Fluids

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Oscillations

Fluids

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Introduction to Fluids

Introduction to Fluids

The other units covered within this package are universally found in all Physics courses. It is true that rotational motion may not be covered in a standard level course, but one and two dimensional kinematics, forces, momentum, and energy taken together form the core of any Physics curriculum.

All other topics - electricity, electrostatics, magnetism, waves, optics, and fluids - are topics that use the core ideas noted above applied to a specific set of physical phenomena.

Historically, AP Physics was a single course which was split into AP Physics C and AP Physics B in 1969. AP Physics C was later split in half into AP C Mechanics and AP C E&M in 1973. AP Physics B was still too extensive in content and was eventually split into AP Physics 1 and AP Physics 2 in 2014.

Since the pandemic in 2020, there has been a lot of discussion about what topics, besides the core topics above, should be included in AP Physics 1. Electrostatics, electricity, mechanical waves, and sound were shifted to AP Physics 2 because of the pandemic, and now Fluids has moved from AP Physics 2 into AP Physics 1.

The topics covered within fluids should be familiar as they will involve forces, energy, and momentum. However, as it is an application of the above topics, fluids feels less fundamental. The same could be said of all the topics in AP Physics 2, but fluids is the only one that we will be dealing with in AP Physics 1.

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Introduction to Fluids

Introduction to Fluids

In Physics, both gasses and liquids are considered fluids. For the AP however, it is restricted toliquids. But it is useful and instructive to look at both initially.

Let's take an extra step and look at the different phases of matter: solid, liquid, and gas. Regardless of the phase of H_2O, for example, the only interactions that are involved are the electrostatic interaction between electrons and protons within each atom or molecule and each pair of molecules. At this level, we ignore any interaction with neutrons because they are neutral.

Each electron repels all other electrons within its own molecule and all the electrons in all other molecules. Each proton repels all other protons within its own molecule and all the protons in all other molecules. Each electron attracts all protons within its own molecule as well as all protons in all other molecules. Each proton attracts all electrons within its own molecule as well as all electrons in all other molecules.

For each molecule, this extremely complicated many-body problem is very successfully approximated by molecular and atomic orbital theory that we all learned in Chemistry. That leaves the intermolecular forces based on the valence electrons, and that force depends only on the inter-molecular distance.

What determines the phase of a substance is the kinetic energy of the molecules, which is proportional to the temperature, in comparison to the electrostatic potential energy between neighboring molecules.

Below the melting temperature, the average kinetic energy is too low to overcome the electrostatic potential energy between neighboring molecules, and the molecules remain in place – a solid. Above the boiling point, the average kinetic energy is more than sufficient to overcome the electrostatic potential energy between molecules, and the molecules move essentially ballistically – think ideal gas. Between the two temperatures, the two energies are comparable – the molecules have too much kinetic energy to be held in place, but not enough to escape the attraction completely – a liquid.

This can be easily demonstrated using billiard balls wrapped with Velcro. If rolled fast, they bounce off easily - gas. If slow, totally inelastic collision – solid. If rolled with medium speed, they sometimes stick, sometimes bounce, but sluggishly – liquid.

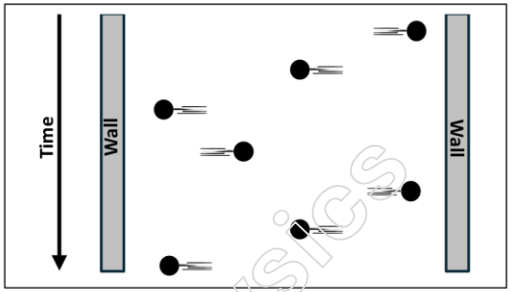
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Force and Pressure

Force and Pressure

To connect pressure within a fluid with the force on the container, let's look at particle of mass m in a box moving in one direction at constant speed. If the collision with the wall is elastic, then for a time interval Δt equal to the time between collisions with the same wall, then $F = \frac{2mv}{\Delta t}$. (If the collision was not elastic, then the particle would be either gaining or loosing kinetic energy with each collision – the temperature would be changing.)



Now if we add a large number of identical particles, then the total force is the sum of the individual forces resulting from each collision. If the distance between the walls is decreased, the time Δt would decrease, and the resulting force on the wall increases from the increased rate of collisions – all assumed to be elastic. If the speed of the particles is increased – an increase in temperature – then the resulting force on the wall increases, again because of an increasing rate of collision with the wall. What is described here is conceptually a one-dimensional ideal gas.

Without modifying the container, we can think of the force on less than the full wall. Given a large enough number of particles, the particles are striking the wall uniformly, so that we can talk about the force per unit area – it will be constant across the face of the wall – which we define to be the pressure. So $\boldsymbol{P = {}^{F}/_{A}}$.

Although simplistic, this analysis captures the essence of the idea. We can imagine relaxing the restriction of one-dimension allowing three dimensions. The collisions, between particles and with the wall, are elastic on average so that the temperature remains constant. The velocities then have a distribution so that v_{rms}^2 is constant and proportional to the temperature.

If we allow for gravitational effects, the density of the particles will be higher near the bottom of the container, increasing the frequency of collision with the wall, and so the pressure will depend on the depth.

Finally, we can increase the density and lower the temperature so that we have a liquid rather the described gas state above. The analysis does not change!

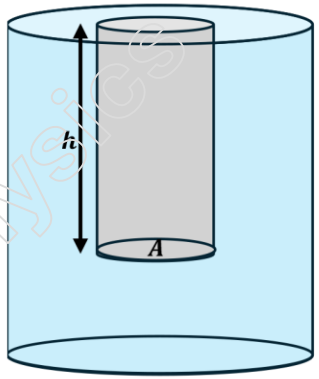
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Force and Pressure

Pressure at Depth – Gauge Pressure

Throughout this unit, we assume that the fluid is ideal – meaning that the fluid has no viscosity (so no frictional losses) and is incompressible resulting in a density that is uniform throughout the fluid volume.

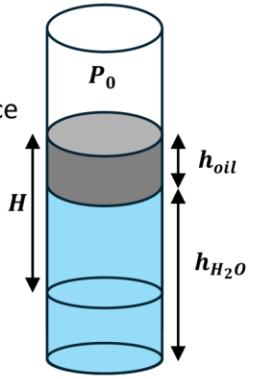


What then is the pressure at a depth h within a volume of ideal fluid? To determine this, consider a cylinder of the fluid that extends from the surface to a depth of h. The force exerted on the bottom surface area A of that cylinder due to the weight of the mass m of the fluid in that cylinder is $mg = (\rho Ah)g$, where ρ is the density of the fluid. The pressure due the fluid above is then $P = {}^{F}/_{A} = \rho gh$.

The absolute pressure at that depth would then be the sum of this ***gauge pressure*** and the pressure from above the fluid, presumable the atmospheric pressure, P_0. So the absolute pressure would then be $P_0 + \rho gh$.

This gauge pressure can be cumulative. Suppose we have a layer of oil having a thickness of h_{oil} that floats on a h_{H_2O} thick layer of water. The absolute pressure at a depth of H below the surface of the oil is

$$\boldsymbol{P_H = P_0 + \rho_{oil} g h_{oil} + \rho_{H_2O} g (H - h_{oil})}$$



The gauge pressure can also be the pressure in a tire, for example, where there is no physical height. In that case, the device has been calibrated so that it could be written in terms of $mm\ of\ Hg$, for instance. The absolute pressure inside the tire would then be the atmospheric pressure plus the measured gauge pressure.

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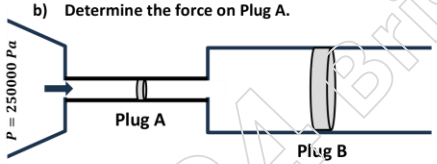
Force-Pressure Four Square

1. Venturi has a mass of $60\ kg$ and his two feet cover a total area of $500\ cm^2$. If Venturi stands on one foot, what is the pressure on the ground under his foot?

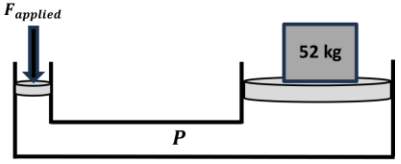
2. A 50 kg woman wears the platform boots shown below. The contact area of the heel is $0.75\ cm^2$ and under the balls of the feet is $38\ cm^2$.Assume that her weight is evenly distributed between the heel and ball area of the boot.
   a) What is the pressure on the floor beneath the heel?
   b) What is the pressure on the floor beneath the balls of the feet?



3. Bernoulli designed a system to pass a fluid from the reservoir at left through a narrow tube having a diameter of 1.2 cm and then through a wider tube having a diameter of 7.2 cm. Each tube has a plug, A and B in the diagram, that seals the tube and measures the force on the plug. The pressure of the fluid in the reservoir is 250000 Pa. Bernoulli measures the force on Plug A, and then opens that plug so the fluid can flow to Plug B.
   a) Determine the force on Plug A.
   b) Determine the force on Plug A.



4. Pascal designed the system below to hold a mass placed on a frictionless plug on the right by applying a force on the frictionless plug on the left. The plugs float on a fluid that has an unknown pressure P. The width of the plug on the right is seven times wider than the plug on the left.
   What applied force $F_{applied}$ is needed to maintain the position of the 52 kg mass placed on the right plug?



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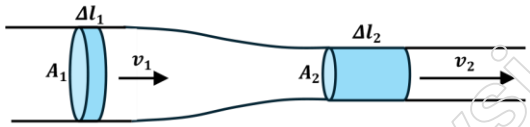
Force
Pressure
Four Square

Student Practice
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Bernoulli Continuity Equations

Bernoulli – Continuity Equation

Let's consider an ideal fluid moving through a frictionless tube from left to right in the figure below. The tube has a cross sectional area that changes. Consider the mass within a cross-sectional volume on the left side, $\rho A_1 \Delta l_1$ moving with speed v_1. As time moves on, that same mass will be contained within the cross-sectional volume on the right side, $\rho A_2 \Delta l_2$, some time Δt later with speed v_2. So $l_1 = v_1 \Delta t$ and $l_2 = v_2 \Delta t$.



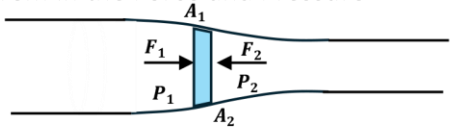
(Because we assume a frictionless tube and a non-viscous constant density fluid, the shape will not be distorted – there is no mechanism that will distort the shape of the mass element. The acceleration of the particles due to the pressure difference on either side of the mass element as it moves through the changing cross-sectional region would simply increase the horizontal speed from left to right.)

Since the volumes are the same, $\rho A_1 v_1 \Delta t = \rho A_2 v_2 \Delta t$, or finally

$$\boldsymbol{A_1 v_1 = A_2 v_2}$$

This is a statement of the conservation of mass as it moves through the tube, sometimes called the **continuity equation** for fluid flow. $\boldsymbol{Av}$ is the **volume flow rate**.

At first glance, the fact the molecules on the right move faster would seem to imply, wrongly, that the pressure on the right side is greater based on the ideas in the Force and Pressure notes earlier in this unit. The question is not the speed, but how the speed changed vis-a-vie the impulse-momentum theorem in the Force and Pressure notes. The speed is not changing in the sections.



Let's look at the constriction region. On the left side the pressure is P_1 and the cross-section area is A_1, resulting in a force on the mass element $F_1 = P_1 A_1$ to the right. On the right side, we have $F_2 = P_2 A_2$ to the left. Since we already know that $v_2 > v_1$, the acceleration of the mass element is to the right. Therefore $F_1 > F_2$ or $P_1 A_1 > P_2 A_2$. Given the continuity equation above, $P_1 A_1 > P_2 A_2 = P_2 A_1 \frac{v_1}{v_2}$. Note that $v_2 = v_1 + a\Delta t$, so that

$P_1 > P_2 \left(\frac{v_1}{v_1 + a\Delta t}\right)$ or $P_1 > P_2 \left(\frac{1}{1+\frac{a\Delta t}{v_1}}\right) = P_2 \left(1 - \frac{a\Delta t}{v_1} + \left(\frac{a\Delta t}{v_1}\right)^2 + \cdots\right)$. For a thin slice, $\Delta t \to 0$, so $P_1 > P_2$. **The pressure decreases as the speed of the fluid increases!**

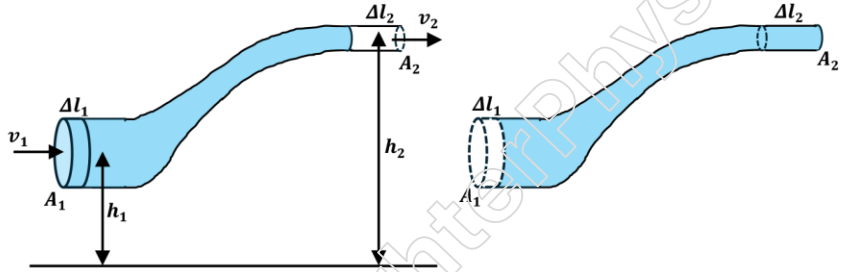
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Bernoulli Continuity Equations

Bernoulli – Continuity Equation

To look at the motion of a mass of fluid for an arbitrary tube shape, we can apply the Work-Energy Theorem, $W_{net} = \Delta KE$. The figure below shows a mass volume of fluid (blue) flowing from left to right. At the left end, the cross-sectional area A_1 is subjected to a force due to the pressure P_1 and the fluid is has a speed v_1 and the center of mass is at a position h_1 above some arbitrary horizontal position of zero. At the right end, the cross-sectional area A_2 is subjected to a force due to the pressure P_2 and the fluid is has a speed v_2 and the center of mass is at a position h_2 above some arbitrary horizontal position of zero. The right side of the figure below is the fluid after flowing for a time Δt.



Because the volume is incompressible, the volume $A_1\Delta l_1 = A_1 v_1 \Delta t$ and $A_2\Delta l_2 = A_2 v_2 \Delta t$, which means $A_1\Delta l_1 = A_2\Delta l_2$ as before.

Assuming a frictionless tube and non-viscous ideal fluid, the only forces acting on the mass element are gravity and the force exerted on both cross-sectional faces of the mass element by the pressure on either end.

The work done by gravity is $W_{gravity} = mg(h_1 - h_2)$.

The center of mass of the middle section does not change. The work done by the pressure is $W_{pressure} = P_1 A_1 \Delta l_1 - P_2 A_2 \Delta l_2$. And finally $\Delta KE = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$. So:

$$\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 = mg(h_1 - h_2) + P_1 A_1 \Delta l_1 - P_2 A_2 \Delta l_2$$

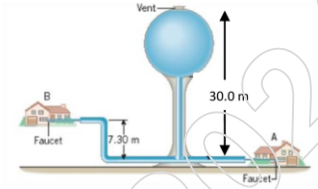
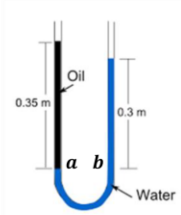
The mass m here is the mass of the left end volume which is equal to the mass of the right end volume. So $m = \rho A_1 \Delta l_1 = \rho A_2 \Delta l_2$. Making this substitution and recognizing that each term has either $A_1\Delta l_1$or $A_2\Delta l_2$ that we can cancel out, we have Bernoulli's Equation:

$$\boldsymbol{P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 = P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1}$$

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Pressure Four Square

1. Torricelli measured the pressure needed to raise a column of water to the height of a tall tree, $46\ m$. What value did he measure?	2. Archimides built a is $28.0\ m$ long, $8.5\ m$ wide, and $1.8\ m$ deep swimming pool. When filled with water, what is the pressure against the *side* of the pool near the bottom.
3. Navier and Stokes build houses near a 30 m tall water tower that supplies water to their houses, as shown in the figure below. The tower has a vent at the top open to the air. When the tower is filled with water, a) what is the gauge pressure at faucet A? b) what is the gauge pressure at faucet B? 	4. Water and then oil are poured into a U-shaped tube by Lord Kelvin. The tube is open at both ends. The fluid comes to equilibrium as shown below. The points a and b lie on the horizontal dashed line that is at the level of the water-oil boundary. What is the density of the oil? 

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Pressure
Four Square

Student Practice
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Bernoulli Four Square

1. Suppose a house with a flat roof is subjected to a hurricane force wind of $180\ km/hr$ which causes the roof to lift off the house. Suppose the roof is $6.2\ m \times 12.4\ m$ in size. Estimate the weight of the roof. (Assume that the roof is not nailed down – it just sits atop the frame of the house.)	2. A very wide 7.4 m tall vented water storage tank has a drain pipe sticking out from the bottom of the tank. What is the speed of the water that comes out of the pipe when opened? 
3. What gauge pressure in the water pipes is necessary if a fire hose is to spray water to a height of $16\ m$?	4. A $6.0\ cm$ diameter horizontal pipe gradually narrows to $4.5\ cm$. When water flows through this pipe at a certain rate, the gauge pressure in these two sections are $33.5\ kPa$ and $22.6\ kPa$ respectively. What is the rate of volume flow through the pipe?

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Bernoulli Four Square

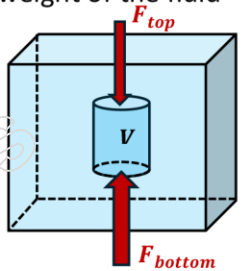
Student Practice Blank

Buoyancy

Archimedes' Principle

Buoyancy

If an object is placed into, or onto, a fluid, there will be an upwards force exerted by the fluid on the object. That so-called buoyant force is equal to the weight of the fluid that is displaced by the object when the object is placed in the fluid.

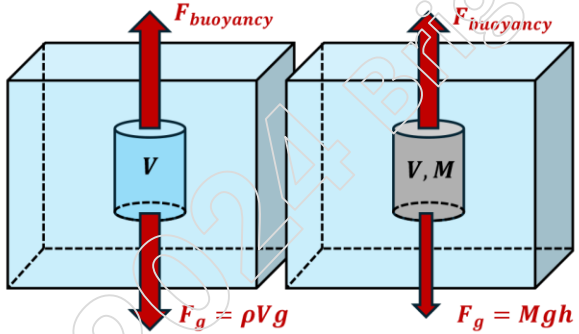


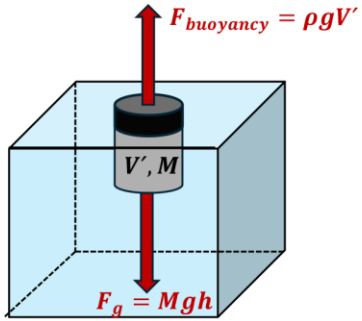
In the figure at right, a large container is filled with an ideal fluid at rest that has density of ρ. The volume V shown is an arbitrary volume V of the fluid – we could image this volume enclosed by an imaginary boundary that separates the inside from the outside fluid.

Since the volume has a vertical size, there is a pressure difference between the top and bottom surfaces of the volume. F_{top} and F_{bottom} is the force exerted by the fluid because of the pressure at the top and bottom surfaces. Not shown is the downward force of gravity on this volume, $F_g = \rho V g$. Since the fluid is stationary, the net force on this volume of fluid is zero:

$$F_{bottom} - F_{top} - \rho V g = 0$$

The buoyancy force is defined to be $F_B = \rho V g$ regardless of the geometry or depth of the volume. For a compressible fluid, where the density depends on the depth, the buoyancy force will depend on the shape and the depth of the volume.





If we replace the volume of fluid with an equal volume of some other material that has a total mass M, as in the figure above left, the buoyancy force will be the same, but the gravitational force will be different. If the new volume has a larger density, then it will accelerate downwards.

If the density is less then the fluid, it will accelerate upwards, break the surface and float as in the figure above right. The volume above the water is black in the figure. The mass of the volume below the water line, gray in the figure. The mass of the water displaced, the volume V', is equal to the mass M of the floating object.

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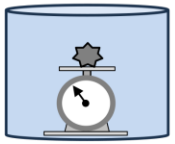
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Archimedes Four Square

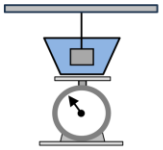
1. A steel marble is dropped into a container of water. What is the acceleration of the marble in the water.
$\rho_{water} = 1.0\ \frac{g}{cm^3}$ $\rho_{steel} = 7.8\ \frac{g}{cm^3}$

2. An underwater buoy is attached to the sea floor $200\ m$ deep by a cable. The tension in the cable is $3500\ N$. When the cable breaks, the buoy floats on the surface so that 25% of its volume is above the surface. What is the mass of the buoy?

3. A $0.45\ kg$ toy is placed on a scale that is submerged in a container of water. The scale reads a weight of $1.25\ N$. What is the average density of the toy?



4. A container of water sits on a scale. The weight of the container + water is $100\ N$. A $50\ N$ object is suspended by a wire to the ceiling and is fully submerged in the water but does not touch the container. The volume of the object is $0.00064\ m^3$. What is the weight according to the scale?



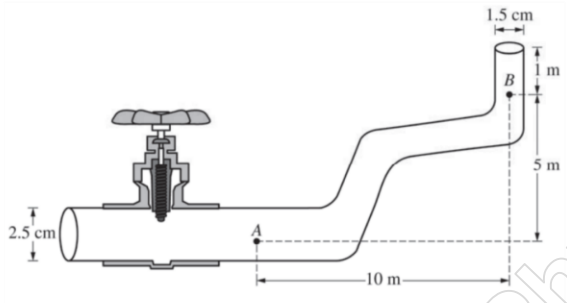
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Archimedes
Four Square

Student Practice
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AP 2017 Fluids



Note: Figure not drawn to scale.

Two students observe water flowing from left to right through the section of pipe shown above, which decreases in diameter and increases in elevation. The pipe ends on the right, where the water exits vertically. At point A the water is known to have a speed of $0.50\ \text{m/s}$ and a pressure of $2.0 \times 10^5\ \text{Pa}$. The density of water is $1000\ \text{kg/m}^3$.

(a) The students disagree about the water pressure and speed at point B. They make the following claims.
Student Y claims that the pressure at point B is greater than that at point A because the water is moving faster at point B.
Student Z claims the speed of the water is less at point B than that at point A because by conservation of energy, some of the water's kinetic energy has been converted to potential energy of the Earth-water system.

i. Indicate any aspects of student Y's claim that are correct.

ii. Indicate any aspects of student Y's claim that are incorrect. Support your answer using appropriate physics principles.

iii. Indicate any aspects of student Z's claim that are correct.

iv. Indicate any aspects of student Z's claim that are incorrect. Support your answer using appropriate physics principles.

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Student Practice
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AP 2017 Fluids

(b) Calculate the following at point *B*.

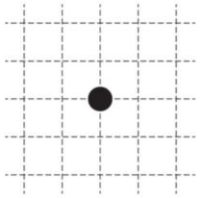
i. The speed of the water

ii. The pressure in the pipe

(c) A valve to the left of point *A* now closes off that end of the pipe. The section of pipe shown is still full of water, but the water is no longer flowing.

i. Calculate the absolute pressure at point *A* (the pressure that includes the effect of the atmosphere).

ii. An air bubble forms at point *A*. On the figure below, where the dot represents the air bubble, draw a free-body diagram showing and labeling the forces (not components) exerted on the bubble. Draw the relative lengths of all vectors to reflect the relative magnitudes of the forces.



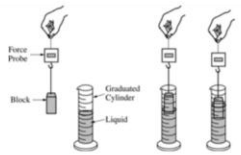
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Fluids
AP Problem
2017
Worksheet
Page 2

Student Practice
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AP 2018 Fluids



Two groups of students are given samples of the same unknown liquid and are asked to identify the liquid. The first group decides to do this by determining its density ρ_L. The students pour a volume V_i of the liquid into a graduated cylinder. They then hang a long solid block of mass m_b from a force probe and lower the block partially into the liquid, as shown above. The students record the reading on the force probe and the volume reading V_f on the graduated cylinder for various amounts of the block lowered into the liquid.

(a)

i. On the square below, which represents the block, draw and label the forces (not components) that are exerted on the block when it is stationary and partially submerged in the liquid. Each force must be represented by a distinct arrow starting on, and pointing away from, the square.

ii. Derive an equation for the force probe reading F_p in terms of ρ_L, m_b, V_i, V_f, and physical constants, as appropriate.

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Fluids
AP Problem
2018
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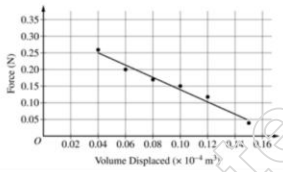
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AP 2018 Fluids

(b)

The data the students collected and the graph they plotted are shown below. The initial volume V_i of liquid in the cylinder is 1.00×10^{-4} m^3.

Volume Reading V_f $\left(\times 10^{-4}\ \text{m}^3\right)$	1.04	1.06	1.08	1.1	1.12	1.15
Volume Displaced ΔV $\left(\times 10^{-4}\ \text{m}^3\right)$	0.04	0.06	0.08	0.10	0.12	0.15
Force Probe Reading (N)	0.26	0.20	0.17	0.15	0.12	0.04



i.

State the physical meaning of the slope of the line and its intercept with the vertical axis.

ii.

Use the graph to calculate the density of the liquid.

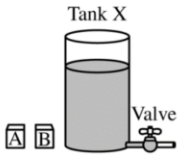
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Note: Figure not drawn to scale.

Figure 1

Tank X is a large cylindrical tank that is partially filled with water, as shown in Figure 1. The bottom of Tank X is connected to a short horizontal pipe. A valve that is initially closed can be opened to allow water to flow through the pipe and exit through the other end of the pipe.

(a) Two blocks, A and B, have identical dimensions and are placed in the tank. Both blocks float at rest and are partially submerged in the water.

i. The water and air can be modeled as consisting of individual particles that are in continuous random motion. In terms of interactions with both water and air particles, explain why there is an upward buoyant force exerted on each block.

ii. The valve is then opened, and water flows out through the pipe. The surface of the water moves downward. When Block A touches the bottom of Tank X, Block B is still above the bottom of Tank X. Which block has a greater density? Briefly explain your reasoning.

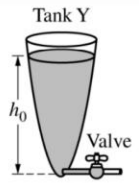
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Note: Figure not drawn to scale.

Figure 2

Tank Y is a large tank with the top open to the air, as shown in Figure 2. The bottom of Tank Y is connected to a short horizontal pipe of radius r with a closed valve. Tank Y is filled with water to height h_0 above the horizontal pipe. Tank Y is specially designed so that when the valve is opened, the surface of the water moves downward at constant speed v_s.

(b) At time $t = 0$, the valve is opened.

i. Derive the relationship between the speed v_p at which water exits the pipe and the changing height h of the surface of the water above the pipe to show that $v_p = \sqrt{v_s^2 + 2gh}$.

ii. Derive the relationship between v_p and the changing radius R of the top surface of the water to show that $v_p = \frac{R^2}{r^2} v_s$.

iii. When the radius R of the tank is sufficiently greater than r, the speed v_p can be approximated as $v_p = \sqrt{2gh}$. Justify this claim.

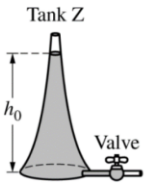
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Note: Figure not drawn to scale.

Figure 3

Tank Z is a large tank whose top is open to the air and is shaped as shown in Figure 3. The bottom of Tank Z is connected to a short horizontal pipe with a closed valve. Tank Z is filled with water to a height h_0 above the horizontal pipe.

At time $t = 0$, the valve of Tank Z is opened.

(c) Does the speed v_s at which the surface of the water moves downward increase, decrease, or remain the same over time as water exits the other end of the pipe? Justify your answer by using or referencing equations from both part (b)(i) and part (b)(ii).

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