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Flow characteristics in a micro-cavity swept by a visco-elastic fluid

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ABSTRACT

Flow characteristics of visco-elastic fluids sweeping a one-side micro-cavity mounted in a micro-duct have been investigated in order to develop a novel technique of a mixing process for micro-reactors. In this paper, effects of the Reynolds number and of the rheological characteristics of the fluids were focused on. The cavity depth, the cavity length and the width of the wider flow path were fixed at 200, 1,000 and 400 μm, respectively. As a visco-elastic fluid, a solution of cationic surfactants with counter-ions was used. The molar ratio of counter-ions to surfactants was changed in four steps in order to change the rheological characteristics of the visco-elastic fluids. The Reynolds number was also changed from 0.100 to 100. From the results, it was found that a tonguing motion of the separation fluid bubble tip formed in the downstream region in the cavity occurs at a certain Weissenberg number larger than 200 due to the elastic instability. The fluctuating bulge structure was also observed on the upstream side wall of the cavity in a higher range of the Weissenberg number. Such a elastic instability can be expected a suitable micro-fluid motion for the micro-mixing.

1. Introduction

A micro-reactor [1–4] is one of promising chemical reactors on the process intensification and miniaturization of the chemical process. Especially on the fabrication of micro- and nano-size particles, emulsions, vesicles and etc., the control of the size can be realized in the micro-channels of such a micro-reactor. So, many researchers have studied about the application of micro-reactors to such solid or gel-like particle production in the chemical engineering fields [5–8]. However, there exists a mixing problem in such a reactor because the Reynolds number is very low. In order to solve this problem, some researchers suggested attractive mixing devices for the micro-reactor. Hessel et al. [9] reviewed the researches on the passive and active micro-mixers. On an active mixer, some interesting works were reported such as by Stoeber et al. [10] and by Park et al. [11], but the majority of micro-mixers has been still using passive methods, because they don't required other control systems. The passive mixing is realized by use of a secondary flow [12] or a chaotic flow [13]. Falk and Commenge [14] and Kashid et al. [15] compared the performances of some mixers. However, the flow path used in such mixers is very narrow and very complex. Then, the blocking and the fouling of the flow path by products as particles often occur and they cause a significant trouble in micro-reactors. Thus, the usage of such micro-reactors is limited.

Many kinds of the fluids used for the solid or gel particle fabrication has visco-elasticity. A visco-elastic fluid shows high-level fluctuation intensity in a flow due to its elasticity described by a parameter of Weissenberg number [16]. It is called elastic instability or elastic turbulence [17]. In a micro-scale flow path, the Weissenberg number is high enough because the shear rate is high, though the Reynolds number is low. Thus, the elastic instability occurs even in such a micro-scale flow path. Some researchers have investigated such an elastic instability using for micro-mixing in a micro-channel. Gulati et al. [18] suggested a strong secondary flow observed in such a visco-elastic fluid can be applied to micro-mixing. Burghelea et al. [19] and Jun and Steinberg [20] reported efficiency mixing can be obtained by use of a curved micro-channel [21]. Larson [22] reviewed elastic instability observed in a macro-scale flow path. Li et al. [23] reviewed the applications of such elastic instability in a micro-channel. Rodd et al. [24] summarized the elastic instability characteristics observed in a symmetric abrupt contraction flow. According to Rodd et al., elastic instability occurs in a range more than 100 of Weissenberg number and the critical Weissenberg number does not depend on the Reynolds number in the higher range than 10 in the case of a symmetric abrupt contraction flow. Joo and Shaqfeh [25] reported elastic instability occurs around 25 of Weissenberg number in the case

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of a Taylor–Dean flow. Such a Weissenberg number can be easily realized in a micro-channel. Thus, it is expected that such elastic instabilities might cause effective mixings in a micro-scale flow path.

In this study, flow and elastic instability characteristics in a cavity mounted on the one-side in a micro-duct have been studied as a first step for developing a technique of micro-mixing using such an elastic instability. A flow path with a cavity over which a fluid flows is a simple and fundamental flow element and is often applied to a static mixer in order to earn the residence time for reactions. As mentioned above, a micro-mixing technique using a curved flow path has been investigated on the same purpose. However, it needs a long flow path in order to earn the residence time. Thus, it is interesting to investigate the micro-mixing using a flow path with a cavity. Pakdel and McKinley [26] discussed a pure elastic instability in a lid-driven cavity flow. However, inertio-elastic instability characteristics of the flow over and in a micro-cavity have not yet been investigated until now, while the elastic instability behaviors are significantly affected by flow geometries. In this paper, the geometry of the micro-duct is fixed as a first step, but the visco-elasticity of the fluids and Reynolds number were changed widely. From the results, the inertio-elastic instability characteristics in a micro-cavity are discussed.

2. Experimental methods

2.1. Materials

A cationic surfactant of oleylbishydroxyethylmethylammonium chloride ($C_{18}H_{35}N(C_2H_4OH)_2CH_3Cl$, Lion Aczo Ltd.) was used with a counter-ion supplier of sodium salicylate as a viscoelastic fluid. The concentration of the surfactants was fixed at 2000 ppm in deionized water and the counter-ion molar ratio to the surfactants, ξ (–), were changed from 1.5 to 10 in four steps in order to change the rheological characteristics of the fluid. The solution was allowed to equilibrate for at least one day prior to any experiments.

2.2. Measurements of rheological characteristics

The rheological characteristics were measured by using a stress-controlled rheometer (MCR301: Anton Paar GmbH). A cone-plate device with the diameter of 50 mm and the cone-angle of 0.04 rad was used for the measurements for the apparent viscosity under the shear rate range from 1.00 to 1000 s^{-1}. The relaxation behavior of each surfactant solution was measured by using a shear-rate controlled rheometer (ARES; Rheometrics) with a cone-device of the same geometry. At first, a certain initial shear rate of 70.0 s^{-1} was added to the fluids. After the sudden release of the shear rate, the relaxation behavior was measured. As reported in the previous study [27], this surfactant system shows multi-relaxation behaviors. Thus, the time-variation of the relaxing stress, τ (Pa) after the sudden release was fitted by a triple exponential Maxwell model as follows:

$$\tau = \tau_1 e^{-t/t_{r1}} + \tau_2 e^{-t/t_{r2}} + \tau_3 e^{-t/t_{r3}} \tag{1}$$

Here, t (s) is time and t_{r1} (s), t_{r2} (s) and t_{r3} (s) are relaxation times ($t_{r1} < t_{r2} < t_{r3}$). τ_1 (Pa), τ_2 (Pa) and τ_3 (Pa) are the contributions to the stress from the respective relaxations. The temperature was set at 25 °C for both experiments.

2.3. Micro-duct

Fig. 1 shows a schematic view of the micro-duct with a cavity used in the present study. The cavity depth, H (m), the cavity length, L (m), the width of wider flow path, W (m), and the spanwise thickness, D (m), were set at 200, 1000, 400 and 200 μm, respectively. From the reservoir with the diameter of 2.00 mm and the depth of 200 μm, the surfactant solution was sent to the micro-duct mounted the 2.00 cm downstream of the reservoir by a syringe pump controlling the flow rate. The entry length was 100 times of the hydraulic diameter of the narrow flow path. The passing time of the fluid through the entry region is almost the same with the largest relaxation time, t_{r3}, when the Reynolds number defined below is 0.4 and the same with the middle relaxation time, t_{r2}, when the Reynolds number is 40. The flow was visualized by using poly styrene particles with 2.1 μm of the diameter. The concentration of the particles in the solution was set at lower than 0.1 vol%. The movie of the visualized flow was taken through a microscope by a high-speed video camera at the frame rate of 60 s^{-1}.

2.4. Dimensionless parameters

The water viscosity Reynolds number, Re (–) and zero-shear viscosity Reynolds number, Re_0 (–), used by Rodd et al. [23] are defined as follows.

$$Re = \frac{\rho U_m H}{\mu} \quad Re_0 = \frac{\rho U_m D_H}{\eta_0} \tag{2}$$

Here, U_m (m s^{-1}) is the mean velocity in the narrow flow path. ρ (kg $m^3$0 and μ (Pa s) are the density and the viscosity of water. η_0 (Pa s) and D_H (m) is the zero-shear viscosity of each solution and the hydraulic diameter of the narrow flow path, respectively.

The Weissenberg number, We (–), with the largest relaxation time for each solution and the elasticity number, El (–) are also defined as follows.

$$We = t_{rmax} \frac{U_m}{(W-H)/2} \quad El = \frac{We}{Re_0} \tag{3}$$

Here, t_{rmax} (s) is the maximum relaxation time for each solution discussed in the next section.

In this study, the water Reynolds number was changed from 1.00×10^{-1} to 100. Table 1 shows the present values of these dimensionless parameters from the results obtained by the rheometer.

3. Results and discussions

3.1. Rheological characteristics

Fig. 2 shows the effect of the shear rate, $\dot{\gamma}$ (s^{-1}) on the apparent shear viscosity, η (Pa s). From Fig. 2, it is found that the apparent viscosity of the surfactant solution when the molar ratio is small takes a very high value at a low shear rate and it decreases with the shear rate. Thus, the surfactant solution shows shear thinning tendency. When the molar ratio increases, the viscosity in the low shear region decreases and the viscosity becomes Newtonian when $\xi = 10$. Fig. 3 shows the effect of ξ on the relaxation time for each solution. From this figure, it is found that, in order to represent the relaxation process of the solution at $\xi = 1.5$, three relaxation times of t_{r1}, t_{r2} and t_{r3} are required. However, the relaxation behavior at $\xi = 3$ can be expressed only by two relaxation times of t_{r1} and t_{r2}, while only one relaxation time, t_{r1}, is needed for $\xi = 5$ and 10. As described above, Weissenberg number was defined with the longest relaxation time for each solution in this study.