P1 Determination of the viscosity of oil

Introduction

In science both liquids and gases are called fluids, because they both can flow. Fluids can flow through tubes, like blood through veins for example, and objects can move through them like aircraft through air. When this happens the moving mass (blood, aircraft) loses energy, so blood has to be continuously pumped by the heart and the aircraft needs an engine or else to glide down, losing potential energy.

This energy loss happens in two ways. If velocities are low then the losses are frictional. Close to the moving body the fluid moves with it, but far away it is stationary. As result, layers of liquid slide over each other, like a stack of cards held between your hands being slightly sheared and each card rubbing against its neighbour. If the flow is fast, then turbulent motion of the fluid occurs, giving it kinetic energy. The low speed frictional losses are described by the viscosity \( \eta \), which has dimensions of N m\(^{-2}\) s, or Pa s if you prefer.

This experiment finds \( \eta \) for a pump oil by dropping a series of spheres through it. The key equation here is Stokes' law, which says that the force acting on a sphere with diameter \( d \) moving through a fluid with velocity \( v \) is

\[
3\pi d \eta v \quad \cdots (1).
\]

This theoretical result is accurate so long as the dimensionless Reynolds number \( R_e \), given by

\[
R_e = \frac{\rho dv}{\eta} \quad \cdots (2)
\]

is comfortably less than 1, when the losses are dominated by friction. \( \rho \) here is the fluid density.

Since from equation (1) the drag force on a falling body increases with speed, it will eventually stop the body accelerating. It then falls with a constant speed, called the terminal velocity: for example a human accelerates to a speed of about 120 m.p.h. when falling in air. The downward force due to gravity, allowing for the buoyancy caused by the displaced fluid is volume\( \times (\sigma - \rho)\times g \), where \( \sigma \) is the density of the body and \( g \) the acceleration due to gravity. So writing the volume of a sphere in terms of \( d \), equating the force to the drag given by equation (1) at terminal velocity \( v_T \) we have

\[
\frac{\pi d^3}{6} (\sigma - \rho) g = 3\pi d \eta v_T,
\]

which tidied up gives

\[
v_T = \frac{\sigma - \rho}{18\eta} \frac{g}{d^2} \quad \cdots (3).
\]

If we measure the terminal velocities of a series a spheres with different diameters and plot \( v_T \) against \( d^2 \) we expect a straight line and we can get the value of \( \eta \) since the slope is given by equation (3). This is what you will do, using two sorts of spheres, steel and nylon.
**Measuring the temperature**

Viscosity is a very temperature dependent property, falling as the temperature rises. There is a digital thermometer immersed in the oil; note its reading.

**Measuring the densities**

You will need to measure the density of the oil and of the two sorts of spheres. You have several large balls set aside for their density measurement; do not drop these in the later measurements. Use the micrometer to measure their diameters, closing the jaws gently by turning the knob, the end which will slip as soon as the jaws are shut. Measure the diameters of at least two steel balls. Now put the plastic cup on the scales and press T (the red strip) to zero them. Next weigh together all the large balls. The density of steel is then \((6 \times \text{mass})/(\pi \times d^3)\) divided by the number of balls you weighed.

Repeat the above for the large nylon balls.

Use the density bottle to find the density of the oil. Weigh it empty, then fill it via the dropper so full that when then stopper is inserted oil flows out of the narrow hole in it. Wipe off any excess and weigh the full bottle. You now know the mass of oil and the bottle has its volume marked on it.

**Measuring \(v_T\)**

Before you start, have a good look at the oil-filled tube. At the top there is a window that lets you see the oil surface. At the top of the lower window there is a region lit with green light, to help you see the ball as it approaches the measurement region where there are three regions illuminated with blue light, each with a pair of marker lines at the front and at the back. Make sure you are looking at the line and not the edge of the perspex strip it is drawn on. You will need to line up each pair to time the ball as it crosses each region in turn. The distance between the top and centre lines is 0.25 m as is the distance from centre to bottom. If the time taken to cover the upper and the lower 0.25 m is the same within the timing errors then the ball has reached terminal velocity and the analysis presented above holds.

The timer first needs putting into “lap” mode using the blue button. Leave it like this throughout. When the ball crosses the upper line (use its leading edge or its trailing edge, but do so consistently), press the green button to start timing. As the ball crosses the centre line, press the red button. Finally, as it crosses the lower line press the green button again. At this point the timer shows the time from top to centre, \(t_1\) say. Record this, then press the red button to get the centre to bottom time \(t_2\). *You might want to practise this a few times against a watch before you start measure the spheres, using different intervals so you are sure you know which is which.*

Pick up the balls with tweezers (this may be easier once the tweezers have oil on them) and release the balls from just **below** the oil surface and as close to the tube centre as possible.
You will notice a near-vertical wire in the oil. This goes to a recovery cup which is only for the lab technician’s use. Before the experiment this wire will have been arranged close to the tube wall; do not move it during the experiment as it might then get in the path of the falling spheres.

**Nylon and steel spheres**

There are 4 sizes of each kind of ball. You may assume the diameters are given by the labels. It is best to measure the drop times for the steel set first and then the nylon. For each set, measure $t_1$ and $t_2$ for two balls of each size. If for each member of the pair $t_1$ and $t_2$ are equal then you have reached terminal velocity; if $t_2$ is the same for both drops you can take the average and calculate $v_T$ for that size.

The nylon balls travel more slowly as their density is closer to that of the oil than for the steel balls. The smallest balls take a long time to travel between the surface window and the lower one, and you will need to be patient whilst this happens. The green lighting is there to help you spot the ball when it reappears.

Then plot separate two graphs, one for the steel balls and one for the nylon set. $v_T$ should be on the vertical axis and $d^2$ on the horizontal one. Get a value of the viscosity from each of them. Estimate the errors using the regression tool on Excel. Are the viscosities the same within the uncertainties? They should be of course, since the viscosity is a property of the oil and not the spheres.

If they are not, which ball-bearing material gives the greater value and which set is on average larger? Think about what the fluid would do if you dropped a very large sphere, not much smaller than the tube. The oil would have to squeeze between the wall and the ball, which would fall more slowly than in a much larger tube, appearing to have a larger viscosity. Does this square with you measurements?

Finally use equation (2) above to work out the Reynolds’ number for the largest steel ball and the largest nylon ball of the two sets. If these two have Reynolds numbers comfortably less than one, so will all the rest.

_TMS_

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