A Study on Vibrational Viscometers Considering Temperature Distribution Effect

Ali AKPEK**, Chongho YOUN***, Toshiharu KAGAWA***

In viscosity measurement, temperature control is very important. In this study, the effects of temperature distribution on vibrational viscometers are investigated. Vibrational viscometers are preferred over other types of viscometers owing to their low cost, easy to use and efficacious continuous viscosity measurement capability. The study was conducted in two parts. In the first part, the challenge of unequal temperature distribution in vibrational viscometers was analyzed. The heat generated by a heater during continuous viscosity measurement disperses every part of a sample fluid and influences the fluid's viscosity. Therefore, the sample fluid may have inhomogeneous viscosity values because temperature distribution cannot be equal at every point in a fluid. This experiment is repeated several times with different temperature gradients for gaining a better understanding about the effect of unequal temperature distribution on fluid viscosity. Experimental outcomes show that under some conditions, viscosity measurement errors could reach 27.9%. This finding has been verified by mathematical calculations. In the second part of the research, for solving the unequal temperature distribution problem, the use of a magnetic stirrer for mixing up the fluid throughout the viscosity measurement with the aim of achieving homogenous temperature distribution is proposed.

Key words: Vibrational Viscometer, Viscosity Control, Heat Transfer, Temperature Control, Measurement Error

1. Introduction

In industry, the ability to gather data on the viscosity behavior of materials is important. Information about any change in the viscosity behavior of materials may reveal to manufacturers important product dimensions. Viscosity measurement is the most convenient way of detecting changes in the color, density, stability, solid content, and molecular weight of a material. Thus, improving existing viscometers is important for furthering the improvements in the quality of materials.

The concept of viscosity was postulated by Sir Isaac Newton as "the resistance which arises from the lack of slipperiness of the parts of the liquid, other things being equal, is proportional to the velocity with which parts of the liquid are separated from one another." This "lack of slipperiness" is viscosity. Using this concept, all fluids can be categorized by examining the relation between the applied shear stresses and the deformation rate of flow of a fluid.

Based on the above definition, a viscometer can be defined as an instrument that measures fluid viscosity. There are many types of viscometers such as capillary, U-tube, falling sphere, falling piston, rotational, electromagnetically spinning sphere, stahinger, bubble, micro-slit, and vibrational viscometers.

All types of viscometers have merits and demerits. However, vibrational viscometers stand out owing to their low cost, easy to use and efficacious continuous viscosity measurement capability. Therefore, we consider vibrational viscometers in this study.

Experimental viscosity-measurement data are often used as the basis for determining the quality of selected fluids. Accuracy is the key point in enhancing viscometers and improving fluid quality. This work is focused on the temperature measurement problem inside a fluid and its effect on viscosity measurement. The temperature measurement problem is known to degrade the accuracy of vibrational viscometers.

For overcoming the problem of unequal temperature distribution, the use of a magnetic stirrer in addition to changing the sample fluid's temperature gradient, which may allow for more uniform distribution of heat in the sample fluid, is proposed. The aim is to obtain more accurate fluid temperature measurements.

2. Vibrational Viscometer

The concept underlying a vibrational viscometer can be...
better comprehended by analyzing a damped spring. The damped vibration of a spring in a liquid is influenced by the restoration force of the spring and the viscous resistance of the liquid.

\[ R_t = \frac{F}{A \sqrt{\pi \eta \rho}} \]  

Fig. 1 Front view of vibrational viscometer

Based on this idea, the following equation can be constituted.

In the above equation, \( f \) denotes the vibration frequency (Hz), \( A \) denotes the planar dimensions of both sides of the oscillators in a liquid, \( \eta \) denotes the liquid viscosity, and \( \rho \) denotes the liquid density. \( F \) is the force using which the electromagnetic driving unit induces a constant-velocity vibration \( V e^{i\omega t} \) in the oscillator.

Therefore, as shown in Fig. 1, it is evident that the force (\( F \)) generated in the electromagnetic driving unit for maintaining constant oscillator amplitude \( (V e^{i\omega t}) \) against viscous resistance is proportional to the product of the fluid’s viscosity and density \( (\eta \times \rho) \).

During experiments, the planar surface area of the oscillator \( (A) \) was 78.5 mm\(^2\), oscillator frequency \( (f) \) was designated as 30 Hz, and the oscillator vibration amplitude was 0.4 mm.

The ASTM D2162-06 Standard Practice for Basic Calibration of Master Viscometers and Viscosity Oil Standards procedure is used for calibrating a vibrational viscometer. Furthermore, JS14000 standard fluid is used for such calibration runs. We used this fluid in our experiments. The characteristics of this standard fluid are listed in Table 1.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Kinematic Viscosity (mm(^2)/s)</th>
<th>Dynamic Viscosity (cP)</th>
<th>Density (g/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>37.290</td>
<td>32.820</td>
<td>0.8800</td>
</tr>
<tr>
<td>20</td>
<td>129.40</td>
<td>11.310</td>
<td>0.8740</td>
</tr>
<tr>
<td>25</td>
<td>8.080</td>
<td>7.940</td>
<td>0.8712</td>
</tr>
<tr>
<td>30</td>
<td>5.188</td>
<td>4.506</td>
<td>0.8685</td>
</tr>
<tr>
<td>35</td>
<td>3.416</td>
<td>2.957</td>
<td>0.8657</td>
</tr>
<tr>
<td>40</td>
<td>2.298</td>
<td>1.983</td>
<td>0.8629</td>
</tr>
</tbody>
</table>

3. Experimental Setup

As shown in Figs. 2 and 3, five thermometers are placed in different parts of the experimental cup, and the experimental cup is immersed into a heating cup. Water is used as the heating fluid. During the experiments, the heating fluid temperature was adjusted by changing the temperature gradient via the heater. The temperature readouts of all thermometers were recorded simultaneously. The aim was to analyze temperature distribution within the fluid.

The height of the cup was 40 mm, and the thermometers and oscillators were located at a depth 20 mm in the fluid.

Thermo 5 and Thermo 1 are referred to as boundary
thermometers, Thermo 2 and Thermo 4 are referred to as oscillator thermometers, and Thermo 3 and the viscometer’s built-in thermometer are referred to as center thermometers.

JIS Class 2 level type K sheet (KS) thermocouples and the viscometer’s built-in thermometer were used during the experiments. All thermometers were calibrated using the ASTM E220-07a standard test method for thermocouple calibration^{10}.

The study was conducted in two parts.

In the first part, the unequal temperature distribution problem of vibrational viscometers was investigated.

In the second part, the experimental setup was modified with the use of a magnetic stirrer, as shown in Fig. 2. It is expected that the use of a magnetic stirrer would solve the unequal temperature distribution problem. In this part, the experiments conducted in the first part were repeated using the modified experimental setup. The magnetic stirrer was operated at 1,500 rpm in all experiments. Additionally, the magnetic stirrer was used as a heater, as shown in Fig. 2.

4. Experimental Results

4.1 Temperature measurement experiments

The experimental setup for the first part of the research is shown in Fig. 2. The experiments were carried out under various temperature gradients.

In Fig. 4, the initial temperature is around 17.5°C, and the experiment proceeded for 800s. The temperature increased by around 5°C/min between 500s and 800s. These points were selected because the viscosity values at 30°C, 40°C, and 50°C lay between these points.

In Fig. 5, the initial temperature is around 15°C, and the experiment duration is 1,500s. The temperature increased by around 2.5°C/min between 900s to 1,500s.

As shown in Fig. 6, the initial temperature is around 17.5°C, and the experiment duration is 5,000s. The temperature increased by around 0.5°C/min between 2,000s and 5,000s.

Figs. 4, 5, and 6 verify that there are severe temperature deviations across thermometers. The degree of unequal temperature distribution varies with the temperature gradient. Therefore, in the second part of the research, for overcoming this unequal temperature distribution problem, the use of a magnetic stirrer that stirs the fluid throughout the viscosity measurement and ensures homogenous fluid temperature is proposed.

In Fig. 7, the initial temperature is around 20°C and the experiment duration is 750s. The temperature increased by around 5°C/min between 450s and 750s in compatible with Fig. 4.

In Fig. 8, the initial temperature is around 21.5°C, and the experiment duration is 1,500s. Temperature increased by around 2.5°C/min between 900s and 1,500s in compatible with Fig. 5.

As shown in Fig. 9, the initial temperature is around 22.5°C and the experiment duration is 4,000s. The temperature increased by around 0.5°C/min between 1,500s and 4,000s in
In all experiments, 30°C, 40°C, and 50°C marks on the boundary thermometers were chosen as reference points and recorded. This was done for measuring the success rate of the methods used herein. These readings recorded at these reference points are listed in Table 2.

<table>
<thead>
<tr>
<th>Fig No</th>
<th>Boundary</th>
<th>Oscillator</th>
<th>Center</th>
<th>Difference 1</th>
<th>Difference 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig 4</td>
<td>30.0</td>
<td>22.6</td>
<td>21.9</td>
<td>1.6</td>
<td>9.1</td>
</tr>
<tr>
<td>Fig 5</td>
<td>40.0</td>
<td>35.4</td>
<td>24.5</td>
<td>3.9</td>
<td>15.5</td>
</tr>
<tr>
<td>Fig 6</td>
<td>50.0</td>
<td>35.9</td>
<td>25.9</td>
<td>7.9</td>
<td>14.1</td>
</tr>
<tr>
<td>Fig 7</td>
<td>30.0</td>
<td>23.8</td>
<td>23.1</td>
<td>0.6</td>
<td>6.9</td>
</tr>
<tr>
<td>Fig 8</td>
<td>40.0</td>
<td>28.7</td>
<td>27.0</td>
<td>1.7</td>
<td>13.0</td>
</tr>
<tr>
<td>Fig 9</td>
<td>50.0</td>
<td>41.8</td>
<td>34.9</td>
<td>7.0</td>
<td>15.2</td>
</tr>
<tr>
<td>Fig 10</td>
<td>30.0</td>
<td>22.6</td>
<td>20.5</td>
<td>2.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Fig 11</td>
<td>40.0</td>
<td>32.6</td>
<td>30.1</td>
<td>2.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Fig 12</td>
<td>50.0</td>
<td>42.0</td>
<td>41.8</td>
<td>0.2</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Difference 1 refers to the temperature difference between the oscillator and the center thermometer, and Difference 2 refers to the temperature difference between the boundary thermometers and the center thermometer.

The experiment involving a low temperature gradient and magnetic stirrer yielded the most homogenous temperature values. The greatest deviations among thermometers temperature readings were recorded in the high temperature gradient experiment. Temperature deviations recorded in the experiments involving the magnetic stirrer are smaller than those in the experiments without the magnetic stirrer. Hence, temperatures are measured more homogenously when the temperature gradient is lower.

4.2 Viscosity measurement experiments

Similar experiments were carried out for measuring viscosity. The thermometer of the vibrational viscometer was used during viscosity measurement experiments. The purpose of these experiments was to acquire information about temperature deviations between the oscillators and the thermometer of the vibrational viscometer and the effect such deviations have on viscosity measurement. Given the presence of a temperature deviation between the oscillators and the thermometer, the measured viscosity values differ from the standard ones.
During the viscosity measurement experiments, high and low temperature gradient experiments were investigated in depth because these experiments correspond to the maximum and minimum scenarios in our study. The results of the viscosity measurement experiments are summarized in Table 3.

The most severe viscosity deviation, as seen in Fig. 10, is observed at 50°C. A 27.90% error in viscosity measurement occurs at that point. This indicates the presence of a considerable temperature difference between the oscillators and the center thermometer.

The highest viscosity measurement error of 14.40%, as seen in Fig. 11, is observed at 50°C. However, without the magnetic stirrer, as seen in Fig. 10, the viscosity measurement error is 27.9%. The viscosity measurement shown in Fig. 11 has a lower measurement error owing to the use of the magnetic stirrer, which mixes the fluid and affords a more homogenous temperature distribution in the fluid.

In Fig. 12, a 10.20% viscosity measurement error is observed at 30°C for the standard fluid under a low temperature gradient.

According to Fig. 13, when the magnetic stirrer is used under the low temperature gradient, the viscosity measurement error is 3.80% at 30°C. This means that the temperature of the fluid around the oscillators and that around the viscometer’s thermometer should be very similar. However, as shown in Fig. 12, the viscosity measurement error is around 10.20% without a magnetic stirrer.

Therefore, it can be deduced that during continuous viscosity measurement, the use of a magnetic stirrer affords measurements of higher accuracy than those without the use of a magnetic stirrer. Additionally, the viscosity values obtained under the low temperature gradient are more accurate than those obtained under the high temperature gradient, even with the use of a magnetic stirrer. These results are in accordance with those of the temperature measurement experiments.

5. Mathematical Background

The problem of unequal temperature distribution problem was also investigated through simulations. The simulations were modeled using high, medium, and low temperature gradients, as shown in Figs. 4, 5, and 6, respectively. The
simulation results were compared with the results of temperature measurement experiments. Heat distribution can be simulated using the heat equation.\[\frac{dT}{dt} = \alpha \left( \frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} \right) \tag{2}\]

In this equation, \(T\) denotes the temperature, \(t\) denotes the time, and \(\alpha\) denotes the thermal diffusivity coefficient.

The thermal diffusivity coefficient of JS14000 Standard Fluid is 0.07 mm\(^2\)/s.

All simulations were designed as per the measurements shown in Fig. 3.

Fig. 14 shows the result of experiment with the largest temperature deviation among simulations; the results are listed in Table 4. This figure is thus chosen for further investigation. As observed, the measured temperatures vary considerably under the high temperature gradient. At the end of the simulation in Fig. 14, when the temperature around the center thermometer (Thermo 3, \(x = 30\) mm, \(y = 125\) mm) was around 40\(^\circ\)C, the temperature around the oscillator (Thermo 2 and Thermo 4, \(x = 15\) mm, \(y = 125\) mm) was 42.4\(^\circ\)C, and the temperature at the edge of the fluid (Thermo 1 and Thermo 5, \(x = 0\) mm, \(y = 125\) mm) was around 49.5\(^\circ\)C.

Therefore, according to the simulation results and based on Table 1, at the end of the simulation, the viscosity measurement error between the center thermometer and the edge of the fluid was around 49.6\%. Furthermore, the viscosity measurement error between the center thermometer and the oscillator was 12\%. As shown in Fig. 10, for measurement using an experimental setup, the corresponding error was 27\%. The difference can be ascribed to additional error sources.

Non-compressible fluid analysis was done for simulations. A MATLAB code was used to generate simulations. During MATLAB code writing, finite difference method was used to solve the heat equation that is given at equation (2). The solution of heat equation with finite difference method can be seen below.

\[
\frac{T_{m,n}^{p+1} - T_{m,n}^{p}}{\Delta t} = \alpha \left( \frac{T_{m+1,n}^{p} - 2T_{m,n}^{p} + T_{m-1,n}^{p}}{\Delta x^2} + \frac{T_{m,n+1}^{p} - 2T_{m,n}^{p} + T_{m,n-1}^{p}}{\Delta y^2} \right) \tag{3}\]

As it is shown in Fig. 3, the sample cup is 60 mm in length and 25 mm in width. Therefore, in order to provide this condition, 61 mesh points in X direction and 26 mesh points in Y direction were used in the MATLAB code. For
boundary condition calculations, Thermometer 5 was used since it was closest thermometer to the heating fluid.

Difference 1 refers to the temperature difference between the oscillator and the center thermometer, and Difference 2 refers to the temperature difference between the boundary thermometers and the center thermometer.

As expected, the simulation with the low temperature gradient yielded the most homogenous temperature results.

6. Discussion

As seen in Figs. 4, 5, and 6, as the heating duration extends, a more uniform heat distribution is observed in the JS14000 standard fluid; this causes a drastic decrease in temperature deviation among thermometers. A similar trend can be observed in Figs. 7, 8, and 9.

The dissimilarity between Figs. 4 and 7 can be ascribed to the fact that under normal conditions, heat dispersion is more homogenous in stirred fluids than in static fluids. Hence, the temperatures recorded by the thermometers may vary moderately.

Furthermore, similar to the viscosity measurement experiments, as the uniformity of temperature distribution increases, the accuracy of viscosity measurements increases. According to the experimental outcomes, it can be stated that the temperature homogeneity of a fluid may depend on the temperature gradient of the heater and devices such as the magnetic stirrer.

Another important result obtained from this research is that low temperature gradients, which afford sufficient time for heat to be transferred throughout the fluid, could yield a homogenous temperature.

During viscosity measurements, temperature deviation between the oscillators and the center thermometer indicated measurement error. This deviation can be ascribed to a 15-mm gap between them, as seen in Fig. 3. This gap results in an unequal temperature distribution, which could lead to grave measurement errors in some cases.

In addition, temperature deviation between the edge of the sample fluid and its center may differ considerably. In this scenario, the viscosity measurements recorded at these two points may vary enormously owing to a 30-mm gap between the two points. This measurement error may lead to serious quality assessment problems, especially in the case of expensive fluids, which may be available only in quantities of up to 100 ml. This problem is described in the Mathematical Background section.

7. Conclusion

This study focused on the problem of unequal temperature distribution in vibrational viscometers.

Vibrational viscometers stand out from other types of viscometers owing to their low cost, easy to use and effective continuous viscosity measurement capability. However, it is understood that the existing vibrational viscometer method has some problems. Consequently, the viscosity values recorded by vibrational viscometers may not be accurate. Experimental outcomes and mathematical calculations verified this conclusion. In our research, high (6°C/min), medium (2.25°C/min) and low (0.5°C/min) temperature gradients were utilized. In addition to that, a magnetic stirrer was also utilized in order to constitute homogenous fluids. Experimental outcomes proved that in high temperature gradient conditions, there may be up to 27.9% viscosity measurement errors. In case of utilizing a magnetic stirrer in high temperature gradient condition, this measurement error decreases to 14.40%. Similarly, in low temperature gradient experiment, 1020% viscosity measurement error was observed. However, in case of utilizing a magnetic stirrer, this measurement error decreased to 380%.

Simulations also verified experimental outcomes. It has been presented that in high temperature gradient condition, the viscosity measurement error between the center thermometer and the edge of the fluid was appeared as 496% and the viscosity measurement error between the center thermometer and the oscillator was appeared as 126%. Similar results were also appeared in medium and low temperature gradient conditions.

Finally, we can conclude that; our study revealed the importance of temperature gradients and devices like magnetic stirrers for viscosity measurement in order to overcome unequal temperature distribution problem.

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