Physics 2: Fluid Mechanics and Thermodynamics

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• No of credits: 02 (30 teaching hours)


• References:
Course Requirements

- Attendance + Discussion + Homework: 15%
- Assignment: 15%
- Mid-term exam: 30%
- Final: 40%
Preparation for each class

- Read text ahead of time
- Finish homework
Chapter 1 Fluid Mechanics

Chapter 2 Heat, Temperature and the First Law of Thermodynamics

Chapter 3 The Kinetic Theory of Gases

✓ Midterm exam after Lecture 6

Chapter 4 Entropy and the Second Law of Thermodynamics

✓ Assignment given in Lecture 11

✓ Final exam after Lecture 12

(Chapters 14-20 of Fundamentals of Physics, Halliday et al.)
Chapter 1 Fluid Mechanics

1.1. Fluids at Rest

1.2. Ideal Fluids in Motion

1.3. Bernoulli’s Equation
**Question:** What is a fluid?

A fluid is a substance that can flow (liquids, gases)

**Physical parameters:**

- **Density:** (the ratio of mass to volume for a material)

\[
\rho = \frac{\Delta m}{\Delta V}
\]

- \(\Delta m\) and \(\Delta V\) are the mass and volume of the element, respectively.

- Density has no directional properties (a scalar property)

**Unit:** kg/m\(^3\) or g/cm\(^3\); 1 g/cm\(^3\) = 1000 kg/m\(^3\)

**Uniform density:**

\[
\rho = \frac{m}{V}
\]
Fluid Pressure:

- Pressure is the ratio of normal force to area
  - Pressure is a scalar property
  - Unit:
    - \( N/m^2 = \text{Pa} \) (pascal)
    - Non-SI: \( \text{atm}=1.01 \times 10^5 \text{ Pa} \)
  - Fluid pressure is the pressure at some point within a fluid:
    \[
    p = \frac{\Delta F}{\Delta A}
    \]

- Uniform force on flat area:
  \[
  p = \frac{F}{A}
  \]
Properties:

- Fluids conform to the boundaries of any container containing them.
- Gases are compressible but liquids are not, e.g., see Table 14-1:
  - Air at 20°C and 1 atm pressure: density (kg/m³)=1.21
  - 20°C and 50 atm: density (kg/m³)=60.5
  - The density significantly changes with pressure
  - Water at 20°C and 1 atm: density (kg/m³)=0.998 x 10³
  - 20°C and 50 atm: density (kg/m³)=1.000 x 10³
  - The density does not considerably vary with pressure
1.1. Fluids at Rest

The pressure at a point in a non-moving (static) fluid is called the hydrostatic pressure, which only depends on the depth of that point.

Problem: We consider an imaginary cylinder of horizontal base area $A$

\[
\begin{align*}
F_2 &= F_1 + mg \\
F_1 &= p_1 A \\
F_2 &= p_2 A \\
p_2 A &= p_1 A + \rho A(y_1 - y_2) g \\
p_2 &= p_1 + \rho (y_1 - y_2) g
\end{align*}
\]

- If $y_1=0$, $p_1=p_0$ (on the surface) and $y_2=-h$, $p_2=p$:

\[
p = p_0 + \rho g h
\]

- Calculate the atmospheric pressure at $d$ above level 1:

\[
p = p_0 - \rho_{\text{air}} gd
\]
Question: There are four containers of water. Rank them according to the pressure at depth $h$, greatest first.

Answer: All four have the same value of pressure.
A. Measuring pressure:

**Mercury barometers**
(atmospheric pressure)

\[ p_0 = \rho gh \]

\( \rho \) is the density of the mercury

**An open-tube manometer**
(gauge pressure)

\[ p_g = \rho gh \]

\( \rho \) is the density of the liquid
The gauge pressure can be positive or negative:

- **Closed tube**
  - \( p_{\text{gas}} = \rho gh_1 \)
  - \( p_{\text{gauge}} = p_{\text{gas}} - p_0 = \rho gh_1 - p_0 \)

- **Open tube**
  - \( p_{\text{gas}} = \rho gh_2 + p_0 \)
  - \( p_{\text{gauge}} = p_{\text{gas}} - p_0 = \rho gh_2 > 0 \)

- **Open tube**
  - \( p_{\text{gas}} + \rho gh_3 = p_0 \)
  - \( p_{\text{gauge}} = p_{\text{gas}} - p_0 = -\rho gh_3 < 0 \)
B. Pascal’s Principle:

A change in the pressure applied to an enclosed incompressible fluid is transmitted undiminished to every part of the fluid, as well as to the walls of its container.

\[ p = p_{\text{ext}} + \rho gh \]

\[ \Delta p = \Delta p_{\text{ext}} \]

- Application of Pascal’s principle:

\[ \Delta p = \frac{F_i}{A_i} = \frac{F_0}{A_0} \]

\[ F_0 = F_i \frac{A_0}{A_i} \]

\( A_0 > A_i \Rightarrow F_0 > F_i \)

The output work:

\[ W = F_i d_i = F_0 d_0 \]
Pascal’s Law
C. Archimede's Principle:

- We consider a plastic sack of water in static equilibrium in a pool:

  \[ \vec{F}_g + \vec{F}_b = 0 \]

  The net upward force is a buoyant force \( \vec{F}_b \)

  \[ F_b = F_g = m_f g \] (\( m_f \) is the mass of the sack)

  \[ F_b = \rho_{\text{fluid}} g V \]

  \( V \): volume of water displaced by the object, if the object is fully submerged in water, \( V = V_{\text{object}} \)

- If the object is not in static equilibrium, see figures (b) and (c):

  \( F_b < F_g \) (case b: a stone)

  \( F_b > F_g \) (case c: a lump of wood)
The buoyant force on a submerged object is equal to the weight of the fluid that is displaced by the object.

Apparent weight in a Fluid:
\[
\text{weight}_{\text{app}} = \text{weight}_{\text{actual}} - F_b
\]

**Question:** Three identical open-top containers filled to the brim with water; toy ducks float in 2 of them (b & c). Rank the containers and contents according to their weight, greatest first.

**Answer:** All have the same weight.
1.2. Ideal Fluids in Motion

We do only consider the motion of an ideal fluid that matches four criteria:

- Steady flow: the velocity of the moving fluid at any fixed point does not vary with time.
- Incompressible flow: the density of the fluid has a constant and uniform value.
- Non-viscous flow: no resistive force due to viscosity.
- Irrotational flow.
The Equation of Continuity

(the relationship between speed and cross-sectional area)

• We consider the steady flow of an ideal fluid through a tube. In a time interval \( \Delta t \), a fluid element moves along the tube a distance:

\[
\Delta x = v \Delta t
\]

\[
\Delta V = A \Delta x = A v \Delta t
\]

\[
\Delta V = A_1 v_1 \Delta t = A_2 v_2 \Delta t
\]

or

\[
A_1 v_1 = A_2 v_2
\]

(Equation of continuity)

• Volume flow rate: \( R_V = A v = \) a constant
• Mass flow rate: \( R_m = \rho R_V = \rho A v = \) a constant
1.3. Bernoulli’s Equation

- An ideal fluid is flowing at a steady rate through a tube.
- Applying the principle of conservation of energy (work done=change in kinetic energy):

$$p_1 + \frac{1}{2} \rho v_1^2 + \rho g y_1 = p_2 + \frac{1}{2} \rho v_2^2 + \rho g y_2$$

$$p + \frac{1}{2} \rho v^2 + \rho g y = \text{a constant}$$

- If $y=0$:  
  $$p_1 + \frac{1}{2} \rho v_1^2 = p_2 + \frac{1}{2} \rho v_2^2$$

⇒ As the velocity of a horizontally flowing fluid increases, the pressure exerted by that fluid decreases, and conversely.
Bernoulli's Principle
**Question:** Water flows smoothly through a pipe (see the figure below), descending in the process. Rank the four numbered sections of pipe according to (a) the volume flow rate $R_V$, (b) the flow speed $v$, and (c) the water pressure $p$, greatest first.

$$R_V = A_1 v_1 = A_2 v_2 = A_3 v_3 = A_4 v_4$$

$$p_1 + \frac{1}{2} \rho v_1^2 + \rho gh = p_2 + \frac{1}{2} \rho v_2^2 + \rho gh = p_3 + \frac{1}{2} \rho v_3^2 = p_4 + \frac{1}{2} \rho v_4^2$$

(a) All tie; (b) 1, 2, 3, 4; (c) $p_4$, $p_3$, $p_2$, $p_1$
Keywords of the lecture:

1. **Pressure** \((\text{N/m}^2 = \text{Pa})\): the ratio of normal force to area
   \[ p = \frac{\Delta F}{\Delta A} \]

2. **Gauge pressure** and **Absolute pressure**:
   \[ p_g = \rho gh \]
   \[ p = p_0 + p_g \ (p_0: \text{atmospheric pressure}) \]

3. **Bouyant force** (Archimedes' principle):
   \[ F_b = \rho g V \]

4. **Volume flow rate** \((\text{m}^3/\text{s})\) and **Mass flow rate** \((\text{kg/s})\):
   \[ R_V = Av \]
   \[ R_m = \rho R_V \]
Homework:

(1) Read “Proof of Bernoulli’s Equation”

(2) Chapter 14: 1, 4, 5, 9, 11, 22, 31, 32, 40, 46, 54, 55, 59