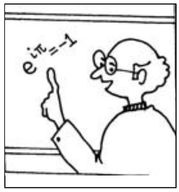
Classroom



In this section of *Resonance*, we invite readers to pose questions likely to be raised in a classroom situation. We may suggest strategies for dealing with them, or invite responses, or both. "Classroom" is equally a forum for raising broader issues and sharing personal experiences and viewpoints on matters related to teaching and learning science.

The Inveterate Tinkerer
5. Experiments with Non-Newtonian Fluids

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In this series of articles, the authors discuss various phenomena in fluid dynamics, which may be investigated *via* table-top experiments using low-cost or home-made instruments. The fifth article in this series is about some fascinating experiments with non-Newtonian fluids.

Materials

Please read through the individual experiments.

Methods

Newton stated that for simple fluids such as water, the shear stress applied is linearly proportional to the shear rate [1, 2]. Here, the shear stress (in units of N/m^2) is the force per unit area applied to shear the fluid (rather than to elongate it, as in Hooke's law), and the shear rate (in units of 1/s) is the rate of deformation. The shear stress divided by the shear rate is a constant called the 'shear viscosity' (units of Ns/m^2) of this Newtonian fluid. However, many fluids that we commonly encounter, including, shampoo, cake batter, chocolate, liquid soaps, bodily fluids such as blood and saliva are non-Newtonian, *viz.* the shear stress is not proportional to the shear rate. Most polymer solutions and polymer melts are

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also non-Newtonian. In [3], the reader may find a picture gallery of diverse and often counter-intuitive phenomena which is observed upon the deformation of non-Newtonian fluids in different flow geometries. The reader may also view the video *Rheological Behaviour of Fluids*, which is part of the series produced by the National Committee for Fluid Mechanics Films (United States) available online at:
web.mit.edu/hml/ncfmf.html

Non-Newtonian fluids behave solid-like under rapid deformation, while a deformation over an extended period of time causes the material to flow like a liquid.

Non-Newtonian fluids such as dimethylsiloxane are commercially available under the trade name 'silly putty'. These materials exhibit viscoelastic behavior, i.e., they behave solid-like under rapid deformation (such as on bouncing a mass of material off a surface), while a deformation over an extended period of time (such as due to gravitational forces on a stationary mass) causes the material to flow like a liquid. See the video:
youtube.com/watch?v=ss5u_g3_BLY

One may also purchase magnetic variants of silly putty which contain embedded iron oxide nanoparticles. Such magnetic fluids show unusual rheological behaviour in the presence of a strong magnet. See the video: youtube.com/watch?v=lEt5brvXYt8

The dissolution of a small amount (~10 ppm) of flexible, long-chain polymer such as polyethylene oxide (Sigma-Aldrich, United States, CAS Number 25322-68-3) in water imparts elasticity to the fluid. The elastic recoil of a polymer solution may be seen quite vividly if the solution is concentrated. Elastic recoil using 6.6% (dyed) aqueous polyacrylamide (HiMedia Laboratories Pvt. Ltd., Mumbai, CAS No: 9003-05-8) solution may be seen in the video: youtube.com/watch?v=XGF5GztBIpI

The dissolution of a small amount of flexible, long-chain polymer such as polyethylene oxide in water imparts elasticity to the fluid.

The formation of elastic filaments may also be seen with mucilage from an okra (or ladies' finger), placed between one's thumb and forefinger. If the distance between the fingers is increased, the mucilage forms filaments between the fingers (*Figure* 1).

We suggest a few experiments which the reader may wish to attempt.

Figure 1. Formation of an elastic filament using okra mucilage.

Experiment 1: Weissenberg Effect

A battery-powered egg beater was used to stir (dyed) 2% aqueous polyacrylamide solution in a beaker. For a Newtonian fluid such as water, centrifugal forces cause the liquid surface to rise near the wall of the beaker, with its lowest point in the middle of the beaker. However, the addition of a polymer imparts an additional tension along the circumferential streamlines, which act similar to hoop stresses on a cylindrical wall (*Figure* 2(a)). The squeezing action of these stresses results in an inward force which causes the fluid to rise along the stirrer rod, as seen in the video: `youtube.com/watch?v=469C8l_wDeg`

Experiment 2: Tubeless Siphon

A beaker was filled with (dyed) 2% aqueous polyacrylamide solution. An empty syringe (with needle removed) was inserted into the solution and suction was applied. During suction, if the syringe is lifted off from the surface of the solution, a thin stream of solution can still be siphoned. See *Figure* 2(b) and the video: `youtube.com/watch?v=DwmLFkCKuig`

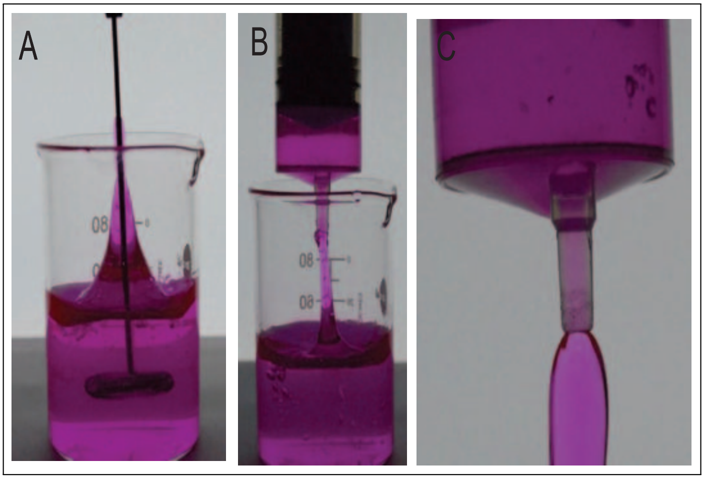

Figure 2. Dyed 2% aqueous polyacrylamide solution for demonstrating **(a)** Weissenberg effect **(b)** Tubeless siphon **(c)** Die swell.

Experiment 3: Die Swell

Under steady shear flow, non-Newtonian fluids generate non-zero normal-stress differences. Dyed 2% aqueous polyacrylamide solution was filled inside the barrel of a syringe (with needle removed). The syringe was clamped to a ring stand with the nozzle facing vertically downwards and the plunger pushed to eject the solution. At the tip of the nozzle, the diameter of the jet increases (to approximately twice the nozzle diameter), for a short distance before decreasing. See *Figure* 2(c), a vivid demonstration of non-zero, first-normal stress difference which acts in a direction normal to the axis of the jet. See the video:
`youtube.com/watch?v=9YJWq3VrQUE`

Experiment 4: Vibrated Cornflour Solution

65 g of cornflour (Weikfield Products Pvt. Ltd., India) was added to 50 ml of deionised water. The mixture was stirred until a homogeneous consistency was obtained. A cone speaker connected to an amplifier was covered with a thin plastic sheet and the solution was poured onto the sheet. The cone speaker was vibrated at 32 hz using a function generator connected to the amplifier. The oscillated cornflour solution exhibits unusual pillar-like structures which indicates a local increase in shear viscosity upon deformation. Upon switching off the function generator, the

Figure 3. A stream of liquid detergent bouncing off a heap of the same liquid as a demonstration of the Kaye effect, imaged using a high-speed camera.

shear viscosity decreases, and the solution subsides into a puddle. See the video: `youtube.com/watch?v=FR50BCxyH98`

Also see [4] for a variant of this experiment.

Experiment 5: Kaye Effect

Glow laundry detergent (Trick-Track, India) was poured onto a glass plate from a height of ~5 cm. A thin stream of detergent falls on a mound of the same fluid, and occasionally a thin fluid stream appears to 'slide' off the mound and fall onto the plate (*Figure* 3). Bio Green Apple shampoo (Biotique Botanicals, India) may also be used to demonstrate the effect. This phenomenon [5] is generally attributed to a local decrease in shear viscosity of the fluid upon contact with a heap of the same fluid, which causes the stream to bounce upwards and emerge with an approximately parabolic trajectory. See the video:
`youtube.com/watch?v=ICtveXTXYxA`

Suggestions for Further Work:

1. ***Droplet Impact of Non-Newtonian Fluid on a Flat Surface***

A drop of 100 ppm aqueous polyacrylamide solution was released from a nozzle at a height of ~45 cm onto the top surface of a cylindrical glass lens (diameter =1 cm, height = 0.5cm). The drop impacts the lens and forms a radially expanding fluid sheet with corona-like filaments at the edges. Rayleigh–Plateau instability [6], which induces formation of droplets at the edge of a sheet of Newtonian fluid is inhibited by the elasticity of the polymer solution. See the video taken with a high-speed camera (Phantom M110) and macro lens: youtube.com/watch?v=GmR1qoX1twM

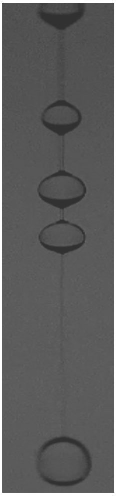

Figure 4. A jet of 100 ppm aqueous polyacrylamide solution, imaged using a high-speed camera.

2. ***Breakup of a Jet of Non-Newtonian Fluid***

A jet of 100 ppm aqueous polyacrylamide solution was ejected from a horizontal syringe and imaged using a high-speed camera with macro lens, with an LED light source as the backdrop. The jet shows drops of polymer solution attached to each other by slender fluid threads. See *Figure* 4 and the video taken with a high-speed camera and macro lens:
youtube.com/watch?v=A_s5lH-kL5E

3. ***Yield Stress***

It is commonly observed that a certain minimum compressive stress must be exerted on the walls of a toothpaste tube to squeeze out the toothpaste. A bottle of tomato ketchup needs vigorous shaking to pour out the sauce. Viscoelastic materials such as toothpaste and tomato ketchup exhibit 'yield stress', i.e., they flow like liquids upon exertion of a (stress greater than) certain minimum stress on the material. Upon diminishing the stress below the yield stress value, the materials behave like a solid and do not flow.

4. ***Thixotropy***

Wall paints, shaving creams, and adhesives flow like liquids when applied on a surface using a brush. After application, they adhere to the surface and do not flow. The shear viscosity of such materials is time-dependent: It decreases upon imposition of a shear stress, however, when no shear stress is imposed (excluding stresses due to the gravitational force), the shear viscosity increases as a function of time, such time-dependent behaviour is termed 'thixotropic'.

Acknowledgement

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Suggested Reading

[1] H Barnes, *A Handbook of Elementary Rheology*, The University of Wales Institute of Non-Newtonian Fluid Mechanics, 2000.

[2] J Walker, Amateur Scientist: Serious Fun with Polyox, Silly Putty, Slime and other Non-Newtonian fluids, *Sci. Amer*., November, p.186, 1978.

[3] D Boger and K Walters, Rheological Phenomena in Focus, *Elsevier*, 1992.

[4] If a thin layer of cornstarch solution is vibrated, stable 'holes' can be created in the layer if a puff of air is blown on the surface. See the video: `youtube.com/watch?v=H1Rzv0HAdug`

[5] A Kaye, A Bouncing Liquid Stream, *Nature*, Vol.4871, p.1001, 1963.

[6] E Guyon, J Hulin, L Petit, and C Mitescu, *Physical Hydrodynamics*, Oxford University Press, 2nd ed., 2015.

[7] A dyed 0.5% aqueous solution of high-molecular weight (~6,000,000 atomic mass unit) polyethylene oxide may be used to demonstrate self-syphoning of a viscoelastic liquid: The extensional viscosity of the fluid increases when a liquid filament is subject to extensional strain (or strain-rate) using a spatula, as shown in the video: `youtube.com/watch?v=g4od-h7VoRk`