the kitchen has vinyl floor covering. The heel on each shoe is circular and has a radius of 0.5cm. If the woman balances on one heel, calculate the,

a) pressure does she exert on the floor,
b) Should the homeowner be concerned,
c) Explain your answer on b.