Physics 2: Fluid Mechanics and Thermodynamics

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Course Description

- 02 credits (30 teaching hours) [25.6-11.8.2018: 7 weeks]
- Textbook: Principles of Physics, 9th edition, Halliday/Resnick/Walker (2011),John Willey & Sons, Inc.

  (Chapters 14, 18, 19, 20)

Course Requirements

- Attendance + Discussion/homework + Assignment: 30%
- Mid-term exam: 30%
- Final: 40%

Absence rate > 20% => not allowed to take the final exam

Note: Finish homework & Read text ahead of time

Contents of Physics 2

Chapter 1 Fluid Mechanics

Chapter 2 Heat, Temperature, and the First Law of Thermodynamics ❖ Assignment 1

Chapter 3 The Kinetic Theory of Gases

✓ Midterm exam

Chapter 4 Entropy and the Second Law of Thermodynamics ❖ Assignment 2

✓ Final exam

(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)

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

- Δm and ΔV 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:

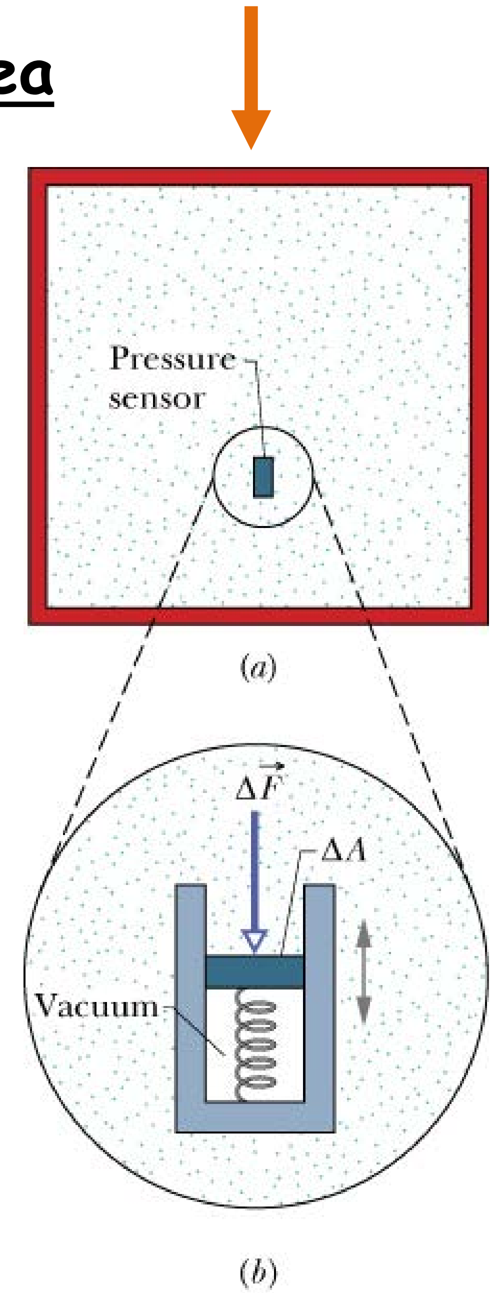
$$\rho = \frac{m}{V}$$

Fluid Pressure:

A fluid-filled vessel

– Pressure is <u>the ratio of normal force to area</u>

- Pressure is a scalar quantity
- Unit:
  - N/m^2=Pa (pascal)
  - Non-SI: atm=1.01 x 10^5 Pa



Fluid pressure is the pressure at some point within a fluid:

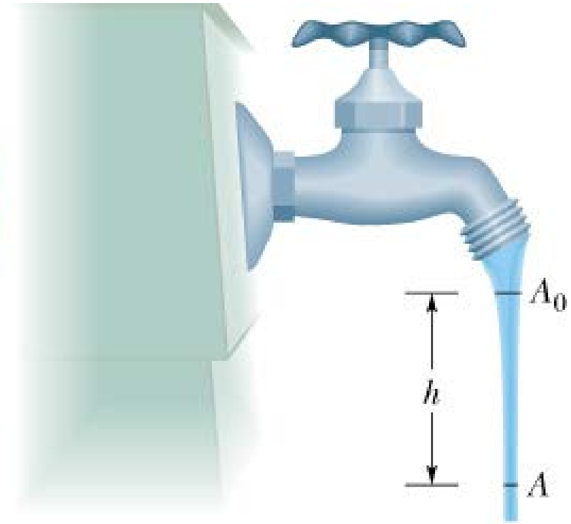
$$p = \frac{\Delta F}{\Delta A}$$

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

  - Air at 20^0C and 1 atm pressure: density (kg/m^3)=1.21
    20^0C and 50 atm: density (kg/m^3)=60.5

  → The density significantly changes with pressure

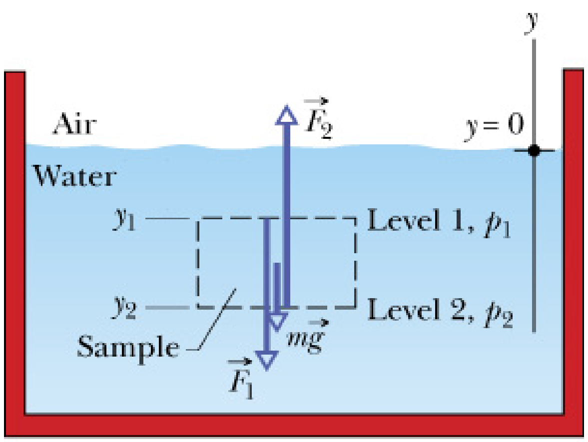
  - Water at 20^0C and 1 atm: density (kg/m^3)=0.998×10^3
    20^0C and 50 atm: density (kg/m^3)=1.000×10^3

  → 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***



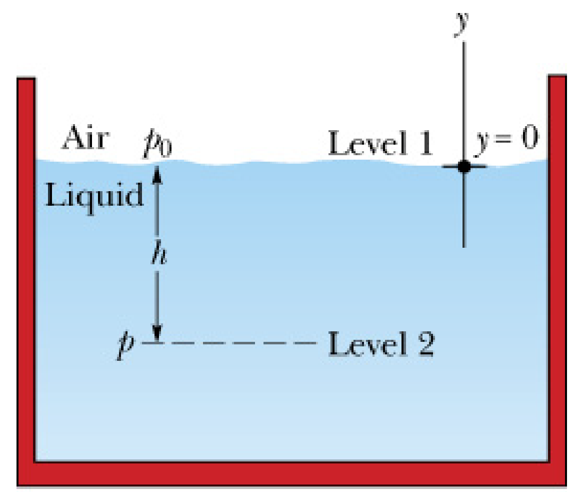
$$F_2 = F_1 + mg$$

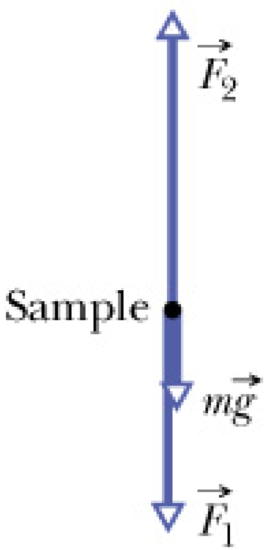
$$F_1 = p_1 A$$

$$F_2 = p_2 A$$

$$p_2 A = p_1 A + \rho A(y_1 - y_2)g$$

$$p_2 = p_1 + \rho(y_1 - y_2)g$$





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

$$p = p_0 + \rho g h$$

gauge pressure

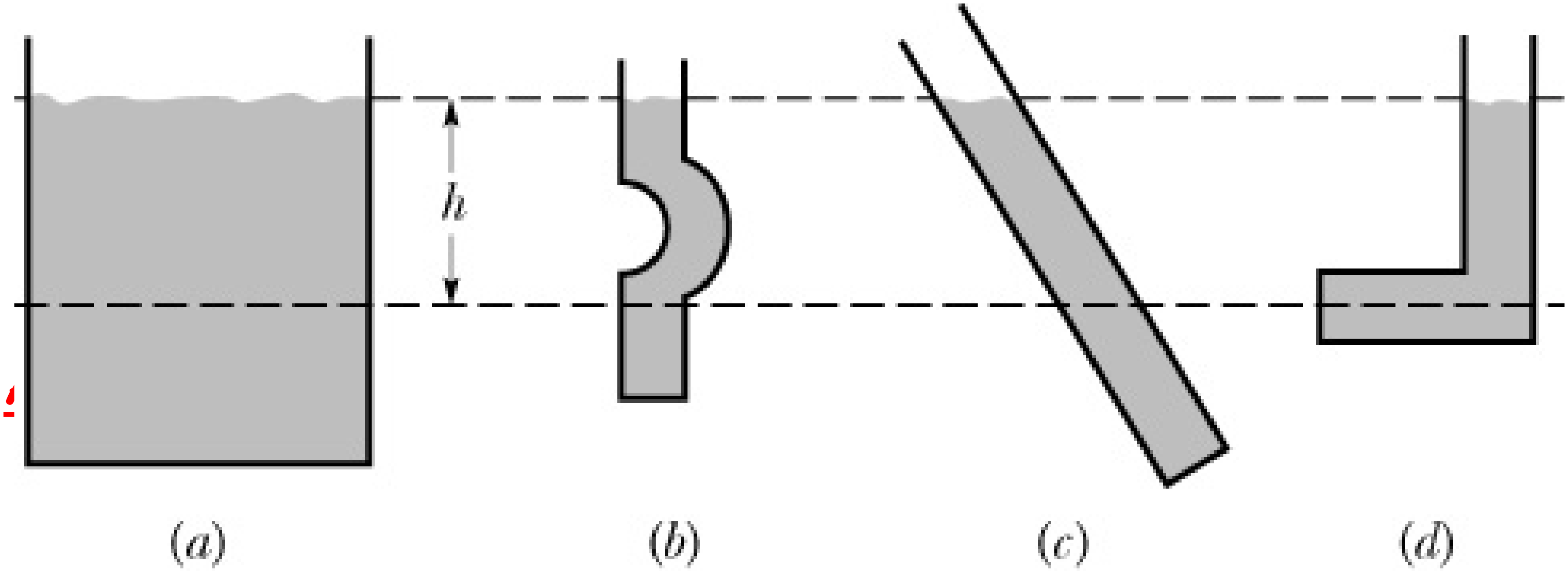
absolute pressure **atmospheric pressure**

Calculate the atmospheric pressure at d above level 1:

$$p = p_0 - \rho_{air} g d$$

Question:

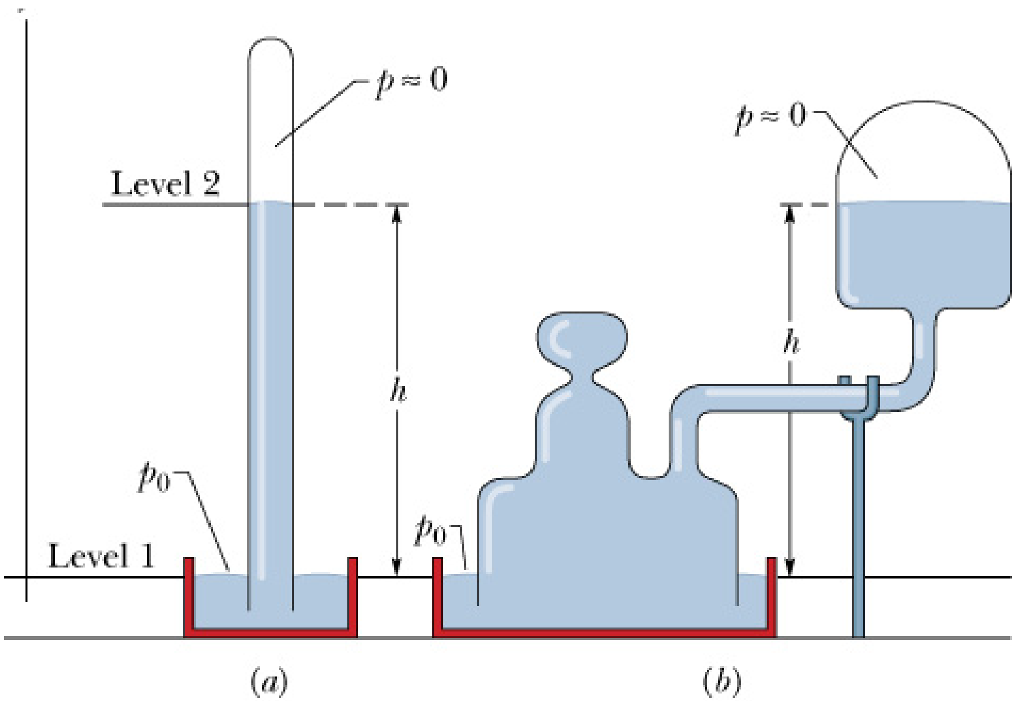
There are four containers of water. Rank them according to the pressure at depth h, greatest first.



$$p = p_0 + \rho g h$$

A. Measuring pressure:

Mercury barometers
(atmospheric pressure)

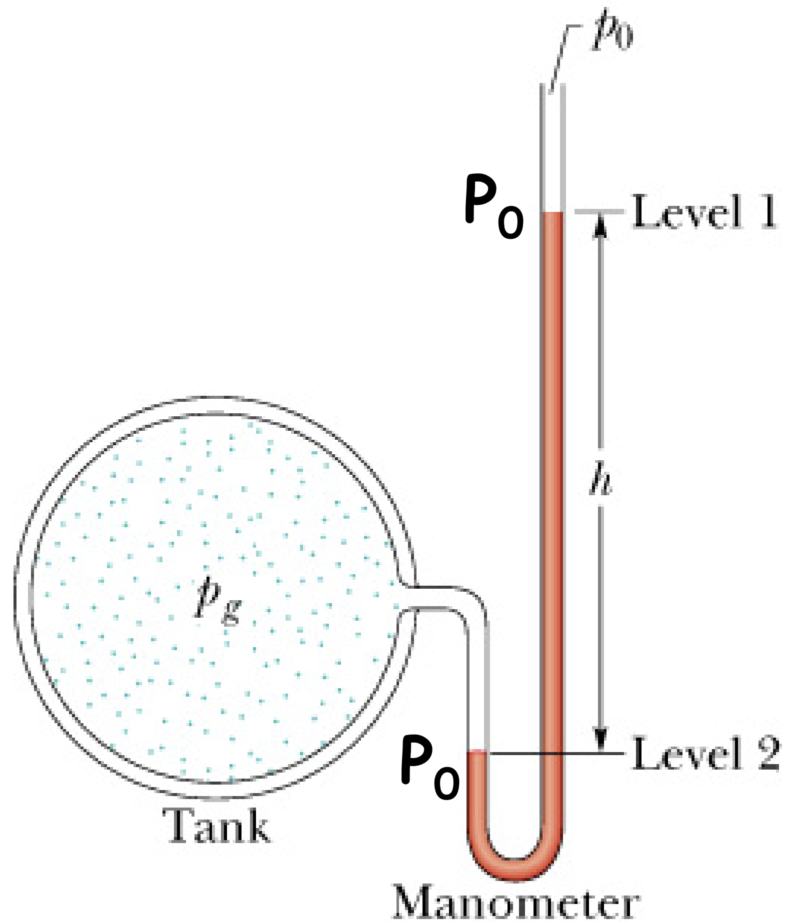


$$p_0 = \rho g h$$

ρ is the density of the mercury

Mercury:
- a heavy silvery toxic
- The only metal that is liquid at ordinary temperatures:

An open-tube manometer
(gauge pressure)

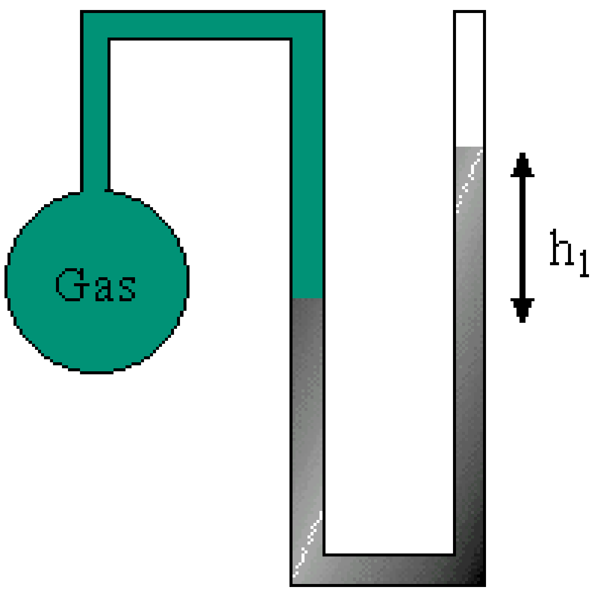


$$p_g = p - p_0 = \rho g h$$

ρ is the density of the liquid

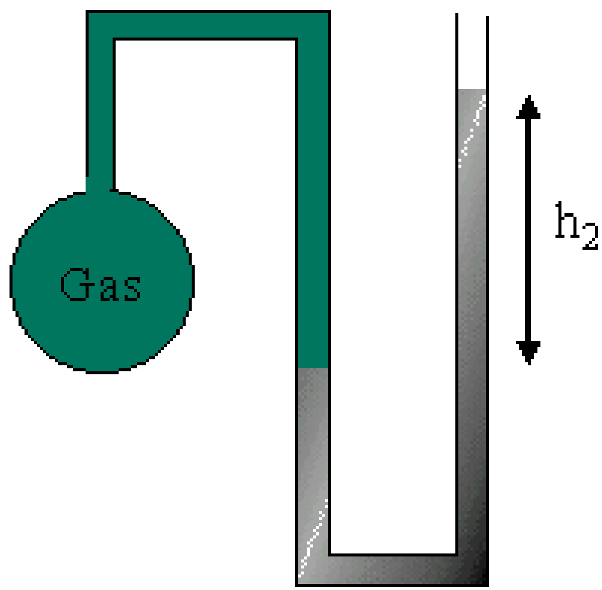
The gauge pressure can be positive or negative: $p_{gauge} = p_{gas} - p_0$

closed tube



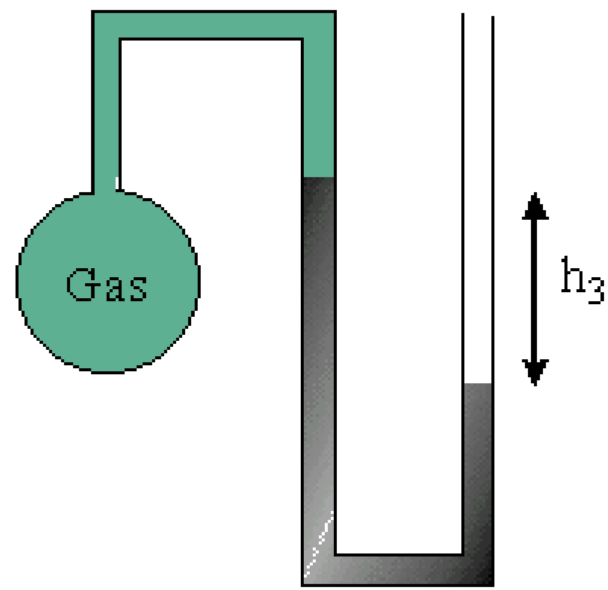
$$p_{gas} = \rho g h_1$$
$$p_{gauge} = p_{gas} - p_0$$
$$= \rho g h_1 - p_0$$

open tube



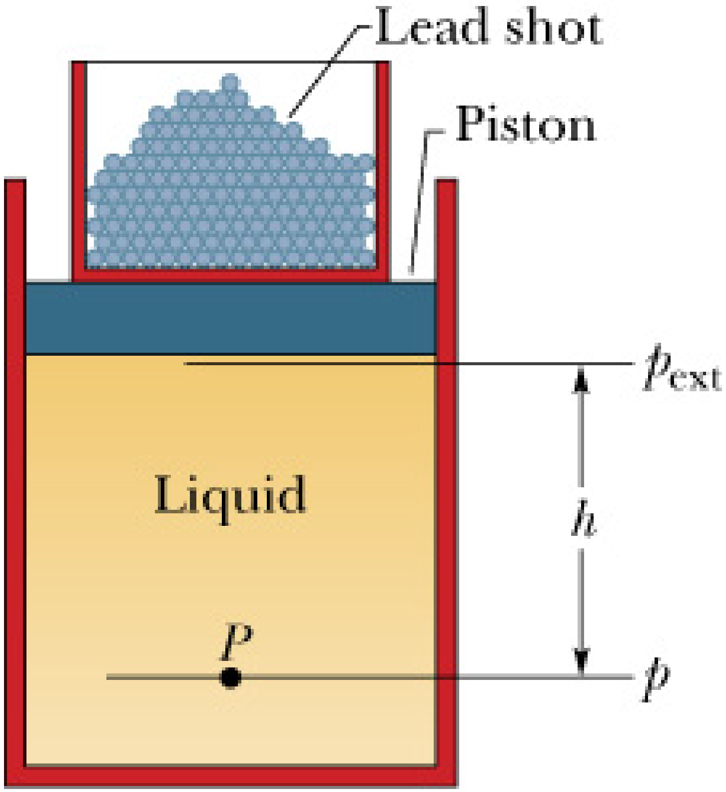
$$p_{gas} = \rho g h_2 + p_0$$
$$p_{gauge} = p_{gas} - p_0$$
$$= \rho g h_2 > 0$$

open tube



$$p_{gas} + \rho g h_3 = p_0$$
$$p_{gauge} = p_{gas} - p_0$$
$$= -\rho g h_3 < 0$$

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.

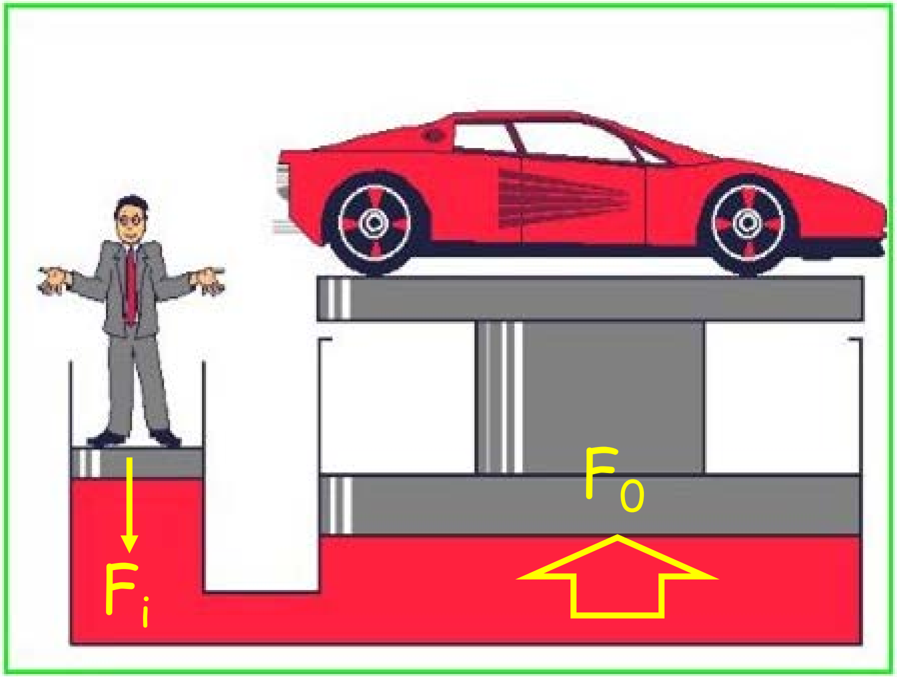
$$p = p_{ext} + \rho g h$$

$$\Delta p = \Delta p_{ext}$$

- Application of Pascal's principle:

$$\Delta p = \frac{F_i}{A_i} = \frac{F_0}{A_0}$$

$$F_0 = F_i \frac{A_0}{A_i}$$



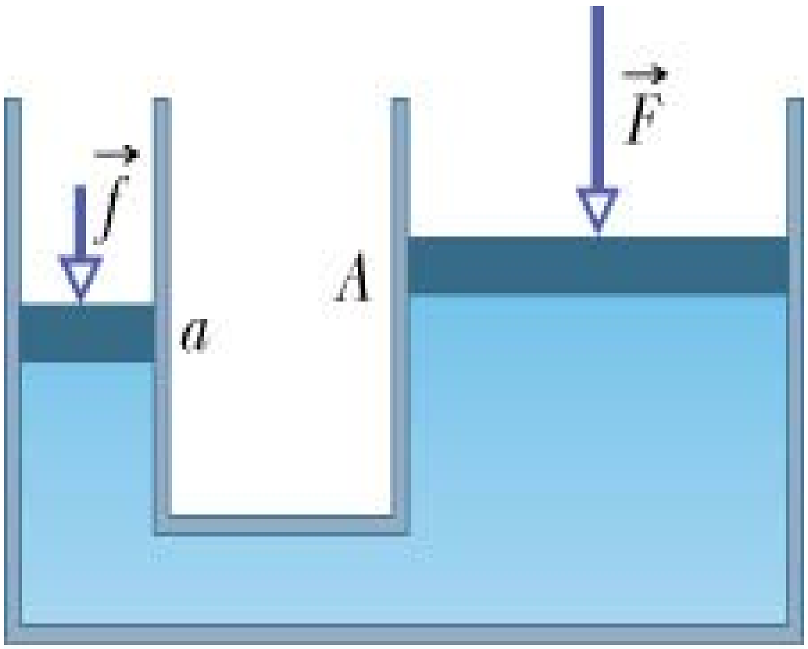
$A_0 > A_i \rightarrow F_0 > F_i$

The output work:

$$W = F_i d_i = F_0 d_0$$

Example (28. Page 381)

A piston of cross-sectional area a is used in a hydraulic press to exert a small force of magnitude f on the enclosed liquid. A connecting pipe leads to a larger piston of cross-sectional area A. (a) What force magnitude F will the larger piston sustain without moving? (b) If the piston diameters are 3.8 cm and 53.0 cm, what force magnitude on the small piston will balance a 20.0 kN force on the large piston.



(a) Applying Pascal's principle:

$$\frac{f}{a} = \frac{F}{A} \;\Rightarrow\; F = \frac{f\,A}{a}$$

(b) We obtain:

$$f = \frac{F\,a}{A}; \qquad f = \frac{F\,\pi\left(\frac{d}{2}\right)^2}{\pi\left(\frac{D}{2}\right)^2} = F\left(\frac{d}{D}\right)^2$$

$$f \approx 103\,(N)$$

➔ f is about 200 smaller than F

C. Archimedes' 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)

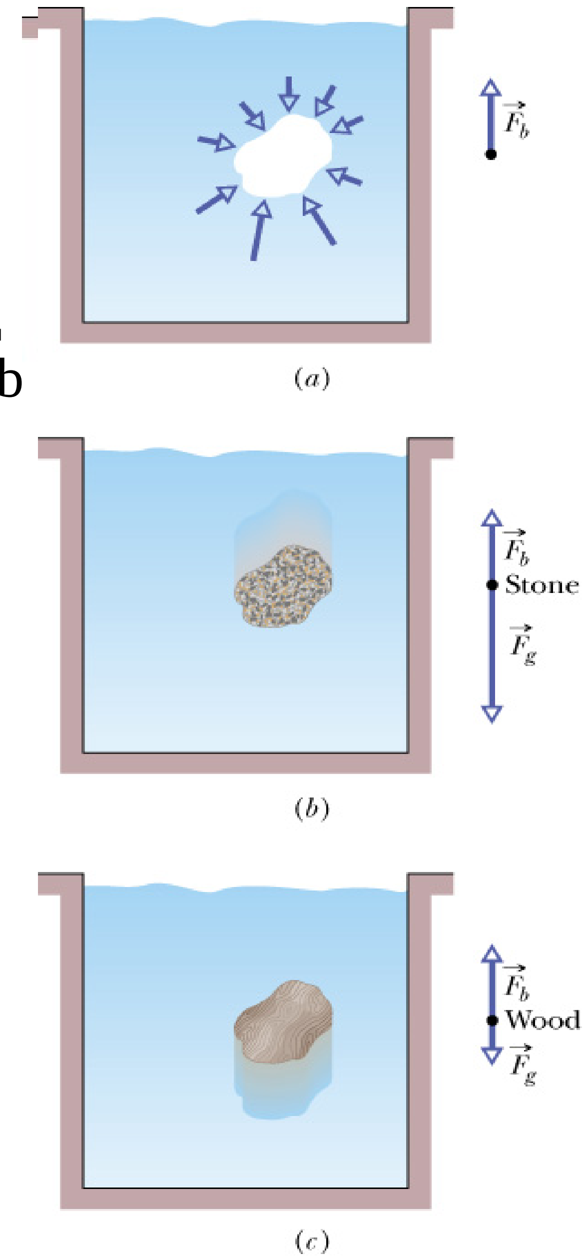
$$F_b = \rho_{fluid}\, g V$$

V: volume of water displaced by the object, if the object is fully submerged in water, $V = V_{object}$

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

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

$$F_b > F_g \ (\text{case c: a lump of wood})$$

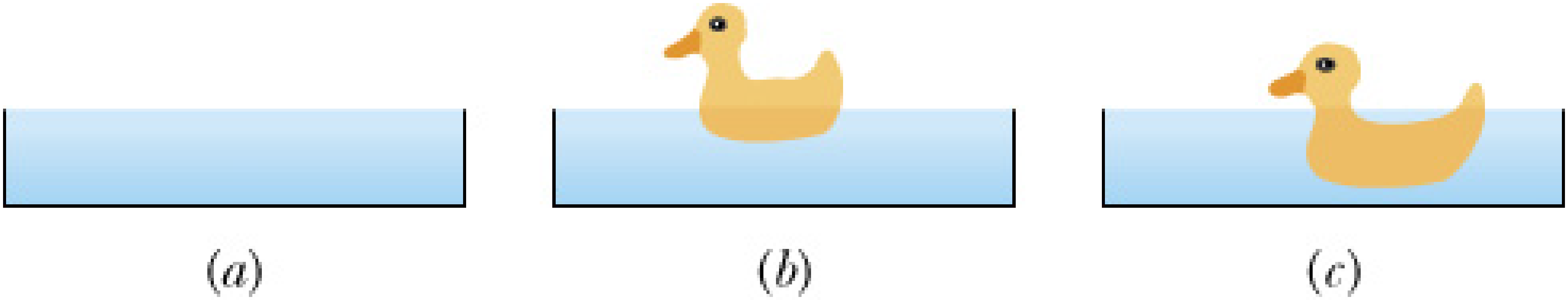


The buoyant force on a submerged object is equal to the weight of the fluid that is displaced by the object.

Apparent weight in a Fluid:

$$weight_{app} = weight_{actual} - F_b$$

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.

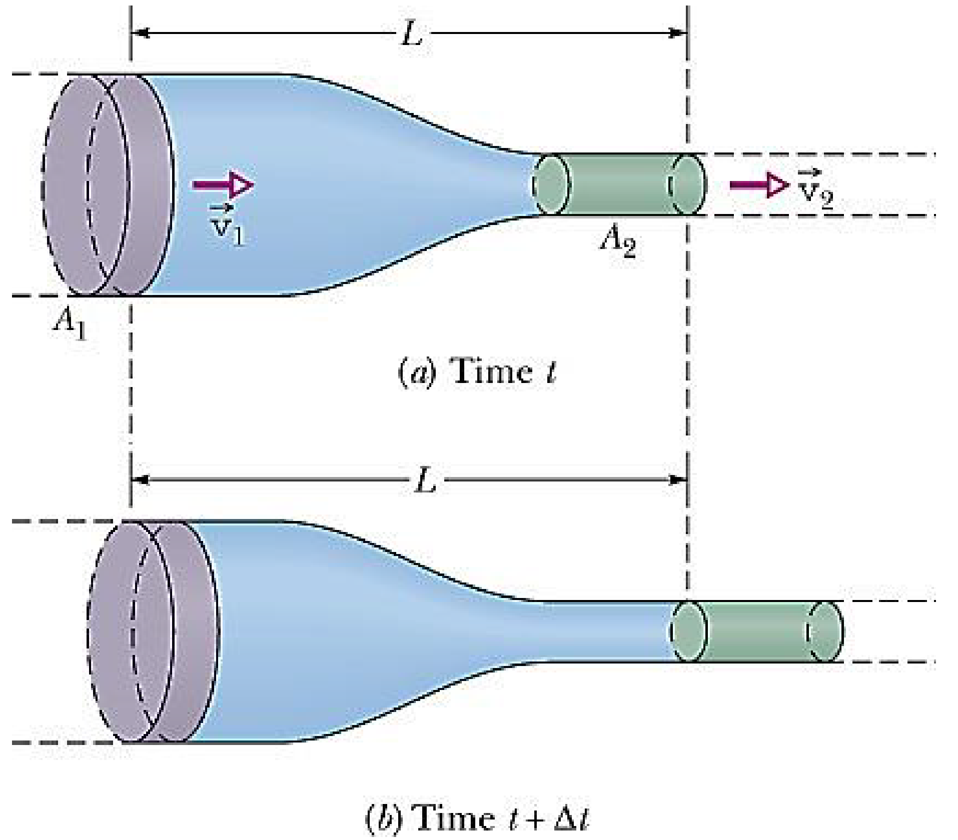
1.2. Ideal Fluids in Motion

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 Δt, a fluid element e moves along the tube a distance:

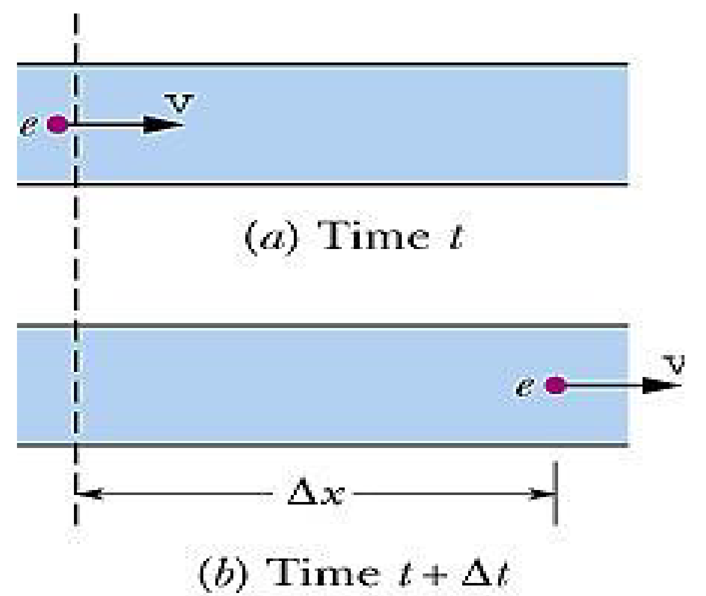
$$\Delta x = v\Delta t$$

Volume: $\Delta V = A\Delta x = Av\Delta t$

$$\Delta V = A_1 v_1 \Delta t = A_2 v_2 \Delta t$$

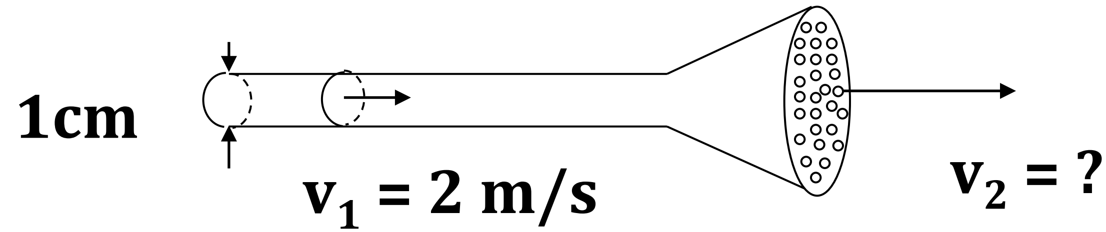
or

$$A_1 v_1 = A_2 v_2$$ (Equation of continuity)



- **Volume flow rate**: $R_V = Av = \text{a constant}$
- **Mass flow rate**: $R_m = \rho R_V = \rho A v = \text{a constant}$

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?



Using the equation of continuity, the speed v_2 is:

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

a_0 is the area of one hole

$$v_2 = \frac{v_1 A_1}{40 a_0} = \frac{2.0 \times \pi \left(\frac{1.0}{2}\right)^2}{40 \times \pi \left(\frac{0.05}{2}\right)^2} = 20 \text{ (m/s)}$$

1.3. Bernoulli's Equation

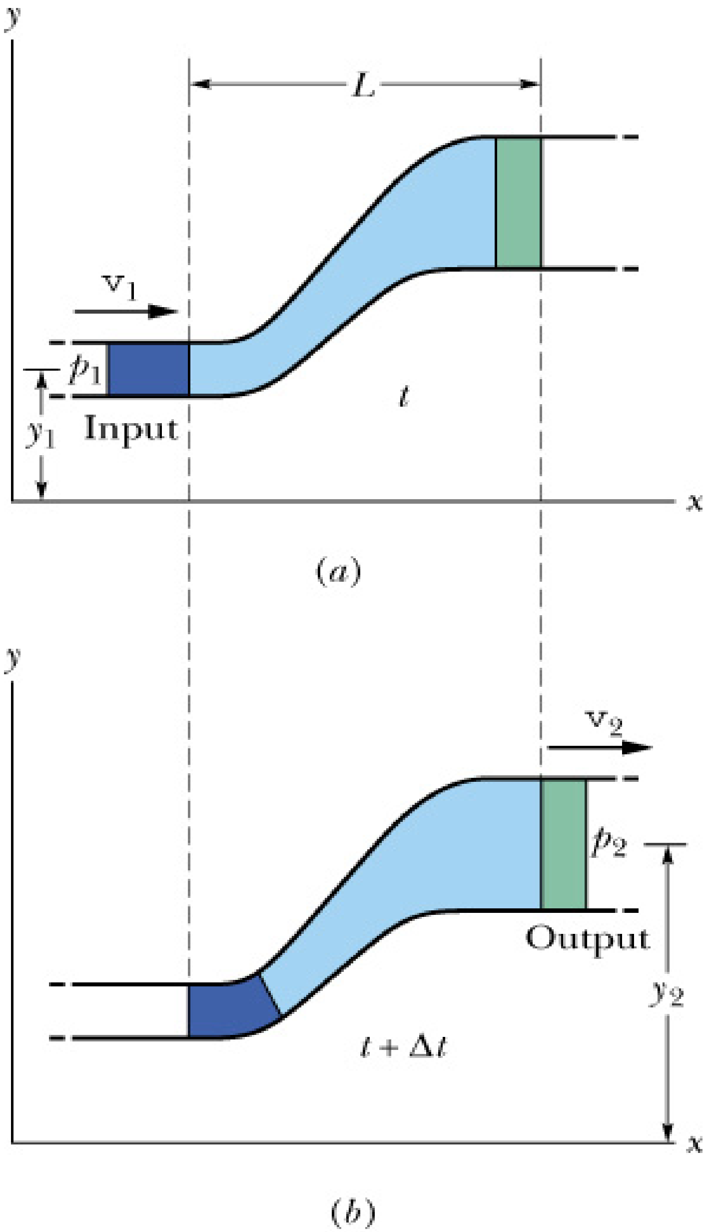
- **An ideal fluid is flowing at a steady rate through a tube.**
- **Applying the principle of conservation of energy (work done=change in kinetic energy):**

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

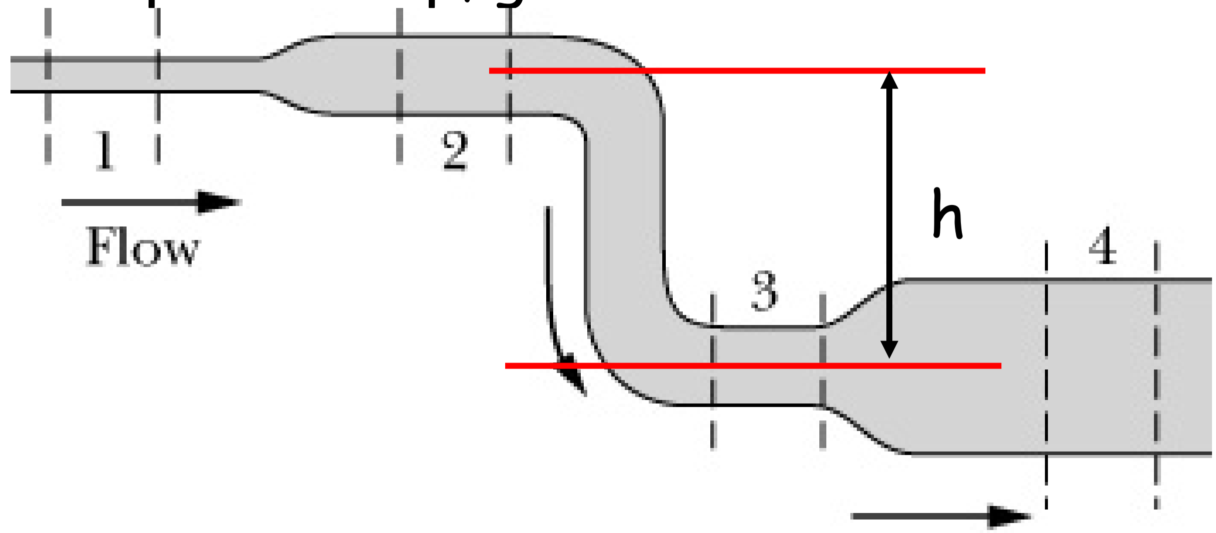
$$p + \frac{1}{2}\rho v^2 + \rho g y = \text{a constant}$$

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

➔As the velocity of a horizontally flowing fluid increases, the pressure exerted by that fluid decreases, and conversely.



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.



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

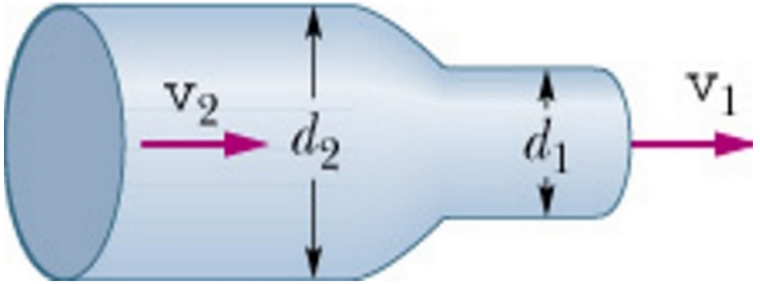
$$p_1 + \frac{1}{2}\rho {v_1}^2 + \rho g h = p_2 + \frac{1}{2}\rho {v_2}^2 + \rho g h = p_3 + \frac{1}{2}\rho {v_3}^2 = p_4 + \frac{1}{2}\rho {v_4}^2$$

(a) All tie; (b) 1, 2, 3, 4; (c) p_4, p_3, p_2, p_1

64. (Page 383)
In the figure below, water flows through a horizontal pipe and then out into the atmosphere at a speed v_1=15 m/s. The diameters of the left and right sections of the pipe are 5.0 cm and 3.0 cm. (a) What volume of water flows into the atmosphere during a 10 min period? (b) In the left section of the pipe, what are (b) the speed v_2 and (c) the gauge pressure?

(a) The volume of water during 10 min is:

$$V = v_1 \times t \times \pi \times \frac{d^2}{4} \approx 6.4\,(m^3)$$



(b) Using the equation of continuity, the speed v_2 is:

$$v_2 = \frac{v_1 A_1}{A_2} = \frac{15 \times 3^2}{5^2} = 5.4\,(m/s)$$

(c) The gauge pressure = the absolute pressure – the atmospheric pressure

Using Bernoulli's equation for a horizontal pipe, we have:

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

$$p_1 = p_0;$$ **where p_0 is the atmospheric pressure**

The gauge pressure of the left section of the pipe is:

$$p_g = p_2 - p_0 = \frac{1}{2}\rho(v_1^2 - v_2^2)$$

$$p_g = \frac{1}{2}10^3 \times (15^2 - 5.4^2) = 0.98 \times 10^5 \text{(Pa)}$$

or

$$p_g = \frac{0.98 \times 10^5}{1.01 \times 10^5} = 0.97 \text{ (atm)}$$

Review (Chapter 1)

density: $\rho = \frac{m}{V}$ **pressure:** $p = \frac{F}{A}$

fluids at rest:

$$p = p_0 + \rho g h$$

absolute pressure → p; atmosphere pressure → p_0; gauge pressure → $\rho g h$

Pascal's law:

$$\frac{F_i}{A_i} = \frac{F_0}{A_0}$$

Archimede's principal: $F_b = \rho_{fluid} g V$: buoyant force

Equation of continuity: $A_1 v_1 = A_2 v_2 = \text{constant}$

Volume flow rate $R_V = Av$ (m^3/s); *Mass flow rate* $R_m = \rho R_V$ (kg/s)

Bernoulli's equation:

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

Homework:

Read "Proof of Bernoulli's Equation"

1, 4, 5, 14, 21, 28, 38, 48, 58, 64, 71

(Page 379- 384) (Chapter 14)