

Article

Pseudo-Laminarization of Mixed Microbubble Water and Complex Fluids in Capillary Flows

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Abstract: Symmetry in fluid flow is determined by external factors such as magnetic or electric fields. Owing to the electrical properties of fluids, liquids containing fine bubble or ionic surfactant molecules differ from the normal fluid flow. Therefore, the pressure drop and frictional coefficient in a pipe are measured and estimated for water alone, for mixed microbubble water (MB), and for complex fluids (anionic surfactant solution and polymer solution) in capillary flow with constant flow rate. For water alone, good agreement is obtained between the experimental and theoretical values for laminar Hagen–Poiseuille flow and the Blasius expression in turbulent flow. For the MB, pseudo-laminarization is suggested up to a Reynolds number of 4.2×10^3 . Both the anionic surfactant solution and the polymer solution exhibit the same tendency as that of the MB. In explaining these behaviors, elasticity and electrical interaction are discussed, and electrical interaction on the capillary wall is strongly suggested to be a contributing factor. Additionally, surface tension is investigated and supports the discussion.

Keywords: pseudo-laminarization; microbubble; complex fluid; pressure drop; capillary flow



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1. Introduction

Active matter is a general term for non-equilibrium systems consisting of elements that move spontaneously and is known as the collective movement of birds and fish and the underwater movement of microorganisms. Active matter has been actively studied in a crossover manner between physics, chemistry, biology, and other fields [1]. It has been pointed out that there is an antisymmetric viscosity even in fluids containing micromachines that break the time reversal symmetry [2]. In these studies, the effects of magnetic and electric fields have been reported [3]. On the other hand, fine bubbles or ionic surfactant molecules in liquids are charged electrically. Therefore, phenomena different from normal fluids could occur. Recently, many studies involving microbubbles (average particle diameter less than 100 μm) have attracted attention. For example, microbubbles have been applied to aquaculture and growth promotion in fisheries and agriculture [4–6]; they have been used to improve water quality (purification effect) in environmental and civil engineering [7–10]; and they have been used for cleaning [11–13], sterilization [14–16], and drag reduction [17–21] in industrial applications. Kodama et al. developed a technology to reduce frictional resistance by injecting air bubbles into the wall of a ship [17], but they used millimeter-sized bubbles. Serizawa et al. reported that mixed microbubble water (hereinafter referred to simply as MB) in a vertical pipe exhibited pressure loss in the turbulent region (Reynolds number $Re > 1.0 \times 10^4$) that was reduced by several percent [18]. They measured the frictional coefficient λ of MB in a vertical pipe and found

pseudo-laminarization that almost coincided with the theoretical value for laminar flow, that is,

$$\lambda = \frac{64}{Re}, \quad (1)$$

up to $Re = 2.0 \times 10^4$. However, the mechanism for that pseudo-laminarization by microbubbles was unclear. In the above studies, the characteristic length was measured in millimeters. These findings were a very useful in fluid transport. On the other hand, it was possible to fabricate micro-sized flow fields with high accuracy due to MEMS technology. However, there is limited knowledge on fluid transport in small-sized flow fields (≤ 1.0 mm). Meanwhile, Ushida et al. reported pseudo-laminarization by adding micellar solutions and dilute polymer solutions [22,23], and they reported that the rheological properties (first normal stress differences) exhibited pseudo-laminarization. However, pseudo-laminarization by microbubble mixtures without rheological properties must be considered from a different perspective. In the present study, water alone, MB, a surfactant solution, and a polymer solution flowed through narrow tubes with inner diameters of 110–750 μm , and the pressure drop was measured to estimate the frictional coefficient at constant flow rate. The purpose of this study is to clarify the mechanism of pseudo-laminarization by microbubbles.

2. Test Fluids

In this study, four types of test fluids were used: deionized water (electric conductivity = 0.055 $\mu\text{S}/\text{m}$; hereinafter referred to simply as water) produced using a distillation apparatus (RFD240NC; ADVANTEC Co., Ltd., Japan), MB, an anionic surfactant solution (sodium dodecyl sulfate, hereinafter referred to simply as SDS; molecular weight = 288; Wako Pure Chemical Industries, Ltd., Japan), and a polymer solution (polyacrylamide, hereinafter referred to simply as PAA; molecular weight = 5×10^6 ; Wako Pure Chemical Industries, Ltd.). The void fraction is very important for MB, so it was measured after 5 min of operation of the commercial microbubble generator (OM1-C200; Aura Tech Co., Ltd., Japan) under the following procedure. Microbubbles were generated in 5.0 L of water in a glass beaker, and the resulting MB was then left at room temperature (22 °C for 60 min); the apparent void fraction, calculated from the decrease in volume, was $0.16 \pm 0.1\%$ (number of trials = 10). Moreover, in a previous study, we showed the lifetime of microbubbles [24]. In the case of the present MB, the particle diameter decreased gradually with elapsed time from an initial mean diameter of 42 μm , and self-collapse was confirmed. It could also be seen that self-collapse occurred within a net time of 130 s. The SDS and PAA were used in the concentrations of 1.0 and 0.10 wt%, respectively. With a concentration (1.0 wt%) greater than the critical micelle concentration (CMC = 0.12 wt%), the SDS formed spherical micelles in water.

Figure 1 shows the relationship (log-log plot) between the wall shear stress τ_w and the wall shear rate SR_w of the test fluids measured by a capillary-type viscosity meter with an inner diameter of $D = 1.4$ mm or 600 μm . The viscosity of MB and SDS agreed with that of water alone ($\mu = 1.0 \times 10^{-3}$ Pa · s), and the density for water ($\rho = 1.0 \times 10^3$ kg/m³) was used to summarize the experimental results. The experimental results did not vary for the density of the test fluids. We checked in pre-experiments. By contrast, the PAA exhibited non-Newtonian viscosity, and the power-law model

$$\tau_w = K(SR_w)^n \quad (2)$$

was used to evaluate the non-Newtonian viscosity, where the constant factor and power-law index of the PAA were $K = 7.84 \times 10^{-2}$ Pa · s^{*n*} and $n = 0.653$, respectively [25]. Although the PAA exhibited non-Newtonian viscosity, zero-shear viscosity was not obtained for limitation of the syringe pump.

Next, the viscoelastic properties of the test fluids were measured as rheological properties by the jet thrust method [26–28]. Figure 2 shows the jet thrust T_m plotted against the

wall shear rate SR_w (log-log plot) measured using a capillary with an inner diameter of $D = 400 \mu\text{m}$. The solid line is the prediction for Hagen–Poiseuille flow, i.e.,

$$T_m = \frac{4}{3}\rho QV, \quad (3)$$

where ρ is the density, Q is the flow rate, and V is the mean velocity passing through the capillary. Good agreement was obtained between the experimental results for water alone and the predictions. The values for MB and SDS were almost the same as those for water alone, while those for PAA were approximate 50% lower, with this being due to the PAA having viscoelastic properties. All measurements were performed at room temperature T .

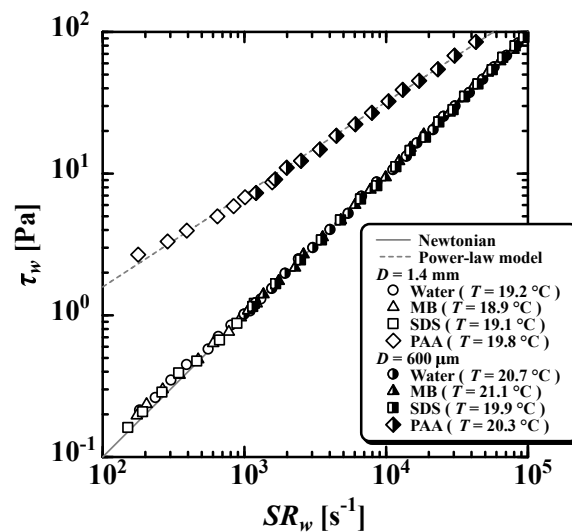


Figure 1. Relationship between wall shear stress τ_w and wall shear rate SR_w of all test fluids using capillary-type viscosity meter with inner diameter $D = 1.4 \text{ mm}$ or $600 \mu\text{m}$. Water alone, mixed microbubble water (MB), and anionic surfactant solution (SDS) exhibited Newtonian viscosity ($\mu = 1.0 \times 10^{-3} \text{ Pa} \cdot \text{s}$). On the other hand, only polymer solution (PAA) exhibited non-Newtonian viscosity (power-law model; constant factor $K = 7.84 \times 10^{-2} \text{ Pa} \cdot \text{s}^n$ and power-law index $n = 0.653$).

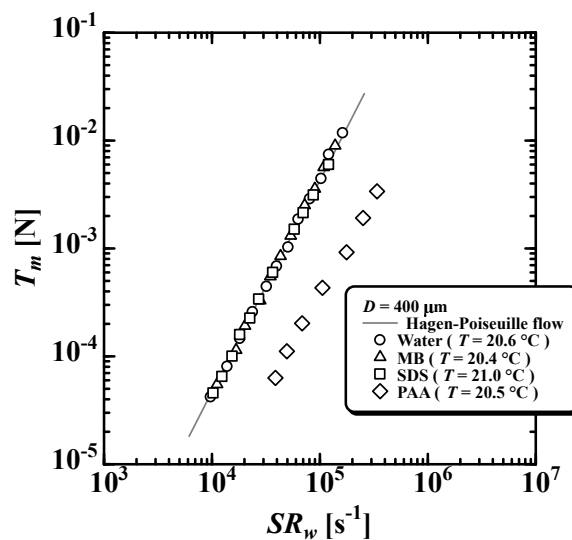


Figure 2. Jet thrust T_m plotted against wall shear rate SR_w of test fluids. Only polyacrylamide (PAA) exhibited elastic properties because of reducing jet thrust.

3. Experimental Setup

3.1. Experimental Apparatus

Figure 3 shows the experimental apparatus used to measure the pressure drop at constant flow rate. The test fluids were transported at constant flow rate Q using a syringe pump (JP-H1 and JP-H5; Furue Science Co., Ltd., Japan), and the differential pressure between sections A and B in Figure 3 was measured as the pressure drop Δp using a pressure transducer (SDP-12; Tsukasa Sokken Co., Ltd., Japan).

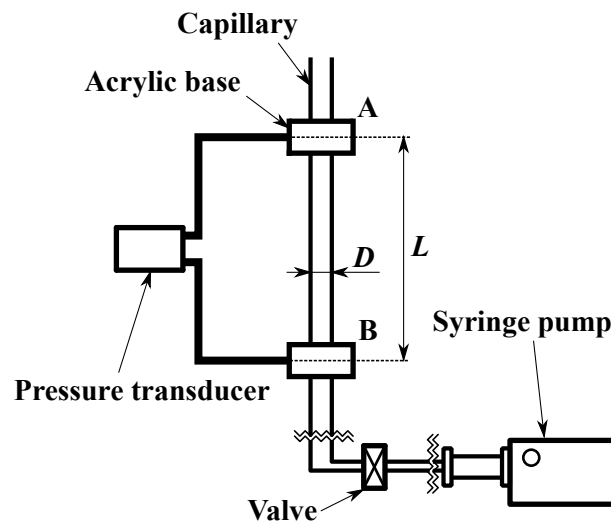


Figure 3. Schematic of experimental apparatus for measuring pressure drop at constant flow rate.

3.2. Capillaries

Three capillaries (SUS304) were used. The inner diameters were $D = 750 \mu\text{m}$ (length $L = 230 \text{ mm}$), $490 \mu\text{m}$ ($L = 120 \text{ mm}$), and $110 \mu\text{m}$ ($L = 80 \text{ mm}$), where L is the distance between sections A and B in Figure 3. Figure 4 shows cross-sectional views of the capillaries with $D = 750 \mu\text{m}$ (Figure 4a) and $110 \mu\text{m}$ (Figure 4b), taken with a commercial microscope (VH-8000; KEYENCE, Japan). The shape is complicated and not perfectly circular, and the inner diameter was measured by approximating a circle.

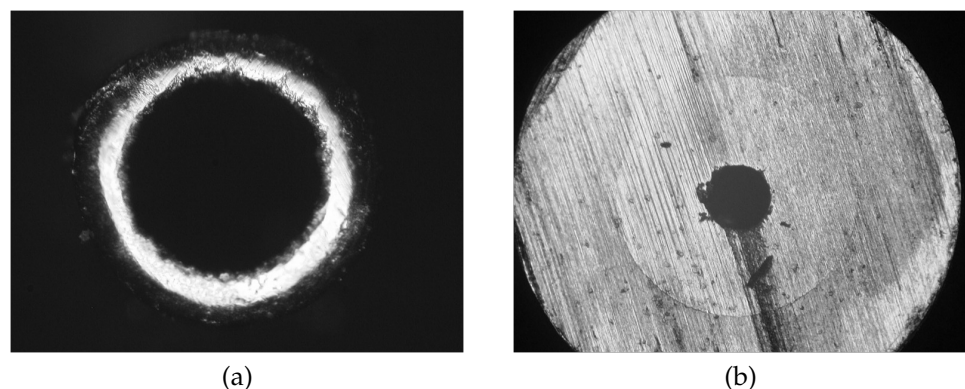


Figure 4. Photographs of the inner diameter for $D =$ (a) $750 \mu\text{m}$ and (b) $110 \mu\text{m}$.

4. Experimental Results

4.1. Frictional Coefficient and Reynolds Number

In the experiment, the pressure drop Δp was measured and the frictional coefficient λ was used to organize the experimental results, where λ is given by

$$\lambda = \frac{2\Delta p}{\rho V^2} \cdot \frac{D}{L} \quad (4)$$

Due to their Newtonian viscosity μ , the Reynolds number Re for water alone, MB, and SDS was obtained using

$$Re = \frac{\rho V D}{\mu} \quad (5)$$

However, the PAA could not be defined in the same way as water alone because it exhibited non-Newtonian viscosity (power-law model). Therefore, the generalized Reynolds number

$$Re^* = \frac{\rho V^{2-n} D^n}{K \left(\frac{3n+1}{4n} \right)^{n-1} 8^{n-1}} \quad (6)$$

reported by Harris [29] was used instead.

4.2. Relationship between Frictional Coefficient and Reynolds Number

Figure 5 shows the experimental results for water alone and MB, where the vertical axis corresponds to the frictional coefficient λ and the horizontal axis corresponds to either the Reynolds number Re or the generalized Reynolds number Re^* . For water alone and MB, λ was consistent with that of laminar flow ($\lambda = 64/Re$) and with the Blasius expression

$$\lambda = 0.3164 Re^{-\frac{1}{4}} \quad (7)$$

in the turbulent flow region ($Re \geq 3.0 \times 10^3$) after the transition region ($2.0 \times 10^3 \leq Re \leq 3.0 \times 10^3$). The critical Reynolds numbers were $Re_c = 2.0 \times 10^3$ ($D = 490 \mu\text{m}$) and 2.3×10^3 ($D = 110 \mu\text{m}$). The MB exhibited $Re_c = 3.5 \times 10^3$ ($D = 490 \mu\text{m}$) and 4.2×10^3 ($D = 110 \mu\text{m}$). Figures 6 and 7 show the experimental results for SDS and PAA, respectively, which also showed pseudo-laminarization with Re (Re^*), remaining in the laminar state up to between approximately 3.0×10^3 and 4.0×10^3 . For SDS, the critical Reynolds numbers were $Re_c = 2.9 \times 10^3$ ($D = 490 \mu\text{m}$) and 3.8×10^3 ($D = 110 \mu\text{m}$). For PAA, the critical Reynolds numbers were $Re_c = 3.1 \times 10^3$ ($D = 490 \mu\text{m}$) and 3.2×10^3 ($D = 110 \mu\text{m}$). For $D = 750 \mu\text{m}$, laminar flow persisted up to the limit of the syringe pump for all test fluids. Moreover, it was confirmed that pseudo-laminarization occurred regardless of whether the inner diameter $D = 110$ or $490 \mu\text{m}$ was used in the experiment.

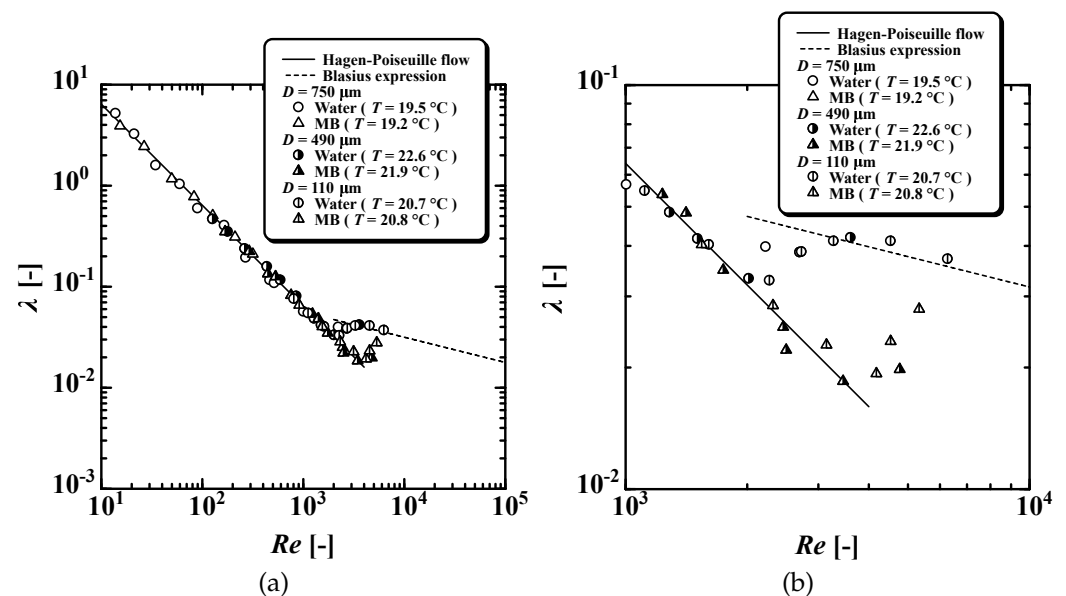


Figure 5. Experimental results for water alone and mixed microbubble water (MB) for frictional coefficient λ plotted against Reynolds number Re : (a) all data; (b) $1.0 \times 10^3 \leq Re \leq 1.0 \times 10^4$. The critical Reynolds number Re_c of water alone is 2.0×10^3 ($D = 490 \mu\text{m}$) and 2.3×10^3 ($D = 110 \mu\text{m}$). Moreover, the Re_c of MB is 3.5×10^3 ($D = 490 \mu\text{m}$) and 4.2×10^3 ($D = 110 \mu\text{m}$).

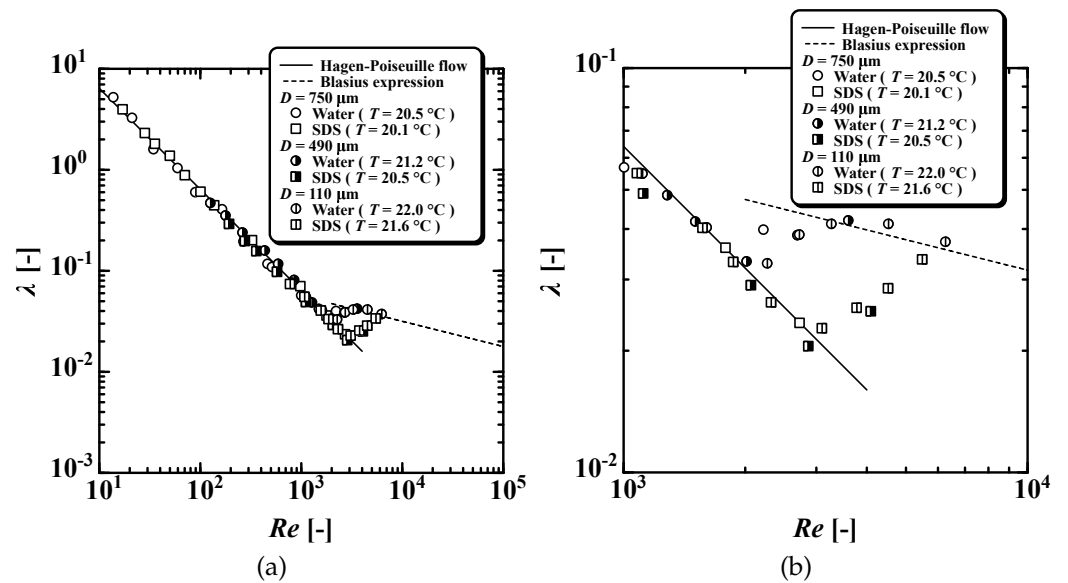


Figure 6. Experimental results for water alone and anionic surfactant solution (SDS) for frictional coefficient λ as a function of Reynolds number Re : (a) all data; (b) $1.0 \times 10^3 \leq Re \leq 1.0 \times 10^4$. The critical Reynolds number Re_c of SDS is 2.9×10^3 ($D = 490 \mu\text{m}$) and 3.8×10^3 ($D = 110 \mu\text{m}$).

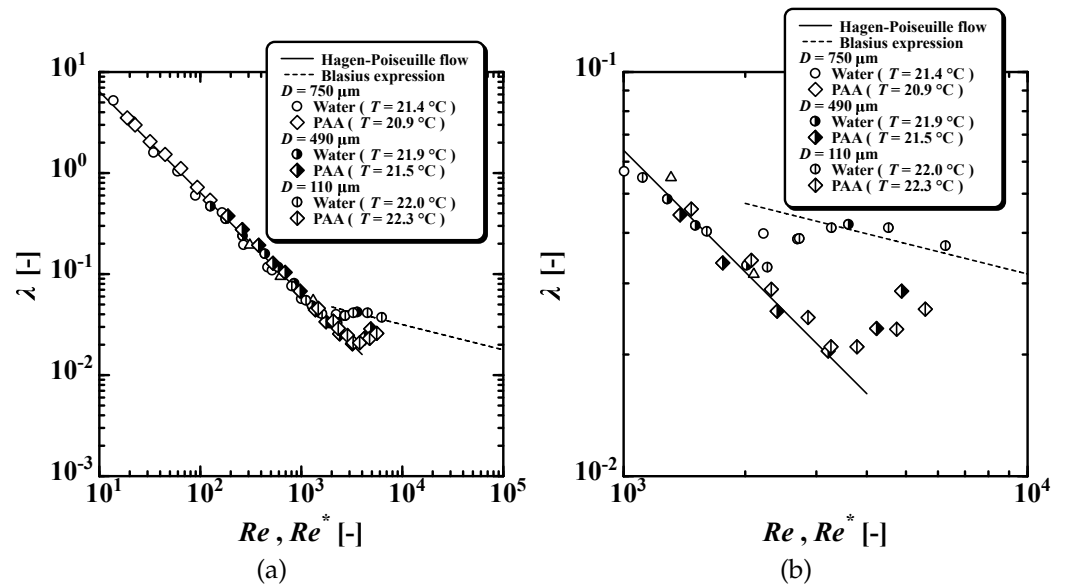


Figure 7. Experimental results for water alone and PAA for frictional coefficient λ versus Reynolds number Re or generalized Reynolds number Re^* : (a) all data; (b) $1.0 \times 10^3 \leq Re \leq 1.0 \times 10^4$. The critical Reynolds number Re_c of PAA is 3.1×10^3 ($D = 490 \mu\text{m}$) and 3.2×10^3 ($D = 110 \mu\text{m}$).

5. Discussion

In this study, it was confirmed that the pseudo-laminarization reported previously [18] occurred when microbubbles were used. This mechanism is discussed together with the experimental results for the PAA and SDS.

5.1. Elastic Properties

For the PAA, pseudo-laminarization was obtained (Figure 7), and it exhibited the elastic properties shown in Figure 2. Meanwhile, Hasegawa et al. reported the possibility of elasticity in water passing through micro-orifices [30–32], but the resultant pressure drops for water alone, MB, and SDS agreed with the predictions for laminar flow (Equation (1)) and turbulent flow (Equation (7)). Furthermore, it was clear that these test fluids could not exhibit elasticity (Figure 2).

5.2. Electric Interaction

In the case of SDS, pseudo-laminarization was observed up to $Re \sim 3.0 \times 10^3$, which was the same as that for MB. The surfactant SDS with a molecular weight of 288 did not show elasticity in the jet thrust measurement. SDS is an anionic surfactant, which means that it becomes anionic in aqueous solution and forms aggregated spherical micelles above a critical micelle concentration (0.12 wt%) [33–35]. This is a major difference from water alone. Moreover, it could be considered a factor in the occurrence of pseudo-laminarization. We discuss SDS and MB in terms of electrical interaction. It is well known that a metallic wall in water forms an electric double layer because of its zeta potential [36–38], and because SDS has negatively charged spherical micelles, they were attracted to the positively charged electric double layer. Thus, the number of spherical micelles near the wall was expected to be larger than that of the bulk. In this condition, the interfacial tension between the wall and the SDS was expected to be much lower than that in water because of the enhanced wettability caused by the surfactant. Meanwhile, it is known that microbubbles are also negatively charged in water [39–41]. In the same way, it could be assumed that the microbubbles were attracted to the electric double layer and gathered near the wall.

5.3. Interface between Solid and Liquid

In Section 5.2, we discussed the possibility that the interfacial tension between the wall and the test fluids decreased because of electric interaction. This was verified by measuring the surface tension using the du Noüy method [42], and Figure 8 shows an overview of the experimental apparatus. A circular ring connected to an electronic balance (GR-200; A&D Co., Ltd., Japan) was lowered via a string, and the ring was gradually pulled away from being in contact with the test fluid. A Petri dish filled with the test fluid was placed on the z-axis stage, which was then raised to bring the ring into contact with the surface. At this time, the scale value H_1 of the z-axis was read. As the stage was lowered gradually, the liquid attached to the lower end of the ring was gradually stretched and eventually broke, whereupon the maximum value F_m of the electronic balance and the scale value H_2 of the z-axis were recorded. If we consider the balance of forces, the force F_m acting on the liquid in contact with the ring and being pulled up is equal to the force due to its own weight (gravity) and the surface tension σ_s , giving

$$\sigma_s = \frac{F_m}{\pi(d_1 + d_2)} - \frac{\rho g(d_1 - d_2)(H_1 - H_2)}{4}, \quad (8)$$

where d_1 is the outer diameter of the ring (=15.5 mm), d_2 is the inner diameter (=15.0 mm), and g is the acceleration due to gravity (= 9.81 m/s²). The values of σ_s were 50.9 ± 1.2 mN/m (MB), 36.3 ± 0.9 mN/m (SDS), and 59.8 ± 2.8 mN/m (PAA). Considering that the value of σ_s for water is 71.6 ± 0.7 mN/m, the surface tension of the MB and SDS was reduced by approximately 30% and 49%, respectively.

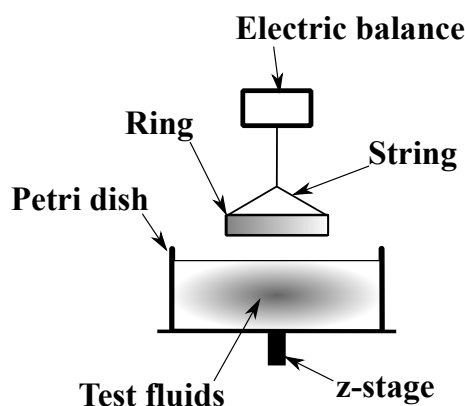


Figure 8. Schematic of experimental apparatus for measuring interfacial tension (du Noüy method).

At this point, it could be suitable to base the discussion on the solid–liquid interface. Figure 9 shows the frictional coefficient plotted against the capillary number

$$Ca = \frac{\mu V}{\sigma_s}, \quad (9)$$

which is defined as the ratio between the force based on viscosity and that based surface tension. Figure 9 shows the critical capillary number Ca_c at which the transition began. For $D = 490 \mu\text{m}$, Ca_c is 5.0×10^{-2} (water), 1.3×10^{-1} (MB), and 1.7×10^{-1} (SDS). For $D = 110 \mu\text{m}$, Ca_c is 2.7×10^{-1} (water), 7.1×10^{-1} (MB), and 7.4×10^{-1} (SDS). It was found that $Ca_c < 10^0$ and the flow field was strongly influenced by the interface.

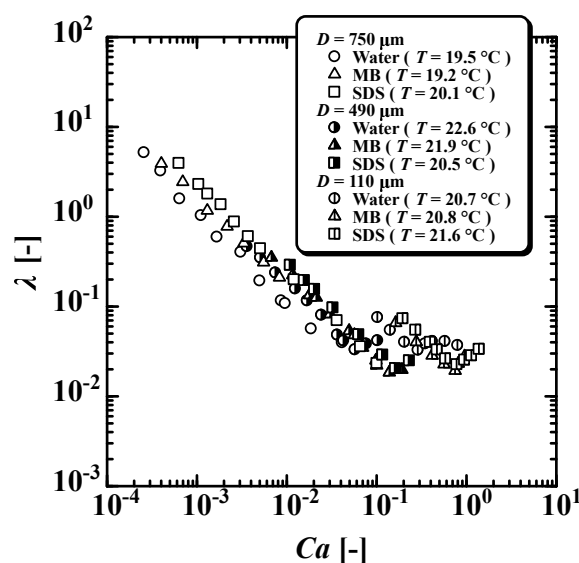


Figure 9. Frictional coefficient λ against capillary number Ca of water alone, MB, and SDS. For water alone, the critical capillary number Ca_c is 5.0×10^{-1} ($D = 490 \mu\text{m}$) and 2.7×10^{-1} ($D = 110 \mu\text{m}$). For MB, the critical capillary number Ca_c is 1.3×10^{-1} ($D = 490 \mu\text{m}$) and 7.1×10^{-1} ($D = 110 \mu\text{m}$). For SDS, the critical capillary number Ca_c is 1.7×10^{-1} ($D = 490 \mu\text{m}$) and 7.4×10^{-1} ($D = 110 \mu\text{m}$).

5.4. Summary of Discussion

The above discussion is summarized here. Ushida et al. measured the frictional loss of ultra-fine bubble (averaged particle diameter = 110 nm) passing through micro-orifices and reported that no drag reduction occurred at the characteristic length used in their experiment [43]. It was also reported that the surface tension of ultra-fine bubble was reduced by approximately 15% [44]. The pseudo-laminarization of the PAA with a 17% decrease in surface tension could be considered to exhibit elasticity rather than a decrease in surface tension. For the pseudo-laminarization of the MB and SDS, the absence of elasticity could be confirmed by jet thrust (Figure 2). As SDS contains negatively charged spherical micelles and the microbubbles of MB are also negatively charged [45], it was thought that their electrical interaction with the electric double layer near the wall lowered the surface tension. Thus, the number of spherical micelles were higher in SDS and MB than in the bulk.

6. Conclusions

In this study, the flow properties of water alone, mixed microbubble water, anionic surfactant solution, and polymer solution were investigated in capillaries with inner diameters of 750, 490, and 110 μm . For water alone, the frictional coefficient agreed with the laminar flow and the Blasius expression. For mixed microbubble water, the same tendency was obtained, but laminar flow persisted up to a Reynolds number of approximately 4.2×10^3 . The anionic surfactant solution and polymer solution exhibited the same results as those of the mixed microbubble water. Thus, pseudo-laminarization

of mixed microbubble water and complex fluids was obtained. When discussing the mechanism, it was considered that the pseudo-laminarization of the polymer solution was caused by elasticity whereas that of the microbubble water and the anionic surfactant solution was caused by the solid–liquid interface due to electrical interaction.

Nomenclature

Ca : capillary number
 Ca_c : critical capillary number
 D : inner diameter (mm, μm)
 K : constant factor ($\text{Pa} \cdot \text{s}^n$)
 L : length between two pressure holes (mm)
 n : power-law index
 Q : flow rate (m^3/s)
 Re : Reynolds number
 Re^* : generalized Reynolds number
 Re_c : critical Reynolds number
 SR_w : wall shear rate (s^{-1})
 T : temperature ($^{\circ}\text{C}$)
 T_m : jet thrust (N)
 V : mean velocity passing through a capillary (m/s)
 Δp : pressure drop (Pa)
 λ : frictional coefficient of pipe
 μ : Newtonian viscosity ($\text{Pa} \cdot \text{s}$)
 ρ : density (kg/m^3)
 σ_s : static surface tension (mN/m)
 τ_w : wall shear stress (Pa)

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