

**Investigation of geometric effects on fluid viscosity using the falling ball method**

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**Abstract**

The falling ball method, based on Stokes' law, is a simple yet accurate technique for determining fluid viscosity. However, its precision is influenced by factors such as wall effects, Reynolds number, end effects, memory effects, and off-center effects. This study aims to determine the impact of spherical geometry on the fluid viscosity value represented by the sphericity factor. An experimental study was conducted to examine the accuracy of viscosity values to produce the correction factor. The sphericity factors studied were 0.993, 0.976, and 0.949. To reduce the uncertainty caused by the wall effect, the ratio  $d_b/D_t$  was 0.071, using a 5.8mm diameter plastic ball and SAE 40 oil fluid at 32.4°C. Terminal velocity ( $V_t$ ) was determined from a video of the ball falling in the fluid, displayed in the tracker software. The video was taken using a 1080p, 60 fps camera. Wall and Reynolds correction factors were used to correct the experimental viscosity values. The results indicate that viscosity can be accurately determined by selecting a larger ball sphericity during the experiment. It will reduce the need for correction factors to obtain the fluid viscosity.

**Keywords:**

Falling ball viscosity, sphericity, sphericity correction factor

**1 Introduction**

Various theories have been developed to estimate the viscosity value of a liquid, which must be verified using experimental data [1], [2], [3]. Falling-ball viscosity is a method for measuring the viscosity of a liquid that uses Stokes' Law as its basis. This falling ball measurement method has several advantages over other methods, namely simplicity in making measurements, can measure various liquids, does not change the properties of the liquid being tested, the equipment used is relatively cheap, and has high accuracy [4][5][6], low uncertainty values [7][8][9], easy and fast to use [10][11].

The viscosity value of a fluid can be determined by dropping a ball into a tube containing a liquid to obtain a terminal velocity. Terminal velocity is a constant velocity that will be achieved by the ball during free fall, by measuring the length of the path passed by the ball against time. By knowing the terminal velocity, fluid density, diameter, and density of the ball, the viscosity value of a fluid can be calculated [5][2]. To obtain an accurate viscosity value, the Reynolds number (Re) of the sphere must be less than 1

[12][13][14][15]. Measurement uncertainty can occur in several parameters, such as diameter measurements, density, temperature, against balls, fluids, and tubes [16][17][18]. The effect of the wall (wall/edge effect), Reynolds (inertia effect), memory effect, density effect, off-center effect, and non-vertical tube effect, which can cause uncertainty in measuring the speed of the ball falling into the fluid [19][20]. To reduce measurement uncertainty due to the influence of the wall, the ratio between the diameter of the ball ( $d_b$ ) and the diameter of the tube ( $D_t$ ) must be very small to approach zero [21][22].

In conducting the viscosity test of the falling ball, it is necessary to use a test tube that is truly in a vertical condition, without using a connection between the tubes [6][23], the ball falls exactly on the centerline of the tube [24][25], the ball is free from defects (surface roughness, surface irregularities, roundness, and porosity) [26][27]. Research on solid objects falling freely through still fluids has been widely conducted [2][28]. However, the uncertainty of measuring the viscosity value of the falling ball, which is influenced by the geometry of the ball, is very minimal or even non-existent, primarily due to irregularities. In this study, the influence of the geometry (roundness) of the falling ball on the viscosity value is studied, which has been corrected with the equations [7] and [22] was then validated with a rotary viscometer.

The falling ball method is one of the most widely used methods for measuring fluid viscosity ( $\mu$ ). However, existing studies generally consider only wall and inertial effects, while ignoring the impact of ball geometry. Previously used correction factors, such as those by Janna and Brizard, cannot correct deviations caused by ball geometry, leaving a research gap. This study investigates the effect of ball sphericity ( $\Psi$ ) on viscosity accuracy, evaluates existing correction factors, and proposes a new correction factor as a function of  $\Psi$ .


**2 Research methodology and materials**

**2.1 Materials**

This research was conducted at the Fluid Laboratory, Politeknik Caltex Riau. This research includes 15W-40 oil as the test fluid and water as the heat transfer fluid. The ball used is a plastic type. The fluid temperature is raised by convection using a 350W heater and maintained at 32.4°C using a thermocontrol and a thermocouple as controllers. To clearly see the ball's movement, a glass tube is used, illuminated. The ball's terminal velocity is obtained by analyzing data from tracker software.

**2.2 Research methodology**

In this study, the ratio of the diameter of the ball ( $d_b$ ) and tube ( $D_t$ ) of 0,071 is used to minimize the influence of the wall (wall effect) [7][22]. According to various reference sources [29][30], the ratio of the tube diameter to the ball diameter must be less than 0.5 mm. In addition, to get an accurate viscosity, the speed of the falling ball should be set very low ( $Re \ll 1$ ), to reduce the Reynolds effect [7]. To get the influence of the value of the roundness of the ball when it falls in a fluid, the variation in ball shape is applied. Variation forms a ball to produce volume and area values for different surfaces [31]. Variations: This ball shape consists of a round ball as a reference, and the ball is not round with three different variations, as seen in Fig. 1.

Geometry of test sphere with variation of roundness value $\Psi$				
$\Psi = \frac{\pi^3 \cdot (6V_p)^{\frac{2}{3}}}{A_p} \quad [31]$				
$\Psi$	1	0.993	0.976	0.949

$V_p$ : Ball volume;  $A_p$ : Surface area of the ball

Fig. 1. Test ball geometry

Fig. 2 shows the test device used in this study, with SAE 15W-40 oil as the test fluid and a plastic ball. The test fluid is heated above room temperature to 32.4°C, with heat transfer from water heated by a 350W heater. The pump is used as a hot-water circulation pump to distribute the temperature throughout the fluid evenly. To maintain the fluid's viscosity (increment T equals 0), the fluid temperature needs to be controlled and displayed. To record the movement of the ball in the fluid using a camera with a resolution of 1080p and a camera speed of 60 fps, assisted by lighting.

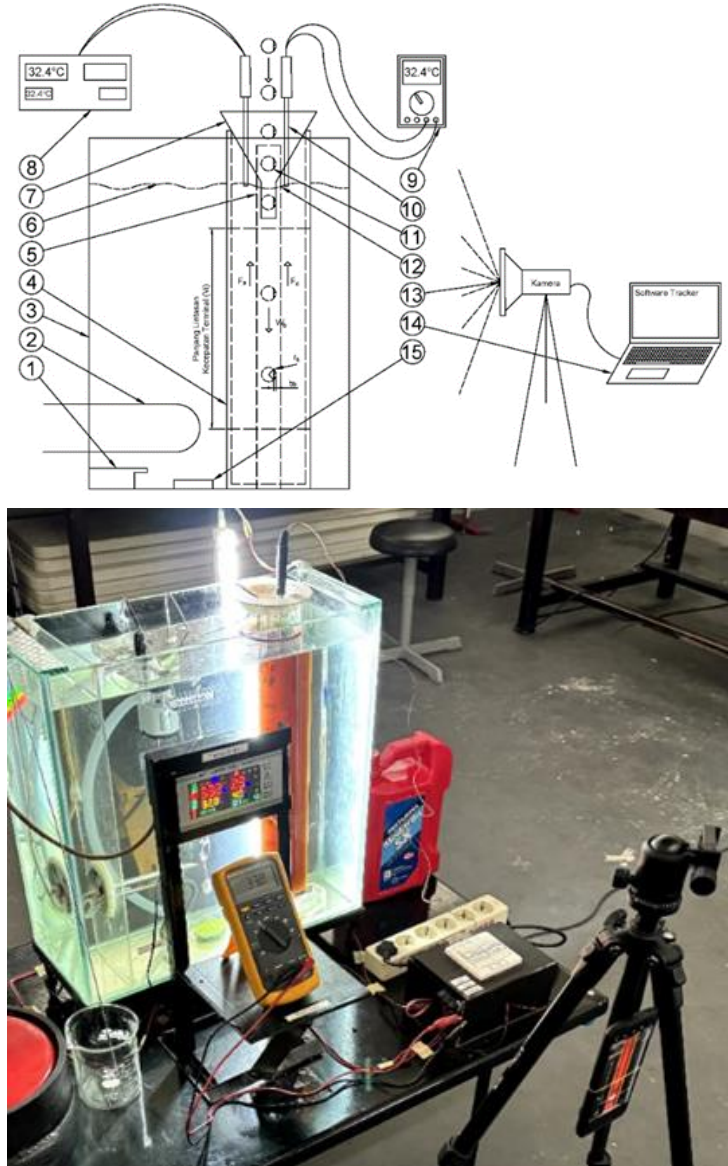


Fig. 2. Eksperimental setup

Description in Fig. 2 are, 1. Pump, 2. Heater, 3. Container, 4. Test tube, 5. Lighting lamp, 6. Heating fluid (water), 7. Guide funnel, 8. Thermo Control, 9. Multimeter, 10. Thermo Couple, 11. Ball, 12. SAE 40 oil, 13. Camera, 14. Tracker software, and 15. Spirit level.

In addition to the influence  $d_b/D_t$  to reduce the influence of the wall in this study, a funnel is used so that the ball dropped into the fluid is right in the middle of the tube (off-center effect) [7][32]. This study began by taking data using a camera that functions to record the movement of the falling ball. The video recording will be analyzed using the help of tracker software (v. 6.1.6), as in Fig. 2, to obtain the value of the length of the path that has been passed by the ball at certain limits within a certain time. The length of the path passed by the ball must have a constant speed without acceleration ( $a = 0$ ). Where the limit is only in the middle of the tube so that the final effect (end effect) is ignored [22]. After the path length and time values have been obtained, the terminal velocity value will be obtained.

From the terminal velocity value that has been obtained, the Reynolds number value can also be calculated, which functions to validate the accuracy of the terminal velocity value test with the provision  $Re < 1$  [22][30]. Once the terminal velocity parameters are experimentally confirmed to be correct, the fluid viscosity value can be calculated using Eqs (1) to (3).

1. Viscosity value without correction using Stokes' law

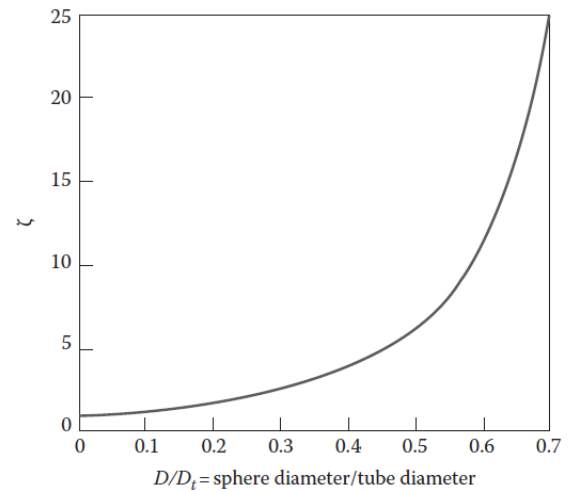
$$\mu = \frac{2 \times g \times r_b^2 (\rho_b - \rho_f)}{9V} \quad (1)$$

2. Reynolds number of the falling ball.

$$Re = \frac{\rho_f v_t d_b}{\mu} \quad (2)$$

3. Viscosity value using correction factor from Janna [22]

$$\mu = \frac{2 \times g \times r_b^2 (\rho_b - \rho_f)}{(9V)\zeta} \quad (3)$$



4. Viscosity value using Brizard correction factor [7]

$$\mu = \frac{2 \times g \times r_b^2 (\rho_b - \rho_f)}{(9 \times V_t) \times (KpRe)^{-1}} \quad (4)$$

what,

$$KpRe = \left[ 1 - \frac{3}{16} Re - \frac{d_b}{D_t} f \left( \frac{Re/4}{d_b/D_t} \right) + 2.09 \left( \frac{d_b}{D_t} \right)^3 - 0.95 \left( \frac{d_b}{D_t} \right)^5 \right]^{-1}$$

and,

$$f \left( \frac{Re/4}{d_b/D_t} \right) = 2.104 - 0.768 \left( \frac{Re/4}{d_b/D_t} \right) + 0.178 \left( \frac{Re/4}{d_b/D_t} \right)^2 - 0.038 \left( \frac{Re/4}{d_b/D_t} \right)^3 + 0.004 \left( \frac{Re/4}{d_b/D_t} \right)^4$$

5. The equation for the correction factor for the roundness of a falling ball

$$f(\Psi) = \frac{2 \cdot g \cdot r_b^2 (\rho_b - \rho_f)}{9 \cdot V_t \cdot \mu} \quad (5)$$

In this study, fluid viscosity testing was carried out using a rotary viscometer as an approach result (validator), as shown in Table 1.

Table 1. Density of fluid and ball

Density	Kg/m <sup>3</sup>
Oil ( $\rho_f$ )	901
Ball ( $\rho_b$ )	1031.3

### 3 Results and discussion

#### 3.1 Viscosity value $\Psi = 1$

Validation mark viscosity fluid is done to ensure that the test equipment used is appropriate and has been fulfilled by reducing the influences as explained in the background. To be able to do validation accuracy mark viscosity on the test tool, then the correction factor is calculated use Eqs. (2) and (3). Then compared

with the value of viscosity without the factor, use Eq. (1) as shown in Table 2.

Table 2. Viscosity test results using rotary viscometer

Fluid temperature (°C)	Test	$\mu$ (Pa.s)	$\bar{\mu}$ (Pa.s)
32.4	I	0.088	0.092
	II	0.098	
	III	0.091	

Viscosity without factor corrects at odds Far its value compared to the rotary viscometer, which is 0.029 Pa.S or 32%. Viscosity value using factor to correct the own value, which is smaller than the difference with the rotary viscometer). The viscosity value with correction [22] has a difference of  $5.10^{-3}$  Pa.S or 5.4% which only accommodates the wall effect correction. While the viscosity value with the correction factor [7] has the smallest difference, namely  $3.10^{-3}$  Pa.S or 3.3% which accommodates the wall effect correction and Reynolds number (inertia effect). Therefore, a factor correction is strongly needed to obtain the appropriate viscosity, especially the wall-influence correction, which can account for up to 27-28%. Even though  $d_b/D_t$  has been designed to be very small, namely 0.071, the correction factor is still very much needed. Similarly, the inertial effect of  $Re=0.86$  also affects the viscosity value obtained by up to 2-3%.

### 3.2 Viscosity at $\Psi < 1$

Terminal velocity will be tracked using tracker software when the ball reaches constant speed in test fluid. Table 3 is the results mark average terminal velocity of 5 trials with variations in mark roundness. Reynolds number is an important factor to validate the experimental testing process. The recommended number of Reynolds is less than 1 [22][30] as the value shown in Table 4 using Eq. (2).

Table 3. Experimental data

Trial No.	Fluid viscosity, $\mu$ (Pa.S)		
	Without correction (stokes)	Janna correction [22]	Brizard correction [7]
1	$1.23 \times 10^{-1}$	$9.84 \times 10^{-2}$	$9.75 \times 10^{-2}$
2	$1.19 \times 10^{-1}$	$9.53 \times 10^{-2}$	$9.39 \times 10^{-2}$
3	$1.20 \times 10^{-1}$	$9.63 \times 10^{-2}$	$9.51 \times 10^{-2}$
4	$1.22 \times 10^{-1}$	$9.80 \times 10^{-2}$	$9.70 \times 10^{-2}$
5	$1.21 \times 10^{-1}$	$9.71 \times 10^{-2}$	$9.60 \times 10^{-2}$
Average	$1.21 \times 10^{-1}$	$9.70 \times 10^{-2}$	$9.59 \times 10^{-2}$

Table 4. Terminal speed ( $V_t$ )

$\Psi$	$V_t$ (m/s)	Re
1	$1.96 \times 10^{-2}$	$8.55 \times 10^{-1}$
0.993	$1.91 \times 10^{-2}$	$8.34 \times 10^{-1}$
0.976	$1.82 \times 10^{-2}$	$7.96 \times 10^{-1}$
0.949	$1.63 \times 10^{-2}$	$7.13 \times 10^{-1}$

Calculation mark viscosity is done to find out how much influence the roundness can have on Eq. (3). In Fig. 3, we can see explained the smaller mark roundness ( $\Psi$ ) applied so mark viscosity ( $\mu$ ) of the fluid. This certainly will not occur under normal conditions, when types and conditions of the fluid used are the same. It can be concluded that this change in viscosity occurs because the geometric shape of the test ball is not round ( $\Psi < 1$ ) (Table 5). So that the value of viscosity does not occur, improvement moment types and conditions normal fluid then needed factor correction, of course this correction factor is different from the previous correction factor in Eqs. (3) and (4).

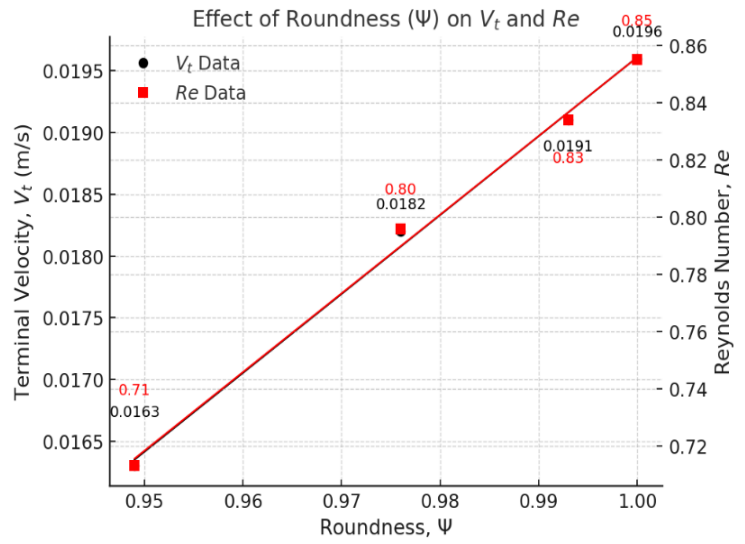


Fig. 3. Relationship  $\Psi$ ,  $V_t$  and  $Re$

Table 5. Viscosity data at  $\Psi < 1$

$\Psi$	$\mu$ at $\Psi=1$ (Pa.S)	$\mu$ at $\Psi < 1$ (Pa.S)
1	0.095	-
0.993	-	0.099
0.976	-	0.104
0.949	-	0.117

Deviation mark viscosity consequence This spherical geometry can be seen in Fig. 4. Where the value viscosity at  $\Psi=1$  which uses Eq. (4) and is shown in table 2 as the value reference i.e. 0.095 Pa.S. This reference value is selected based on corrected and approaching values mark viscometer rotary in table 1. Point a mark viscosity at  $\Psi=0.949$  is 0.117 Pa.S with a value of deviation of 0.0211 Pa.S and must corrected so that reach point reference a', point b for  $\Psi=0.976$  is 0.104 Pa.S with a deviation of 0.0081 Pa.S and point c for  $\Psi=0.993$  is 0.0986 Pa.S with a deviation of 0.0027 Pa.S. By using Eq. (5) value factor correct roundness  $f(\Psi)$  (Fig. 5) obtained.

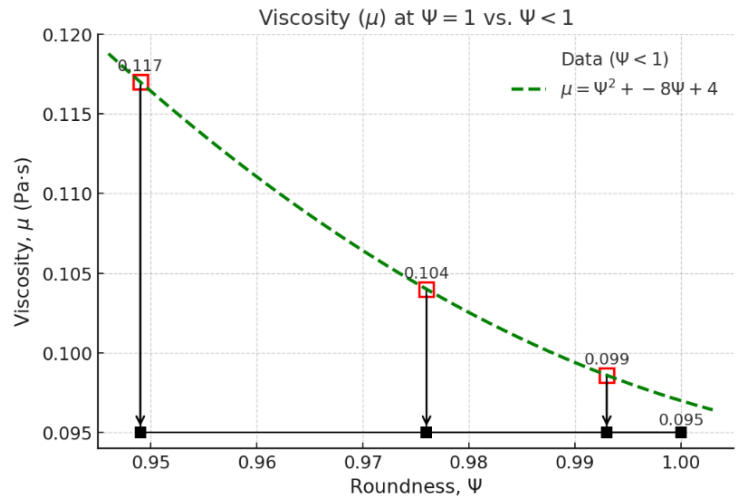


Fig. 4. Viscosity due to  $\Psi < 1$

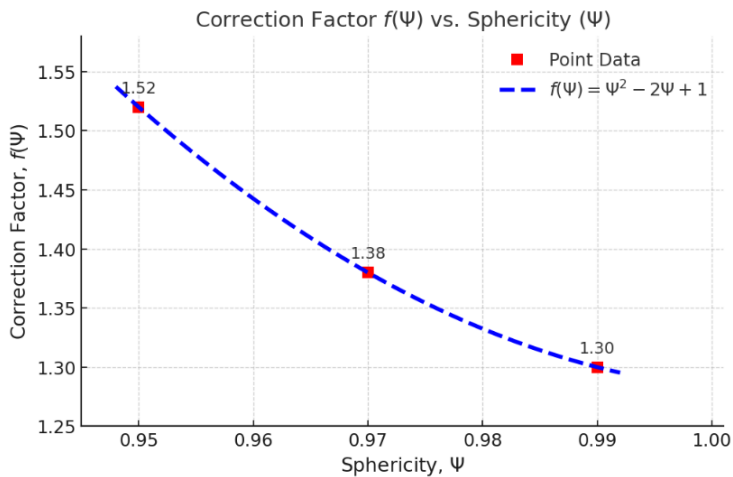


Fig. 5. Correction factor  $f(\Psi)$

Correction factors mark the roundness consequences. This test ball  $\Psi < 1$  can produce a mark viscosity fluid approach even equal to the expected value (viscosity  $\Psi = 1$ ). The less round the test ball  $\Psi \ll 1$  the bigger the correction factor value required to obtain the desired viscosity.

#### 4 Conclusions

In this study, variations in ball geometry were tested using established correction factors, revealing that the viscosity measurements from the falling ball method were strongly affected by the ball's sphericity. The obtained viscosity showed an increasing deviation when the sphericity value moved away from 1 ( $\Psi \ll 1$ ). To obtain accurate viscosity, the sphericity value requires a correction factor. The Janna correction factor can eliminate viscosity inaccuracies caused by wall effects, resulting in higher accuracy, at 84–88%. The Brizard correction factor tends to be better, reducing wall and inertial effects, resulting in a correction of around 90–96%. However, neither the Janna nor the Brizard correction factors can address viscosity inaccuracies caused by the sphere's geometry, particularly its sphericity. To minimize the influence of sphere non-sphericity on viscosity measurements, an additional correction factor  $f(\Psi)$  is introduced, defined by the relationship  $\Psi \cdot f(\Psi) = \Psi^2 - 2\Psi + 1$ . This approach offers a simple and cost-effective means to improve viscosity measurement accuracy related to sphere geometry. Future studies should incorporate precise sphericity measurements to establish more reliable correlations.

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