Unit 3

Fluid Mechanics

Introduction

Matter exists in three common states: solids, liquids, and gases. Liquids and gases are both considered fluids because they can flow and do not resist deformation like solids. Fluid mechanics is the study of how fluids behave, both when they are at rest and when they are in motion. This field is essential in various applications, such as engineering and biology.

3.1 Fluid Statics

Fluid statics, also known as hydrostatics, is the study of fluids at rest. In this state, there is no relative motion between adjacent layers of fluid, and the only force present is the pressure acting perpendicular to any surface within the fluid.

Properties of Solids, Liquids, and Gases

Solids: In solids, atoms are closely packed together and are held in place by strong forces, allowing them only to vibrate without changing positions. Solids resist all types of stress and do not compress easily because their atoms are fixed at specific distances from each other.

Liquids: Like solids, the molecules in liquids are also close to one another, but they can move around freely, sliding over each other. This allows liquids to flow. The forces between liquid molecules are weaker than those in solids but stronger than in gases. Liquids resist compression because their molecules are still relatively close together.

Gases: In gases, molecules are far apart compared to their size, and they move freely. The forces between gas molecules are weak, except when they collide. Gases are easily compressible and expand to fill the entire space of their container.

Pressure in Fluids

Pressure is a crucial concept in fluid statics. It is defined as the force exerted per unit area on a surface by the fluid. The formula to calculate pressure is:

$P=F/A$

where P is the pressure, F is the force, and A is the area. Pressure is measured in pascals (Pa), where 1 Pa = 1 N/m^2.

Different units of pressure include:

- 1 atm = 760 mmHg = 760 torr = 101.3 kPa = 14.7 psi

Example Problems

Example 1: Calculating Pressure

If a woman weighing 55 kg stands on one foot with a shoe area of 0.03 m^2, the pressure she exerts on the floor is:

$P=539\ N/0.03\ m^2=17966.67\ Pa\approx 18\times 103\ Pa$

Example 2: Force on a Nail

For a nail with a tip diameter of 1 mm, to create a pressure of 3×10^9 Pa, the force required is:

$F=P\times A=3\times 10^9\ Pa\times 7.85\times 10^{-7}\ m^2=2.36\times 10^3\ N$

Pressure in Gases

In gases, pressure results from the collisions of gas molecules with the walls of their container. The absolute pressure is the total pressure measured relative to a vacuum, while gauge pressure is the difference between absolute pressure and atmospheric pressure.

Example Problems

Example 3: Absolute Pressure

Given a gauge pressure of 32 psi and atmospheric pressure of 14.3 psi, the absolute pressure is:

$P_{abs}=P_{atm}+P_{gauge}=14.3\ psi+32.0\ ps\ i=46.3\ psi$

Density

Density is the mass per unit volume of a substance, given by:

$\rho=m/V$

The SI unit of density is kg/m^3. Density is a crucial factor in determining whether objects sink or float in a fluid.

Example 4: Density Calculation

For a person with a mass of 80 kg and a volume of 0.054 m^3:

$\rho=80\ kg/0.054\ m^3\approx1481.48\ kg/m^3$

Conclusion

Understanding the properties of solids, liquids, and gases, along with concepts like pressure and density, is fundamental in fluid mechanics. These principles are essential for various practical applications, such as designing hydraulic systems, understanding atmospheric phenomena, and even everyday activities like swimming and flying.

Relative Density (Specific Gravity)

Definition:
Relative density, also known as specific gravity, is a measure of how dense a substance is compared to a reference substance, usually water at 4°C. It is calculated as the ratio of the density of the substance to the density of water at a specific temperature. This ratio is dimensionless, meaning it has no units.

Formula:

Specific Gravity=Density of the Substance/Density of Water at 4°C

Specific Gravity=$\rho/\rho H_2O$

Example:
The density of mercury at 20°C is $13.6\times10^3\ kg/m^3$. The density of water at 4°C is $1\times10^3\ kg/m^3$.
Relative density of mercury is:
Relative Density=$(13.6\times10^3\ kg/m^3)/(1\times10^3\ kg/m^3)=13.6$

Since relative density has no units, the specific gravity of mercury is 13.6. The specific gravity of a substance in g/cm^3 is numerically equal to its density.

Key Point:

- Substances with specific gravity less than 1 are lighter than water and float on it.

Ideal Gas Equation

Definition:
The Ideal Gas Equation relates the pressure, volume, temperature, and number of moles of a gas under ideal conditions.

Formula: $PV=nRT=(m/M)RT=\rho R\_specificT$ Where:

- P is the absolute pressure,
- V is the volume,
- n is the number of moles,
- R is the universal gas constant (8.314 J/mol·K),
- T is the absolute temperature,
- ρ is the density,
- R_specific is the specific gas constant (R/M , where M is the molar mass of the gas).

Example:
To find the density of air in a room with dimensions 4 m×5 m×6 m at 100 kPa and 25°C, using the ideal gas relation:
$\rho=P/RspecificT=100\ kPa/(0.287\ kPa\backslash m^3/kg)(25+273.15)\ K=1.17\ kg/m^3$

The relative density of air is:

Relative Density$=1.17\ kg/m^3/1000\ kg/m^3=0.00117$

The volume of the room: $V=4\times5\times6=120\ m^3$

The mass of air: $m=\rho V=1.17\times120=140\ kg$

Pressure in Fluids at Rest

Definition:
In a fluid at rest, the pressure is exerted equally in all directions. This pressure is caused by the collisions of the fluid particles with the walls of the container.

Pascal's Principle:
A change in pressure applied to an enclosed fluid is transmitted undiminished to every point within the fluid and to the walls of the container.

Formula: $P=P0+\rho ghP$ Where:

- $P0$ is the atmospheric pressure,
- ρ is the density of the fluid,
- g is the acceleration due to gravity,
- h is the depth of the fluid.

Hydraulic Press:
A hydraulic press uses Pascal's principle to multiply force. A small force applied on a small piston generates a larger force on a larger piston.

Example:
If a hydraulic lift has a small piston with an area of 0.0020 m^2 and a larger piston with an area of 0.20 m^2, to lift a car of mass 1800 kg, the force required on the smaller piston is:
$F\_small=(A\_small/A\_large)\times(mcar\times g)=(0.00200.20)\times(1800\times 9.8)=18$ N

This demonstrates how a small force can lift a heavy load using a hydraulic press.

Atmospheric Pressure

Concept of Atmospheric Pressure: Atmospheric pressure is the force per unit area exerted by the weight of the air above a given point on Earth's surface. At sea level, the average atmospheric pressure is about 101.325 kPa. As you ascend in altitude, the atmospheric pressure decreases because there is less air above you, resulting in a lower weight of air pressing down.

Why Atmospheric Pressure Decreases with Altitude:

1. **Density of Air:** The density of air is highest near the Earth's surface due to gravity, which pulls most gas molecules close to the surface. More molecules in a given volume mean higher pressure due to more frequent collisions.

2. **Depth of the Atmosphere:** The atmosphere is deepest at sea level, with more air pressing down from above. As you go higher, the depth of the atmosphere decreases, resulting in lower pressure.

Example of Atmospheric Pressure Change with Altitude: At sea level, the pressure is 101.325 kPa. As you ascend to 1000 meters, it drops to about 89.88 kPa, and it continues to decrease with higher altitudes.

Effects of Atmospheric Pressure:

- **Cooking:** Water boils at a lower temperature at higher altitudes, making cooking slower.
- **Breathing:** The lower air pressure at high altitudes means less oxygen, which can cause fatigue and breathing difficulties.

Measuring Atmospheric Pressure

Pressure Underwater: Pressure increases with depth underwater due to the weight of both the water and the atmosphere above you. For example, diving just one meter underwater increases the pressure noticeably more than moving up or down in an elevator.

The Barometer: A barometer measures atmospheric pressure. It was invented by Evangelista Torricelli, who demonstrated that atmospheric pressure could be measured by the height of a mercury column in a tube. The formula for calculating pressure with a barometer is:

$P_{atm} = \rho g h$

Where:

- ρ is the density of mercury,
- g is the gravitational acceleration,
- h is the height of the mercury column.

At sea level, standard atmospheric pressure can support a mercury column of 760 mm (also called 760 torr).

Example Calculation: If a barometer reads 740 mmHg, and the gravitational acceleration is 9.805 m/s^2, the atmospheric pressure can be calculated as 98.5 kPa.

The Manometer

Purpose of a Manometer: A manometer is used to measure the pressure of a gas in a container. It is similar to a barometer but usually has a U-shaped tube.

Types of Manometers:

1. **Closed-end Manometer:** Measures the absolute pressure of a gas.

   $P_{gas}=\rho gh$

2. **Open-end Manometer:** Measures the difference between gas pressure and atmospheric pressure.
   - If atmospheric pressure is greater than gas pressure: $P_{gas}=P_{atm}-\rho gh$
   - If atmospheric pressure is less than gas pressure: $P_{gas}=P_{atm}+\rho gh$

Example Calculation: If a manometer connected to a gas tank shows a fluid column height difference of 55 cm with a fluid of specific gravity 0.85, and the local atmospheric pressure is 96 kPa, the absolute pressure in the tank is 100.6 kPa.

Archimedes' Principle and Buoyant Force

Buoyant Force: Buoyant force is the upward force exerted by a fluid on an immersed object. This force exists because the pressure at the bottom of an object in a fluid is greater than at the top, creating a net upward force.

Archimedes' Principle: The buoyant force on an object is equal to the weight of the fluid displaced by the object.

$F_B=\text{Weight of fluid displaced}$

For a totally submerged object, if the object's density is less than the fluid's density, it will float; if it's greater, it will sink.

Example of Buoyancy: An iceberg floating in seawater displaces 89% of its volume underwater because the density of ice (917 kg/m^3) is less than seawater (1030 kg/m^3). This is why only 11% of the iceberg is visible above the surface.

Practical Example: If a 10,000 metric ton steel object is submerged in water, the buoyant force is 1.3×10^7 N. This force is much less than the weight of the steel, so it will sink.

Summary:

Understanding atmospheric pressure, buoyant forces, and the principles of Archimedes and manometers is crucial for explaining various natural phenomena, from why we feel pressure changes when climbing mountains to how ships float and sink.

Fluid Flow

Fluid flow occurs when there is a difference in pressure within a fluid. Fluids naturally move from regions of higher pressure to regions of lower pressure, similar to how wind is created in Earth's atmosphere by air moving from high-pressure areas to low-pressure areas.

Steady and Turbulent Fluid Flow

When a fluid flows, its motion can be described in two primary ways:

1. **Steady (Laminar) Flow**: In this type of flow, each particle of the fluid follows a smooth, continuous path that does not intersect with the paths of other particles. The velocity of the fluid at any point remains constant over time. This smooth flow typically occurs at low velocities and in pipes with small diameters.
2. **Turbulent Flow**: When the fluid's velocity increases beyond a certain point, the flow becomes irregular and chaotic. In turbulent flow, the fluid particles move in a random, zigzag manner, creating small whirlpool-like regions. This flow is common in fluids moving at high speeds or through larger diameter pipes.

Viscosity

Viscosity is the internal frictional force within a fluid, analogous to the friction between solid surfaces. It occurs when adjacent layers of fluid move relative to each other, causing a portion of the fluid's kinetic energy to convert into internal energy. Higher viscosity means more resistance to flow.

Streamlines and Flow Rate

- **Streamline**: The path that a fluid particle follows in steady flow is called a streamline. The velocity of the fluid particle is always tangent to its streamline. In laminar flow, streamlines do not cross each other, which helps maintain a steady flow.

- **Flow Rate (Q)**: Flow rate is the volume of fluid that passes through a given area per unit of time. It is calculated using the formula:

  $Q=V/t$

  where V is the volume of fluid and t is the time. The SI unit of flow rate is cubic meters per second (m^3/s).

Equation of Continuity

For an incompressible fluid (one that does not change in volume), the flow rate must remain constant throughout a pipe, regardless of changes in the pipe's cross-sectional area. This is expressed by the equation of continuity:

$A_1v_1=A_2v_2$

where A_1 and A_2 are the cross-sectional areas at two different points, and v_1 and v_2 are the corresponding fluid velocities. This equation shows that as the cross-sectional area decreases, the fluid velocity increases.

Bernoulli's Principle

Bernoulli’s principle states that as the speed of a fluid increases, the pressure it exerts on surfaces decreases. This principle explains various phenomena in nature and technology, such as why blood pressure decreases when blood flows faster through narrow blood vessels or why a snoring sound is produced when airflow through a narrow passageway causes a drop in pressure.

Safety and High Pressure

High pressure, typically defined as pressure greater than 50 atmospheres, is used in various applications, such as high-pressure cookers, gas cylinders, and high-pressure washers. High pressure can significantly alter the physical and chemical properties of materials and is used in processes like pascalization, which extends the shelf life of perishable foods by reducing microbial activity.

High-Pressure Equipment

High-pressure systems include components like compressors, high-pressure vessels, safety accessories, and instrumentation. Compressors increase gas pressure by reducing volume, while high-pressure vessels are designed to contain fluids under pressure. Safety accessories, such as safety valves and bursting discs, are essential for preventing accidents, and high-pressure instrumentation is necessary for measuring and controlling system parameters.

Safety Precautions

Working with high-pressure equipment requires strict safety measures to prevent accidents. Common risks include explosions, equipment failure, and operator errors. Safety measures include using proper protective gear, following correct operating procedures, and ensuring regular maintenance and inspection of the equipment.