Lesson Plan: Viscosity

Background

Viscosity is a property of a substance that describes how "thick" it is and how quickly it flows. For example, cells in the human body consist largely of cytoplasm, a substance that flows very slowly. This property of the cytoplasm indicates that it is very viscous. Viscosity is also a property of other substances and refers to their ability to flow. The viscosity of a given substance can be affected by temperature – higher temperatures usually result in faster flow and lower temperatures in slower flow.

This laboratory demonstrates that **density**, which is mass per unit volume, is related to (but not the same as) **viscosity**, which is resistance to flow. This laboratory will also show that different substances have different viscosities, and that viscosity can change with temperature. One of the substances, molasses, has a viscosity that scientists think is similar to cytoplasm. We also demonstrate how an object moving through a viscous fluid like molasses is opposed by drag forces.

Objectives & Grade Level

Demonstrate the relationship between viscosity and density, viscosity as a property of fluids and the effect of temperature on viscosity, and the viscous or drag forces that oppose movement of an object through the fluid. Appropriate for middle school to advanced high school science classes; see notes for advanced students.

Materials & Equipment

- Water, Vegetable Oil (corn), Molasses or Light Corn Syrup
- Pipettes or Hypodermic syringes (10 *ml*)
- Beakers (50 *ml*, 80 *ml*, 200 *ml*)
- Small spoon (~2-3 *cm* bowl diameter)
- Pipetman (1,000 μl) with tips, Stopwatch, Top-pan Balance, Thermometer

Procedure

1. Density refers to how heavy a substance is. Because substances can vary greatly in size and shape, density is given as mass per volume, so that different substances can be compared with one another. You can measure the density in *g/ml* of water, vegetable oil and molasses by weighing 1 *ml* of each into a container and recording the weights.

Remember to subtract the weight of the container. Are the densities of vegetable oil and molasses the same, less than, or greater than the density of water? Which of the three has the lowest density? Which has the highest density?

2. While you were measuring the densities of the three fluids, you probably noticed that they differed in how quickly they flow. This property is known as viscosity.

Which of the three flows the most quickly? This fluid is the least viscous of the three. The one that flows the slowest is the most viscous. Is the most viscous fluid also the one with the highest density? What about the least viscous fluid – is it the one with the lowest density?

3. Warm the water, vegetable oil and molasses in a container of hot water from a faucet for 5-10 minutes, then repeat your density measurements by weighing 1 *ml* of each into a container and recording the weights. Make sure each fluid is warm when you measure it this time.

Do the warm fluids differ in density from the fluids at room temperature? What about their viscosity – was it easier or more difficult to measure the warm fluids or those at room temperature? Which one showed the greatest difference? What do you think the effect of temperature on density is? What about the effect of temperature on viscosity?

4. You can use a method similar to the U-tube or Ostwald Viscometer (Amrita Vlab, 2010) to determine the viscosity of the fluids by measuring the time in seconds required for 1 *ml* of water, vegetable oil or molasses to fall from a pipette (or hypodermic syringe) into a container. Note that water will fall very fast, so try recording it with a cell phone and including a timer in the movie – this may be the easiest way of determining the time (**Figure 1**). Be sure to write down the time required for each fluid.

Which of the three fluids took the longest time? This is the most viscous of the three. Is it also the densest of the three fluids? Did the fluid that took the shortest time to flow also have the lowest density?

5. Advanced students can calculate the viscosity of vegetable oil or molasses relative to water from the flow times, the densities determined above, and the following equation:

$$\eta / \eta_w = \rho\, t / \rho_w\, t_w$$

where

- η is the relative viscosity of vegetable oil or molasses
- η_w is the viscosity of water = 1 *mPa·s* (*milli-Pascal·seconds*) at room temperature (20°*C*)
- ρ is the density of vegetable oil or molasses
- t is the time required for 1 *ml* of vegetable oil or molasses to fall from the pipette (or hypodermic syringe)
- ρ_w is the density of water = 1 *g/ml* at 20°*C*
- t_w is the time required for 1 *ml* of water to fall from the pipette or hypodermic syringe

Are the viscosities of vegetable oil and molasses the same, less than, or greater than the viscosity of water? If the viscosities differ from water, approximately how many times less than or greater than water are they? Note that your viscosity values for vegetable oil and molasses may differ from those in the table below because of experimental errors that can occur. As long as your values are in the same order from lowest to highest viscosity, they will correctly reflect the viscosities measured using a viscometer.

How is density of a substance related to its viscosity? This may be difficult to answer knowing only the densities and viscosities of vegetable oil and molasses compared to water – see ***Note 1*** *below.*

6. Warm the vegetable oil and molasses in a container of hot water to ~40°*C* and repeat the flow assays. Record the times.

Are the flow times longer, short or the same as for the fluids at room temperature? What do you think that the effect of temperature is on the viscosity of the fluids?

7. Advanced students can determine the viscosity of the warm vegetable oil and molasses relative to water at room temperature, as in **step 5** above.

Is the viscosity of warm vegetable oil or molasses the same, less than, or greater than its viscosity at room temperature?

8. Viscous forces can be demonstrated by the following example, modified from (Howard, 2001). Pour 40 *ml* of molasses (or light corn syrup) into a 50 *ml* beaker, 80 *ml* into a 100 *ml* beaker, and 200 *ml* into a 250 *ml* beaker. Weigh the beakers and record the weights (total weight with molasses). Insert a small spoon with a bowl diameter of ~2-3 *cm* into the molasses in the smallest beaker. Then, holding onto the handle of the spoon, quickly pick up the beaker with the spoon (**Figure 2**). Try the same with the other two beakers – you should be able to pick up one but not the other. Determine the largest amount of molasses that you can pick up with the spoon by adding molasses to one of the beakers and trying again. Important: when doing this last step, try your best to pull at the same velocity each time!

Does picking up the beaker with the spoon faster change the amount of molasses that you can pick up in the beaker?

After you determine the largest amount you can pick up with the spoon, weigh the beaker without the spoon in *grams*, convert to *kilograms* by multiplying by 10^{-3}, and multiply by 10 to obtain the approximate force due to gravity in *Newtons* (*N*) (see **Note 4**). This value is approximately equal to the viscous or drag force of molasses on the spoon at the (hopefully) consistent velocity with which you picked up the spoon (Howard, 2001). *Example republished with permission from Sinauer Associates, Inc.*

Now, with the largest amount, try to pull the spoon up at a faster velocity.

What happens? Does picking up the beaker with the spoon faster change the amount of molasses that you can pick up in the beaker?

What do you think will happen if you were to try this experiment with vegetable oil? Do you think the viscous or drag force of vegetable oil is greater or less than that of molasses? (Hint: the viscous or drag force of a substance is directly dependent on its viscosity – see ***Note 4****.)*

Notes

1. Density and viscosity of a given substance are not always correlated. The density of vegetable oil is less than water, but vegetable oil is more viscous than water. The density and viscosity of water, vegetable oil and molasses are given in the table below; light corn syrup is shown for comparison:

	Density at 20°*C*	Viscosity at 20°*C*
Water	1 *g/ml*	1 *mPa·s*
Vegetable oil (corn)	0.92 *g/ml*	65 *mPa·s*
Molasses	1.41 *g/ml*	5000-10000 *mPa·s*
Light corn syrup (20 *g* sugar/30 *ml*)	~1.34 *g/ml*	2000-3000 *mPa·s*

2. Increasing the temperature should have little effect on density, but warmer temperatures usually reduce viscosity causing fluids to flow faster.

3. **Advanced topic 1**: the **Reynolds number**, *Re*, is the ratio between inertial forces and viscous forces experienced by an object moving in a viscous fluid. It is given by

$$Re=\rho L\upsilon/\eta$$

where

- ρ is the density of the liquid
- L is the object length in the direction of movement
- υ is the speed of the object
- η is the viscosity of the fluid

By moving the spoon in the beaker of molasses or oil at a given speed (e.g., 0.5 *m/s*), you can calculate the Reynolds number of the spoon (Howard, 2001). Low Reynolds numbers (<1) are expected for small objects moving in a viscous fluid. The Reynolds number increases as the viscosity of the fluid decreases; it is also larger for large objects compared to small objects moving in a fluid of the same viscosity. The table shows the Reynolds numbers for different-sized objects moving in water:

	Object Size	Object Speed	Fluid Density (kg/m^3)	Fluid Viscosity (*Pa·s*)	Reynolds Number
Ocean liner	100 *m*	30 *m/s*	1000	10^{-3}	3×10^9
Human swimming	2 *m*	1 *m/s*	1000	10^{-3}	2×10^6
Bacterium in H_2O	2 μm	25 $\mu m/s$	1000	10^{-3}	5×10^{-5}

Data from (Howard, 2001). Republished with permission from Sinauer Associates, Inc.

4. **Advanced topic 2**: at low Reynolds number, the forces resisting forward motion of a spherical object in a viscous fluid, or drag force, F_d, is given by **Stokes' law**:

$$F_d = -6\pi\eta r\upsilon$$

where

- η is the viscosity of the fluid
- r is the radius of the sphere
- υ is the speed of the object

The drag force required to pull a sphere (spoon of a given radius) out of a small container of a viscous fluid such as molasses is the sum of the viscous forces of molasses on the spoon, estimated experimentally by converting the maximal weight lifted by the spoon at a given speed to force (Howard, 2001). From this experiment you can calculate the viscosity of a fluid from

$$F_d(v) = F_{g,max}$$

where

- $F_d\,(\upsilon)$ is the force at velocity υ
- $F_{g,max}$ is the force due to gravity = mass x 9.81 m/s^2 (acceleration due to gravity)

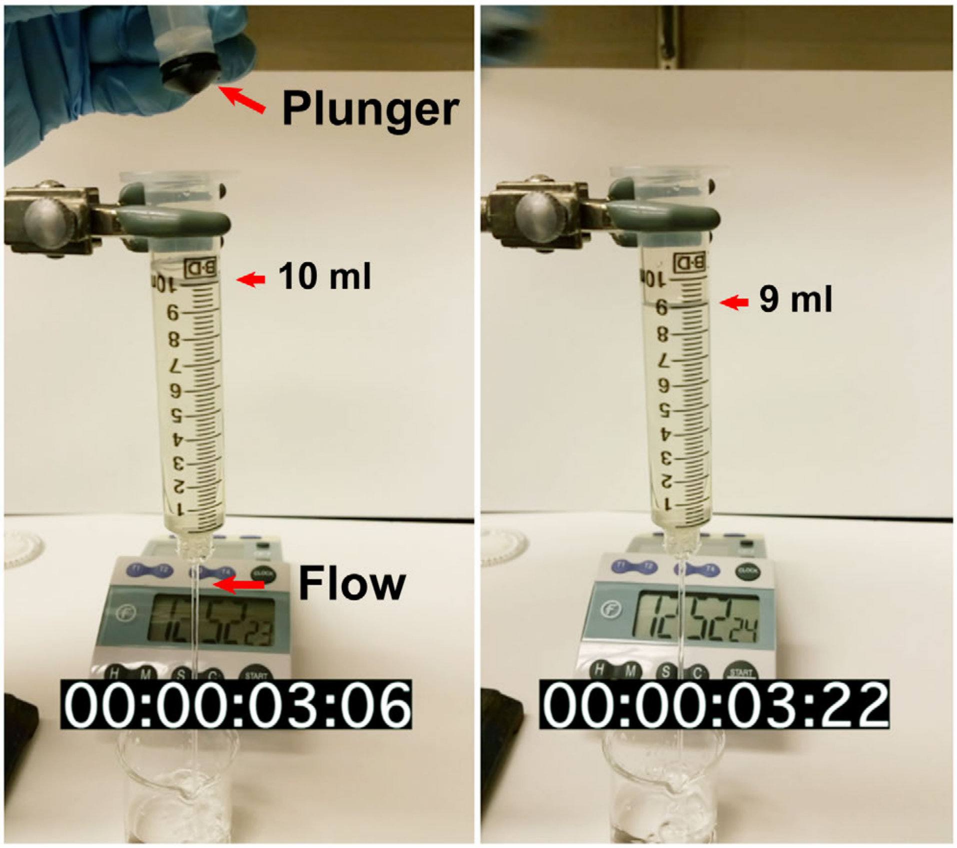
From Stokes' law, $F_d(v) = -6\pi\eta r\upsilon$

then, $-6\pi\eta r\upsilon = F_{g,max}$

Solving for η gives the viscosity of the fluid.

Figures

Figure 1 Measuring the Viscosity of Water

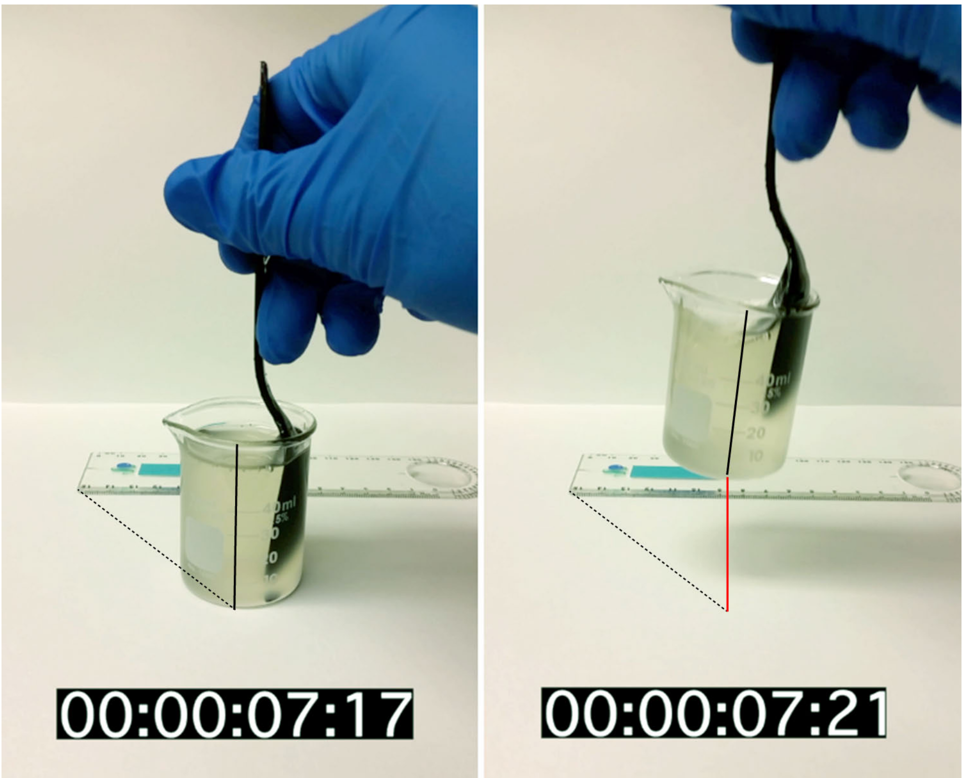


Viscosity of water measured by flow through a hypodermic syringe. The syringe was filled with water and the flow was started by pulling the plunger out of the syringe (Left top, arrow). The flow of the water from the syringe (Left bottom, arrow) was recorded with a cell phone. Two frames from the video sequence show the water level at 10 *ml* (Left middle, arrow) and 9 *ml* (Right middle, arrow) (see **Video 1**).

Time stamps (hours:minutes:seconds:seconds/30) were added using a video-editing software program (note that seconds/30 corresponds to the video rate of 30 frames/sec for the standard video format used in North and South America and Japan, which is called NTSC). The time required for the water to fall from 10 *ml* to 9 *ml* was 16/30 seconds = 0.533 seconds from the time stamps, while the time change on the timer was 1 second.

Experimental errors in recording the time, as well as differences in the diameter of the syringe or pipette, and the size of the hole through which the fluid flows, will cause your viscosity values to differ from those shown in the table. However, the values for water, vegetable oil and molasses (or corn syrup) should be in the same order from lowest to highest as those shown in the table.

Figure 2 Lifting a Beaker of Light Corn Syrup with a Spoon by Viscous Drag



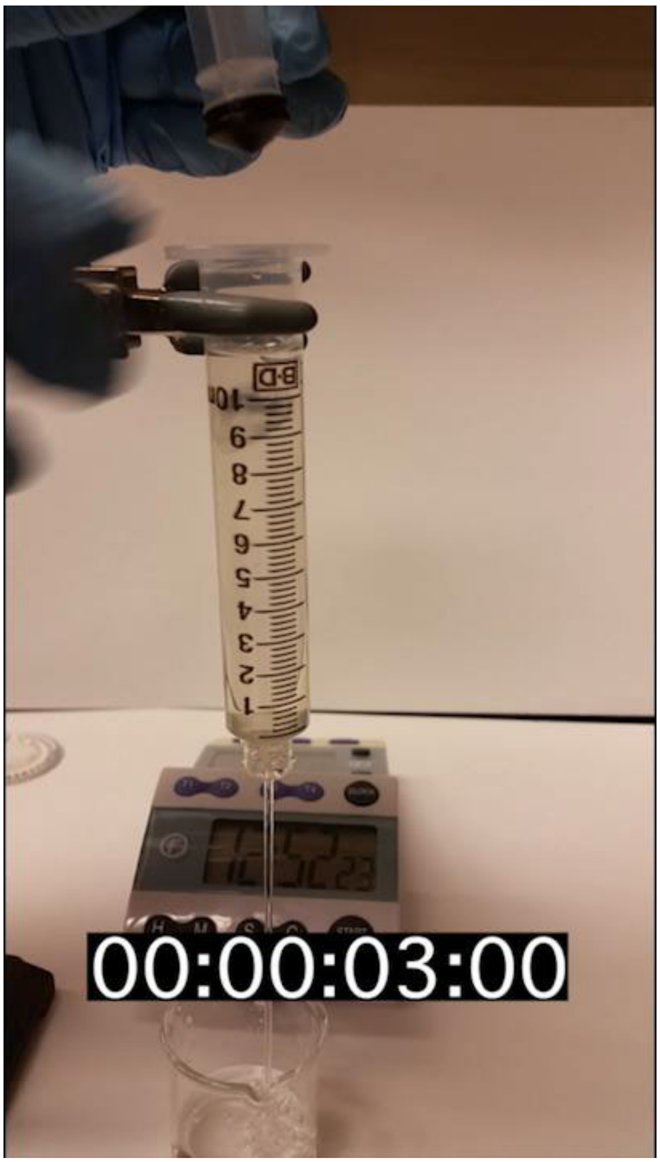
A spoon was inserted into a small beaker filled with ~56 *ml* of light corn syrup (total weight without spoon = 100 *g*) and pulled quickly, lifting the beaker. The two frames from the video sequence show the beaker just before being lifted and at its highest height (See Video 2).

The distance the beaker was lifted (4.63 *cm* = 0.0463 *m*) was estimated by measuring the actual height of the beaker (5.7 *cm*, black line) and drawing a line from the end of the ruler to the bottom of the beaker (dotted line), then measuring the distance from the bottom the beaker to its original position (red line).

The time of the lift was estimated from the time stamps (hours:minutes:seconds:seconds/30) = 4/30 or 0.13 seconds. The velocity that the spoon was lifted was calculated from the distance the beaker was lifted divided by the time, and found to be 0.356 *m/s*.

Videos

Video 1 Measuring the Viscosity of Water



Video showing assay of water flow through a hypodermic syringe to measure the viscosity of water (download the movie and double click on the icon to play). See **Figure 1** for further information about the assay. Similar assays were performed using vegetable oil and light corn syrup.

Movies were made by opening videos recorded on a cell phone in Adobe Premiere Pro, exporting a section of recorded video in *.tiff* format, then opening frames as a stack in ImageJ, cropping, and saving as an *.avi* file.

ImageJ is a public domain image processing program developed at the National Institutes of Health (Rasband, 1997-2015) and available at *http://imagej.nih.gov/ij/*

Video 2 Lifting a Beaker of Light Corn Syrup with a Spoon by Viscous Drag

Video showing a beaker of light corn syrup being lifted by a spoon due to viscous drag (download the movie and double click on the icon to play). See **Figure 2** for further information about the weight of the beaker and how high it was lifted.

References

Howard, J. 2001 *Mechanics of Motor Proteins and the Cytoskeleton*. Sinauer Associates, Inc.

Amrita Vlab 2010 Viscosity Measurement using Ostwald's Viscometer – Amrita University. *https://www.youtube.com/watch?v=Gs3gfwG9a7k*

Rasband, W.S., ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, *http://imagej.nih.gov/ij/,* 1997-2015.

Authors

Adam P Russell & Peter LZ Young
Sharyn A Endow

Duke University Medical Center
Durham, NC
122115