Core practical 4: Use a falling-ball method to determine the viscosity of a liquid

Objective

- To time the fall of a ball through washing-up liquid to determine the viscosity

Safety	Specification links
• Washing-up liquid spills are very slippery and must be cleared up at once. Have paper towels to hand. • Normal laboratory safety procedures should be followed.	• Practical techniques 1, 2, 3, 4, 5 • CPAC 1a, 3a

Procedure	Notes on procedure
1. Weigh the balls, measure their radius r and hence calculate the density ρ of the balls. 2. Place three rubber bands around the tube. The highest should be far enough below the surface of the liquid to ensure the ball is travelling at terminal velocity when it reaches this band. This is where the timer is started. The remaining two bands should be far enough apart to allow two reasonable time intervals to be measured. This will enable you to measure the terminal velocity twice for each falling ball. 3. Start the timer when the ball passes the highest rubber band. Use the lap timer facility to record the time taken t_1 to fall to the middle rubber band and stop the timer when the ball passes the lowest rubber band, this is t_2. Adjust the position of the rubber bands if your first test is not suitable. 4. Once you are happy with the position of the rubber bands, measure the distance d_1 between the highest and middle rubber band. Then, measure the distance d_2 between the highest and lowest bands. 5. Repeat at least three times for balls of this diameter and three times for each different diameter.	• If the ball can be released from rest in the liquid, the tube need not be so long. One method of release for ball bearings is to use a simple electromagnet. The highest rubber band can then be almost at the surface. • If the only tubes available are very short, you can use two rubber bands and measure only one time interval. • The tube should have a large enough diameter so that the ball can be dropped and not move towards the wall under Bernoulli's principle. This will change the flow regime rendering Stokes' law an inappropriate model.

Answers to questions

1. The liquid is coloured and the low intensity of the light transmitted will make the timing unreliable. It is likely that the ball will not fall through the relatively narrow beam of the light gate.
2. Bernoulli's principle means that, as the ball approaches the wall, the liquid is accelerated. Because of this, the pressure reduces and the ball moves closer to the wall making any effect more pronounced. The streamlines for the flow will no longer be symmetrical and Stokes' law is unlikely to be an appropriate mathematical model.
3. Time is being measured at two intervals for each ball, it is possible to estimate an uncertainty for the terminal velocity of each ball. Using balls of the same diameter will allow a mean value to be found for the terminal velocity of balls of that diameter. Thus a viscosity can be calculated for each diameter of balls and the overall mean found using the value from each diameter.

   The terminal velocity is likely to be the major source of uncertainty since we are ignoring the uncertainty in the densities. You can compare the percentage differences between your values for viscosity for different diameters and the calculated uncertainty from your measurements.

Sample data

Values quoted are the mean of at least three readings.

For r = 4.75 mm, terminal velocities were 0.169 ms^{-1} and 0.185 ms^{-1}.

For r = 3.0 mm, terminal velocities were 0.0820 ms^{-1} and 0.0786 ms^{-1}.

The density of the steel balls was 7840 kg m^{-3} and that of the washing up liquid was 1020 kg m^{-3}.

This yields $\eta = 1.78 \pm 0.11$ Pa s or 6.2% which is better than might be expected from the uncertainties in the terminal velocities.

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All the maths you need

- At terminal velocity, the vector sum of the forces on the ball is zero.

  weight – drag – upthrust = 0
- From this it can be shown that $\eta = \dfrac{2r^2\boldsymbol{g}(\rho-\sigma)}{9\boldsymbol{v}}$, where η is the viscosity of the liquid, r is the radius of the ball, ρ is the density of the ball, σ is the density of the liquid and v is the terminal velocity.
- The percentage uncertainty in r^2 is double the percentage uncertainty in r. The percentage uncertainties in the densities should be small enough to ignore.
- Recognise and make use of appropriate units in calculations.
- Recognise and use expressions in decimal and standard form.
- Use ratios, fractions and percentages.
- Use an appropriate number of significant figures.
- Find arithmetic means, identify uncertainties in measurements and use simple techniques to determine uncertainty when data are combined by addition, subtraction, multiplication, division and raising to powers.
- Substitute numerical values into algebraic equations using appropriate units for physical quantities.

Equipment

- long tube made of transparent material filled with washing up liquid – supported so it stays vertical
- spherical objects of various diameters
- stop clock or timer
- rubber bands to mark distances
- metre ruler
- micrometer screw gauge

Procedure

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2. Place three rubber bands around the tube. The highest should be far enough below the surface of the liquid to ensure the ball is travelling at terminal velocity when it reaches this band. This is where the timer is started. The remaining two bands should be far enough apart to allow two reasonable time intervals to be measured. This will enable you to measure the terminal velocity twice for each falling ball.
3. Start the timer when the ball passes the highest rubber band. Use the lap timer facility to record the time taken t_1 to fall to the middle rubber band and stop the timer when the ball passes the lowest rubber band, this is t_2.
   Adjust the position of the rubber bands if your first test is not suitable.
4. Once you are happy with the position of the rubber bands, measure the distance d_1 between the highest and middle rubber band. Then, measure the distance d_2 between the highest and lowest bands.
5. Repeat at least three times for balls of this diameter and three times for each different diameter.

Analysis of results

1. For each diameter, calculate mean values for t_1 and t_2.
2. Use these mean values and the distances to calculate mean values for the terminal velocity of each ball. Repeat for all the balls to obtain a mean value.
3. By considering the spread in your repeated readings, estimate the uncertainty of your mean values. This is usually half of the range.

Learning tips

- Position your eyes at the horizontal level of the rubber bands when starting and stopping the timer. You need to develop a good technique for measuring the time so that you are consistent. For example, if you read the time as the bottom of the ball crosses the top of the band, you should always do so. Make sure you also measure your distances from this point.

Questions

1. Explain why you would not use light gates to measure the time.
2. Sometimes the balls fall close to the wall. Comment on the effect that this will have on the measurements.
3. Use your uncertainty values to estimate the uncertainty in your value for the viscosity of the washing-up liquid.

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Equipment per student/group	Notes on equipment
long tube made of transparent material filled with washing up liquid – supported so it stays vertical	This could be a *Perspex* tube sealed at the lower end or a large measuring cylinder. It is helpful if you can measure the density of the washing up liquid, perhaps weigh a measured volume of a smaller sample in a measuring cylinder. It is approximately 1020 kgm^{-3}.
spherical objects of various diameters	Stainless steel ball bearings or glass marbles work well. It is best to have at least three of each diameter to be used.
magnet (optional)	If using steel ball bearings, provide a magnet so that students can retrieve the ball bearings between runs of the experiments.
stop clock/timer	
rubber bands to mark distances	
metre ruler	
micrometer screw gauge	

Notes