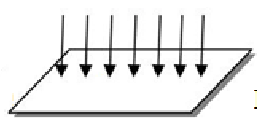
Physics 17 Part H

Fluids and Pressure

Uni-Directional Pressure

The pressure P that is applied over an area is the force F applied, divided by the area.  The effect of the applied force is to create a pressure over the area that acts in one direction only--downward. Such a pressure is one-directional--"*unidirectional*." SI Units of pressure: N/m^2 1 "pascal" (Pa) = 1 N/m^2 Let 1.0 kilopascal (kPa) = 1000 Pa	<u>Example</u>: A 400-N force is applied over a square surface with 20-cm side-length. P = ? $A = (0.20\ m)^2$ $= 0.04\ m^2$ P = F/A $= 400\ N / 0.04\ m^2$ $= 10{,}000\ N/m^2$ = 10,000 Pa =10 kPa

Example A:

A 100-lb (445 N) person wearing stiletto heels, standing on one leg, rocks back onto the heel. The base of the heel is circular, with a radius of 0.20 cm (0.20×10^{-2} m).

What pressure does the heel exert on the floor?

$A = \pi r^2$
$= \pi (0.20 \times 10^{-2}\ m)^2$
$= 1.26 \times 10^{-5}\ m^2$
$P = F/A$
$= 445\ N / (1.26 \times 10^{-5}\ m^2)$
$= 3.54 \times 10^7$ Pa

Heel pressure is unidirectional.

Example B:

The chest of an average human can be punctured or crushed by a unidirectional pressure of about six million pascals.

What would have to be the radius (in cm) of the stiletto heal worn by the 100-lb person in Example A to puncture a chest?

$P = F/A$
$6.0 \times 10^6\ N/m^2 = (445\ N)/(\pi r^2)$
$r = 0.0049$ m
$= 0.49$ cm

Example C:

A lead blanket having an area of 0.40 m^2 and weighing 10 lbs (45 N) is placed on the chest of a patient in the dentist's chair.

What pressure does the chest experience?

$P = 46\ N/0.40\ m^2$
$= 115\ N/m^2$
$= 115$ Pa

Omni-Directional Pressures

"Omni": In all ways or places.

Earth's atmosphere is a roughly 40-mile thick blanket of oxygen, nitrogen, and other gases weighing 5.17×10^{19} N. This blanket of air--whose surface area equals Earth's area--of rests on of Earth, exerting a downward force on it.

R = radius of Earth
$= 6.38 \times 10^6$ m

$A = 4\pi R^2$ (surface area of a sphere)
$= 4\pi (6.38 \times 10^6)^2$
$= 5.12 \times 10^{14}\ m^2$
$P_o = F/A$
$= 5.17 \times 10^{19}\ N / 5.12 \times 10^{14}\ m^2$
$= 101{,}000\ N/m^2$
$= 101{,}000$ Pa
$= 101$ kilo-pascals (kPa)

(The subscript zero indicates that this is atmospheric pressure at zero elevation, i.e., "sea-level.")

Non-Standard Pressure Units:

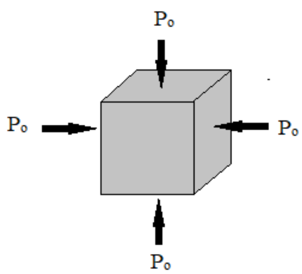
Pounds per Square Inch
1.0 psi = 1.0 lbs/in^2
$P_o = 14.7$ psi

Millibars
1.0 millibar (mb) = 100 Pa
$P_o = 1010$ mb

Atmospheric Pressure is Omni-Directional

The "blanket" model of atmospheric pressure presented above might lead the student to believe falsely that air pressure is "unidirectional," i.e., that atmospheric pressure acts only downward.

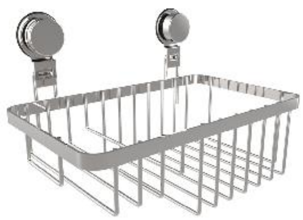
Atmospheric pressure is "*omni*-directional: its effect isn't in one direction only. It applies a 101,000 Pa pressure in *all* directions--downward, upward, rightward, leftward, forward, backward, as suggested in the figure below, where we show an object immersed in the atmosphere experiencing downward, upward, leftward, and rightward air pressure forces.

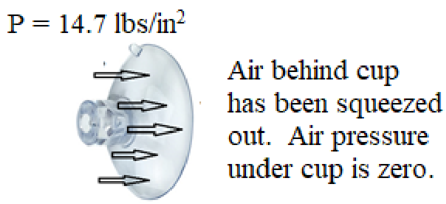


The shower "caddy" example below is an example of atmospheric pressure directed horizontally.

Shower Caddy

"Suction" Cups





The omni-directional atmospheric pressure outside of the cup exerts a force on the cup that's directed toward the wall. There is no air behind the cup and therefore no counteracting air pressure force directed outward. The force that is required to counteract the atmospheric pressure force and remove the cup is calculated at the right.

<u>Example</u>:

Calculate the force in pounds due to atmospheric pressure on one of the shower caddy "suction cups," assuming the cups are circular and the radius of each cup is 0.70 inch.

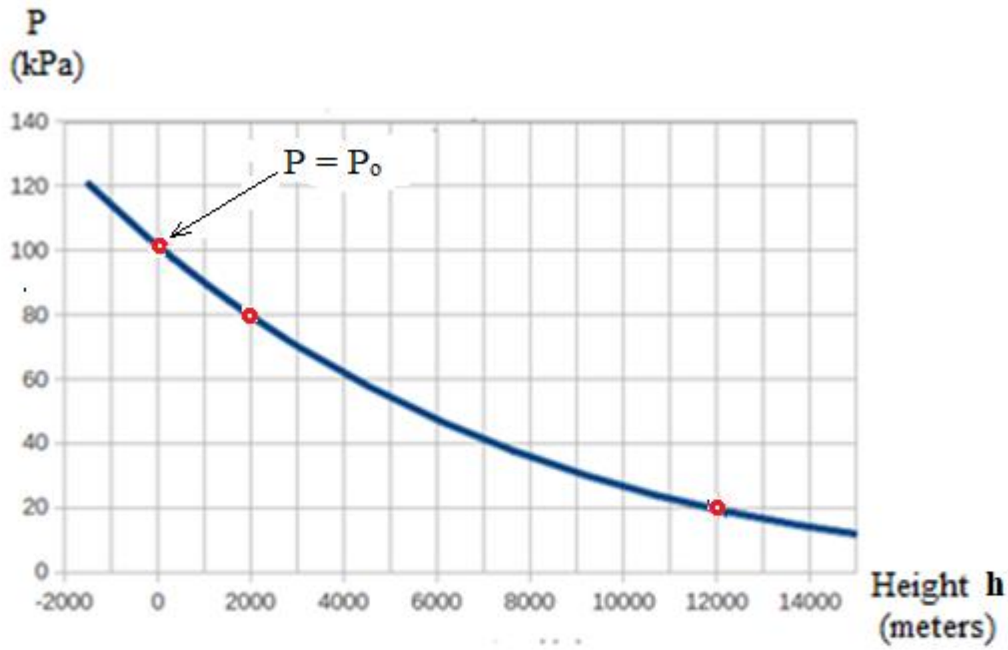
Recall: $P_o = 14.7$ lbs/in^2 (psi)

$F = PA$
$= (14.7 \text{ lbs/in}^2)\ \pi(0.70 \text{ in})^2$
$= 22.6$ lbs

Variation of Atmospheric Pressure with Altitude

Atmospheric pressure in kilopascals (kPa) varies with height (h) in meters above Earth's surface according to the equation below.

$$P = 101\,(1 - 2.3 \times 10^{-5}\,h)^5$$



Notice that pressures at negative elevations (below sea-level) are greater than P_o (101 kPa). Atmospheric pressure in Badwater Basin in Death Valley, where the elevation is negative (-85 m) is 102.6 kPa.

Example A:	Example B:
What is atmospheric pressure 2000 meters above sea-level?	At what altitude is atmospheric pressure 20 kPa?
$P = 101\,(1 - 2.3 \times 10^{-5} \times 2000)^5$ $= 79.8$ kPa	$20 = 101\,(1 - 2.3 \times 10^{-5}\,h)^5$ $h = 12{,}029$ m

Boiling Point versus Pressure

The higher the temperature of water, the faster are surface water molecules are moving. The greater their speed, the more easily will those molecules that happen to be moving toward the surface be able to escape. However, fighting against the possible escaping of the water molecules is the forces associated with atmospheric pressure.

The greater atmospheric pressure is, exerting a downward force on the surface of water, the harder it is for water vapor to escape the water's surface, and therefore the greater must be the temperature of the water before vaporization (boiling) to occur.

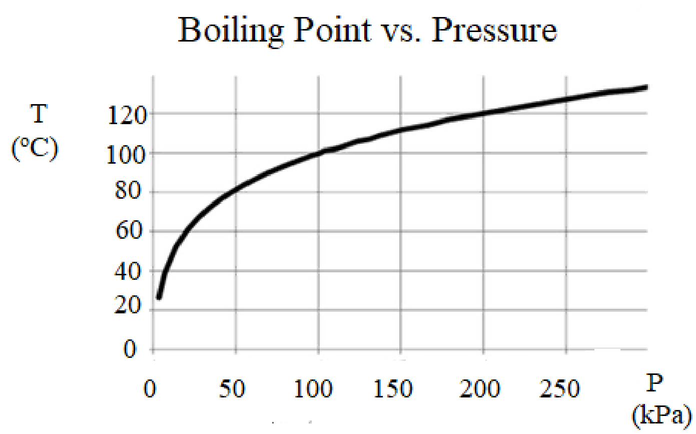
And, vice-versa.

The temperature in degrees Celsius at which water boils, as a function of the atmospheric pressure (in kilo-pascals) is shown at the right.

$$T = 71.6 + (7/25)\,P$$

This equation is accurate only over the range of atmospheric pressures from 50 to 150 kilopascal.

The graph of this equation is shown below.



Note that the higher the temperature, the harder it is to boil water.

Example A :

(a) At what air pressure will the boiling point of water be 90°C?

$90 = 71.6 + (7/25)\,P$
$P = 65.7$ kPa

(b) What altitude is this?

$P = 101\,(1 - 2.3 \times 10^{-5}\,h)^5$
$65.7 = 101\,(1 - 2.3 \times 10^{-5}\,h)^5$
$h = 3583$ m

Absolute Pressure vs Gauge Pressure

Gauge Pressure = $P - P_o$

Pressure gauges measure how much greater than atmospheric pressure is the pressure inside the tire.

Gauge Pressure = $P - P_o$

Example B:

The air pressure P inside an inflated tire is 50.0 psi.

What is the gauge pressure?

Gauge Pressure = $P - P_o$
= 50.0 - 14.7
= 35.3 psi

Example C:

The air pressure inside a slashed tire is 14.7 psi. What is the gauge pressure?

Gauge Pressure = $P - P_o$
= 14.7 - 14.7
= 0 psi

Density

The density of a substance is its mass per volume. The "rule of 1000" explains the values in the table below: The density in standard units (kg/m^3) is 1000 times the density in grams per cubic centimeter (g/cm^3).

$$\rho = m/V$$

Substance	ρ (kg/m^3)	ρ (g/cm^3)
Gold	19,300	19.300
Fresh Water	1,000	1.000
Saltwater	1,029	1.029
Ice	920	0.920
Wood	800	0.800
Air	1	0.001

Example A:

Convert 1 kg/m^3 to g/cm^3

$kg/m^3 = (1000\ g)/(100\ cm)^3$
$= 1/1000\ g/cm^3$

Example B:

Convert 19,300 kg/m^3 to g/cm^3

$19{,}300\ kg/m^3 = 19{,}300\ (1/1000\ g/cm^3)$
$= 19.3\ g/cm^3$

Example B:

What must be the radius of a solid gold sphere for it to have a mass of 238 grams?

Recall: The volume of a sphere is

$V = (4/3)\ \pi r^3$
and
$\rho V = m$

$(19.3\ g/cm^3)\ (4/3)\ \pi r^3 = 238\ g$
$r = 1.4\ cm$

Compare this to the radius of a golf ball: 2.0 cm

Gold sold for $42 per gram on February 28, 2018. How much was this ball of gold worth on that day?

238 g ($42 /g) = $9,996

Example:

A 0.004 m^3 object weighs 60 N. What is its density?

Mass = 60/9.8
= 6.12 kg
Density = 6.12 kg/0.004 m^3
= 1530 kg/m^3

Note the following rule: Objects whose density is greater than the density of water (1000 kg/m^3), sink.

Omni-Directional Water Pressure

In a liquid the omni-directional water pressure at points at a distance h below the surface is calculated using the equation below:

$$P = \rho g h$$

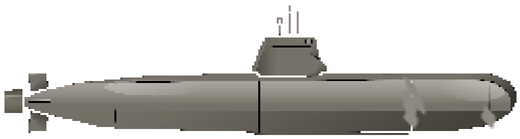
If the liquid is water, then for points at a depth h below the surface

$$P = (1000)(9.8)\,h$$
$$= 9800\,h$$

If the water is at sea-level, and one adds the weight of Earth's atmosphere blanket, then the total fluid (atmosphere + water) pressure under water is

$$P = 101{,}000 + 9800\,h$$

Example:



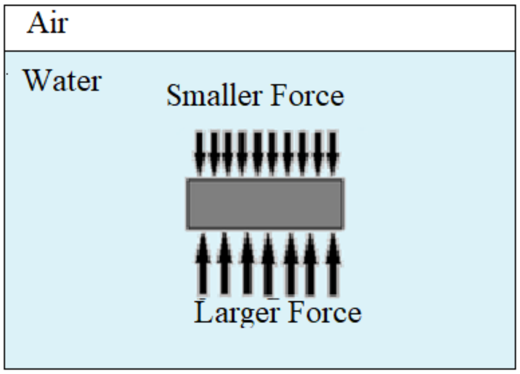
The “crush” pressure for World War II German submarines (“U-boats”) was about 3.0×10^6 Pa. How many meters below the surface of the ocean could these submarines dive?

U-boats occasionally opened their hatches to allow noxious gases to escape, and let fresher air in; as a consequence the air pressure inside is always P_o. When the boat was out of water the internal P_o pressure canceled the outside P_o. When under water, the water pressure is unbalanced:

$$3.0 \times 10^6 = 9800\ h$$
$$h = 306.12\ m$$

Destroyer depth charges could be set to detonate at depths greater than 300 m, so diving didn’t always prevent the submarines from being crushed.

Buoyancy



The underside of the block is at a greater depth h below the water's surface than is the higher upper side, so the water pressure below acting upward is greater than the water pressure above acting downward as the equation, $P = \rho gh$, predicts. The difference between the greater upward force, and the lesser downward force is the buoyant force, B:

B = Upper Water Pressure Force – Downward Water Pressure Force

This equation will never be used to calculate buoyant forces. Instead, we will use the following principle, stated without proof:

Archimedes' Principle

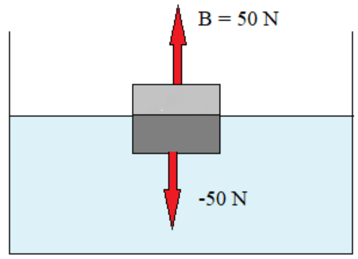
"The buoyant force acting on an object equals the weight of the water it displaces."

V = volume of water displaced (in m^3)
m = mass of water displaced
= (1000 kg/m^3) V
w = weight of water displaced
= mg
= (1000 kg/m^3) V(9.8)
= (9800 N/m^3) V

<u>Example</u>:

An object in water displaces 0.04 cubic meters of water. What buoyant force does the object experience?

$B = (9800 \text{ N/m}^3)(0.04 \text{ m}^3)$
$= 392$ N

Example A:	
An object weighing 50 N is floating in water. What is the buoyant force on the object? Two forces act on the object, its weight mg, and the buoyant force, B. The object is at rest, so its acceleration is zero and the sum of the two forces is zero: The buoyant force on a floating object equals the weight of the object. B - 50 N = 0 B = 50 N	

Example B:

A 0.006-m^3 object weighing 80.0 N is placed in water and it begins to sink. What is its acceleration?

Mass of water displaced = $(1000\ kg/m^3)(0.006\ m^3)$
= 6.0 kg
Weight of water displaced = $(6.0\ kg)(9.8\ m/s^2)$
= 58.8 N
Mass of object = 80.0/9.8
= 8.16 kg

F = ma
58.8 – 80.0 = 8.16 a
a = 2.6 m/s^2

Example A:

A solid cubic block of metal whose side lengths are 0.30 m, is placed in a tank of water and sinks.

What is the buoyant force acting on the cube?

Mass of water = $(1000\ kg/m^3)\ (0.30\ m)^3$
= 300 kg
Weight of water = $(300\ kg)(9.8\ m/s^2)$
= 2940 N
B = 2940 N

Example B:

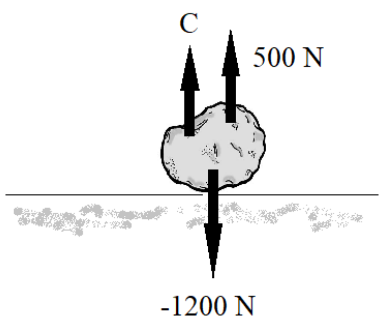
A rock weighing 1200 N is resting at the bottom of a river bed. The buoyant force acting on the rock is 500 N.

What is the contact force between the rock and the river bottom?

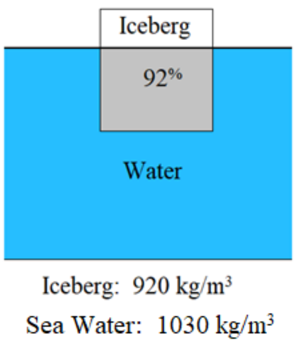
Solution:

The rock, at rest, has zero acceleration, so the net force, by Newton's Second Law, is likewise zero:

F = ma
C - 1200 N + 500 N = 0
C = 700 N



Icebergs



The fraction of a floating object
that is below the water equals
the ratio of the densities.

F = 920/1030
= 0.89

In the case of icebergs, what you see is only 11% of the iceberg—just the tip.

Pascal's Principle

"Pressure added to any part of a completely enclosed fluid is transmitted undiminished to all parts of the fluid."
--*Blaise Pascal*

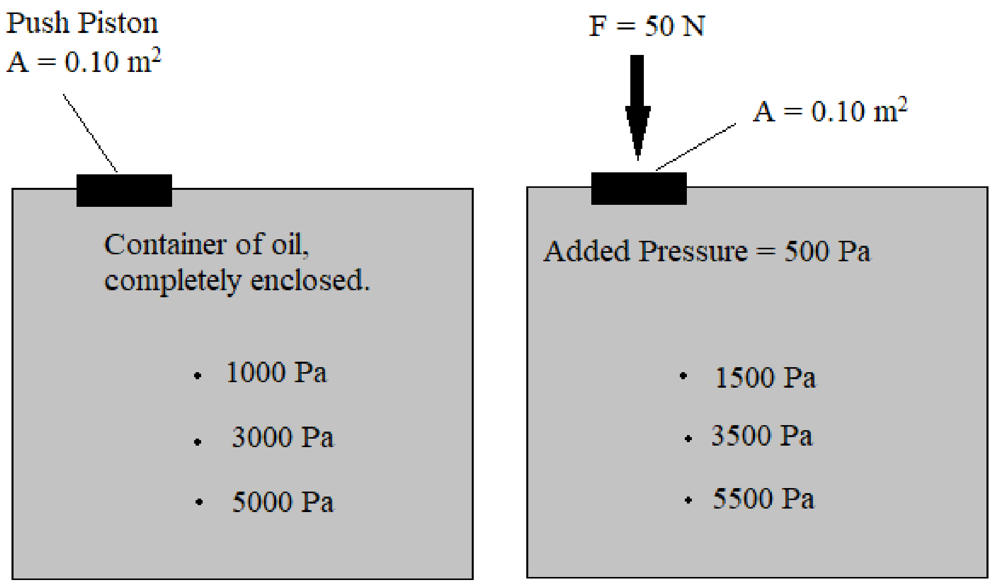
1623-1662
French mathematician, physicist and religious philosopher

In the figures below, pressures at three locations are indicated before and after the application of a 50-N force on the $0.10\ m^2$ "push piston."

The added pressure is

$$F/A = 50\ N/0.10\ m^2$$
$$= 500\ N/m^2$$
$$= 500\ Pa$$

According to Blaise Pascal, this pressure is added to the existing pressure *everywhere*.

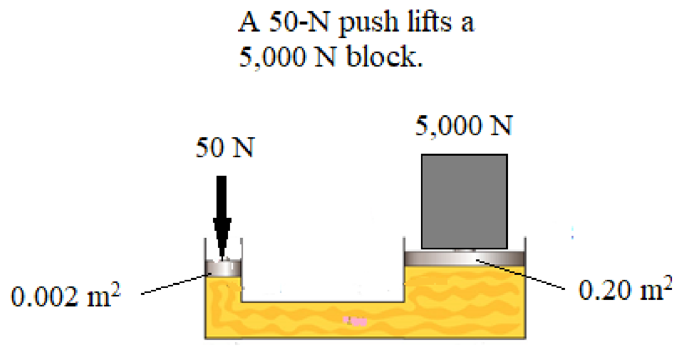


Above: Before Added Pressure

Above: After Added Pressure

Pascal's Principle Application

The Hydraulic Lift

<u>Example</u>: What force F must be applied to the top of the push piston to lift the 5,000-N block? The pressure created under the smaller piston is shown below: $P = 50\ N/0.002\ m^2$ $= 25{,}000\ Pa$ By Pascal's Principle, the pressure created everywhere else in the fluid--including under the larger piston--is likewise 25,000 Pa. The upward force acting from below under the larger piston is calculated below: $F = PA$ $= 25{,}000\ N/m^2\ (0.20\ m^2)$ $= 5{,}000\ N.$	 Figure 2

Blasting Cap with Wires Attached

Robert DeNiro and Edward Norton co-starred in the movie, "The Score," in which a safe-cracker tells his accomplice that the method he plans to use in blowing up the safe is "just simple physics."

It's done like this:

Water passing into the safe through a tiny hole drilled in the top fills the safe, whose interior surface area is 2.4 m^2.

A tiny explosive device ("blasting cap") has a surface are of 2.0 cm^2 (2.0 x 10^{-4} m^2). The cap is connected to detonating wires and lowered through the hole into the safe. Upon detonation, a force 3.0 N acts on the 2.0 x 10^{-4} m^2 of water. The resulting pressure added to all parts of the water is

$3.0 \text{ N} / (2.0 \times 10^{-4} \text{ m}^2) = 1.5 \times 10^4 \text{ N/m}^2$

The interior areas of the safe experience a total outward force equal to this added pressure, times the surface area:

$F = (1.5 \times 10^4 \text{ N/m}^2)(2.4 \text{ m}^2)$
$= 36{,}000 \text{ N}$

This is about 9000 lbs, or 4.5 tons of force.

Volume Flow Rate

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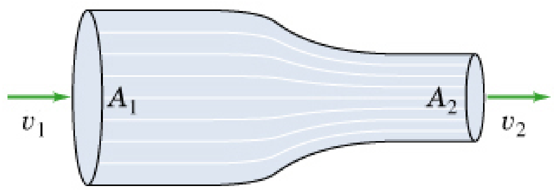
The figure below shows a portion of a pipe through which water is flowing.



Av = Volume Flow Rate
Units: m^3/s

Volume Flow Rate is Conserved:

$A_1v_1 = A_2v_2$

The number of cubic meters of water flowing past any cross-section is the same as the flow rate through any other cross-section.
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<u>Example A</u>:

$A = 0.12\ m^2$
$v = 3.0\ m/s$

After how much time (in seconds) will $100\ m^3$ of water pass through any cross-section?

$R = Av$
$= (0.12\ m^2)(3.0\ m/s)$
$= 0.36\ m^3/s$

$t = 100\ m^3 / 0.36\ m^3/s$
$= 277.78\ s$
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<u>Example B</u>:

$A_1 = 0.04\ m^2$
$v_1 = 2.0\ m/s$
$v_2 = 8.0\ m/s$

$A_2 = ?$

$A_1v_1 = A_2v_2$
$0.04\ (2.0) = A_2\ (8.0)$
$A_2 = 0.01\ m^2$
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Example:

A hose filling a 64 m^3 pool has an inside radius of 4.0 cm. Water exiting the hose has a speed of 2.0 m/s. How long (in hours and minutes) will it take to fill the pool?

$R = Av$
$= \pi(0.04\ m)^2\ (2.0\ m/s)$
$= 0.0101\ m^3/s$

$t = (64\ m^3) / (0.0101\ m^3/s)$
$= 6337\ s$
= One hour and 46 minutes