Physics Education

A simple capillary viscometer

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A simple capillary viscometer

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The viscosity of a fluid is most conveniently determined by measuring the rate of flow through a capillary tube. Because the experimental arrangement is so similar to many practical situations the results are useful and illuminating even for non-newtonian fluids for which the method should not properly be used because the shear rate varies across the bore of the tube. It is extremely easy to measure relative viscosities using an instrument such as the Ostwald U tube viscometer in which the fluid flows under a falling pressure head but investigation of the variation of viscosity of a fluid with pressure usually requires a more complex apparatus to provide a constant pressure head. The viscometer described here is of simple design and students have had no difficulty in understanding and operating it.

The viscometer can be quickly and cheaply constructed from a disposable plastic syringe and a hypodermic needle. Using different sized needles it is possible to determine a large range of viscosities of liquids. The viscosity of air can be measured by the same method. This has the great advantage for teaching of giving a direct comparison between the viscosities of liquids and a typical gas.

Viscometer

The instrument is illustrated in figure 1. Gillette 'Scimitar' disposable syringes and disposable hypodermic needles were used. The syringes with capacities 2–20 ml have a hollow plunger terminated with a rubber seal. A serum II needle was pushed through this and connected to a manometer which recorded the pressure in the air space over the liquid in the syringe. Disposable needles of the following sizes are available from Gillette at about 1p each when bought in bulk:

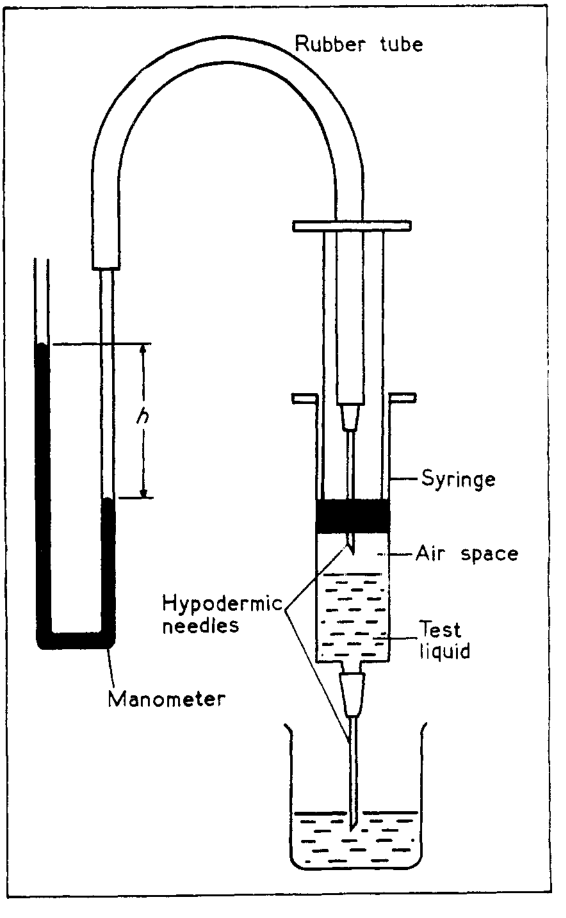
Serum II	0·69 mm ID
No. 1	0·51 mm ID
No. 12	0·33 mm ID
No. 17	0·25 mm ID

Suitable disposable syringes of capacities 2 ml, 5 ml, 10 ml and 20 ml are also available at about 2–5 p each when bought in bulk. These prices make it economically possible to provide each student with a viscometer and eliminate cleaning at the end of the practical session.

Experiment

The liquid under test was poured into the syringe with the plunger removed. The plunger was replaced leaving an air space above the liquid. Using finger pressure on the plunger it was easily possible to maintain a steady pressure in the air space to force the liquid through the lower hypodermic needle provided the bore of the needle was not so large as to give too free a flow. Pressure differences of up to about 22 cm Hg (30 kPa) were easily maintained for studying the effect of pressure on flow and viscosity. The tip of the needle through which the liquid flowed dipped into some of the test liquid to eliminate surface tension effects. The rates of flow through the needle

Figure 1 Capillary viscometer constructed from a disposable syringe



were found by measuring the time the liquid level took to move through a fixed volume using the calibrated scale on the side of the syringe. It is possible to perform the experiment single handed but it would be preferable for students to work in pairs with one student maintaining the constant pressure and the other timing the flow.

The nominal internal diameters ($2r$) of the needles were given by the manufacturers. These can only be easily checked at the ends using a calibrated microscope. Measurements of the rate of flow through five different needles with the same nominal bore indicated a 2·5% variation in diameter. Hypodermic needles are pointed, but rates of flow increased by less than 5% when the point was ground off. For student use the point could be ignored.

Rather than calculate the viscosity at a single pressure it is more instructive to plot the rate of flow against the pressure recorded by the manometer to (i) see if there is newtonian behaviour, (ii) obtain the best estimate of pressure per unit volume rate of flow from the slope of the graph to determine the coefficient of viscosity. Figure 2 shows such plots for the flow of water and ethanol through a No. 17 needle. The lines of best fit do not pass through the origin but cut the ordinate at a small negative pressure equal to the head of liquid in the syringe. This was checked by repeating the measurements with the syringe immersed in the liquid up to the mean level of the liquid in the syringe. The lines then passed through the origin but with the same slopes as in the first experiment. The lengths (l) of the steel needles were finally measured after breaking them out of the plastic fittings. The coefficients of viscosity (η) were calculated from Poiseuille equation

$$\eta = \frac{\pi r^4}{8l} \times \text{slope of the graph.}$$

Figure 2 yields the values η (water 21·5 °C) = 0·98 cP (0·98 mN s m^{-2}) which is close to the accepted value (0·97 cP) and η (ethanol 21·4 °C) = 1·31 cP (1·31 mN s m^{-2}) which is higher than the accepted value (1·20 cP) and could be due to contamination with water.

Blood is often quoted as an anomalous fluid but its anomalous behaviour is not easily apparent as may be seen from figure 2. The rate of flow through the needle is directly proportioned to the pressure drop along it over the range of at least 2–20 cm Hg (3–27 kPa). Note, however, that the graph if extrapolated would cut close to the origin and this without taking the extra pressure due to the head of blood in the syringe into account. Clearly the straight line extrapolation is not justified and the gradient must increase at pressures below 2 cm Hg (3 kPa). (Ancillary experiments with a water manometer showed that the critical pressure must be below 6 cm water (590 Pa).) It has been shown (eg Stacy *et al* 1955 *Essentials of Biological and Medical Physics*) that the viscosity of blood increases for pressures less than about 5 cm water (490 Pa) though this is a function of the red cell density. The viscosity of blood at 22·5 °C calculated using the slope from figure 2 is 4·16 cP (4·16 mN s m^{-2}) which is within the normal range for whole blood with normal red cell concentrations. The blood used was old stock from a hospital blood bank and contained an anticoagulant.

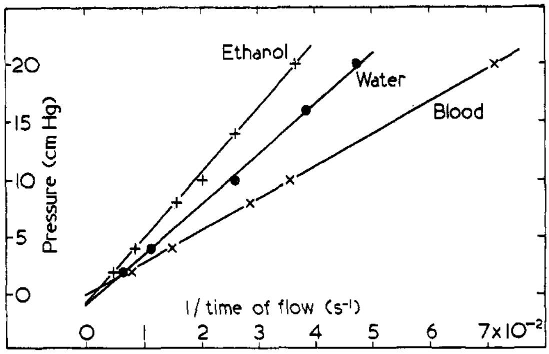


Figure 2 Pressure (h) against reciprocal time of flow for ethanol, water and blood. Ethanol and water: No. 17 needle, length 2·8 cm, flow volume 2 ml, 21·5 °C. Blood: No. 1 needle, length 4·6 cm, flow volume 3 ml, 22·5 °C. 5 cm Hg ≈ 6·7 kPa

The viscosity of air can be found by the same method provided the pressure gradient along the capillary is small. For a gas flowing through a capillary tube of internal radius r and length l the volume per second V entering the tube at pressure P_1 is not equal to the volume per second of gas leaving at pressure P_2 (atmospheric pressure) due to the compressibility of gases. The mass of gas crossing every section of the tube is constant in steady flow and it can be shown that (see for example Worsnop E L and Flint H T *Advanced Practical Physics for Students*)

$$P_1V_1 = P_2V_2 = \frac{\pi r^4}{16\eta l}(P_1^2 - P_2^2).$$

But $P_1 - P_2$ = the pressure indicated by the manometer (h).

$$\text{Therefore } V_1 = \frac{\pi r^4\{P_1^2 - (P_1 - h)^2\}}{16\,\eta\, l\, P_1}$$

$$= \frac{\pi r^4(2\,P_1 h - h^2)}{16\,\eta\, l\, P_1}$$

$$= \frac{\pi r^4 h}{8\,\eta\, l} \text{ if } h \ll 2\,P_1 = 2\,(h + P_2).$$

For h below 1·5 cm Hg the error in applying the Poiseuille equation for liquid flow to a gas will be less than 1%. Using a 10 ml syringe with a No. 17 needle a coefficient of viscosity of 0·015 cP (0·015 mN s m^{-2}) for air at 19 °C under a pressure of 1 cm Hg was found. The accepted value for this is 0·018 cP (0·018 mN s m^{-2}).