

Measurement by Uniform Falling Ball Method Viscosity Coefficient of Rapeseed Oil

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Abstract

The viscosity coefficient of liquid is an important parameter to characterize the properties of liquid, which is great significance in production and life. In this paper, the viscosity coefficient of rapeseed oil is measured by the falling ball method. Experimentally, the method of determining the uniform downward motion of a ball is to use different liquid depths to ensure that the time for the ball to move within a fixed distance is equal. Therefore, a suitable depth is selected to measure the viscosity coefficient of rapeseed oil. The factors affecting the measurement of rapeseed oil viscosity coefficient are studied by changing the ball diameter, liquid depth and temperature experimentally, thus providing a reliable method for the experimental optimization measurement of liquid viscosity coefficient.

Keywords

Falling Ball Method; Viscosity Coefficient; Mechanical Equilibrium.

1. Introduction

When the fluid flows, there is internal friction in the relative motion between different laminar flows. When the object moves in the fluid, it is also affected by the internal friction, which is shown as resistance to the object. Stokes proposed that the internal friction of the sphere in the liquid is: ^[1]

$$F = 6\pi\eta vr \quad (1)$$

where r is the radius of the ball, v is the velocity of the ball, and η is viscosity coefficient (the physical quantity describing the viscosity of the fluid, in centipoise (cp)). Formula (1) is the Stokes formula in the formula in conditions of no eddy current and infinite extension. Liquid viscosity is widely used in many fields such as production, life, chemical industry, engineering technology, medical treatment and national defense ^[2]. For example, human cardiovascular health is judged by measuring human blood viscosity in medicine; the efficiency of oil transportation is improved by measuring the viscosity of oil in pipeline transportation. Domestic and foreign scholars have studied the viscosity of liquid in depth. The common methods for measuring the viscosity coefficient are falling ball method, rotating method and capillary method (constant flow method) ^[3].

In this paper, the viscosity coefficient of rapeseed oil was measured by falling ball method, the influence of error sources on the experimental results was analyzed, and the experimental results were corrected to make the measurement more accurate. According to the experimental principle, the oil depth of the ball falling at a uniform speed was judged to ensure that the ball fell at a uniform speed firstly. Then the influence of the ball diameter, liquid depth and temperature on the experimental results was emphatically studied. Through experiments, the influence factors of measurement results such as the ball falling off the axis, the temperature change of the experiment, and the uneven density inside the liquid are analyzed. Combining the experiment process and results, suggestions are provided for the optimization of the experiment.

2. Experimental Principle and Device

2.1 Principle and Method of Measuring Liquid Viscosity Coefficient

When an object moves in the liquid, it will be subject to the viscous resistance of the liquid. The falling ball method is used to measure the viscosity coefficient of liquid: let the ball fall freely, and it will be subjected to gravity G , buoyancy F_0 and liquid viscous resistance F . The force of the ball under the liquid surface is shown in Fig.1. We determine the liquid viscosity coefficient by analyzing the force and motion state of the ball. It can be seen from Fig.1 that the downward gravity G is opposite to the upward buoyancy F_0 and viscous resistance F . It can be seen from Formula (1) that the viscous resistance is proportional to the velocity of the ball. Since the ball is still in the process of accelerated motion when it just enters the liquid surface, F gradually increases. When F increases to a certain extent, the three forces G , F_0 and F are satisfied the conditions of equilibrium:

$$G = F_0 + F \tag{2}$$

where $G = mg = 4\rho_0 g\pi r^3 / 3$, $F_0 = 4\pi\rho g r^3 / 3$, m is the mass of the ball, ρ_0 and ρ are the density of the ball and the density of the measured liquid respectively.

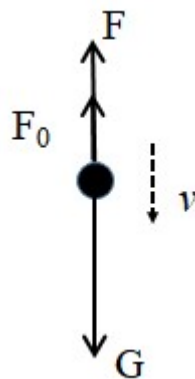


Fig. 1 Schematic diagram of the force exerted on the falling ball in liquid

Formula (1) combined with formula (2), the viscosity coefficient of liquid in ideal state can be obtained:

$$\eta = \frac{(\rho_0 - \rho)}{18v} g d^2 \tag{3}$$

where d is the diameter of the ball. The uniform speed of the ball in liquid can be expressed as $v=l / t$. In the experiment, due to the limitation of experimental conditions, the depth of the liquid is always limited. Formula (3) can be modified as:

$$\eta = \frac{(\rho_0 - \rho)}{18v} g d^2 \frac{1}{(1 + 2.4 \frac{d}{D})(1 + 3.3 \frac{d}{2H})} \quad (4)$$

where D and H are the diameter of the measuring cylinder and the depth of liquid in the cylinder respectively. In the experiment, when the falling velocity of the ball is large, which may lead to turbulence, the viscosity coefficient is small. In the case of laminar flow, the viscosity coefficient of the liquid is larger, it can be modified by the Reynolds number Re [5]. Re is expressed as:

$$Re = \frac{\rho v d}{\eta} \quad (5)$$

Generally, when $1 < Re < 10$, the viscous resistance F can be expressed as:

$$F = 6\pi\eta'vr(1 + \frac{3}{16}Re - \frac{19}{1080}Re^2) \quad (6)$$

η' indicates the modified viscosity coefficient. It can be expressed as [6]:

$$\eta' = \frac{(\rho_0 - \rho)d^2g}{18v(1 + 2.4 \frac{d}{D})(1 + 3.3 \frac{d}{2H})} \frac{1}{(1 + \frac{3}{16}Re - \frac{19}{1080}Re^2)} \quad (7)$$

2.2 Experimental Device

According to Stokes formula, the viscous resistance F of the small ball in the liquid is proportional to the moving speed of the small ball. When the three forces G , F_0 and F of the small ball is balanced, the ball will fall at a uniform velocity, which is called the limited velocity [7]. According to this feature, the viscosity coefficient of rapeseed oil is measured at uniform velocity of the small ball in the experiment.

According to the above ideas, we designed the experimental device as shown in Fig.2. The distance between the two photoelectric gates (PG1 and PG2) on the viscosity coefficient tester remains unchanged $l=100\text{mm}$. The distance between the upper photoelectric gate and the liquid surface is AB , recorded as L , and its initial value is $L_0 = 20\text{mm}$. Then, the whole photoelectric gates are moved downward x , $2x$, $3x$, ..., where $x=50\text{mm}$. At this time, the distance from the photoelectric gates to the water surface is L_0 , L_0+x , L_0+2x , L_0+3x , In the experiment, we successively lowered the photoelectric gates to measure the fall time of the ball when between the two photoelectric gates. Whether the distance of the photoelectric gate from the liquid surface is L_0+nx or $L_0+(n+1)x$, the duration over which the small ball passes through it remains consistent. Then we found the limit velocity of the ball.

In the experiment, the liquid (rapeseed oil) temperature $T= 22 \text{ }^\circ\text{C}$, the liquid depth $H=335\text{mm}$, and the inner diameter of the measuring cylinder $D=61.38\text{mm}$. In order to find the limit velocity of the ball with different diameters ($d=20\text{mm}$, 30mm), we moved the photoelectric gate down 50mm , 100mm , 150mm , 200mm in order to measure the fall time between the two photoelectric gates. See Table 1 for the measurement data.

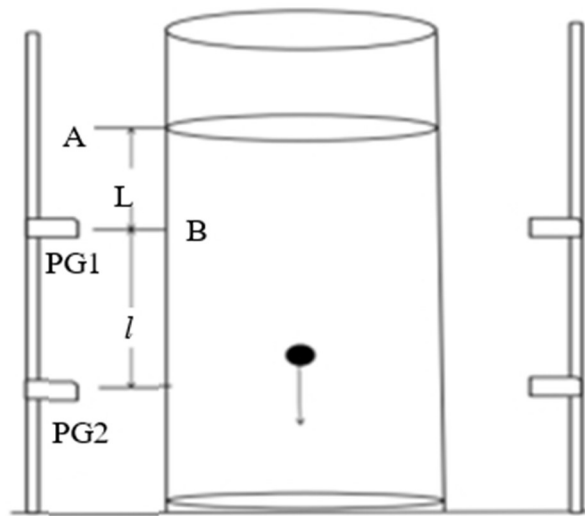


Fig. 2 Schematic diagram of experiment

Table 1. The fall time with different distance L (l=100mm)

	L/mm	20	70	120	170	220
d=2mm	t ₁ /s	0.62	0.65	0.68	0.68	0.68
d=3mm	t ₂ /s	0.32	0.35	0.37	0.38	0.38

It can be seen from Table 1 that for a small ball with d=2mm, the velocity of the small ball below 120mm from the water surface reaches the limit velocity. For a small ball with d=3mm, the velocity of the small ball below 170mm from the liquid surface reaches the limit velocity. Therefore, we can place the photoelectric gate below 170mm from the liquid surface to ensure that the small ball with a distance of 2mm to 3mm falls at a uniform velocity during the falling process.

3. Factors Affecting the Viscosity Coefficient of Rapeseed Oil

3.1 The Influence of Ball Diameter on the Determination of Rapeseed Oil Viscosity Coefficient

Density of rapeseed oil and steel ball are $\rho = 0.917 \times 10^3 \text{ kg/m}^3$ and $\rho_0 = 7.87 \times 10^3 \text{ kg/m}^3$ respectively. The depth of rapeseed oil is H=335mm. the distance between the two photoelectric gates is l=100mm. In order to ensure that the ball moves at a uniform velocity when passing through the two photoelectric gates, the distance between the upper photoelectric gate and the liquid surface is L=200mm. The movement time of the ball between the photoelectric gates is taken as the average time of multiple measurements value, recorded as \bar{t} . The experimental temperature is always maintained at 22°C and internal diameter of measuring cylinder D=61.38mm. The measurement results of balls with different diameters (d=2.0mm, 2.5mm and 3.0mm) are shown in Table 2.

Table 2. The viscosity coefficient of rapeseed oil with different ball diameter

d/mm	l/mm	H/mm	\bar{t} /s
2.0	100	335	0.60
2.5	100	335	0.44
3.0	100	335	0.34

The movement time of the balls with diameters of 2mm, 2.5mm, and 3mm measured to pass through the two photoelectric gates is 0.60s, 0.44s and 0.34s respectively, as shown in Table 2. According to formulas (4) and (5), the viscosity coefficient and Reynolds number of rapeseed oil measured when small balls with three different diameters are calculated, as shown in Table 3. The Reynolds number calculated is too large, so the viscosity coefficient of rapeseed oil is modified by formula (7). The modified results are basically consistent with the recognized values of rapeseed oil at 22 °C. But there are still errors. The main factors are as follows. Firstly, the estimate reading error. The error generated when measuring the diameter of a small ball using a caliper. The error generated by estimating the depth of a liquid using a ruler. The method of taking the average of multiple measurements was used in the experiment, to reduce accidental errors [8]. Secondly, the small ball falling off-center. When the small ball falls in the measuring cylinder, the fluid velocity is maximum at the center, and the velocity near the wall of the measuring cylinder gradually decreases. If the small ball falls off the center axis, the final measurement result of the viscosity coefficient may also be too large. In the experiment, the small ball is dropped through the funnel. The small ball rotates and falls, and collides with the funnel wall at the exit of the funnel after it is put into the funnel. The small ball has a certain distance before entering the liquid, so it may be falling off-center, and even cause turbulence after contacting the liquid. In the experiment, the Reynolds number is too large, and the small ball will cause turbulence after falling into the liquid. Therefore, the experimental results are modified by formula (7). Finally, uneven density of liquid. The main reason for the uneven density is that there are a few small bubbles in the measured liquid. The contact between the small ball and the small bubble in the fall has a certain impact on the movement of the small ball. So the multiple measurements are used to reduce such errors in the experiment.

According to the analysis of the measurement results of the viscosity coefficient of rapeseed oil, the diameter of the small ball has a great influence on the measurement results of the viscosity coefficient of rapeseed oil. In the experiment of falling ball method, the measurement results of the viscosity coefficient of rapeseed oil are larger with increasing the diameter of the ball. Meanwhile, the error between the measurement results and the correction results increases as the diameter increases. So choosing the appropriate size of the small ball can improve the accuracy of the measurement results. Obviously, it is more appropriate to choose a 2mm or 2.5mm diameter ball for the experiment.

Table 3. The viscosity coefficient of rapeseed oil with different ball diameter

d / mm	Re	η/cp	η'/cp	Relative error/%
2.0	3.68	82.62	56.91	3.9%
2.5	5.59	92.76	61.90	4.5%
3.0	7.96	101.16	70.89	19.7%

3.2 The Influence of Rapeseed Oil Depth on the Determination Viscosity Coefficient

Table 4. The viscosity coefficient of rapeseed oil with different liquid depth

H/mm	t/s	η'/cp	Relative error/%
335	0.66	64.57	0.47
305	0.66	64.47	0.31
275	0.65	63.08	1.90
245	0.64	61.66	4.10
215	0.51	46.44	27.70

The ideal condition of this experiment is that the ball falls in an infinitely extended liquid at a uniform speed [9]. In this experiment, the depth of rapeseed oil in the measuring cylinder is limited, which affects the experimental results. The diameter of the ball used in the experiment is 2.5mm. The temperature of the rapeseed oil is always 20°C. And the depth of rapeseed oil is changed. The experimental data and calculation results are shown in Table 4.

According to the data in Table 4, we conducted fitting analysis on the viscosity coefficient with liquid depth H and relative error with depth H, as shown in Fig.3 and Fig.4 respectively. The results in Fig.3 indicate that the viscosity coefficient η' of rapeseed oil increases with the increasing H and tends to stabilize at 300-350mm. Fig.4 shows that the relative error decreases as the liquid depth H increases. The error is less than 5% within the depth range of 300-350mm, which is within the allowable range of experimental error. Therefore, in order to improve the accuracy of the experimental results when measuring the viscosity coefficient of rapeseed oil using the falling ball method at room temperature, the liquid depth should be greater than 300 mm.

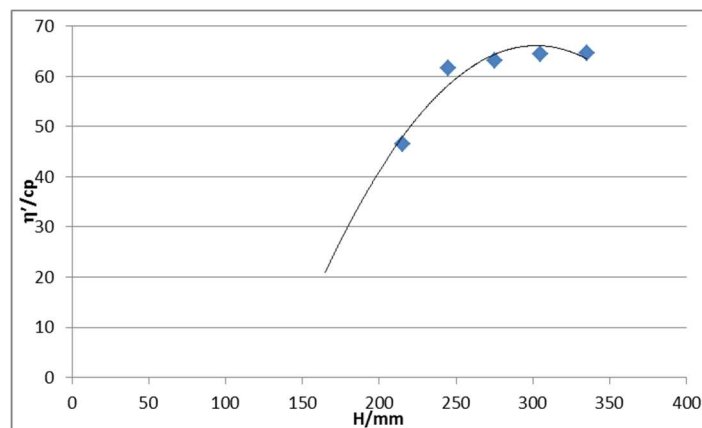


Fig. 3 Variation curve of viscosity coefficient with liquid depth

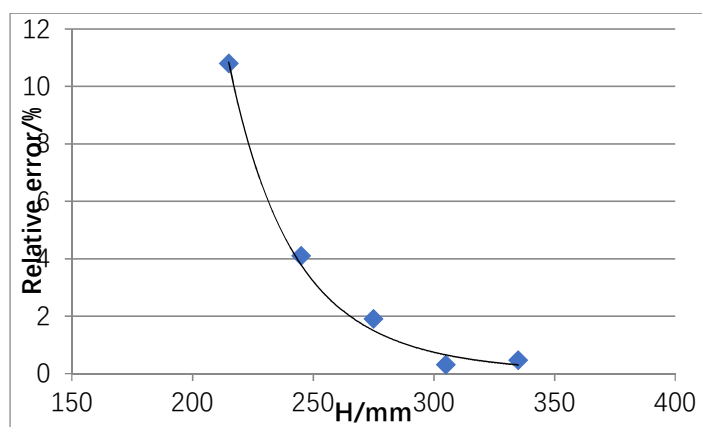


Fig. 4 Variation curve of relative error with liquid depth

3.3 The Influence of Temperature on the Viscosity Coefficient of Rapeseed Oil

Temperature is an important parameter that affects the viscosity of a liquid. Generally, the viscosity of a liquid decreases as the temperature increasing [10]. In this paper, the relationship between the viscosity coefficient of rapeseed oil and the change range of temperature at room temperature was measured by falling ball method.

In the experiment, the depth of rapeseed oil $H=315mm$, the distance between two photoelectric gates $l=100mm$, with different diameter of the falling ball ($d=2mm, 2.5mm, 3.0mm$). The falling time t of the ball and the calculation results of Re and η' are shown in Table 5. According to the data in Table 5, the relationship between Reynolds number Re and temperature T is shown in Fig.5, and the

relationship between viscosity coefficient η' and H is shown in Fig. 6. Re is a criterion for the flow condition of a liquid. When $Re < 1$, the measured value of η is close to the true value and does not need to be corrected. In the experiment, Re of rapeseed oil increases with temperature and the value is larger than 1, as shown in Fig.5. Therefore, the viscosity coefficient of rapeseed oil was corrected with formula (7) and the value is η' , as show in Table 5. The viscosity coefficient η' of rapeseed oil decreases with the increase of temperature in the range of room temperature change in Fig.6. The main reason for this result is that rapeseed oil has a smaller specific heat capacity, so a small change in room temperature can cause a significant change of rapeseed oil, which accelerates the movement of internal molecules and increases its fluidity.

Table 5. Viscosity coefficient of rapeseed oil at different temperatures

$T/^\circ\text{C}$		16	18	22	24
$d=2.0\text{mm}$	t/s	0.70	0.68	0.60	0.56
	Re	2.7	2.8	3.7	4.2
	η'	69.95	67.51	56.91	52.2
$d=2.5\text{mm}$	t/s	0.51	0.49	0.44	0.41
	Re	4.1	4.5	5.6	6.4
	η'	72.99	69.44	61.90	58.44
$d=3.0\text{mm}$	t/s	0.39	0.38	0.34	0.31
	Re	6.0	6.4	7.4	8.2
	η'	77.79	76.42	70.89	67.34

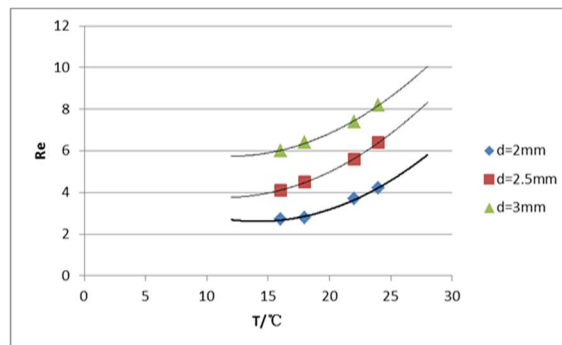


Fig. 5 Variation curve of Reynolds number with temperature

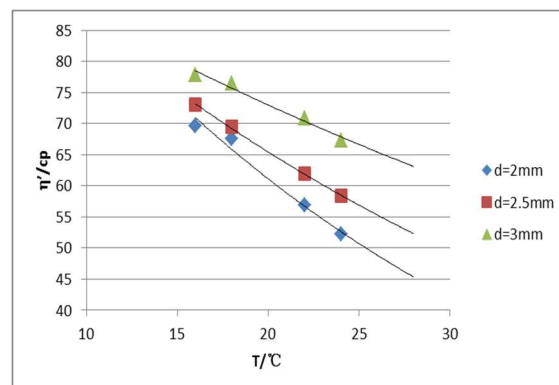


Fig. 6 The relationship between viscosity coefficient of rapeseed oil and temperature

4. Summary

In this paper, the viscosity coefficient of rapeseed oil is determined through constant velocity falling ball method of the experiment. By changing the diameter of the ball, the depth of the rapeseed oil, and the temperature, the influencing factors of the liquid viscosity coefficient are studied. From the experimental results, it is found that to obtain experimental results close to the true value, the Reynolds number must be reduced. This can be done from the following three aspects: (1) The diameter of the experimental ball should not be too large, generally around 2mm. (2) The depth of the liquid should be sufficient, generally greater than 300mm. (3) The temperature should be as low as possible, preferably below room temperature.

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