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Anomalous phenomena in several types of liquid flows through small orifices in a range of low Reynolds numbers

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ABSTRACT

Micro- and nano-scale fluid mechanics is one of the most intriguing and attractive fields in modern fluid mechanics and engineering because it can be applied in various physicochemical, industrial, and biological fields. In the present study, pressure drops were observed in a number of applications for several types of liquid flows through orifices of various sizes at low Reynolds numbers. In the case of water and an aqueous solution of glycerol, although the resultant pressure drops and Euler numbers agreed almost exactly with the values calculated by using the Navier–Stokes equations for an orifice with a diameter of 50 μm, the values increased as compared with the calculated values for orifices with a diameter of 100 μm and 200 μm. The values for the pressure drops of surfactant solutions were similar to those for water. The measured values for some dilute surfactant and polymer solutions appeared to be uncorrelated with the Reynolds number. Several contributing factors are discussed, such as elasticity, cavitation, electric effect, and micro-aperture effect. The formation of a solid-like layer at the solid–liquid interface around the orifice wall is inferred at slow flows and flows with low Reynolds numbers, in agreement with previous studies.

1. Introduction

In recent studies [1–4], reductions in pressure drops were found for several types of liquids passing through micro-orifices. Furthermore, the following phenomena were observed. First, the pressure drops for water and aqueous solutions of glycerol for microscopic orifices (<100 μm in diameter) were smaller than those calculated by using the Navier–Stokes equations in the range of $Re = 1.0 \times 10^2–3.0 \times 10^3$ [1]. Furthermore, drag coefficients and pressure drops for surfactant solutions exhibited anomalous changes [2,3]. Lastly, polyethylene oxide and polyethylene glycol, which are viscoelastic liquids, exhibited smaller pressure drops than those for water [1,3]. Previous studies have also discussed the phenomena of wall slip, viscous heating, and cavitation, but without consideration of experimental results. Hasegawa et al. [1] suggested elasticity of water in high elongational flows. In contrast, in a related study, Hasegawa et al. [5] measured a more drastic pressure drop for water as compared with that calculated for water passing through a micro-orifice. Furthermore, Hsiai et al. [6] observed that the pressure drops for water agreed with the calculations. However, the orifice investigated in [6] was of complex shape and configuration. Oliveira et al. [7] conducted experiments and numerical simulations regarding pressure drop in orifice and slit flows, where the experimental results were almost identical with the calculated ones and appeared to be dependent on the contraction and aspect ratio. Additionally, intriguing results regarding orifice flows were reported by Lew et al. [8], Piau et al. [9], and Cruickshank [10]. As in the studies mentioned above, there is no agreement on the properties of elongational flows (orifice and slit flows). Also, the properties of elongational flows at low Reynolds numbers are still unclear. In the present study, pressure drops were measured for several types of liquid flows through small orifices in a range of low Reynolds numbers ($Re = 10^{-2}–10^1$), and the results are presented together with a discussion on anomalous phenomena.

2. Experimental setup

2.1. Test liquids

The test liquids used in this research were ion-exchanged water, 50/50 water/glycerol mixtures, polyoxyethylene (23) lauryl ether (a non-ionic surfactant), benzalkonium chloride (a cationic surfactant), and sodium dodecyl sulfate (an anionic surfactant) [3]. These surfactants are commonly used in laundry detergents [2]. The concentration of aqueous solutions of surfactants was 1.0 wt% (=1.0×10^4 ppm). Polyethylene glycol and polyacrylamide were also tested because previous studies found that their

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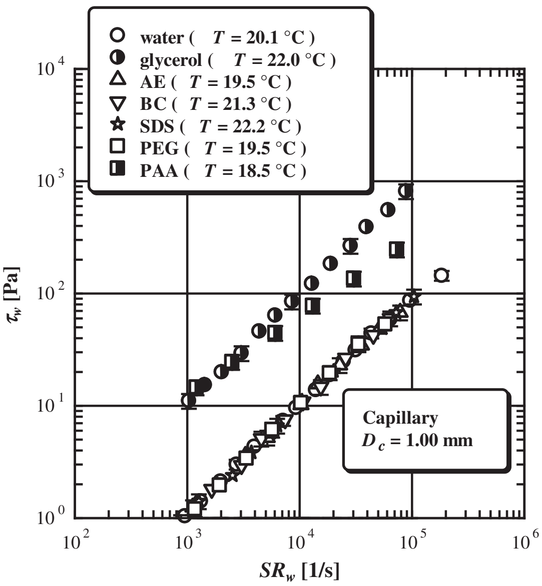

Fig. 1. Relation between shear stress and shear rate on wall, which is evaluated from the pressure drop and the flow rate in the case of a Hargen-Poiseuille flow.

solutions exhibited elasticity [11,12]. Furthermore, the concentration of aqueous solutions of PEG and PAA was 0.10 wt% (=1.0 × 10^3 ppm). The abovementioned test liquids are hereafter abbreviated as water, glycerol, AE, BC, SDS, PEG, and PAA, respectively. Fig. 1 shows the wall shear stress τ_w plotted against the wall shear rate SR_w as measured using a capillary viscometer with an inner diameter D_c of 1.00 mm. Furthermore, Table 1 shows the estimated physical properties of the test liquids, where the viscosity refers to the Newtonian viscosity μ, except for PAA [3,12], which is commonly known as a power-law liquid, for which

$$\tau_w = m(SR_w)^n \tag{1}$$

where m and n denote the dilatant viscosity and the power law index, respectively, c.m.c. denotes the critical micelle concentration. All the surfactants were used at a concentration higher than their c.m.c. Fig. 2(a) shows the experimental apparatus for measuring the elasticity of the test liquids. A special setup was necessary since the elasticity of the liquids was found to be too small to measure with a conventional rheometer. Therefore, a jet thrust method available for high shear rates was adopted, because jet thrusts are closely related to the viscoelasticity of liquids [13–15]. Even with this method, a special technique was necessary for measuring such small thrusts, and thus a technique proposed by Hasegawa et al. [16] was used. A jet of liquid was issued from the capillary into a cup, which was immersed in a vessel filled with water. Since the area of the cup mouth was considerably larger than the cross-sectional area of the jet, it was possible to ignore the momentum flux out of the cup relative to the momentum of the jet. The force measured by this method is denoted as T_m below. The cup was suspended on strings connected to an electronic balance for measuring the thrust T_m, and the material of the cup was chosen to be only marginally denser than water in order to reduce the extra weight acting on the balance. The measured T_m values are plotted as a function of the wall shear rate SR_w in Fig. 2(b), where the solid line shows the theoretical line for a Hargen-Poiseuille flow. We can see that all data on the test liquids, except PEG and PAA, generally agree with the theoretical line, showing no discernible differences. Solutions of PEG and PAA are well known as viscoelastic liquids. Therefore, the lower values for the PEG and PAA solutions are considered to be due to elasticity. However, as the jet thrust for the other liquids was the same as that of water within the experimental error, it was concluded that the test liquids possess no measurable elasticity in this range of shear rate. Moreover, all experiments described herein were carried out at room temperature.

Table 1
Properties of the test liquids.

Test liquid	Density, ρ (kg/m^3)	Viscosity, μ (Pa s)	
Water	1.0 × 10^3	1.0 × 10^{-3}	
Glycerol	1.0 × 10^3	1.0 × 10^{-2}	
AE	1.0 × 10^3	1.0 × 10^{-3}	
BC	1.0 × 10^3	1.0 × 10^{-3}	
SDS	1.0 × 10^3	1.0 × 10^{-3}	
PEG	1.0 × 10^3	1.0 × 10^{-3}	
Test liquid	Density, ρ (kg/m^3)	Dilatant viscosity, m (Pa s^n)	Power law index, n ×10^{-1} [–]
PAA	1.0 × 10^3	1.0 × 10^{-1}	0.74

2.2. Experimental apparatus

Fig. 3 shows the experimental apparatus used in this study, where the configuration is essentially the same as that described in previous studies [1,3,17]. Test liquids were pushed into a liquid stored in a vessel, with the aid of a syringe pump (JP-HP1, Furue Science Co. Ltd., Japan), through a micro-orifice installed at the

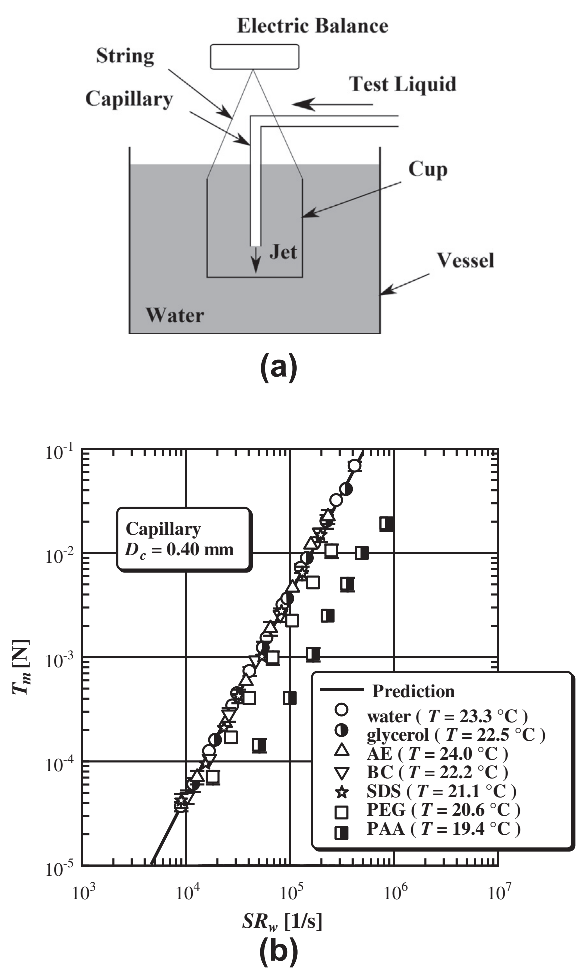

Fig. 2. (a) Experimental apparatus for measuring jet thrusts and (b) measured jet thrust as a function of shear rate on wall.