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Anomaly of pressure drops of rod-like micelle surfactant solutions passing through small orifices

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A B S T R A C T

The flow properties of water and surfactant solutions mixed with counter ions were investigated in flows through small orifices. Good agreement between the resultant pressure drops of water and the numerical predictions of the Navier–Stokes equations was obtained. Compared with those of water, the pressure drops of surfactant solutions were larger for molar concentration ratios of 1.0. Moreover, an anomalous flow pattern was observed in the flows through a slot channel: an unstable vortex and unsteady flow were found before the slot for a molar concentration ratio of 1.0, whereas a steady flow pattern was observed for a molar concentration ratio of 10.0. Thus, we conclude that the anomalous pressure drops for surfactant solutions were caused by the unsteady flows.

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1. Introduction

Engineering is segmented into various field including, bioengineering, environmental science, and other disciplines. In fluid mechanics, the importance of investigating several types of surfactant solutions, polymer solutions, suspensions, and gels (so-called complex fluids) has been increasing; For example, in vivo analysis about blood flows, swallowing test, food product development, polymer molding process, mixing process, contaminant flow in the ocean, etc. Furthermore, it is well-known that frictional resistance is reduced by using dilute aqueous solutions of surfactants, which form rod-like (worm-likes) micelles in aqueous solutions, in turbulent flows [1–3]. This phenomenon is generally called the drag reduction effect in non-Newtonian fluid mechanics, and it contributes to energy saving in fluid transportation [4,5]. However, characteristic length scales investigated in the above studies were relatively large with diameters of more than 1.0 mm even though they were described as "small-sized" [6,7]. On the other hand, micro-sized channels and tubes were easily made with the developments in MEMS (Micro-Electro-Mechanical System) technique. Thus, it was very necessary and important for fluid mechanics to understand micro-sized flows. For example; membrane filters, medical filters, and biological membranes used in water treatment, food science, and medical engineering. However, Studies involving micrometer-sized channels and tubes are limited. In addition, many studies of the drag reduction effect have used pipe flows in tubes. Studies of flows through a tube with a sudden contraction and rapid expansion, example for orifice flows and slit flows, are rare cases [8,9]. In particular, there are very few studies involving micrometer-sized orifices. In the present study, pressure drops of water and rod-like micelle surfactant solutions were measured, and flow properties of liquids passing through small orifices with diameters ranging from 100 μm to 1.0 mm were observed. The mechanism producing anomalous pressure drops in surfactant solutions was clarified. It would be possibility to understand elongational flows (especially, the flows passing through micro-sized orifices) in microscale non-Newtonian fluid flows.

2. Test fluids

Water and surfactant solutions were used in the present study. Deionized water was made using the same distillation apparatus (GSR-200, ADVANTEC Co. Ltd., Japan) as in previous studies [10,11]. The deionized water, simply called water in this paper, has electric resistivity = 18.2 MΩ cm. Cocoyl alkyltrimethyl ammonium chloride (Arquad C-50, Lion-Akuzo Co. Ltd., Japan) was used as cationic surfactant solutions. The molecular weight is

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Nomenclature

C_s	molar concentration for surfactant solution (mol/L)
C_c	molar concentration for counter ion (mol/L)
D	orifice diameter (μm)
D_c	capillary diameter (mm)
D_H	hydraulic diameter (μm)
h	slot size (μm)
K	dimensionless pressure drop (–)
L	thickness of orifice (μm)
L/D	thickness ratio (–)
L_c	length between two pressure holes (mm)
m	dilatant viscosity (Pa s^n)
n	power law index (–)
Q	flow rate (m^3/s)
Re	Reynolds number (–)
Re^*	generalized Reynolds number (–)
Re_w	asymptotically approached Reynolds number for water (–)
SR_{app}	apparent strain rate (s^{-1})
SR_w	shear rate on wall (s^{-1})
V	mean velocity (m/s)

Greek letters

Δp	pressure drop (Pa)
η	viscosity estimated by τ_w/SR_w (Pa s)
μ	Newtonian viscosity (Pa s)
ρ	density (kg/m^3)
τ_w	wall shear stress (Pa)
φ	molar concentration ratio (–)

320.0 g/mol and the molar concentration is $C_s = 0.10$ mol/L [12–14]. When a counter ion is mixed in surfactant solutions, rod-like micelles can be formed [15–18]. In this study, the widely used counter ion sodium salicylate (NaSal, Wako Pure Chemical Industries Co. Ltd., Japan) was used. The molecular weight of NaSal is 160.1 g/mol. When mixed with surfactant solution, the molar concentration ratio

$$\varphi = \frac{C_c}{C_s} \tag{1}$$

where C_c is the molar concentration of NaSal, was adjusted to range from 0.10 to 10.0. Hereinafter, these mixtures are called A/N Mixtures in this paper. The preparation of surfactant solutions proceeded as follows. Arquad and NaSal were dissolved in water at room temperature, which was controlled by air conditioners. Since there is almost no mechanical degradation, the liquids were dissolved using relatively strong stirring. They were used in the experiment after being left to stand for about a half day. When investigating flow properties, it is important to clarify the physical properties of the test fluid. In particular, viscosity is a very important parameter for complex fluids. The viscosity was measured using a capillary type viscosity meter (Fig. 1), which has the advantage that non-Newtonian properties can be evaluated. A power law relationship (Eq. (2)) between wall shear stress, τ_w, and shear rate on the wall, SR_w, was assumed:

$$\tau_w = m(SR_w)^n \tag{2}$$

where m is the dilatant viscosity and n is the power law index. The quantities τ_w and SR_w were estimated from pressure drop, Δp, and flow rate, Q, as shown in Eqs. (3) and (4).

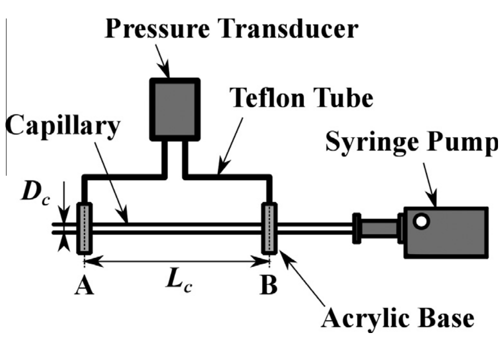

Fig. 1. Schematic image of the capillary type viscosity meter.

$$\tau_w = \frac{D_c \Delta p}{4L_c} \tag{3}$$

$$SR_w = \frac{3n+1}{4n} \cdot \frac{32Q}{\pi D_c^3} \tag{4}$$

where D_c is the capillary diameter and L_c is the length between two pressure holes (length between A and B shown in Fig. 1). Moreover, two diameters were used because of measuring the large SR_w ranges. $SR_w < 10^3$ s^{-1} was observed by $D_c = 0.8$ mm, and the range

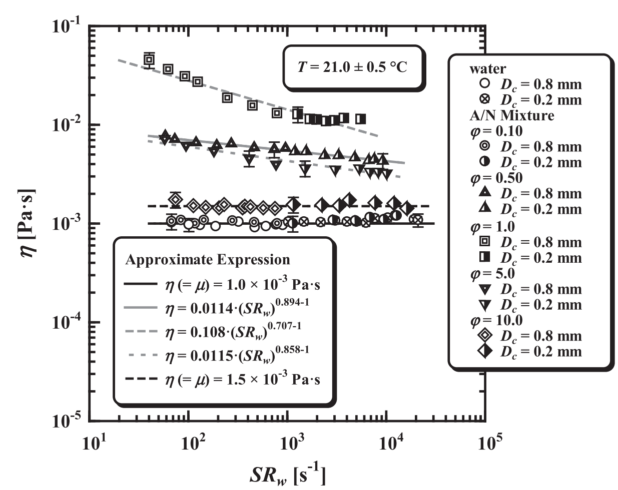

Fig. 2. Relationship between measured viscosity, η, and shear rate on wall, SR_w, which are estimated from pressure drops and flow rate with Hagen–Poiseuille flow assumptions.

Table 1
Fluid properties for test fluids.

φ (–)	Dilatant viscosity, m (Pa s^n)	Power law index, n (–)
0.10	1.0×10^{-3}	1.0
0.50	1.14×10^{-2}	0.894
1.0	1.08×10^{-1}	0.707
5.0	1.15×10^{-2}	0.858
10.0	1.5×10^{-3}	1.0
(Water)	1.0×10^{-3}	1.0

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