Flow Properties of Several Types of Liquid Flows through Micro-Orifices*

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Abstract
The flow properties of several types of liquid passing through various sizes of micro-orifices were investigated in this paper. The jet thrust and pressure drops were measured for two polyethylene glycol solutions and four surfactant solutions. Different flow properties were found for the various surfactant solutions depending on the charge of the solute. For an anionic surfactant, the results were similar to those for water, whereas in the case of a cationic surfactant, both the jet thrust and pressure decreased greatly in comparison with the other test liquids. Finally, a nonionic surfactant exhibited a steep rise in the pressure drop at a particular value of the Reynolds number. In explaining this behavior, the liquid-solid interface and alignment of the surfactant molecules are considered, and consequently, it is strongly suggested that the elastic stress on elongational flows is a contributing factor. In addition, the decreases in pressure and thrust for polyethylene glycols are attributed to viscoelastic properties, regardless of the molecular weight of PEG.

Key words: Orifice Flow, Surfactant, Polyethylene Glycol, Thrust, Pressure Drop

1. Introduction
Microfluid mechanics has attracted much interest in recent years because of its many industrial and biological applications (1-2). Although microchannel flows have been extensively studied (3-6), studies on flows through micro-orifices are limited (7-8). Also, for many applications, finding the viscoelastic properties for elongational flows is important. Generally, a cone-plate type rheometer is used to measure viscoelastic stress. However, measurements on this type of apparatus are difficult at high shear rate. In particular, the viscoelastic stress of dilute solutions of macromolecules cannot be measured in this way.

As an alternative approach, the jet thrust method was designed to measure small values of viscoelastic stress (9-11). First, Harris measured the viscoelastic stress on high shear flows by measuring the thrust of flows through capillary tubes (9). Subsequently, Oliver measured the first normal stress difference (FNSD) (10), and Metzner et al. examined the elongational stress for solutions of macromolecules in orifice flows (11). In these methods, the jet flowed in air, which is a critical defect.

Hasegawa et al. have developed an improved jet thrust method (12-15), and they have also investigated water flows through micro-orifices by measuring jet thrust and pressure drop (16-17). They found that the viscoelastic stress for water in high elongational flows was
strongly suggested. By contrast, in our laboratory, we have measured pressure drops for several types of silicone oils, surfactant solutions and polyethylene glycol solutions\(^{(18)}\). In the present study, we measured jet thrust and pressure drop as flow properties for several types of surfactants and polyethylene glycols. Measured thrusts and pressure drops were compared with the previous results for water\(^{(16,17)}\). In addition, the flow properties of several types of liquids were clarified.

2. Test liquids

The test liquids used in this research were polyoxyethylene (23) lauryl ether (AE) as a nonionic surfactant; benzalkonium chloride (BC) as a cationic surfactant; and laurylbenzene sulfonic acid sodium salt (LAS) and sodium dodecyl sulfate (SDS) as anionic surfactants\(^{(18,19)}\). These surfactants are commonly used in laundry detergents\(^{(20)}\). Additionally, polyethylene glycol 8000 and 20000 (PEG8000 and PEG20000) were also tested. It was found that PEGs had elasticity in previous research\(^{(21)}\).

Table 1 shows the properties of the test liquids, where the viscosity refers to the Newtonian viscosity\(^{(18)}\) and CMC is the critical micelle concentration. All the surfactants were used at a higher concentration than their CMC. Moreover, all experiments described herein were carried out at room temperature.

<table>
<thead>
<tr>
<th>Test liquid</th>
<th>Concentration [%]</th>
<th>Density (\times 10^3) [kg/m(^3)]</th>
<th>Viscosity (\times 10^{-3}) [Pa s]</th>
<th>M.W. [-]</th>
<th>CMC [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>-</td>
<td>1.0</td>
<td>1.0</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>AE</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1199.5</td>
<td>100</td>
</tr>
<tr>
<td>BC</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>354.0</td>
<td>400</td>
</tr>
<tr>
<td>LAS</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>348.5</td>
<td>150</td>
</tr>
<tr>
<td>SDS</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>288.4</td>
<td>1200</td>
</tr>
<tr>
<td>PEG8000</td>
<td>0.1</td>
<td>1.0</td>
<td>1.1</td>
<td>8000</td>
<td>-</td>
</tr>
<tr>
<td>PEG20000</td>
<td>0.1</td>
<td>1.0</td>
<td>1.1</td>
<td>20000</td>
<td>-</td>
</tr>
</tbody>
</table>

3. Experimental apparatus

Figure 1 shows the experimental apparatus. Test liquids are transported from a syringe pump (JP-H1, Furue Science Co., Ltd.) to the channel at a constant flow rate. A micro-orifice is attached to the channel. The pressure drop, \(\Delta p\), was measured with a pressure transducer (SPX-D SDP-12, Tsukasa Sokken Co., Ltd.) and the jet thrust was measured with an electronic balance (GR-200, A&D Co., Ltd.).

3.1 Micro-orifices

In the experiments, orifices of 15~100 \(\mu\)m were used. All orifices were made from nickel foils and had a thickness of 20 \(\mu\)m. Together these values then give a thickness ratio of L/D.

By way of example, images of the front and back of a 50 \(\mu\)m orifice are shown in Figs 2. As can be seen, there are differences between the front (Fig. 2(a)) and back (Fig. 2(b)) of the orifice; however, these differences do not account for the changes in the flow properties seen in previous research\(^{(17)}\). In the current study, liquids pass from the front to the back of the orifices.
3.2 Jet thrust method

Figure 3 shows the method for measuring jet thrust. $T_M$ is the thrust of the jets, and $T'_M$ is the momentum flowing out of the control volume. The force, $F$, which is measured on an electronic balance, is the combination of these two values as given in (1):

$$F = T_M + T'_M. \tag{1}$$

When the inner diameter of the cup (=120 mm) is much greater than that of orifice diameter, $T_M \gg T'_M$, (1) becomes

$$F = T_M. \tag{2}$$

Thus, the detected forces are expressed as the jet thrust $T_M$.

Figure 4 shows the dimensionless jet thrust, $T_M/\rho QV$, plotted against the Reynolds number, $Re = \rho DV/\mu$, where $\rho$ is density and $\mu$ is viscosity, for flows through capillaries of 0.75 mm and 1.20 mm in diameter. The solid line is the theoretical value (=1.33) in the case of Poiseuille flow. With the output for both capillaries matching the theoretical value accurately, it can be seen that the present apparatus gives valid results.
4. Experimental results

4.1 Jet thrusts for surfactants

Figure 5(a)–(e) shows the experimental results in the form of $T_m/\rho QV$ plotted versus $Re$. Numerical predictions from the Navier-Stokes equation are also given for water (solid lines in figures). It can be seen that the data for LAS and SDS fit reasonably well with the results for water. However, the results (Fig. 5(a)) for AE are about 10% less than the results for water flowing through a 100 µm orifice. As the orifice size was made smaller, the extent of this decrease became greater (Fig. 5(b)–(e)). Hence, the smaller orifice diameter is, the bigger the difference between and actual velocity and the prediction is. This phenomenon are relation to shear rate, $V/D (=4Q/\pi D^3)$. Now, Flow rate is constant. For this reason, as the diameter is smaller, shear rate become much bigger. For instance, shear rate ranges from $10^3$ to $10^7$ s$^{-1}$ for 20 µm. Hasegawa et al. and Ushida et al. have reported huge reduction of Newtonian fluids in high shear rate flows. It was found that the present results agreed with the previous results. A different reduction was observed for BC (Fig.5(a)–(e)).

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Fig. 5 Experimental results for dimensionless jet thrust $T_m/\rho QV$ plotted against Reynolds number $Re$ for orifices with diameter of (a) 100 µm, (b) 50 µm, (c) 25 µm, (d) 20 µm, and (e) 15 µm.
4.2 Pressure drops for surfactants

Figure 6(a)–(e) shows $2\Delta p/\rho V^2$ plotted against Re. The results for LAS and SDS (anionic surfactants) closely agreed with the results of numerical calculations for water\(^{(17)}\)\(^{(22)}\). Pressure drops for BC (cationic surfactant) exhibited the greatest reduction. Also, $2\Delta p/\rho V^2$ for AE (nonionic surfactant) rose up steeply at a particular Re. Okawara et al. have shown structure of surfactant micelle was changed by passing through small apertures\(^{(23)}\). The steep rises for AE solution were caused by structure changes.

![Graphs showing pressure drops for surfactants](image)

Fig. 6 Experimental results for dimensionless pressure drop $2\Delta p/\rho V^2$ versus Re for orifice diameters of (a) 100 µm, (b) 50 µm, (c) 25 µm, (d) 20 µm and (e) 15 µm.

4.3 Results for PEG

Figures 7(a)–(c) and 8(a)–(c) show the results for PEG8000 and PEG20000. Substantial
decreases in pressure and thrust were observed for all orifices. Previous numerical calculations have suggested that PEG solutions have viscoelastic properties\(^{(21)}\), to which we attribute the present results. It found that thrust and pressure drop were reduced by existence of viscoelasticity.

**Fig. 7** Measurements of PEG solutions for dimensionless jet thrust, \(T_M/\rho QV\), plotted against Reynolds number, \(Re\), for orifices with diameters of (a) 100 \(\mu\)m, (b) 50 \(\mu\)m, and (c) 15 \(\mu\)m.

**Fig. 8** Measurements of PEG solutions for \(2\Delta p/\rho V^2\) versus \(Re\) for orifice diameters: (a) 100 \(\mu\)m, (b) 50 \(\mu\)m, and (c) 15 \(\mu\)m.
5. Discussion

5.1 Viscous heating

Viscous heating causes a reduction in viscosity and is an essential consideration for viscous liquids\(^{(23)}\). In particular, it is thought to be important in high strain flows, such as those presented in this paper. The temperature rise, \(\Delta T_{\text{rise}}\), is given by \(\Delta T_{\text{rise}} = \Delta p/\rho c\), where \(c\) is specific heat \((= 4 \times 10^3 \text{ J/(kg K)})\)\(^{(25)}\), and with \(\Delta p = 5 \times 10^5 \text{ Pa}\) taken from the results above, a value of \(\Delta T_{\text{rise}} = 0.12 \text{ K}\) is obtained. Thus, only a small temperature rise occurs in the current experiments and heat generation due to viscosity is negligible.

5.2 Boundary slip

Theoretical and experimental studies have been conducted on the flow of liquids near solid-liquid interfaces. In previous research\(^{(17)}\), we conducted numerically analyzed orifice flows by Newtonian fluids, finding that slip conditions lead to reductions in pressure and thrust\(^{(17)}\). However, the experimental values found in the present work are even lower than those predicted from slip conditions alone.

5.3 Elastic stress

Measured thrusts and pressure drops were less than the prediction for PEG solutions which have viscoelastic property. Therefore, the reductions are caused by viscoelasticity. It is known that elasticity makes reducing thrust and pressure drops, so-called drag reduction, in the previous studies\(^{(26),(27)}\) by using polyethylene oxide (PEO, M.W.=1.5 \times 10^6 \sim 4.0 \times 10^6). Whereat, elastic stress of surfactants is discussed in this section. Wall surfaces are negatively charged under water, as are nickel foils\(^{(22)}\). On the other hand, liquids surrounding the wall become positively charged. This phenomenon is the well-known electric double layer\(^{(28)}\), which is thought to strongly affect the behavior of the system, depending on the type of surfactant (cationic, anionic or nonionic).

Figure 9 shows a simple illustration of the conditions at the wall and in the surrounding liquids. In water (Fig. 9(a)), positive ions (H\(^+\)) surrounding the orifice assemble along the wall. Positive ions (H\(^+\) and BC\(^+\)) in aqueous solution gravitate toward the negatively charged wall (Fig. 9(b)). In this case, the BC\(^+\) concentration near the wall is larger than that at a distance from wall (in the bulk liquid). For AE (Fig. 9(c)), the AE concentration near the wall is almost equal to that in the bulk, as AE has no ions. In the case of anionic surfactants (LAS and SDS) (Fig. 9(d)), the surface repels LAS- or SDS-, lowering their concentration near the wall. In summary, comparing the concentrations, it is found that LAS<AE<BC near the surface of the wall.

Surfactant molecules or spherical micelles, both of which are larger than water molecules, are present near the wall where the strain rate is at a maximum. Generally, it is known that viscoelastic properties occur as a consequence of the stretching of macromolecular chains. The surfactant molecules (Fig. 9(b) and (c)) are regarded as molecular chains in the present discussion, and the viscoelastic properties that develop have been studied previously\(^{(29)-(32)}\).

This development of viscoelastic properties by certain surfactants agrees qualitatively with the results presented in Section 4 (Figs 5(a)–(e) and 6(a)–(e)). Therefore, it is considered that the decrease in both jet thrust and pressure in these experiments is caused by elastic stress, ES, which is expressed using either (3) or (4)\(^{(15),(32)}\).

\[
\text{ES} = \frac{T_{\text{water}} - T_{\text{surfactant}}}{\pi D^2 / 4}, \quad (3)
\]

\[
\text{ES} = \Delta p_{\text{water}} - \Delta p_{\text{surfactant}} \quad (4)
\]

Where, Hasegawa et al. have reported elastic stress of water in orifice flows\(^{(17)}\). The reductions of thrust and pressure drop include elasticity of water. Hence, in this research, ES is estimated by differences between water results and results of surfactant.

Figure 10 shows ES plotted against the mean velocity, V, for AE (Fig. 10(a)) and BC solutions (Fig. 10(b)). These plots exhibit a linear relationship, revealing that ES is dependent on V. Because these results agree with those for water, from (3) and (4) it can be seen that ES = 0 for LAS and SDS.
6. Concluding remarks

Jet thrusts and pressure drops were measured for aqueous solutions of several types of surfactants and polyethylene glycols in flows through micro-orifices. The orifice diameter ranged from 15 µm to 100 µm, and the orifice thickness was 20 µm.

Experiments showed that the results for the anionic surfactants, namely, LAS and SDS, were in agreement with the results obtained for water. In contrast, the cationic surfactant (BC) and nonionic surfactant (AE) showed an effective reduction in both the jet thrust and pressure drop. The plots for AE also revealed a steep rise at a particular Reynolds number for all of the orifices tested.

By studying the behavior of surfactant molecules at the liquid-solid interface, it can be seen that the alignment of the molecules acts like a macromolecular chain, strongly suggesting that the observed flow properties were caused by elastic stress.

The jet thrusts and pressure drops for the 0.1 wt % aqueous solution of PEG20000 was almost the same as that for PEG8000 for orifices of 15~100 µm.
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References


