Physics 2: Fluid Mechanics and Thermodynamics

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• No of credits: 02 (30 teaching hours)


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

Questions, Discussion

• Wednesday’s morning and afternoon: see the secretary of the department (room A1.413) for appointments
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, 18, 19, 20 of Principles 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:
    - $N/m^2=Pa$ (pascal)
    - Non-SI: $atm=1.01 \times 10^5 \text{ Pa}$
- 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 $A$

- **Equations:**
  \[
  F_2 = F_1 + mg \\
  F_1 = p_1 A \\
  F_2 = p_2 A \\
  p_2 A = p_1 A + \rho A(y_1 - y_2)g \\
  p_2 = p_1 + \rho(y_1 - y_2)g
  \]

- **Conditions:**
  - If $y_1 = 0$, $p_1 = p_0$ (on the surface) and $y_2 = -h$, $p_2 = p$:
    \[
    p = p_0 + \rho gh
    \]

- **Calculation:** Calculate the atmospheric pressure at $d$ above level 1:
  \[
  p = p_0 - \rho_{air} gd
  \]
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**

\[
\begin{align*}
  p_{\text{gas}} &= \rho g h_1 \\
  p_{\text{gauge}} &= p_{\text{gas}} - p_0 \\
  &= \rho g h_1 - p_0
\end{align*}
\]

**Open tube**

\[
\begin{align*}
  p_{\text{gas}} &= \rho g h_2 + p_0 \\
  p_{\text{gauge}} &= p_{\text{gas}} - p_0 \\
  &= \rho g h_2 > 0
\end{align*}
\]

\[
\begin{align*}
  p_{\text{gas}} + \rho g h_3 &= p_0 \\
  p_{\text{gauge}} &= p_{\text{gas}} - p_0 \\
  &= -\rho g h_3 < 0
\end{align*}
\]
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:**

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

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

\[ A_0 > A_i \implies F_0 > F_i \]

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 $\vec{F}_b$

$$F_b = F_g = m_f g \text{ (} m_f \text{ is the mass of the sack)}$$

$$F_b = \rho_{\text{fluid}} g V$$

$V$: 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):

  $$F_b < F_g \text{ (case b: a stone)}$$

  $$F_b > F_g \text{ (case c: a lump of wood)}$$
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 $e$ 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: $R_V = A v = a \text{ constant}$
- Mass flow rate: $R_m = \rho R_V = \rho A v = a \text{ constant}$
Sample problem: A sprinkler is made of a 1.0 cm diameter garden hose with one end closed and 40 holes, each with a diameter of 0.050 cm, cut near the closed end. If water flows at 2.0 m/s in the hose, what is the speed of the water leaving a hole? (Midterm 2014)

Using the equation of continuity, the speed $v_2$ is:

$$v_1 A_1 = v_2 A_2 = v_2 (40a_0)$$

$a_0$ is the area of one hole

$$v_2 = \frac{v_1 A_1}{40a_0} = \frac{2.0 \times \pi \left(\frac{1.0}{2}\right)^2}{40 \times \pi \left(\frac{0.05}{2}\right)^2} = 20 \text{ (m/s)}$$
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** (N/m² = Pa): the ratio of normal force to area
   \[ p = \frac{\Delta F}{\Delta A} \]

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

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

4. **Volume flow rate** (m³/s) and **Mass flow rate** (kg/s):
   \[ R_V = Av \]
   \[ R_m = \rho R_V \]
Homework:

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

(2) Chapter 14: 1, 2, 5, 14, 17, 28, 38, 39, 48, 58, 64, 65, 71