IS-PHYS Lab3

Lab3: Viscosity

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Abstract

In this lab, we measured the dynamic viscosity of castor oil and kinetic viscosity of oil and 10% w/v sodium solution spiritedly by the falling ball method and capillary method and calculated the uncertainty of the dynamic viscosity of oil. We calculated the dynamic viscosity of castor oil is 0.491($Pa \cdot s$) and $U_\eta = 5.912 \times 10^{-3}(Pa \cdot s)$ and kinetic viscosity of oil and 10% w/v sodium solution is $1.\times 10^{-3}(Pa \cdot s$).
During this lab, we also acquired the skills of how to use the instruments for measurement properly to reduce the error and learned the change of viscosity with temperature.

1 Introduction

Viscosity is an important physicochemical property of a fluid. The estimation of fluid velocity is important to our daily life. Viscosity measurements are widely made in a variety of industries involving petroleum, pharmaceuticals, medical devices, coatings, adhesives, food and so on.

In this lab, we used two methods to measure the fluid velocity: the falling ball method and the capillary method.

Background of viscosity

Viscosity describes the fluid's resistance to flow. It can be classified into dynamic (or absolute) viscosity and kinematic viscosity. However, viscosity is usually referred to as dynamic viscosity.

Dynamic viscosity can be understood as the friction between the adjacent layer of water when they have different speeds. The unit for the dynamic viscosity is Pa·s.
When the shear stress is linearly proportional to the velocity gradient, the viscosity is constant for a given temperature or pressure. A fluid that behaves in this way is called Newtonian fluid. All gases and most simple liquids such as water and castor oil are Newtonian.

Kinematic viscosity v is the measure of the fluid's inherent resistance to the flow. It is given by

$$v = \frac{\mu}{\rho} \tag{1}$$

where ρ is fluid density and the unit of kinematic viscosity is m^2/s or mm^2/s.

Measure the viscosity of fluids is typically based on one of three phenomena—an object moving through a fluid, fluid flowing through a resistive component, and a moving surface in contact with a fluid. These phenomena utilize three major viscometers in the industry, falling-ball, capillary, and rotational viscometers. In this lab, we will use the former two, namely the falling ball method and the capillary method.

Experiment 1. Viscosity measurement using a falling ball viscometer

Theory

A small steel ball dropping into the castor oil is measured, and this technique is based on Stroke's law. We determine the velocity by measuring the time the ball dropping through the oil via gravity.

According to Stoker's law, when the ball is falling, the viscous drag force is given by

$$f = 3\pi\eta v d \tag{2}$$

where η is the viscosity of the castor oil, v is the velocity of the ball， and d is the diameter of the ball.

When the ball is dropping, there are three forces exerted on the ball: the weight of the ball mg, buoyant force Fb, and viscous drag force f.

This buoyant force experienced by the ball can be described as:

$$F_b = \frac{1}{6}\rho g\pi d^3 \tag{3}$$

where ρ is the density of the castor oil.

The density of the castor oil ρ (kg/m^3) using the empirical formula:

$$\rho(T) = 974 - 0.614\,T \tag{4}$$

where T is the temperature in Celsius.

The ball will first accelerate, and the magnitude of the viscous drag force will grow. When the three forces satisfy the equation:

$$mg = F_b + f \tag{5}$$

The ball started to move uniformly.

As the weight of ball mg can be written as:

$$mg = \frac{1}{6}\rho_0 g\pi d^3 \tag{6}$$

where ρ_0 is the density of the steel ball.

So combining the above formulas we get the viscosity η of the castor oil:

$$\eta = \frac{(\rho - \rho_0)gd^2}{18v} \tag{7}$$

Equipment

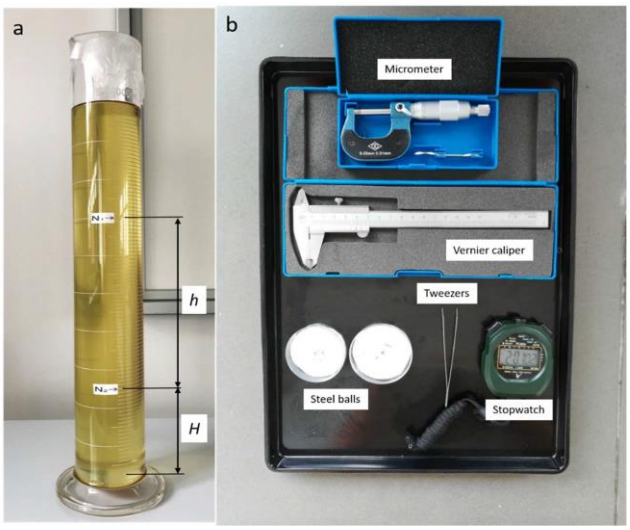


Figure 1: Experiment set-up of the falling ball method

Figure 1 shows the experiment set-up for the falling ball method. The measuring cylinder was filled with the caster oil, whose viscosity η is to be measured. The N_1 and N_2 value is the distance where the ball is moving uniformly, and $h = N_1$ - N_2 is the magnitude of the distance.
The ball is to drop. The micrometer is used to measure the diameter of the little ball. The Vernier caliper is used to measure the inner diameter of the measuring cylinder. The tweezer is used to hold the ball, because if hands hold the ball directly, the ball will get easily rust and the diameter and mass will be hard to measure. The Stopwatch is used to measure the time of the dropping process.
Besides we also need a thermometer to measure the temperature of the room, which indicates the temperature of the oil.

Procedures
Firstly, we measured the temperature T of the room. Then we used the vernier cylinder to measure the inner diameter D_0 of the inner measuring cylinder.

Then we chose the 0.9 mm steel balls, measuring their diameter with a micrometer and tweezer. For each ball, we measured its diameter 6-8 times from different angles and took the average, to reduce the error.

Then we drop the ball from the center of the liquid surface. When we do this, we drop it very low to reduce the initial speed of the ball. And we use the stopwatch to record the travel time t of the ball over the measured distance h.

Then we repeat this measurement with 3 steel balls of the same size. Then we calculated the velocity v of the ball and the viscosity of the castor of the ball and analyzed the measurement error.

Experiment 2. Viscosity measurement using a capillary viscometer

Theory

The capillary viscometer is widely used for Newtonian fluids. The glass capillary is the simplest and least expansive viscometrical system available commercially.

In this method, the viscosity is determined by measuring the time required for a given fluid volume to flow through a defined length l of glass capillary due to the hydrostatic pressure of the fluid column itself.
This method is based on Poiseuille's law or Hagen-Poiseuille's law:

$$Q = \frac{V}{t} = \frac{\pi r^4 \delta P}{8\eta l} \tag{8}$$

where ρ is the fluid density. In practice, it is hard to obtain precise values for δP, l and r.

We used the normal water as the standard liquid for comparison purpose. The flow time for a standard liquid and the liquid to be tested is proportional when they have the same volume and the same capillary. And the ration is the same with their viscosity. So we have:

$$\frac{v}{v_s} = \frac{t}{t_s} \tag{9}$$

Therefore:

$$v = \frac{v_s}{t_s} = \frac{\eta_s}{\rho_s t_s} t \tag{10}$$

Equipments

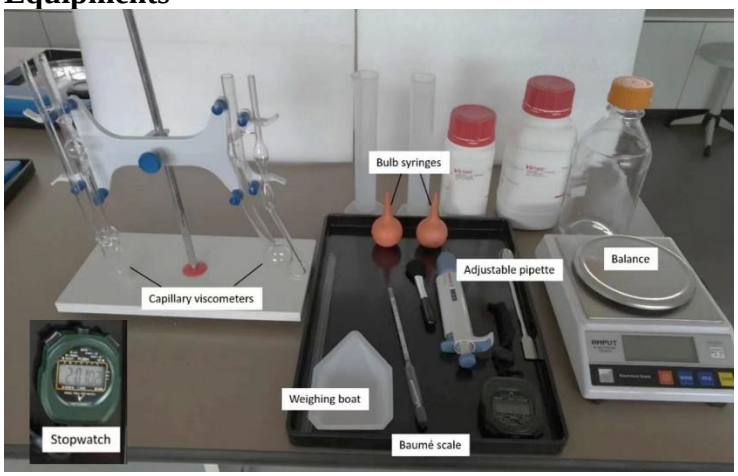


Figure 2: Experiment set-up of capillary viscometer method

Figure 2 shows the experiment set-up for the capillary viscometer method.
The balance is used to weigh the sodium. The weight boat is used to hold the sodium on balance. The capillary is used to measure the flow velocity of the solution and water. The stopwatch is used to count the time. The Baume scale is used to measure the density of the prepared sodium solution. The bulb syringe are used to push or draw away the air into or from the capillary to fill in or push out the water by changing air pressure in the capillary.

Besides, we also need a glass stirrer, a volumetric, a cylinder, and a beaker to prepare the sodium solution.

Procedures
Firstly, we measured the temperature T of the room in order to know the tabulated values of water of water density.

Then, we prepared the 10% w/v (mass/value) sodium water. Firstly, we added about 70 mL water into a beaker and weighed 10.00 ± 0.20 g sodium. Then we added the sodium chloride carefully to the beaker and stirred it with a glass stirrer. After fully dissolving, we transferred the solution to the 100 mL volumetric flask and used the disposable pipette to carefully bring water to the solution until the volume reaches 100 mL. At last, we transferred the 10% w/v sodium water to the cylinder for later usage.

Then we used the Baumé to calculate the density of the prepared solution. The specific gravity of the solution:

$$specific\ gravity = \frac{144.3}{144.3\ -\ \text{degrees Baumé}} \tag{11}$$

Specific gravity measures the density of a liquid ρ in relation to water ρ_s to determine the prepared solution's density ρ , which is given by

$$specific\ gravity = \frac{\rho}{\rho_s} \tag{12}$$

Then we chose the Cannon-Fenske viscometer to measure the viscosity of water as a standard fluid. We used the adjustable pipette to transfer 8.00 mL of water to the Cannon-Fenske viscometer and record the flow time t_s required for the water to go through the capillary between two lines M1 and M2. When the temperature is between 0 – 40℃, we can use the formula:

$$\eta_s(T) = 4.040625 \times 10^{-5} \frac{418.6263}{e^{T+110.4}} \tag{13}$$

After washing the viscometer, we recorded the time t for the 8.00 mL solution to go through the same capillary, and washed the viscometer for at least three times. At last, we calculated the viscosity and kinetic viscosity of the test solution.

2 Data

The falling ball experiment
The Room temperature: T = 23.5 ± 0.2℃. The density of the oil undert this temperature is 959.5 kg/m^3.
Table 1 shows the diameter measured by the micrometer caliper.
The d_n is the number we read from the caliper. And the $d_{average}$ is the average number of d_n , and minus the zero error.

Table 1. Diameter of the 3 steel balls

Ball 1	d (1.2mm)	Ball 2	d (1.2mm)	Ball 3	d (1.2mm)
$d_0(zero\ error)$	-0.010	d_0	-0.010	d_0	-0.010
d_1	1.190	d_1	1.190	d_1	1.190

d_2	1.193	d_2	1.180	d_2	1.195
d_3	1.185	d_3	1.180	d_3	1.197
d_4	1.182	d_4	1.182	d_4	1.187
d_5	1.187	d_5	1.186	d_5	1.195
d_6	1.186	d_6	1.182	d_6	1.196
d_7	1.191	d_7	1.170	d_7	1.195
$d_{average}$	1.197	$d_{average}$	1.188	$d_{average}$	1. 203

The capillary viscometer experiment

In this experiment we measured the temperature of solution is 23.5 Celsius degree, the Bé value is 10 Bé, the flowing time of 8 mL prepared solution is 272.32 s, the flowing time for 8 mL water is 251.67 s.

3 Analysis and Discussions

The falling ball experiment

The zero error is -0.010 mm. The calculated value of density of oil is 959.5 kg/m^3 according to equation (4).

Table 2 shows the measured value traveling time of the balls and the calculated value of the average time, velocity, and viscosity of the oil according to equation (1) and (7).

Table 2. Travel time and velocity of the ball and the viscosity of castor oil

t (s)	$t_{average}$(s)	v(m/s)(v=h/t)	η(Pa·s)
33.47	33.3	0.0060	0.491
34.06			
32.37			

So the dynamic viscosity of castor oil is 0.491 (Pa·s).

According to lab manual,

The uncertainty of liquid error:$U_{\rho_0} = 0.5 \cdot 10^3\ kg/m^3$,

The uncertainty of distance of dropping:$U_h = 1.0\ mm$,

The uncertainty of temperature: $U_T = 0.2\ Celsius$ degree

The uncertainty of dropping time: $U_t = 0.2s$

The uncertainty of diameter of the steel of balls:$U_d = 0.004\ mm$

The uncertainty of the castor oil viscosity:

$$U\eta \cong \eta \sqrt{\left(\frac{\sqrt{2}U_\rho}{\rho_0 - \rho}\right)^2 + \left(\frac{2U_d}{d}\right)^2 + \left(\frac{U_h}{h}\right)^2 + \left(\frac{U_t}{t}\right)^2} \quad (14)$$

So the uncertainty of castor oil dynamic viscosity:$U_\eta = 5.912 \times 10^{-3}(Pa \cdot s)$

So we determined the $\eta' = \eta \pm U_\eta = 0.4916 \pm 5.912 \times 10^{-3}(Pa \cdot s)$.

Error Analysis for experiment 1
The error may be caused by the parallax. If eyes are higher than the scale, the time will be recorded later than the ball reach the scale. This will lead to incorrect time t. To reduce this, we should read several times, and take the average value of the time as t.

If the cylinder is tilted, as long as we read the scale N1 and N2 parallelly, then the time will be accurate. However, the dropping distance will shrinked, so the viscosity will smaller than the real value.

The position where we drop the ball is important because the fluid flows differently regarding the position. If we drop the ball very close to the wall of the cylinder, if will drop at different speed thus affecting the measure of time and viscosity.

I think the cross-sectional area of the ball affect the experiment most. The balls are rusted and their diameters from different angles differed significantly. Also, the rust steel has a rough surface which will add to the drag force. To improve, we can use new steel ball.

The capillary viscometer experiment
Table 3 shows the calculation value using equation (9)(10)(11)(12)(13) with the measured value: temperature of solution is T=23.5°C, the Bé value is 10 Bé, the flowing time of 8 mL prepared solution is 272.32 s, the flowing time for 8 mL water is 251.67 s. And the water density is looked up in the appendix A in lab manual.

Table 3. Viscosity measurement using a capillary viscometer

		Cannon-Fenske
T(°C)		23.5
Water	ρ_s (kg/m^3)	997.417
	η_s (Pa·s)	9.210 x 10^{-4}
	v_s (m2/s)	9.234 x 10^{-7}
	t_s (s)	251.67
NaCl (10% w/v)	Bé	10.0
	ρ (kg/m^3)	1071.236
	t (s)	272.32
	ν (m^2/s)	1.001 x 10^{-6}
	η (Pa·s)	1.072 x 10^{-3}

Error Analysis for experiment 2
If the viscometer is tilted, which means the dilution of the gravity, and lead to a larger viscosity.

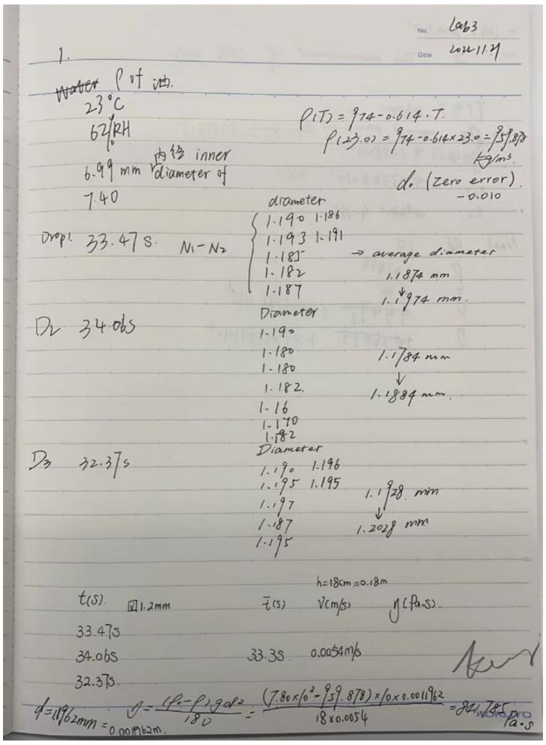
If the temperature rises during the test, the viscosity will increase. If the temperature decreases, the viscosity will decrease.

Whether the glass viscosimeter is infiltrated by the solution or water before it is filled with the type of liquid also determines whether the error is big. If we did not infiltrate the viscosimeter of the sodium solution after we measured the water, the ID water left in the viscosimeter will dilute the solution and reduce its viscosity.

4 Conclusions

In this lab, we used two methods to measure the fluid velocity: the falling ball method and the capillary method and we analyzed the uncertainty of the viscosity. During this lab, we also acquired the skills of how to use the instruments for measurement properly to reduce the error and learned the change of viscosity with temperature, like read the scale of cylinder parallelly and weigh the steel ball with micrometer.
Since we do not have a theoretical value, we cannot estimate the error of our value. But we can still improve by using more standard steel balls, measuring several times and taking the average value to make the value more accurate.

Raw data



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1.
~~Water~~ ρ of 油.
23°C
62%RH
6.99 mm 内径 inner diameter of
7.40

$\rho(T) = 974 - 0.614 \cdot T$
$\rho(23.0) = 974 - 0.614 \times 23.0 = 959.878$ kg/m³

d_0 (zero error) −0.010

Drop1 33.47s $N_1 - N_2$

diameter
1.190 1.186
1.193 1.191
1.185 → average diameter
1.182 1.1874 mm
1.187 ↓ 1.1974 mm

D2 34.06s

Diameter
1.190
1.180
1.180 1.1784 mm
1.182 ↓
1.16 1.1884 mm
1.170
1.182

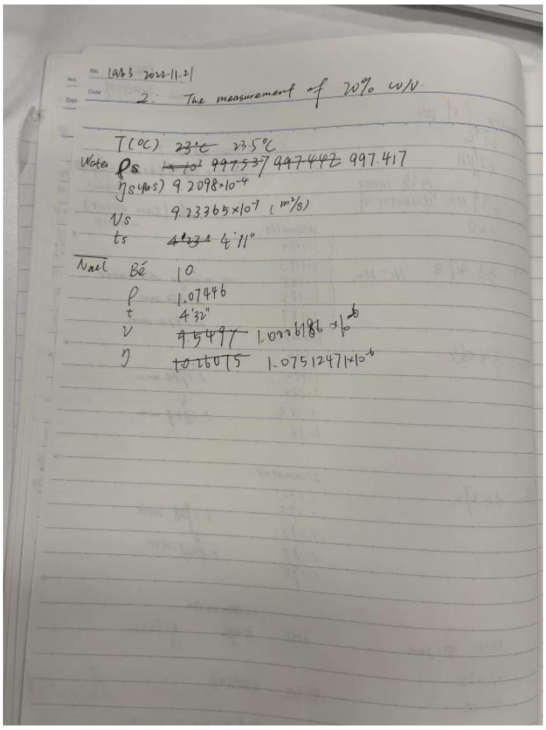
D3 32.37s

Diameter
1.190 1.196
1.195 1.195
1.197 1.1928 mm
1.187 ↓
1.195 1.2028 mm

h=18cm=0.18m

t(s)	d 1.2mm	$\bar{t}$(s)	V(m/s)	η(Pa·s)
33.47s				
34.06s		33.3s	0.0054m/s	
32.37s				

d=1.1962mm=0.0011962m. $\eta = \frac{(\rho_s - \rho_l) g d^2}{18v} = \frac{(7.80\times10^3 - 959.878)\times10\times0.0011962^2}{18\times0.0054} = 981.785$ Pa·s



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Date

2. The measurement of 20% w/v.

T(°C) ~~23°C~~ 23.5°C
Water ρ_s ~~1×10³~~ ~~997.537~~ ~~997.442~~ 997.417
η_s(Pa·s) 9.2098×10⁻⁴
V_s 9.23365×10⁻⁷ (m²/s)
t_s ~~4'23"~~ 4'11"

NaCl Bé 10
ρ 1.07496
t 4'32"
ν ~~9.5497~~ 1.0006186×10⁻⁶
η ~~1.0260T5~~ 1.07512471×10⁻⁶