Flow Properties of Microbubble/Polyethylene Glycol Mixtures Passing through Orifices and Slits

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Flows of microbubble/liquid mixtures have been extensively studied in both theoretical and applied research, and important results, such as drag reduction effects, have been reported. However, the majority of researchers have focused on only mixtures of microbubbles and water. Studies on microbubble mixtures in complex liquids, for example, for surfactant solutions and polymer solutions, are limited. The present study considers the flow of microbubble mixtures in a dilute polymer solution. In the present research, microbubbles (particle size: 20 μm) are suspended in either water or a dilute solution of polyethylene glycol. The liquids and suspensions were passed through various sizes of orifices (200 μm to 1.0 mm) and slits (397 μm and 596 μm), pressure drops were measured, and elongational stresses were estimated. Pressure drops of the polyethylene glycol solution were less than those of water, and the measured pressure drops of both microbubble mixtures were greater than those of the polyethylene glycol solution. As a result, polymer chains in the polyethylene glycol solution are considered to be laden with microbubbles, and this effect is seen in the corresponding elongational stress estimates.

Key Words: Orifice / Slit / Microbubble / Polyethylene Glycol / Pressure Drop

1. INTRODUCTION

Recently, a considerable amount of research has been conducted on microbubbles, and accordingly many papers have reported on the research results. For a microbubble/water mixture passed through a capillary tube to which lard oil had been applied, a mass removal rate of 0.3 was found, whereas a rate of 0.9 for only the microbubble/water mixture. Gotoh et al. separated oils in an emulsion by using microbubbles, and Tachibana reported on the medical application of a microbubble/liquid mixture as an ultrasonic contrast agent. Suzuki et al. showed that by suspending microbubbles in liquids, the turbulent structure was changed and the Reynolds stress was lowered. In addition, the drag coefficient was found to be reduced for microbubble/liquid mixtures in rectangular channels and capillary tubes by Murai et al. and Guin et al. Thus, as seen above, a number of theoretical and applied studies have been previously conducted. However, only microbubble/water mixtures have been typically investigated. Studies on microbubble mixtures in complex liquids, for example, surfactant solutions and polymer solutions, are limited. In general, anomalous and interesting results have been reported from investigations on complex liquids. Okawara et al. measured the pressure drop in slit flows of a wormlike micelle surfactant and found that flow properties changed as the surfactant structure was changed. Ouchi et al. conducted an experiment using an aqueous solution of cetyltrimethylammonium bromide and sodium salicylate, which form wormlike micelles, and reported on the shear induced structure and instabilities. Ushida et al. examined the flow properties of several types of surfactants that form spherical micelles, and found a drag reduction in elongational flows. Hasegawa et al. measured the flow properties and the rheological properties of dilute aqueous solutions of polyethylene oxide. Furthermore, Ushida et al. investigated the pressure drops of surfactant/nanobubble mixtures. However, the study of nano- and micro-bubble/dilute polymer mixtures was rare case. In the present research, a dilute polymer solution in which microbubbles were suspended was passed through different sizes of orifices and slits. The
resultant pressure drops were measured as characteristic flow properties, and the elongational stresses were estimated.

2. EXPERIMENTAL APPARATUS

2.1 Apertures

Tables I and II, and Figs. 1 and 2, show the specifications of the orifices and slits used in the experiments. For the orifices, the diameter, \( D \), ranged from 200 μm to 1.0 mm, the thickness, \( L \), was 20 μm or 0.5 mm, and the material was nickel, stainless steel, or acrylic. To construct a slit, two pieces of stainless steel having thickness \( H = 200 \mu m \) were attached to a stainless steel base plate (Fig. 2). Here, the slit width, \( B \), was 397 or 596 μm, and the slit length, \( W \), was 20 mm. The present orifices and slits were the same as those used in previous researches.9-15)

2.2 Experimental Setup

Figure 3 shows the experimental apparatus for measuring pressure drops. The basic setup is the same as that in previous research.9-15) Test liquids were transported from a 200 or 400 mL syringe pump (JP-H1, Furue Science Co. Ltd.) at a constant flow rate, \( Q \), to an acrylic channel (inner diameter: 25 mm; length: 180 mm) having an attached orifice or slit. The test liquid was thus passed through the orifice or slit, and the pressure drop, \( \Delta P \), was measured with a pressure transducer (SPD-12, Tsukasa Sokken Co. Ltd.) in measurement ranges of up to 500 Pa, 10 kPa, and 500 kPa.

2.3 Test Liquids

In the present research, ion-exchanged water and polyethylene glycol with a molecular weight of M.W. = 8000, were used as test liquids. These liquids are simply referred to as water and PEG hereinafter. The PEG was diluted to a concentration of 0.1 wt% (1000 ppm). Table III lists the properties of test liquids, where density, \( \rho \), and viscosity, \( \mu \), were measured with a Baumé hydrometer and a capillary viscometer, respectively, and surface tension, \( \sigma \), was observed by the du Noüy method.16,17) As confirmed in a previous studies18-22), the dilute aqueous solution of PEG has Newtonian viscosity and an elastic property. Lüsse et al.18) have reported relaxation time, \( \lambda \), of PEG was about \( 10^{-4} \) s in the concentration of the ranges from 0.1 wt% to 10 wt%. Furthermore, microbubble/liquid mixtures were used as

Table I Orifice specifications.

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<td>0.50</td>
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<td>Nickel</td>
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<tr>
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<td>1.51</td>
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<td>200</td>
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<td>0.10</td>
<td>Nickel</td>
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Table II Slit specifications.

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<td>Stainless steel</td>
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test liquids. The microbubble/PEG and microbubble/water mixtures are called MB/PEG and MB/water hereinafter. These mixtures contained 1.5 vol % of microbubbles, and the mean microbubble diameter, measured on a particle analyzer, was approximately 20 μm. The viscosity and surface tension of both microbubble/liquid mixtures were approximately the same. However, the density of the microbubble mixture was 1.0 % less than that of the water and PEG, owing to these mixtures containing 1.5 vol % air. The Reynolds number, Re, was calculated from $\rho DV/\mu$ for orifice flows and from $\rho BV/\mu$ for slit flows by using the fluid properties in Table III. Here, the mean velocity, $V$, is given by $4Q/\pi D^2$ and $Q/WB$ for the orifice and the slit, respectively.

### 3. NUMERICAL ANALYSIS

A numerical analysis was conducted for the orifice and slit flows by using dimensionless Navier-Stokes equations, where the numerical and boundary conditions were as follows.

#### 3.1 Orifice Flows

A direct numerical simulation (DNS) was carried out for orifice flows in the cylindrical coordinate system: $(r, \theta, z)$. $r$ and $z$ is radial direction and flow direction, respectively. $\theta$ is circumferential direction. The two-dimensional cylindrical dimensionless Navier-Stokes equations are

$$
\frac{\partial \hat{u}^*}{\partial t} + \hat{u}^* \frac{\partial \hat{u}^*}{\partial r} + \hat{u}_r^* \frac{\partial \hat{u}^*}{\partial z} = -\frac{\partial \hat{p}^*}{\partial z} + \frac{1}{Re} \left\{ \frac{\partial}{\partial r} \left[ r \frac{\partial \hat{u}^*}{\partial r} \right] + \frac{\partial^2 \hat{u}^*}{\partial z^2} \right\}, \tag{1}
$$

$$
\frac{\partial \hat{u}^*}{\partial t} + \hat{u}_r^* \frac{\partial \hat{u}^*}{\partial r} + \hat{u}_z^* \frac{\partial \hat{u}^*}{\partial z} = -\frac{\partial \hat{p}^*}{\partial r} + \frac{1}{Re} \left\{ \frac{\partial}{\partial z} \left[ r \frac{\partial \hat{u}^*}{\partial r} \right] + \frac{\partial^2 \hat{u}^*}{\partial z^2} \right\}. \tag{2}
$$

The azimuth, $\theta$, is ignored here, because the axisymmetric flow can be assumed to have zero tangential velocity. $u_r$ and $u_z$ show a velocity component of $r$ and $z$ direction, respectively. $t$ shows time. Index, $^*$, means dimensionless components; $u_r^* = u_r/V$, $u_z^* = u_z/V$, $r^* = r/D$, $z^* = z/D$, $p^* = p/\rho V^2$, and $t^* = t/(DV)$. Here, $V$ and $D$ are characteristic velocity and characteristic length, respectively. In the present study, $D$ is an orifice diameter, and $V$ is a mean velocity passing through the orifice. Fig. 4 shows the numerical regions. The diameter of the channel upstream and downstream of the orifice is $60D$, and the upstream and downstream lengths are $60D$. To solve equations (1) and (2) numerically, the finite volume method for a Newtonian fluid passing through an orifice was applied as in previous studies. In this numerical scheme the velocity and pressure are coupled by the SIMPLE method and are expressed on a staggered grid in a two-dimensional cylindrical coordinate system. The grid number is 1024 in each direction. Furthermore, the convective term is discretized by the first-order upwind finite difference method, and the viscous term is discretized by the second-order central difference method. The following boundary conditions are adopted: (a) Hargen-Poiseuille flow exists at the inlet boundary; (b) the pressure and velocity in the radial direction are zero at the outlet boundary; (c) the radial component of the velocity is zero along the center line; and (d) all velocities are zero at the wall (wall conditions). Figs. 5(a) and (b) show predicted results (dimensionless pressure drops, $K_o$, over changes in Reynolds number, $Re$) for cases when $L/D$ = 0.05 (Fig. 5(a)) and 1.51 (Fig. 5(b)). For comparison, previous results are also shown in these figures, and the current results agree with the previous results for both the cases.

#### 3.2 Slit Flows

A numerical analysis was also conducted for slit flows by using nondimensionalized two-dimensional Navier-Stokes equations in Cartesian coordinates $(x, y, z)$: 

![Fig. 4. Numerical regions and boundary conditions for orifice flows.](image)
\[ \frac{\partial u^*}{\partial t} + u^* \frac{\partial u^*}{\partial x} + u_y^* \frac{\partial u^*}{\partial y} = - \frac{\partial p^*}{\partial x} + \frac{1}{Re} \left( \frac{\partial^2 u^*}{\partial x^2} + \frac{\partial^2 u^*}{\partial y^2} \right), \]

\[ \frac{\partial u^*}{\partial t} + u^* \frac{\partial u^*}{\partial x} + u_y^* \frac{\partial u^*}{\partial y} = - \frac{\partial p^*}{\partial y} + \frac{1}{Re} \left( \frac{\partial^2 u^*}{\partial x^2} + \frac{\partial^2 u^*}{\partial y^2} \right). \]

Here, \( x \) is the flow direction, and \( y \) is the vertical direction. The \( z \) direction is ignored because we assume a zero velocity component in the span direction. \( u_x \) and \( u_y \) show a velocity component of the flow and vertical direction, respectively. Additionally, \( u_x^* = u_x/V \), \( u_y^* = u_y/V \), \( x' = x/B \), and \( y' = y/B \). Here, \( V \) and \( B \) are characteristic velocity and characteristic length, respectively. In the slit flows, \( B \) is a slit width, and \( V \) is a mean velocity passing through the slit. Fig. 6 shows a schematic of the numerical regions and boundary conditions, which almost match those for the orifice flows. The differences are that the diameter of the channel upstream and downstream of the slit is now \( 60B \), the upstream and downstream lengths are \( 60B \), and two-dimensional Poiseuille flow exists at the inlet boundary.

The grid number is 1024 in each direction. Figs. 7(a) and (b) show numerical predictions for the slit flows when \( H/B = 0.34 \) (Fig. 7(a)) and 0.50 (Fig. 7(b)). The dimensionless pressure drops, \( K_o \), of the slit flows are similar to those from previous numerical results.\(^{24} \)

4. EXPERIMENTAL RESULTS

4.1 Orifice Flows

Figures 8(a)–(d) shows experimental pressure drops, \( \Delta p_o \), plotted against strain rate, \( \nu/D \), for the case of orifice flows. The results for water agree with the numerical predictions in Section 3, and with the results for MB/water. In contrast, the results for PEG and MB/PEG are smaller than those for water. However, the pressure drops of MB/PEG are larger than the corresponding drops of PEG. Figs. 9(a)–(d) shows dimensionless pressure drops, \( K_o (= 2\Delta p_o / \rho V^2) \), with changing Reynolds number, \( Re \), for flow through an orifice. For comparison, the predictions found through the numerical analysis are shown, and the \( K_o \) values for water and MB/water agree with the predicted values. However, the \( K_o \) values of PEG and MB/PEG are considerably smaller.
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Fig. 8. $\Delta p$ plotted against $V/D$ for $D =$ (a) 1.0 mm, (b) 400 $\mu$m, (c) 330 $\mu$m, and (d) 200 $\mu$m.

Fig. 9. $K_o$ plotted against $Re$ for $D =$ (a) 1.0 mm, (b) 400 $\mu$m, (c) 330 $\mu$m, and (d) 200 $\mu$m.
4.2 Slit Flows

Figures 10(a) and (b) show pressure drops, Δp, for changing strain rate, V/B, for slit flows. As for the orifices, the pressure drops of water and MB/water agree with predictions from the Navier-Stokes equations. However, pressure drops for the PEG and MB/PEG were typically smaller than those. As V/B increases, the difference between the water results and the experimental pressure drops of PEG and MB/PEG both increase. In addition, the values of Δp for the slit flows are higher than those for the orifice flows. Figs. 11(a) and (b) show dimensionless pressure drops, K_s (= 2Δp/ρV^2), plotted against Reynolds number, Re. The K_s values of MB/PEG are higher than those of PEG.

5. DISCUSSION

5.1 Effect of Microbubbles on Pressure Drops

The pressure drops measured for the MB/PEG mixtures containing 1.5 vol % microbubbles, when passed through orifices and slits, were higher than those of the PEG-only solutions. This difference is attributed to the elastic property found in PEG in previous numerical and experimental researches. Steuter et al., Torchilin et al., and Mao et al. reported the elasticity of PEG was caused by the entanglement of polymer chains. Jin et al., Terasaka et al., and Yamada et al. discovered that microbubbles existed in the solutions at steady state, and that the microbubble diameter did not change. In light of the above findings, we propose models of PEG flow and MB/PEG flow based on the structures shown in Figs. 12(a) and (b). For PEG, the elastic property occurs due to tangles of PEG chains (Fig. 12(a)). However, tangles are disturbed by microbubbles in MB/PEG (Fig 12(b)), and thus pressure drops increased in these mixtures.

5.2 Elastic Property in Orifice and Slit Flows

Since microbubbles disturbing the PEG polymer tangles are considered to increase experimental pressure drops, the elastic properties of PEG and MB/PEG were estimated. Following previous researches, elongational stress, the elasticity property under elongational (orifice and slit) flows, was expressed by the reduction in the pressure drops:

\[ ES = \Delta p_{\text{water}} - \Delta p_{\text{PEG, MB/PEG}} \]  

Fig. 10. Δp, plotted against V/B for B = (a) 596 μm and (b) 397 μm.

Fig. 11. K_s plotted against Re for B = (a) 596 μm and (b) 397 μm.
Here, “water” denotes the corresponding pressure drop for water, and “PEG” and “MB/PEG” indicate the experimental pressure drops for PEG and MB/PEG, respectively. Figs. 13(a) and (b) show the resultant elongational stress, $ES$, plotted against mean velocity, $V$, for the orifice (Fig. 13(a)) and slit flows (Fig. 13(b)). The $ES$ in the both liquids was approximately proportional to the square of the $V$. In the previous result\(^\text{11}\), it was found that elastic stress of a dilute aqueous solution of polyethylene oxide was expressed as Eq.(6).

$$ES = \rho V^2$$  \hspace{1cm} (6)

The present results in the case of PEG were the same as the previous results.\(^\text{11}\) In both flows, $ES$ values for MB/PEG are about 30 \% less than those for PEG. Additionally, the interface material (nickel, stainless steel, and acrylic) was independent of the values of $ES$. These results correspond to the above discussion on PEG chains tangles being disturbed by the existence of microbubbles.

### 6. CONCLUDING REMARKS

In the present research, water, polyethylene glycol (M.W. = 8000), and microbubble/liquid mixtures (with 1.5 vol \% microbubbles) were passed through various sizes of orifices and slits, and pressure drops were measured. The following results were found.

1. The pressure drops of water for both types of flows agree with those predicted by the Navier-Stokes equations. However, the experimental results for PEG were lower than those of water.
2. Pressure drops for the MB/PEG mixture were less than those for water and higher than those for PEG in the experiments.
3. Estimated elongational stresses in the MB/PEG mixture were smaller than those in only PEG.

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**Fig. 12.** Schematic images of the fluid structure for the case of (a) PEG and (b) MB/PEG flow.

**Fig. 13.** $ES$ plotted against $V$ for (a) orifice and (b) slit flows.
REFERENCES