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Thermo and Fluid Dynamics of a Homemade "Lava Lamp"

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Overview:

Lava lamps are just cool, that's all there is to it. Almost everyone has spent at least an hour of their life just staring at a lava lamp. While the experiment outlined here isn't really the same as a commercial lava lamp it does demonstrate many of the important fluid and thermodynamic properties. Most importantly it provides students with an interesting and fun visual demonstration intended to motivate thought about the physics behind the experiment itself.

The "lava lamp" created in the following experiments displays a multitude of important fluid and thermodynamic properties. Concepts such as: convection, surface tension, buoyancy, density, fluid drag, and the differences between heat convection and other convective processes are evident simply by observation.

Experiments:

Equipment:

- 1x 800ml Beaker
- 1x 100ml Graduated Cylinder
- 1x Hotplate

Supplies (per experiment):

- 10ml Fountain Pen Ink (I used Higgins Eternal Black Ink but any will do)
- 90ml Water (Graduated Cylinder)
- 600ml Vegetable Oil (Beaker)
- Alka-Seltzer Tablets

Heated Convection Procedure:

1. Fill the beaker with 600ml of Vegetable Oil.
2. Fill the graduated cylinder with 90ml of water.
3. Mix the water with the vegetable oil in the beaker and allow the water to settle to the bottom.
4. Fill the graduated cylinder with 10ml of ink and then pour that with the oil/water mixture.
5. The ink droplets then settle down on top of the oil/water barrier but won't break through due to the surface tension caused by the hydrophobic barrier.
6. Place the beaker on a hotplate and heat up to 100° Celsius. Shortly thereafter the 'lava lamp' should begin to convect because the water is at its boiling point. The beaker should not be left to boil for too long or hot oil/water/ink could bubble out and splash upon onlookers.

Unheated Convection Procedure[1]:

1. Fill the beaker with 600ml of Vegetable Oil.
2. Fill the graduated cylinder with 90ml of water.
3. Mix the water with the vegetable oil in the beaker and allow the water to settle to the bottom
4. Fill the graduated cylinder with 10ml of ink and then mix that with the oil/water mixture.
5. The ink droplets then settle down on top of the oil/water barrier but won't break through due to the surface tension caused by the hydrophobic barrier.
6. An Alka-Seltzer is then dropped into the middle of the beaker. When the Alka-Seltzer hits the oil/water barrier it breaks the surface tension and the ink mixes with the water. Once the Alka-Seltzer is in the water it begins to react and release gas triggering the convection process.

Explanations and Exercises:

Buoyancy and Convection:

It should be clear to anyone who observes these two experiments that they are remarkably similar. This demonstrates the connection between buoyancy and density as well as indicating that there are methods of producing convection other than by heating.

Traditionally students are often introduced to heat convection in schools. Heat convection occurs when a liquid is heated, causing the density of the liquid at the bottom to be less than the density of the liquid on the top. The less dense liquid flows to the top because it is more buoyant than the colder liquid. At the same time, the colder liquid on top flows downward because it is more dense and therefore less buoyant. This process continues as the liquid undergoes convective flow.

In the unheated experiment, the gas created by the Alka-Seltzer reaction is responsible for the buoyant force lifting droplets of water/ink to the top surface. The low density gas

[1] An experiment similar to this one can be found here…
http://www.sciencebob.com/experiments/lavalamp.php

bubbles form on droplets of water/ink and cause the droplets to be more buoyant. Once the droplets reach the surface, the gas bubbles escape from the mixture and the dense water/ink droplets fall back down to the oil/water barrier.

Students can demonstrate their understanding by solving for the necessary gas bubble volume required to balance the force acting on a droplet with diameter of 1cm. This represents a situation often called "neutral buoyancy." There are three forces acting on this stationary droplet. The buoyancy due to the gas (F_{gb}) and the buoyancy due to the droplet (F_{db}) both act upward against the force due to gravity (F_g).

$$F_{total} = F_{gb}^{\uparrow} + F_{db}^{\uparrow} - F_{grav}^{\downarrow} = 0 \qquad (1)$$

Thus the droplet will simply float in place neither moving upwards nor falling. (Note: if there were no gas bubbles on the droplet it would fall due to its own weight because F_{bg} no longer helps to balance the equation)

The force of gravity pulling down on the droplet is:

$$F_{grav}^{\downarrow} = mg \text{ (where } m \equiv \rho_{drop} \cdot V_{drop}) \qquad (2)$$

Where g is the acceleration due to gravity on the surface of Earth, and the density of the droplet (ρ_{drop}) is approximately 1 g/cm^3, the density of water (ρ_{water}).

The volume of a spherical droplet is given by the equation:

$$V_{drop} = (4/3)\pi \cdot r_{drop}^3 \qquad (3)$$

Buoyancy is created by the displaced volume of the fluid (in this case, vegetable oil) in which the droplet resides[22], sometimes called Archimedes principle:

$$F_{db}^{\uparrow} = \rho_{water} \cdot V_{drop} \cdot g \qquad (4)$$

Where $\rho_{f\,luid}$, the density of vegetable oil at room temperature, is ρ_{oil} = 0.894 g/ml. So the net force on the droplet, in the absence of gas bubbles, is:

$$F_{drop} = F_{db}^{\uparrow} - F_{grav}^{\downarrow} = (\rho_{oil} - \rho_{water}) \cdot V_{drop} \cdot g \qquad (5)$$

As ρ_{oil} is less than ρ_{drop}, the droplet will sink, unless the additional upward force of buoyant gas (or convection in the case of the heated experiment) compensates. So the additional upward force that the gas bubble must provide is:

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[2] The volume of oil displaced by the droplet is of course the same as the volume of the droplet, because the droplet is completely submerged in the oil.

$$F_{gb}^{\uparrow} = (\rho_{oil} - \rho_{gas}) \cdot V_{gas} \cdot g = -F_{drop} = -(\rho_{oil} - \rho_{water}) \cdot V_{drop} \cdot g \qquad (6)$$

Assuming the mass of the gas is negligible (ρ_{gas}= 0), we can solve for the volume of the gas:

$$V_{gas} = \frac{\rho_{water} \cdot V_{drop}}{\rho_{oil}} - V_{drop} \qquad (7)$$

Droplets in a lava lamp exhibit that special, slowed motion because they are nearly neutrally buoyant.

Hydrophobia:

The oil used in these experiments forces the water/ink mixture to bead into droplets as it moves throughout the oil. This occurs because the oil is hydrophobic. Hydrophobic sounds exactly as it means; the water/ink mixture does not "want" to mix with the oil.

In a more scientific sense the water molecules are minimizing the energy of interaction by bonding to themselves rather than the oil. Water can very easily form hydrogen bonds with itself because it is a very polar molecule but the oil, which is non-polar, is not capable of forming these bonds with water. The water molecules therefore favor interaction between themselves, and form into droplets to minimize contact with the oil surrounding them.

Drag:

Droplets *moving* through the oil experience fluid drag among other forces[3]. Fluid drag is a force that opposes the movement of the droplets in the oil due to friction between the droplet and the oil surrounding it. In the buoyancy problem above, the drag force was zero because the droplet wasn't moving. Drag is something most people have heard of in reference to the aerodynamics of cars. If the car is not shaped properly a lot of drag force will be resisting it as it moves quickly, due to the air moving around it.

[3] Students could be asked to draw a force vector diagram or list all of the forces involved in the motion of the droplet and their relative magnitudes (eg. $F_{drag} < F_{grav}$). (Forces: Gravity, Buoyancy, Drag)