Fundamentals Physics

Eleventh Edition

Halliday

Chapter 14

Fluids

1

14-1 Fluid Density and Pressure (1 of 6)

Learning Objectives

14.01 Distinguish fluids from solids.

14.02 When mass is uniformly distributed, relate density to mass and volume.

14.03 Apply the relationship between hydrostatic pressure, force, and the surface area over which that force acts.

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14-1 Fluid Density and Pressure (2 of 6)

- Physics of fluids is the basis of hydraulic engineering
- A **fluid** is a substance that can flow, like water or air, and conform to a container
- This occurs because fluids cannot sustain a shearing force (tangential to the fluid surface)
- They can however apply a force perpendicular to the fluid surface
- Some materials (pitch) take a long time to conform to a container, but are still fluids
- The essential identifier is that fluids do not have a crystalline structure

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14-1 Fluid Density and Pressure (3 of 6)

- The **density**, ρ, is defined as:

$$\rho = \frac{\Delta m}{\Delta V}.$$ **Equation (14-1)**

- In theory the density at a point is the limit for an infinitesimal volume, but we assume a fluid sample is large relative to atomic dimensions and has uniform density. Then

$$\rho = \frac{m}{V}$$ **Equation (14-2)**

- Density is a scalar quantity
- Units kg/m^3

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14-1 Fluid Density and Pressure (4 of 6)

- The **pressure**, force acting on an area, is defined as:

$$P = \frac{\Delta F}{\Delta A}. \qquad \textbf{Equation (14-3)}$$

- We could take the limit of this for infinitesimal area, but if the force is uniform over a flat area A we write

$$P = \frac{F}{A} \qquad \textbf{Equation (14-4)}$$

- We can measure pressure with a sensor

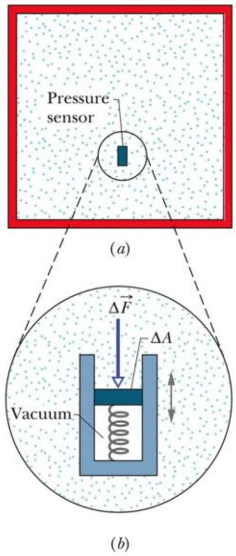

Figure 14-1

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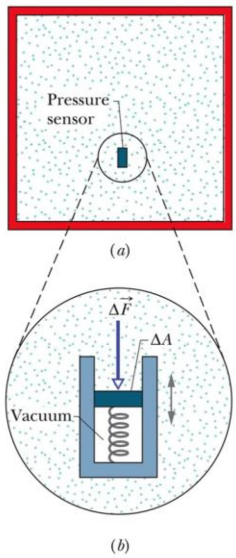
14-1 Fluid Density and Pressure (6 of 6)

- We find by experiment that for a fluid at rest, pressure has the same value at a point regardless of sensor orientation
- Therefore, static pressure is scalar, even though force is not
- Only the magnitude of the force is involved
- Units: the pascal $\left(1\text{ Pa} = 1\text{ N/m}^2\right)$
  the atmosphere (atm)
  the torr (1 torr = 1 mm Hg)
  the pound per square inch (psi)

$$1\text{ atm} = 1.01\times10^5\text{pa} = 760\text{ torr} = 14.7\text{ lb/in.}^2$$



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14-2 Fluids at Rest (1 of 6)

Learning Objectives

14.04 Apply the relationship between the hydrostatic pressure, fluid density, and the height above or below a reference level.

14.05 Distinguish between total pressure (absolute pressure) and gauge pressure.

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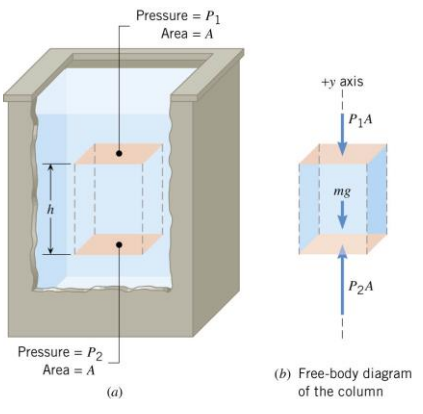
14-2 Fluids at Rest (2 of 6)

- Hydrostatic pressures are those caused by fluids at rest (air in the atmosphere, water in a tank)



$$F_2 = F_1 + mg.$$

$$p_2A = p_1A + \rho Ag(y_1 - y_2)$$

$$P_2 = p_1 + \rho g(y_1 - y_2).$$

- For a depth h below the surface in a liquid this becomes:

$$p = p_0 + \rho gh$$

Equation (14-8)

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14-2 Fluids at Rest (4 of 6)

For a depth h below the surface in a liquid this becomes:

$$p = p_0 + \rho g h$$ **Equation (14-8)**

The pressure at a point in a fluid in static equilibrium depends on the depth of that point but not on any horizontal dimension of the fluid or its container.

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14-2 Fluids at Rest (4 of 6)

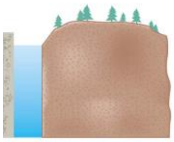
The Hoover Dam

Lake Mead is the largest wholly artificial reservoir in the United States. The water in the reservoir backs up behind the dam for a considerable distance (120 miles).

Suppose that all the water in Lake Mead were removed except a relatively narrow vertical column.

Would the Hoover Same still be needed to contain the water, or could a much less massive structure do the job?


(a)


(b)

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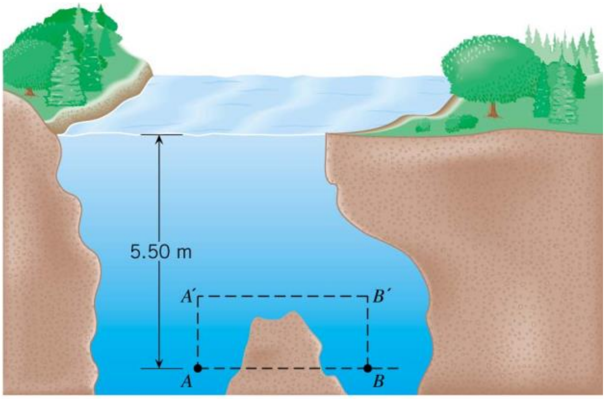
14-2 Fluids at Rest (4 of 6)

The Swimming Hole

Which point, A or B, has a larger pressure?



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14-2 Fluids at Rest (5 of 6)

- The pressure in 14-8 is the absolute pressure
- Consists of p_0, the pressure due to the atmosphere, and the additional pressure from the fluid
- The difference between absolute pressure and atmospheric pressure is called the **gauge pressure** because we use a gauge to measure this pressure difference
- The equation can be turned around to calculate the atmospheric pressure at a given height above ground:

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

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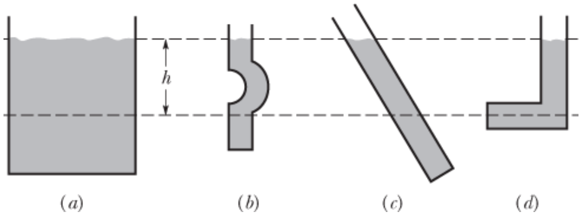
14-2 Fluids at Rest (6 of 6)

Checkpoint 1

The figure shows four containers of olive oil. Rank them according to the pressure at depth *h*, greatest first.



Answer:

All the pressures will be the same. All that matters is the distance *h*, from the surface to the location of interest, and *h* is the same in all cases.

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14-3 Measuring Pressure (1 of 5)

Learning Objectives

14.06 Describe how a barometer can measure atmospheric pressure.

14.07 Describe how an open-tube manometer can measure the gauge pressure of a gas.

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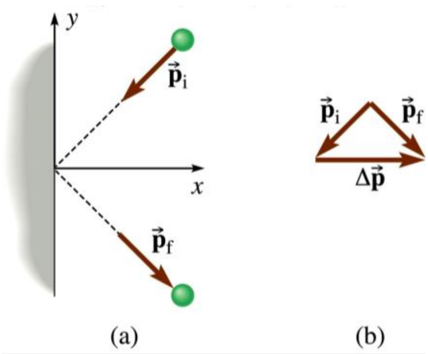
14-3 Measuring Pressure (2 of 5)

Atmospheric Pressure at Sea Level:

$1.013\text{x}10^5$ Pa = 1 atmosphere

- Pressure = Force due to molecules of fluid colliding with container.
  - Impulse = Δp
- Average Pressure = $\frac{F}{A}$



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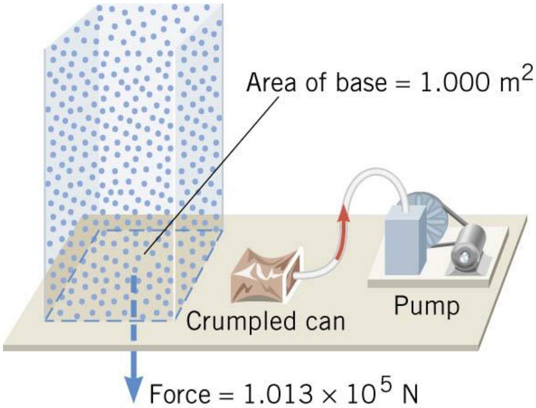
14-3 Measuring Pressure (2 of 5)

Atmospheric Pressure at Sea Level:

$1.013\text{x}10^5$ Pa = 1 atmosphere



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14-3 Measuring Pressure (2 of 5)

- Figure 14-5 shows mercury barometers
- The height difference between the air-mercury interface and the mercury level is *h*:

$$p_0 = \rho g h, \quad \textbf{Equation (14-9)}$$

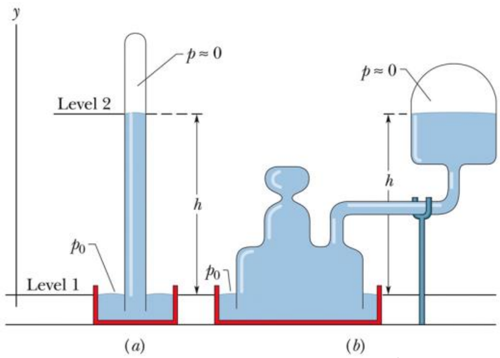

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Figure 14-5

- Only the height matters, not the cross-sectional area
- Height of mercury column is numerically equal to torr pressure only if:
  - Barometer is at a place where g has its standard value
  - Temperature of mercury is 0°C

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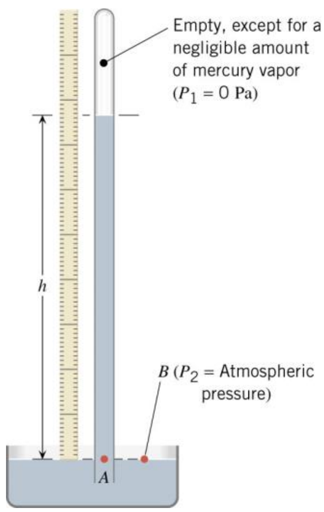
14-3 Measuring Pressure (2 of 5)



$$p_0 = \rho g h,$$

$$p_{atm} = \rho g h$$

$$h = \frac{p_{atm}}{\rho g}$$

$$= \frac{(1.01 \times 10^5 \text{ Pa})}{(13.6 \times 10^3 \text{ kg/m}^3)(9.80 \text{ m/s}^2)}$$

$$= 0.760 \text{ m} = 760 \text{ mm}$$

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14-3 Measuring Pressure (4 of 5)

- The height difference between the two interfaces, *h*, is related to the gauge pressure:

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

Equation (14-10)

- The gauge pressure can be positive or negative, depending on whether the pressure being measured is greater or less than atmospheric pressure

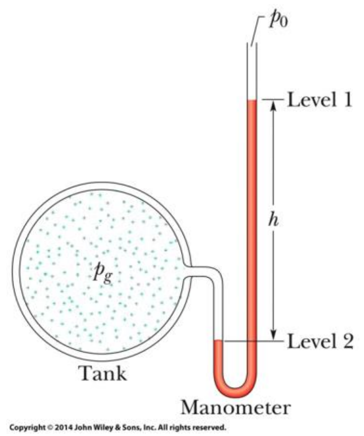

Figure 14-6 shows an open-tube manometer

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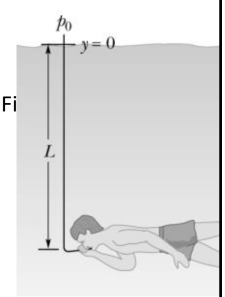
14-3 Measuring Pressure (4 of 5)

Example : the Lung

The human lungs can operate against a pressure differential of up to about 1/20 of an atmosphere. If a diver uses a snorkel for breathing, about how far below water level can he or she swim?



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Pressure inside the lung: p_0 because a snorkel is used

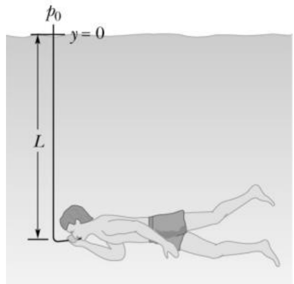
Pressure outside of the lung: $p = p_0 + \rho g h$

Pressure differential: $\Delta p = \rho g h$

$$h_{max} = \frac{\Delta p_{max}}{\rho g} = \frac{(1/20)(1.0\times10^5 \text{ Pa})}{(1.0\times10^3 \text{ kg/m}^3)(9.8 \text{ m/s}^2)}$$

14-3 Measuring Pressure (4 of 5)

Example : the Lung



The human lungs can operate against a pressure differential of up to about 1/20 of an atmosphere. If a diver uses a snorkel for breathing, about how far below water level can he or she swim?

Pressure inside the lung: p_0 because a snorkel is used

Pressure outside of the lung: $p = p_0 + \rho g h$

Pressure differential: $\Delta p = \rho g h$

$$h_{max} = \frac{\Delta p_{max}}{\rho g} = \frac{(1/20)(1.0 \times 10^5 \text{ Pa})}{(1.0 \times 10^3 \text{ kg m}^3)(9.8 \text{ m/s}^2)} = 0.51 \text{ m}$$

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14-4 Pascal's Principle (1 of 6)

Learning Objectives

14.08 Identify Pascal's principle.

14.09 For a hydraulic lift, apply the relationship between the input area and displacement and the output area and displacement.

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14-4 Pascal's Principle (2 of 6)

- **Pascal's principle** governs the transmission of pressure through an **incompressible fluid**:

A change in the pressure applied to an enclosed incompressible fluid is transmitted undiminished to every portion of the fluid and to the walls of its container.

- Consider a cylinder of fluid (Figure 14-7)
- Increase p_{ext}, and p at any point must change

$$\Delta p = \Delta p_{\text{ext}}. \quad \textbf{Equation (14-12)}$$

- Independent of h

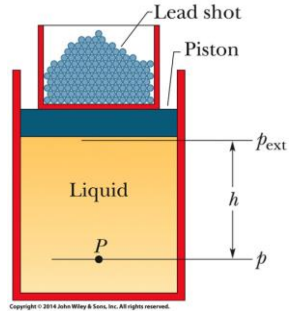

Figure 14-7

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14-4 Pascal's Principle (4 of 6)

- Describes the basis for a hydraulic lever
- Input and output forces related by:

$$F_o = F_i \frac{A_o}{A_i}.$$ **Equation (14-13)**

- The distances of movement are related by:

$$d_o = d_i \frac{A_i}{A_o}.$$ **Equation (14-14)**

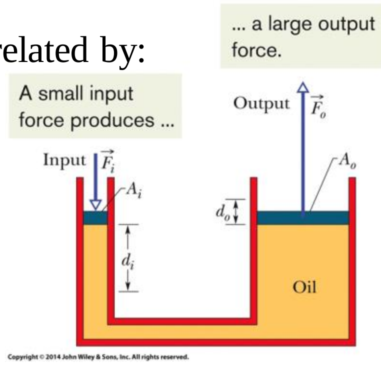

Figure 14-8

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14-4 Pascal's Principle (6 of 6)

- So the work done on the input piston equals the work output

$$W = F_o d_o = \left(F_i \frac{A_o}{A_i}\right)\left(d_i \frac{A_i}{A_o}\right) = F_i d_i,$$ **Equation (14-15)**

- The advantage of the hydraulic lever is that:

With a hydraulic lever, a given force applied over a given distance can be transformed to a greater force applied over a smaller distance.

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14-5 Archimedes' Principle (1 of 7)

Learning Objectives

14.10 Describe Archimedes' principle.

14.11 Apply the relationship between the buoyant force on a body and the mass of the fluid displaced by the body.

14.12 For a floating body, relate the buoyant force to the gravitational force.

14.13 For a floating body, relate the gravitational force to the mass of the fluid displaced by the body.

14.14 Distinguish between apparent weight and actual weight.

14.15 Calculate the apparent weight of a body that is fully or partially submerged.

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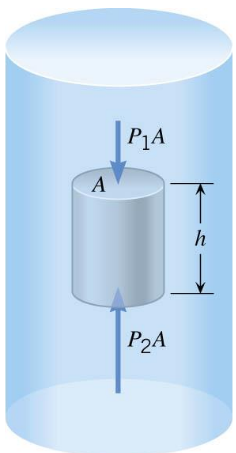
14-5 Archimedes' Principle (2 of 7)

- The **buoyant force** is the net upward force **on** a submerged object **by** the fluid in which it is submerged
- This force opposes the weight of the object.
- It comes from the increase in pressure with depth



$$p_2 - p_1 = \rho g h$$

$$F_B = p_2A - p_1A = (p_2 - p_1)A$$

$$\Downarrow \qquad V = hA$$

$$F_B = \rho g h A$$

$$\Downarrow$$

$$F_B = \underbrace{\rho V}_{\text{mass of displaced fluid}} g$$

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14-5 Archimedes' Principle (3 of 7)

- The stone and piece of wood displace the water that would otherwise occupy that space
- **Archimedes' Principle** states that:

When a body is fully or partially submerged in a fluid, a buoyant force $\vec{F}_b$ surrounding fluid acts on the body. The force is directed upward and has a magnitude equal to the weight $m_f g$ of the fluid that has been displaced by the body.

- The buoyant force has magnitude

$$F_b = m_f g$$ **Equation (14-16)**

- Where m_f is the mass of displaced fluid

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14-5 Archimedes' Principle (4 of 7)

- A block of wood in static equilibrium is floating:

When a body floats in a fluid, the magnitude F_b of the buoyant force on the body is equal to the magnitude F_g of the gravitational force on the body.

- This is expressed:

$$F_b = F_g \quad \text{(floating).}$$ **Equation (14-17)**

- Because of Equation 14-16 we know:

When a body floats in a fluid, the magnitude F_g of the gravitational force on the body is equal to the weight $m_f g$ of the fluid that has been displaced by the body

- Which means:

$$F_g = m_f g \quad \text{(floating).}$$ **Equation (14-18)**

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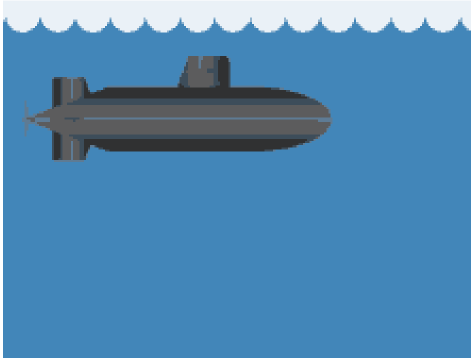
14-5 Archimedes' Principle (5 of 7)



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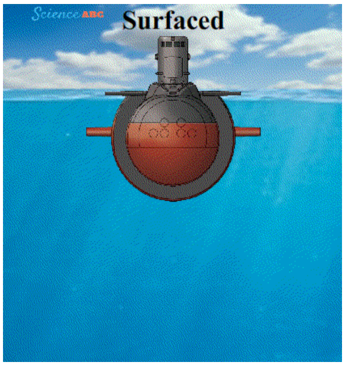

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14-5 Archimedes' Principle (6 of 7)

- The apparent weight of a body in a fluid is related to the actual weight of the body by:

$$(\text{apparent weight}) = (\text{actual weight}) - (\text{buoyant force})$$

- We write this as:

$$\text{weight}_{\text{app}} = \text{weigth} - F_b \quad (\text{apparent weight}).$$

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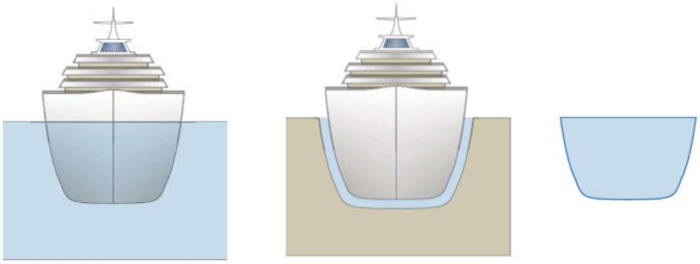
14-5 Archimedes' Principle (6 of 7)

How Much Water is Needed to Float a Ship?

A ship floating in the ocean is a familiar sight. But is all that water really necessary? Can an ocean vessel float in the amount of water than a swimming pool contains?



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14-5 Archimedes' Principle (6 of 7)

Melting Ice Cube

Suppose you float a large ice-cube in a glass of water, and that after you place the ice in the glass the level of the water is at the very brim. When the ice melts, the level of the water in the glass will:

1. Go up, causing the water to spill out of the glass.

2. Go down.

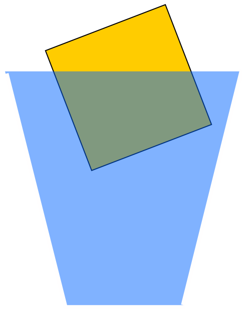
3. Stay the same.

$$B = \rho_w \, g \, V_{displaced}$$

$$W = \rho_{ice} \, g \, V_{ice} \rightarrow \rho_w \, g \, V$$

They are same!

$V_{ice} > V_{displaced}$, but $\rho_{ice} < \rho_w$



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14-5 Archimedes' Principle (6 of 7)

Example : Titanic Disaster

What fraction of volume of an iceberg floating in seawater is visible ? ($\rho_{ice} = 917\ kg/m^3$, $\rho_{sea} = 1024\ kg/m^3$)

Solution:

The fraction of volume of the iceberg that is visible is

$$frac = \frac{V_i - V_w}{V_i} = 1 - \frac{V_w}{V_i}$$

V_i is the total volume of the iceberg

V_w is the volume of the displaced seawater

The iceberg floats in seawater, hence by Archimedes law,

$$m_i g = m_w g \quad \rightarrow \quad \rho_i V_i = \rho_w V_w \quad \rightarrow \quad \frac{V_w}{V_i} = \frac{\rho_i}{\rho_w}$$

Thus, $frac = 1 - \frac{\rho_i}{\rho_w} = 1 - \frac{917}{1024} = 0.1$

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14-5 Archimedes' Principle (7 of 7)

Checkpoint 2

A penguin floats first in a fluid of density ρ_0, then in a fluid of density $0.95\rho_0$, and then in a fluid of density $1.1\rho_0$. (a) Rank the densities according to the magnitude of the buoyant force on the penguin, greatest first. (b) Rank the densities according to the amount of fluid displaced by the penguin, greatest first.

Answer:

(a) all the same

(b) $0.95\rho_0, 1\rho_0, 1.1\rho_0$

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14-6 The Equation of Continuity (1 of 7)

Learning Objectives

14.16 Describe steady flow, incompressible flow, nonviscous flow, and irrotational flow.

14.17 Explain the term streamline.

14.18 Apply the equation of continuity to relate the cross-sectional area and flow speed at one point in a tube to those quantities at a different point.

14.19 Identify and calculate volume flow rate.

14.20 Identify and calculate mass flow rate.

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14-6 The Equation of Continuity (2 of 7)

- Motion of real fluids is complicated and poorly understood (e.g., turbulence)
- We discuss motion of an **ideal fluid**
  1. **Steady flow**: Laminar flow, the velocity of the moving fluid at any fixed point does not change with time
  2. **Incompressible flow**: The ideal fluid density has a constant, uniform value
  3. **Nonviscous flow**: Viscosity is, roughly, resistance to flow, fluid analog of friction. No resistive force here
  4. **Irrotational flow**: May flow in a circle, but a dust grain suspended in the fluid will not rotate about com

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14-6 The Equation of Continuity (3 of 7)

- Visualize fluid flow by adding a tracer
- Each bit of tracer (see figure 14-13) follows a streamline
- A streamline is the path a tiny element of fluid follows
- Velocity is tangent to streamlines, so they can never intersect (then 1 point would experience 2 velocities)

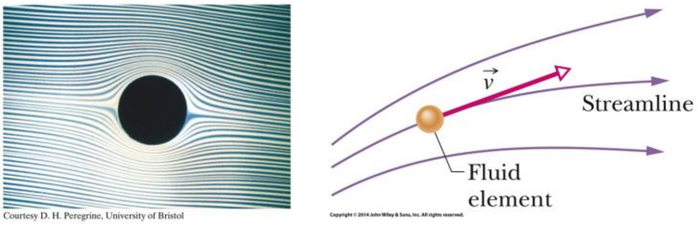

Figure 14-13

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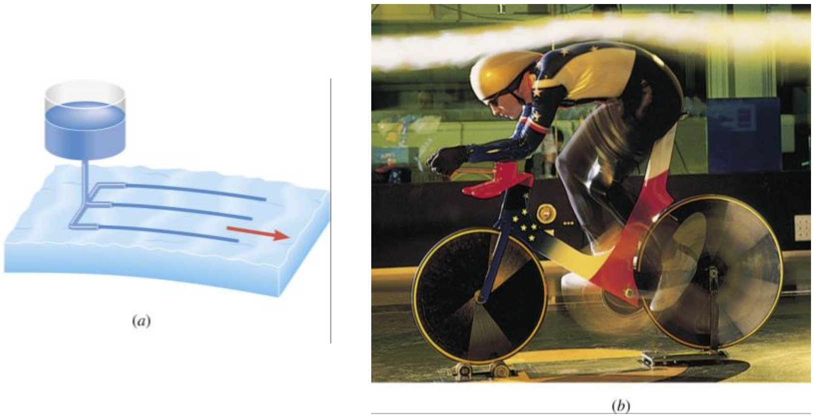
14-6 The Equation of Continuity (3 of 7)

Making streamlines with dye and smoke.



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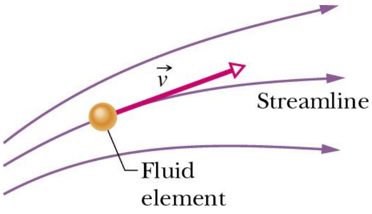
14-6 The Equation of Continuity (3 of 7)

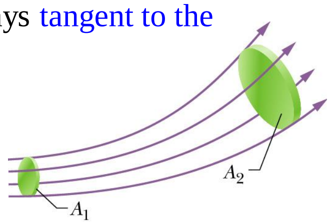
Streamline: a path followed by a particle in the fluid.



The velocity vector of the particle is always tangent to the streamline.

Therefore, streamlines do not cross. No fluid will flow across a streamline.

Streamlines defines a flow tube.



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14-6 The Equation of Continuity (4 of 7)

- Fluid speed depends on cross-sectional area
- Because of incompressibility, the volume flow rate through any cross-section must be constant
- We write the equation of continuity:

$$A_1 v_1 = A_2 v_2$$ **Equation (14-23)**

- Holds for any tube of flow whose boundaries consist of streamlines
- Fluid elements cannot cross streamlines

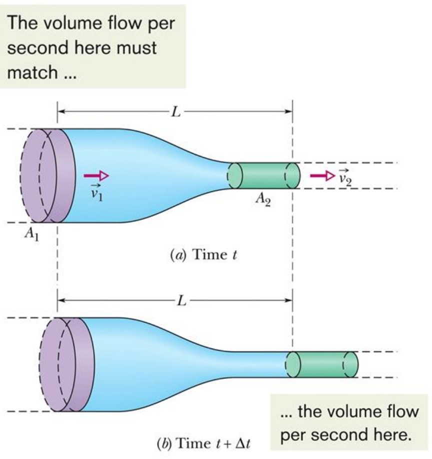

Figure 14-15

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14-6 The Equation of Continuity (6 of 7)

- We can rewrite the equation as:

$$R_V = Av = \text{a constant}$$ **Equation (14-24)**

- Where R_V is the **volume flow rate** of the fluid (volume passing a point per unit time)
- If the fluid density is uniform, we can multiply by the density to get the **mass flow rate**:

$$R_m = \rho R_V = \rho Av = \text{a constant}$$ **Equation (14-25)**

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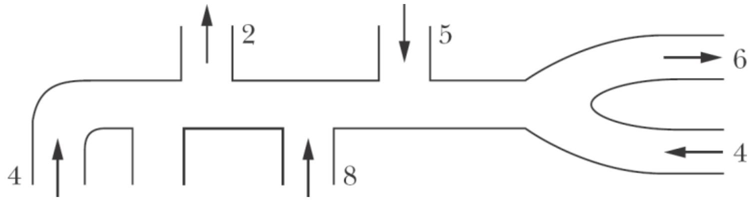
14-6 The Equation of Continuity (7 of 7)

The figure shows a pipe and gives the volume flow rate (in cm^3/s) and the direction of flow for all but one section. What are the volume flow rate and the direction of flow for that section?



Answer:

13, out

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14-7 Bernoulli's Equation (1 of 6)

Learning Objectives

14.21 Calculate the kinetic energy density in terms of a fluid's density and flow speed.

14.22 Identify the fluid pressure as being a type of energy density.

14.23 Calculate the gravitational potential energy density.

14.24 Apply Bernoulli's equation to relate the total energy density at one point on a streamline to the value at another point.

14.25 Identify that Bernoulli's equation is a statement of the conservation of energy.

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14-7 Bernoulli's Equation (2 of 6)

- Figure 14-19 represents a tube through which an ideal fluid flows
- Applying the conservation of energy to the equal volumes of input and output fluid:

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

Equation (14-28)

- The $\frac{1}{2}\rho v^2$ term is called the fluid's **kinetic energy density**

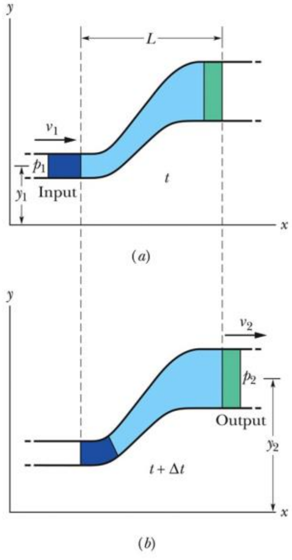

Figure 14-19

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14-7 Bernoulli's Equation (4 of 6)

- Equivalent to Eq. 14-28, we can write:

$$p + \frac{1}{2}\rho v^2 + \rho g y = \text{ a constant} \qquad \textbf{Equation (14-29)}$$

- These are both forms of **Bernoulli's Equation**
- Applying this for a fluid at rest we find Eq. 14-7
- Applying this for flow through a horizontal pipe:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2, \qquad \textbf{Equation (14-30)}$$

- If the speed of a fluid element increases as the element travels along a horizontal streamline, the pressure of the fluid must decrease, and conversely.

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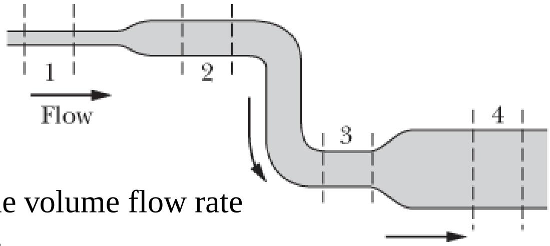
14-7 Bernoulli's Equation (6 of 6)

Checkpoint 4

Water flows smoothly through the pipe shown in the figure, descending in the process. Rank the four numbered sections of pipe according to (a) the volume flow rate R_V through them, (b) the flow speed *v* through them, and (c) the water pressure p within them, greatest first.



Answer:

(a) all the same volume flow rate
(b) 1, 2 & 3, 4
(c) 4, 3, 2, 1

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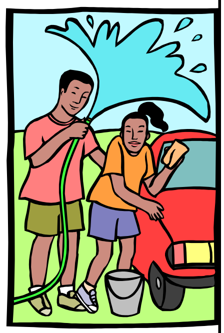
14-7 Bernoulli's Equation (6 of 6)

Garden Hose

A garden hose with inner diameter 2 cm, carries water at 2.0 m/s. To spray your friend, you place your thumb over the nozzle giving an effective opening diameter of 0.5 cm. What is the speed of the water exiting the hose? What is the pressure difference between inside the hose and outside?



Continuity Equation

$$A_1 v_1 = A_2 v_2 \rightarrow v_2 = \left(\frac{A_1}{A_2}\right) v_1 = \left(\frac{r_1^2}{r_2^2}\right) v_1 = (16)\left(2\,\frac{\text{m}}{\text{s}}\right) = 32\,\frac{\text{m}}{\text{s}}$$

Bernoulli Equation

$$P_1 + \rho g y_1 + ½\rho v_1^2 = P_2 + \rho g y_2 + ½\rho v_2^2$$

$$P_1 - P_2 = \frac{1}{2}\rho(v_2^2 - v_1^2) = ½\left(1000\,\frac{\text{kg}}{\text{m}^3}\right)\left(1020\,\frac{\text{m}^2}{\text{s}^2}\right) = 5.1 \times 10^5 \text{ Pa}$$

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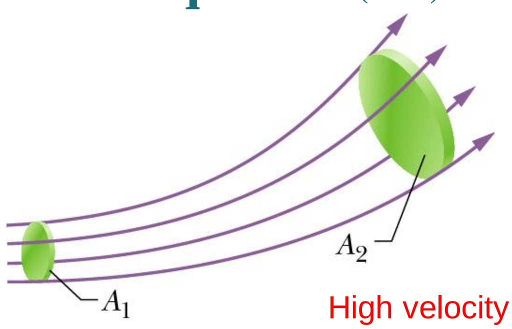
14-7 Bernoulli's Equation (6 of 6)



High density of streamlines (small *A*)

High velocity of fluid (large *v*)

Low pressure of fluid (low p)

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

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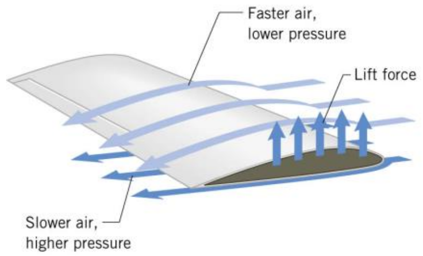
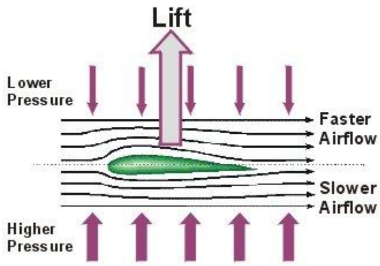
14-7 Bernoulli's Equation (6 of 6)



(*a*)

(*b*)



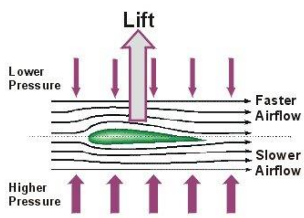
14-7 Bernoulli's Equation (6 of 6)

Lift on a Wing

Air flows over the top of an airplane wing of area A with speed v_t and past the underside of the wing (also of area A) with speed v_u. Show that in this simplified situation Bernoulli's equation predicts that the magnitude L of the upward lift force on the wing will be

$$L = \frac{1}{2}\rho A(v_t^2 - v_u^2),$$

where ρ is the density of the air.



$$p_t + \frac{1}{2}\rho v_t^2 + \rho g h_t = p_u + \frac{1}{2}\rho v_u^2 + \rho g h_u$$

$$L = A\Delta p = A(p_u - p_t) = \frac{1}{2}\rho A(v_t^2 - v_u^2) + \rho g A(h_t - h_u)$$

The thickness of the wing $h_t - hu$ is negligible: $L \approx \frac{1}{2}\rho A(v_t^2 - v_u^2)$

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14-7 Bernoulli's Equation (6 of 6)

Lift on a Wing

If the speed of flow past the lower surface of an airplane wing is 110 m/s, what speed of flow over the upper surface will give a pressure difference of 900 Pa between the upper and lower surfaces? Take the density of air to be $1.30\text{x}10^{-3}$ g/cm^3.

$$A\Delta p = \frac{1}{2}\rho A(v_t^2 - v_u^2)$$

$$v_t = \sqrt{\frac{2\Delta p}{\rho} + v_u^2}$$

$$= \sqrt{\frac{2(900\ \text{Pa})}{1.30\ \text{kg/m}^3} + (110\ \text{m/s})^2} = 116\ \text{m/s}$$

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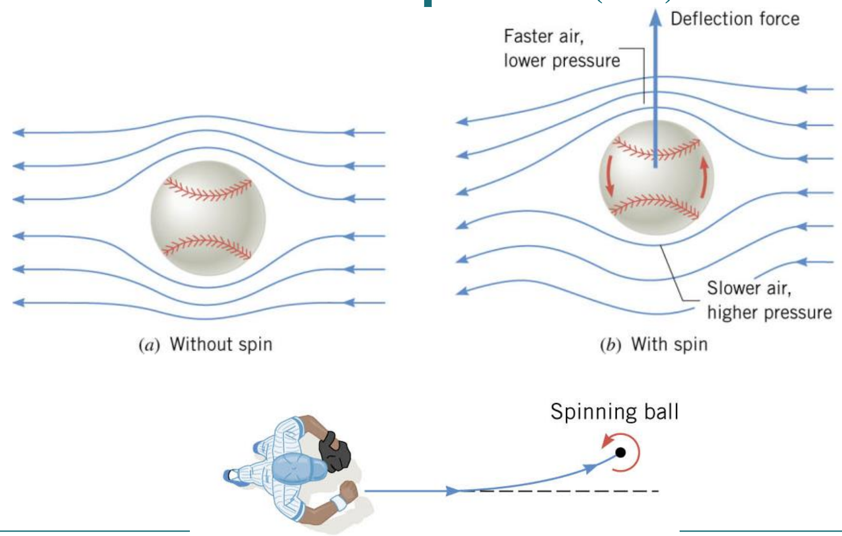
14-7 Bernoulli's Equation (6 of 6)



(a) Without spin

(b) With spin

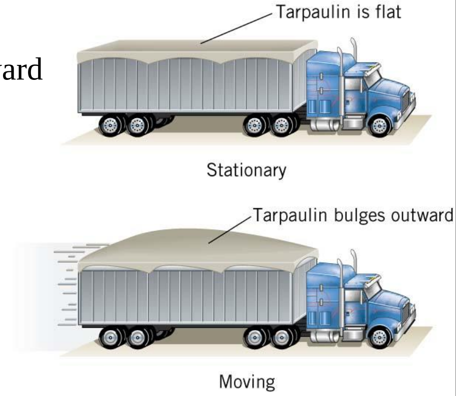
(c)

14-7 Bernoulli's Equation (6 of 6)

Tarpaulins and Bernoulli's Equation

When the truck is stationary, the tarpaulin lies flat, but it bulges outward when the truck is speeding down the highway.

Account for this behavior.



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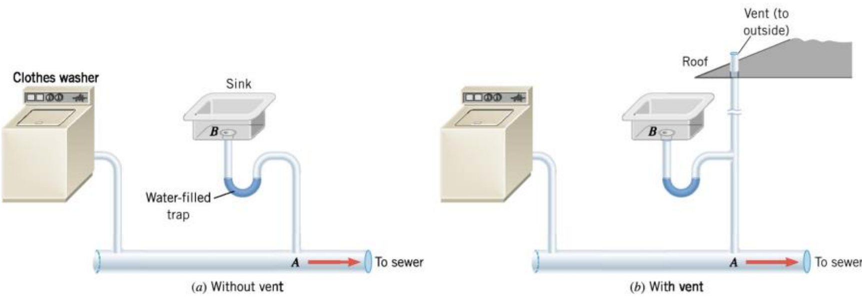
14-7 Bernoulli's Equation (6 of 6)



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Summary (1 of 4)

Density

$$\rho = \frac{m}{V}$$ **Equation (14-2)**

Fluid Pressure

- A substance that can flow
- Can exert a force perpendicular to its surface

$$p = \frac{F}{A}$$ **Equation (14-4)**

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Summary (2 of 4)

Pressure Variation with Height and Depth

$$p = p_0 + \rho g h$$ **Equation (14-8)**

Pascal's Principle

- A change in pressure applied to an enclosed fluid is transmitted undiminished to every portion of the fluid and to the walls of the containing vessel

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Summary (3 of 4)

Archimedes' Principle

$$F_b = m_f g \quad (\text{buoyant force}),$$ **Equation (14-16)**

$$\text{weight}_{\text{app}} = \text{weight} - F_b$$ **Equation (14-19)**

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Summary (4 of 4)

Flow of Ideal Fluids

$$R_V = A_v = \text{a constant}$$ **Equation (14-24)**

$$R_m = \rho R_V = \rho A v = \text{a constant}$$ **Equation (14-25)**

Bernoulli's Equation

$$p + \frac{1}{2}\rho v^2 + \rho g y = \text{a constant}$$ **Equation (14-29)**

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