UM-SJTU JOINT INSTITUTE
PHYSICS LABORATORY
(VP141)

LABORATORY REPORT

EXERCISE 2
Measurement of the Fluid Viscosity

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1 Introduction and Theoretical Background

1.1 Objectives

In this exercise I'll get familiar with the constant-torque method for measuring the fluid viscosity, which is one of the most important properties of fluids, determining the fluid's flow. Student will learn Stokes' method, which is a common and simple method for characterizing transparent and translucent fluids with high viscosity.

1.2 Basic Concepts of Fluid's Viscosity

The viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. For liquids, it corresponds to the informal concept of "thickness"; for example, honey has a much higher viscosity than water.

Viscosity is a property of the fluid which opposes the relative motion between the two surfaces of the fluid in a fluid that are moving at different velocities. When the fluid is forced through a tube, the particles which compose the fluid generally move more quickly near the tube's axis and more slowly near its walls; therefore some stress (such as a pressure difference between the two ends of the tube) is needed to overcome the friction between particle layers to keep the fluid moving. For a given velocity pattern, the stress required is proportional to the fluid's viscosity.

Fluid's viscosity only determined by its type and temperature.

2 Measurement of Fluid's Viscosity

Motion of an object in a fluid is hindered by a drag force acting in the direction opposite to the direction of motion,for example, opposite to the object's velocity. The magnitude of the drag force is related to the shape and speed of the object as well as to the internal friction in the fluid. This internal friction can be quantified by a number known as the viscosity coefficient η

For a spherical object with radius R moving at speed v in an infinite volume of a liquid, the magnitude of the drag force is usually modeled as linear in the speed

$$F_1 = 6\pi\eta v R \tag{1}$$

When a spherical object falls vertically downwards in a fluid, it is being acted upon by the following three forces: The viscous force F_1 and the buoyancy force F_2 both act upwards, and the weight of the object F_3 is directed downwards. The magnitude of the buoyancy force is

$$F_2 = \frac{4}{3}\pi R^3 \rho_1 g \tag{2}$$

ρ_1:Density of the fluid
g:Acceleration due to gravity

$$F_3 = \frac{4}{3}\pi R^3 \rho_2 g \tag{3}$$

ρ_2:Density of the object

After sometime, the three forces will balance each other

$$F_1 + F_2 = F_3 \tag{4}$$

so that the net force on the object will be zero and from that instant on, the object will be moving with constant speed v_t, known as the terminal speed. Applying the condition (4), we can find

$$\eta = \frac{2}{9} g R^2 \frac{\rho_2 - \rho_1}{v_t} \tag{5}$$

Therefore, the fluid viscosity can be found by measuring the terminal speed. Taking into account that the motion with terminal speed is a motion with constant velocity, equation (5) can be rewritten as

$$\eta = \frac{2}{9} g R^2 \frac{(\rho_2 - \rho_1)t}{s} \tag{6}$$

s:Distance travelled in time
t after reaching the terminal speed

Since the volume of the fluid used in the measurement is not infinite, the results are affected by some boundary effects due to the presence of the container. Therefore, equation (1) should be modified, and the formula for the corrected magnitude of the viscous force for a infinitely long cylindrical container with radius R_c is

$$F_1 = 6\pi\eta v R(1 + 2.4\frac{R}{R_c}) \tag{7}$$

so the equation (6) becomes

$$\eta = \frac{2}{9} R^2 \frac{(\rho_2 - \rho_1)gt}{(1 + 2.4\frac{R}{R_c})s} \tag{8}$$

Since the length L of the container is limited, there may be further corrections introduced, depending on the ratio on R_c/L

3 Apparatus

As shown in the measurement setup part,we have many apparatus in our exercise. I classify them into two parts.

3.1 Stokes' Viscosity Measurement Apparatus.

The experimental setup consists of a Stokes' viscosity measurement device filled with castor oil in which motion of small metal balls will be observed. Measurements of various physical quantities in the experiment are performed with a number of measurement devices: micrometer, calliper, densimeter, electronic scales, stopwatch, and thermometer.

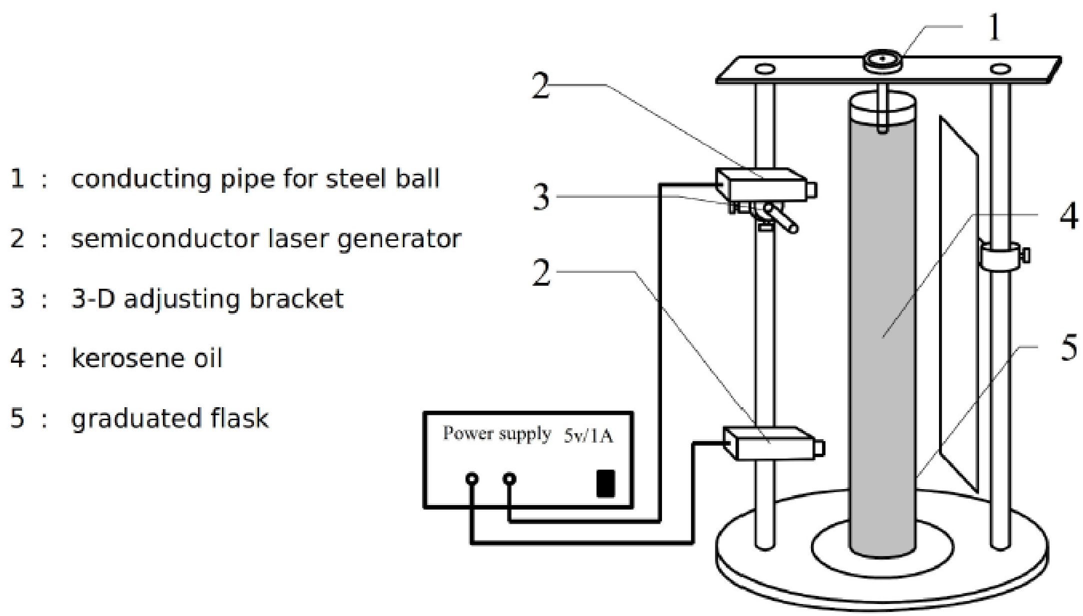

Figure 1: Stokes' viscosity measurement apparatus.

3.2 Tools

The second part is tools, I used the steel ruler and stopwatch to measure the velocity of the falling ball. Electronic scales and micrometer are used to measure the mass of 40 balls and their diameter so that I can calculate its density ρ_2. In addition, densimeter is provided for us to measure the castor oil's density ρ_1. I also used a calliper to measure the inner diameter D of the graduated flask and read the ambient temperature from the thermometer.

Figure 2: The densimeter

Figure 3: The calliper

Tools	Resolution
Steel Ruler	1mm
Stopwatch	0.01s
Micrometer	0.004mm
Calliper	0.02mm
Densimeter	0.001g/cm^3
Electronic scales	0.001g
Thermometer	2^oC

Table 1: Precision of the measurement instruments

4 Measurement Procedure

1. Adjustment of the Stokes' viscosity measurement device.

   (1) Adjust the knobs beneath the base to make the plumb aiming at the center of the base.

   (2) Turn on the two lasers, adjust the beams so that they are parallel and aim at the plumb line.

   (3) Remove the plumb and place the graduated flask with castor oil at the center of the base.

   (4) Place the guiding pipe on the top of the viscosity measurement device.

   (5) Put a metal ball into the pipe and check whether the ball, falling down in the oil, can blocks the laser beams. If not, repeat Step 1.

2. Measurement of the constant velocity of a falling ball.

   (1) Measure the vertical distance s between the two laser beams at least three times.

   (2) Put a metal ball into the guiding pipe. Start the stopwatch when the ball passes through the first beam, and stop it when it passes through the second one. Record the time t and repeat the procedure for at least six times.

3. Measurement of the ball density ρ_2.

   (1) Use electronic scales to measure the mass of 40 metal balls. Calculate the average to find the mass of a single ball.

   (2) Use a micrometer to measure the diameter of the metal balls. Repeat for ten times and calculate the average value.

   (3) Calculate the ball density ρ_2.

4. Measure of the density ρ_1 of the castor oil by using the provided densimeter (one measurement). Use a calliper to measure the inner diameter D of the graduated

flask for six times. Read the ambient temperature from the thermometer placed in the lab.

5. Calculate the value of viscosity coefficient η using equation (8).

5 Calculation and Results

5.1 Measurement Results

5.1.1 Distance between Two Laser Beams

I used a steel ruler to measure the distance between two laser beams.

	initial reading	ending reading	distance S[mm]±1[mm]
S_1	0.000	159.5	159.5
S_2	0.000	159.0	159.0
S_3	0.000	158.0	158.0
$\bar{S}$	0.000	158.8	158.8

Table 2: Distance measurement data

5.1.2 Time of the Ball Passing through Two Laser Beams

I used a stopwatch to measure the time of the ball passing through two laser beams.

time t[s]±0.01[s]	
t_1	7.66
t_2	7.68
t_3	7.69
t_4	7.78
t_5	7.62
t_6	7.85
$\bar{t}$	7.71

Table 3: Time measurement data

5.1.3 The Diameters of the Balls

Micrometer is used to measure the diameters of the balls. I recorded the initial readings and measured 10 balls.

initial reading[mm]		0.005
	end reading	diameter d[mm]±0.004[mm]
d_1	2.000	1.995
d_2	1.995	1.990
d_3	1.990	1.985
d_4	1.990	1.985
d_5	1.995	1.990
d_6	2.005	2.000
d_7	1.995	1.990
d_8	1.990	1.985
d_9	1.995	1.990
d_{10}	2.000	1.995
$\bar{d}$	1.996	1.991

Table 4: Measurement data for the diameters of the balls

5.1.4 Inner Diameter of the Flask

I used a calliper to measure the inner diameter of the flask. Since the inner shape of the flask is not a standard circle, I measured 6 times

diameter D[mm]±0.02[mm]	
D_1	59.00
D_2	60.10
D_3	58.88
D_4	59.68
D_5	60.32
D_6	58.82
$\bar{D}$	59.47

Table 5: Measurement data for the inner diameter of the flask

5.1.5 Other Physical Quantities

I also measured the castor oil's density, the mass of 40 metal balls, temperature in the lab once, and the acceleration due to gravity is given to us.

density of the castor oil [g/cm^3]±0.001[g/cm^3]
0.955
mass of 40 metal balls m[g]±0.001[g]
1.358
temperature in the lab T[^{o}C]±2[^{o}C]
26
acceleration due to gravity in the lab g[m/s^2]
9.794

Table 6: Values of other physical quantities

5.2 Calculation of Viscosity Coefficient η

$$R_c = 0.5 \times \bar{D} = 29.74[mm] = 2.974 \times 10^{-2}[m]$$
$$R = 0.5 \times \bar{d} = 0.9955[mm] = 9.955 \times 10^{-4}[m]$$
$$t = 7.71[s]$$
$$S = 158.8[mm] = 1.588 \times 10^{-1}[m]$$
$$\rho_1 = 0.955[g/cm^3] = 0.955 \times 10^3[kg/m^3]$$
$$\rho_2 = \frac{3m}{160\pi R^3} = 8.215[g/cm^3] = 8.215 \times 10^3[kg/m^3]$$
$$\eta = \frac{2}{9}R^2\frac{(\rho_2 - \rho_1)gt}{(1 + 2.4\frac{R}{R_c})s} = 7.003 \times 10^{-1}[kg/(m \cdot s)]$$

6 Measurement Uncertainty Analysis

6.1 Multiple Measurements Yield to Type A Uncertainty

For multiple measurements' uncertainty:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

$$S_X = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{X})^2}$$

$$\triangle_A = \frac{S_X t_{0.95}}{\sqrt{n}}$$

The value of $t_0.95$ and $\frac{t_{0.95}}{\sqrt{n}}$ are giving in Table 7

n	3	4	5	6	7	8	9	10	15	20	≥ 100
$t_0.95$	4.30	3.18	2.78	2.57	2.45	2.36	2.31	2.26	2.14	2.09	≤ 1.97
$\frac{t_0.95}{\sqrt{n}}$	2.48	1.59	1.204	1.05	0.926	0.834	0.770	0.715	0.553	0.467	≤ 0.139

Table 7: The values of $t_{0.95}$ and $\frac{t_{0.95}}{\sqrt{n}}$

6.1.1 Type A Uncertainty of Distance S

$$\bar{S} = \frac{1}{3}\sum_{i=1}^{3} S_i = 158.8[mm]$$

$$S_S = \sqrt{\frac{1}{2}\sum_{i=1}^{3}(S_i - 158.8)^2} = 0.7638$$

$$\triangle_A = 2.48 S_S = 1.894[mm]$$

6.1.2 Type A Uncertainty of Time t

$$\bar{t} = \frac{1}{6}\sum_{i=1}^{6} S_i = 7.71[s]$$

$$S_t = \sqrt{\frac{1}{5}\sum_{i=1}^{6}(S_i - 7.71)^2} = 0.08524$$

$$\triangle_A = 1.05 S_t = 0.08951[s]$$

6.1.3 Type A Uncertainty of Balls' Diameters

$$\bar{d} = \frac{1}{10}\sum_{i=1}^{1} 0 S_i = 1.991[mm]$$

$$S_d = \sqrt{\frac{1}{9}\sum_{i=1}^{1} 0(S_i - 1.991)^2} = 4.792 \times 10^{-3}$$

$$\triangle_A = 0.715 S_d = 3.555 \times 10^{-3}[mm]$$

6.1.4 Type A Uncertainty of Flask's Inner Diameters

$$\bar{D} = \frac{1}{6}\sum_{i=1}^{6} S_i = 59.47[mm]$$

$$S_d = \sqrt{\frac{1}{5}\sum_{i=1}^{6}(S_i - 7.71)^2} = 0.6565$$

$$\triangle_A = 1.05 S_d = 0.6893[mm]$$

6.2 Uncertainty of Directly Measured Physical Quantities

6.2.1 Uncertainty of Distance S

Since the steel ruler's resolution is $\pm 1[mm]$, its data's $\triangle_B$=1[mm]

$$u = \sqrt{\triangle_B^2 + \triangle_A^2} = \sqrt{1 + 1.894^2} = 2.142[mm] = 2.142 \times 10^{-3}[m]$$

$$u_r = \frac{u}{\bar{S}} \times 100\% = \frac{2.142 \times 10^{-3}}{1.588 \times 10^{-1}} \times 100\% = 1.34\%$$

6.2.2 Uncertainty of Time t

Since the stopwatch's resolution is $\pm 0.011[s]$, its data's $\triangle_B$=0.01[s]

$$u = \sqrt{\triangle_B^2 + \triangle_A^2} = \sqrt{0.01^2 + 0.08524^2} = 8.582 \times 10^{-2}[s]$$

$$u_r = \frac{u}{\bar{t}} \times 100\% = \frac{8.582 \times 10^{-2}}{7.71} \times 100\% = 1.11\%$$

6.2.3 Uncertainty of Ball's Diameter d

Since the micrometer's resolution is $\pm 0.004[mm]$, its data's $\triangle_B$=0.004[mm]

$$u = \sqrt{\triangle_B^2 + \triangle_A^2} = \sqrt{0.004^2 + (3.555 \times 10^{-3})^2} = 5.351 \times 10^{-3}[mm] = 5.351 \times 10^{-6}[m]$$

$$u_r = \frac{u}{\bar{d}} \times 100\% = \frac{5.351 \times 10^{-6}}{1.991 \times 10^{-3}} \times 100\% = 0.27\%$$

6.2.4 Uncertainty of Flask's Inner Diameter D

Since the calliper's resolution is $\pm 0.02[mm]$, its data's $\triangle_B$=0.02[mm]

$$u = \sqrt{\triangle_B^2 + \triangle_A^2} = \sqrt{0.02^2 + 0.6893^2} = 0.6896[mm] = 6.896 \times 10^{-4}[m]$$

$$u_r = \frac{u}{\bar{D}} \times 100\% = \frac{6.896 \times 10^{-4}}{5.947 \times 10^{-2}} \times 100\% = 1.16\%$$

Physical quantities	Measurement	Uncertainty	Relative uncertainty
Distance S[m]	1.588×10^{-1}	2.142×10^{-3}	1.34%
Time t[s]	7.71	8.582×10^{-2}	1.11%
Ball's diameter d[m]	1.991×10^{-3}	5.351×10^{-6}	0.27%
Inner diameter D[m]	5.947×10^{-2}	6.896×10^{-4}	1.16%
$\rho_1[kg/m^3]$	955	1	0.1%
40 ball's mass [kg]	1.358×10^{-3}	10^{-6}	0.07%
Lab Temperature T $[^oC]$	26	2	7.69%

Table 8: Uncertainty of directly measured physical quantities

6.3 Uncertainty of Indirectly Measured Physical Quantities

6.3.1 Uncertainty of the Ball's Radius

$$R = \frac{d}{2}$$

$$u_R = \sqrt{(\frac{\partial r}{\partial d}u_d)^2} = \frac{u_d}{2} = 2.676 \times 10^{-6}[m]$$

6.3.2 Uncertainty of the Flask's Radius

$$R_c = \frac{D}{2}$$

$$u_{R_c} = \sqrt{(\frac{\partial R_c}{\partial D}u_D)^2} = \frac{u_D}{2} = 3.448 \times 10^{-4}[m]$$

6.3.3 Uncertainty of the Metal's Density

$$\rho_2 = \frac{3m}{160\pi R^3}$$

$$u_{\rho_2} = \sqrt{(\frac{\partial \rho_2}{\partial m}u_m)^2 + (\frac{\partial \rho_2}{\partial R}u_R)^2} = \sqrt{(\frac{3}{160\pi R^3}u_m)^2 + (\frac{-9m}{160\pi R^4}u_R)^2} = 89.72[kg/m^3]$$

6.3.4 Uncertainty of the Coefficient η

$$\eta = \frac{2}{9}R^2\frac{(\rho_2 - \rho_1)gt}{(1 + 2.4\frac{R}{R_c})s}$$

$$u_\eta = \sqrt{(\frac{\partial \eta}{\partial R}u_R)^2 + (\frac{\partial \eta}{\partial R_c}u_{R_c})^2 + (\frac{\partial \eta}{\partial t}u_t)^2 + (\frac{\partial \eta}{\partial S}u_S)^2 + (\frac{\partial \eta}{\partial \rho_1}u_{\rho_1})^2 + (\frac{\partial \eta}{\partial \rho_2}u_{\rho_2})^2}$$

$$\frac{\partial\eta}{\partial R}u_R = \frac{2(\rho_2-\rho_1)gt}{9S}\cdot\frac{2R(1+\frac{2.4R}{R_c})-R^2\cdot\frac{2.4}{R_c}}{(1+\frac{2.4R}{R_c})^2}\cdot u_R = 3.643\times 10^{-3}$$

$$\frac{\partial\eta}{\partial R_c}u_{R_c} = \frac{2(\rho_2-\rho_1)R^2gt}{9S}\cdot\frac{2.4R}{(R_c+2.4R)^2}\cdot u_{R_c} = 6.067\times 10^{-4}$$

$$\frac{\partial\eta}{\partial t}u_t = \frac{2}{9}R^2\frac{(\rho_2-\rho_1)g}{(1+2.4\frac{R}{R_c})s}\cdot u_t = 7.095\times 10^{-3}$$

$$\frac{\partial\eta}{\partial S}u_S = -\frac{2}{9}R^2\frac{(\rho_2-\rho_1)gt}{(1+2.4\frac{R}{R_c})s^2}u_s = 9.493\times 10^{-3}$$

$$\frac{\partial\eta}{\partial\rho_1}u_{\rho_1} = -\frac{2}{9}R^2\frac{gt}{(1+2.4\frac{R}{R_c})s}u_{\rho_1} = -8.779\times 10^{-5}$$

$$\frac{\partial\eta}{\partial\rho_2}u_{\rho_2} = \frac{2}{9}R^2\frac{gt}{(1+2.4\frac{R}{R_c})s}u_{\rho_2} = 7.877\times 10^{-3}$$

$$u_\eta = 0.0147[kg/(m\cdot s)]$$

$$u_{r_\eta} = \frac{u_\eta}{\eta}\times 100\% = \frac{0.0147}{7.003\times 10^{-1}}\times 100\% = 2.1\%$$

Physical quantities	Measurement	Uncertainty	Relative uncertainty
Ball's radius R[m]	9.955×10^{-4}	2.676×10^{-6}	0.26%
Flask's inner radius R[m]	2.974×10^{-2}	3.448×10^{-4}	1.16%
Ball's density$[kg/m^3]$	8215	89.72	1.09%
Coefficient$[kg/(m\cdot s)]$	7.003×10^{-1}	0.0147	2.10%

Table 9: Uncertainty of indirectly measured physical quantities

7 Conclusion and Discussion

7.1 Conclusion

In the exercise, Stokes' method is used to measure the viscosity coefficient η, and my final result is $7.003\times 10^{-1}\pm 1.47\times 10^{-2}[kg/(m\cdot s)]$ with relative uncertainty equals 2.1%.

The Stokes' method is based on Stokes' Law established by an English scientist Sir George G Stokes: When a spherical body moves down through an infinite column of highly viscous liquid, it drags the layer of the liquid in contact with it. As a result, the body experiences a retarding force and we can use the force as an intermediate quantity to measure η.

After the exercise, I become familiar with fluid's viscosity and Stokes' method, a basic and simple way to calculate the viscosity. In addition, I also learned how to use micrometer and densimeter to calculate micro diameter and fluid's density.

7.2 Discussion

7.2.1 Measurement of Non-transparent Fluid's Viscosity

However, our method can't be easily applied to measure the η of non-transparent fluid because I can't measure the time for the metal ball to pass through the two laser beams. I find other three methods to measure the fluid viscosity.

1. Use the rotational viscometer to measure the torque required to turn an object in the fluid, which is a function of η, and η can be calculating as following formula:

Figure 4: The rotational viscometer

$$\eta = \frac{\tau}{\gamma}$$

τ:shear stress
γ:shear rate

$$\tau = \frac{T}{2\pi R_s^2 L}$$

T:the torque
R_s:spindle radius
L:effective spindle length

$$\gamma = \frac{2\omega R_s^2 R_c^2}{x^2(R_s^2 - R_c^2)}$$

ω:rotational speed
x:radial location where shear rate is being calculated

2. We can use vibrational viscometer ,which operating by measuring the damping of an oscillating electromechanical resonator immersed in a fluid whose viscosity is to be determined.The resonator generally oscillates in torsion or transversely. The higher the viscosity, the larger the damping imposed on the resonator. The resonator's damping may be measured by one of several methods:

   (1) Measuring the power input necessary to keep the oscillator vibrating at a constant amplitude. The higher the viscosity, the more power is needed to maintain the amplitude of oscillation.

   (2) Measuring the decay time of the oscillation once the excitation is switched off. The higher the viscosity, the faster the signal decays.

   (3) Measuring the frequency of the resonator as a function of phase angle between excitation and response waveforms. The higher the viscosity, the larger the frequency change for a given phase change.

3. Rectangular-slit viscometer can also be used to measure the viscosity.The basic design of a rectangular-slit viscometer consists of a rectangular, slit channel with uniform cross-sectional area. A test liquid is pumped at a constant flow rate through this channel. Multiple pressure sensors flush mounted at linear distances along the stream-wise direction measure pressure drop as depicted in Figure 5.

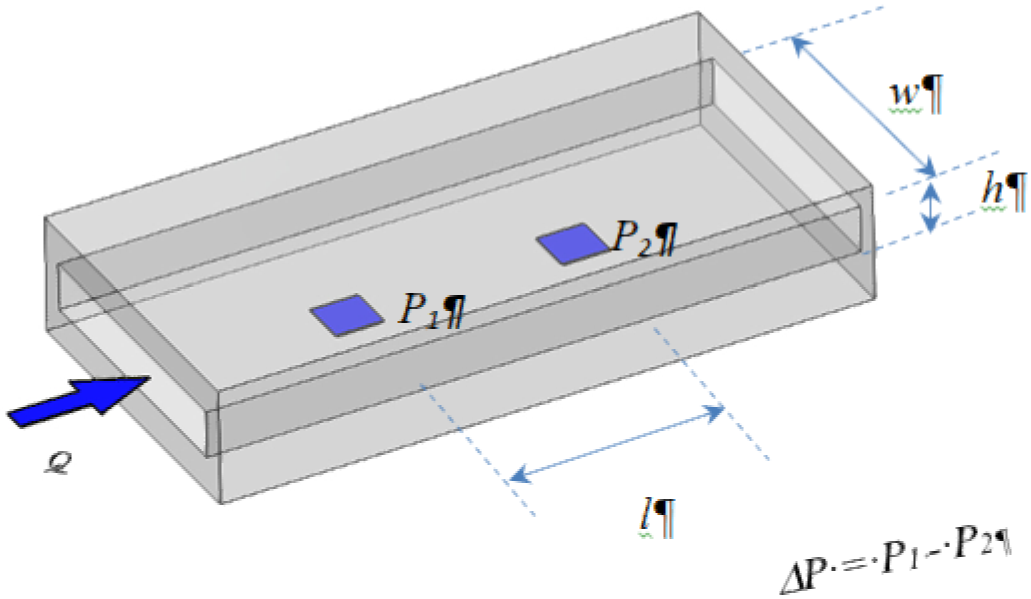

Figure 5: Rectangular-slit viscometer

The slit viscometer is based on the fundamental principle that a viscous liquid resists flow, exhibiting a decreasing pressure along the length of the slit. The pressure decrease or drop $\triangle P$ is correlated with the shear stress at the wall boundary. The apparent shear rate is directly related to the flow rate and the dimension of the slit. The apparent shear rate, the shear stress, and the apparent viscosity are calculated:

$$\gamma = \frac{6Q}{wh^2}$$

γ:apparent shear rate
Q:flow rate
w:width of the flow channel
h:depth of the flow channel

$$\sigma = \frac{hw \triangle P}{2(w+h)l}$$

$\triangle P$:pressure difference between the leading pressure sensor and the last pressure sensor
l:the distance between the leading pressure sensor and the last pressure sensor

$$\tau_a = \frac{\sigma}{\gamma}$$

To determine the viscosity of a liquid, pump the liquid sample to flow through the slit channel at a constant flow rate and measure the pressure drop. Following these equations, calculate the apparent viscosity for the apparent shear rate. For a Newtonian liquid, the apparent viscosity is the same as the true viscosity and the single shear rate measurement is sufficient. For non-Newtonian liquids, the apparent viscosity is not true viscosity. In order to obtain true viscosity, measure the apparent viscosities at multiple apparent shear rates. Then calculate true viscosities, τ, at various shear rates using Weissenberg-Rabinowitsch-Mooney correction factor:

$$\frac{1}{\tau} = \frac{1}{2\tau_a}(2 + \frac{dln\gamma}{dln\sigma})$$

7.2.2 Error Analysis

1. The biggest cause for error in measurement is time. Since I clicked the stopwatch when I saw the ball block the laser, it's very inaccurate for my eyes to determine the time.

2. The second cause is the temperature in the lab. Even though I have measured the temperature in the lab through thermometer, the temperature is still changing in the lab and the thermometer also has a quite big relative uncertainty. Since fluid's viscosity is determined by temperature and its type, the temperature could have a significant impact on the fluid's viscosity.

3. We measure the mass of forty metal balls at one time because their mass is about 1.3[g]. If I measure one or ten balls at a time, the significant figures may not be enough for me to get a precise value of one ball's mass. However, since I only measure the time for six times, the mass of the six balls may be slightly different from the 40 balls, which might cause error.

4. Since the flask is not a standard circle, I measure its inner diameter for six times but I think it's not enough because their relative uncertainty is big.

7.2.3 Improvements and Suggestions

1. Use laser sensors and a computer system to measure the time travelled. When the laser is blocked it will start timing and stop until another laser is blocked. I think it'll be more accurate.

2. When I use the steel ruler to measure the distance S, my initial reading is always 0.000, which is not good for measurement because the 0 point of the ruler may be not accurate. I should use different initial reading when I use a steel ruler later.

8 Data Sheet

Data sheet is attach to the report

9 Reference

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