Bulge structure in a cavity swept by a viscoelastic fluid

H Suzuki*, H Sato1, R Hidema2 and Y Komoda1
1Department of Chemical Science and Engineering, Kobe University, Kobe, Japan
2Organization of Advanced Science and Technology, Kobe University, Kobe, Japan
E-mail: hero@kobe-u.ac.jp

Abstract. In order to study a bulge structure observed in a cavity swept by a viscoelastic fluid, flow visualization experiments have been performed. The cavity depth, the cavity length and the width of flow path were fixed while the water Reynolds number based on the narrow flow path was changed from 680 to 4,200. From the results, the bulge structure formed on the upstream backward-facing side wall of the cavity in the mid-range of the Reynolds number was found to lead a fresh fluid into a cavity and to sweep the fluid near the cavity bottom wall. The bulge structure fluctuates very slowly and this fluctuation induces a tonguing motion of the tip of the separation bubble formed in the downstream region of the cavity. Thus, this structure can be expected to enhance the heat transfer from the cavity bottom.

1. Introduction
In order to expand the heat transfer area in a heat exchanger, rib-like promoters are often mounted on a heat transfer wall. Classically, Han et al. [1] and Han [2] investigated the heat transfer augmentation methods with rib-like promoters. Such technologies are still important for a compact heat exchanger and then lots of studies have been performed by such as Taslim [3] and Murata et al. [4]. Liu et al. [5] recently summarized such heat transfer enhancement technologies. However, thermal accumulation occurs in a cavity between ribs because of the recirculating flow formation when a Newtonian fluid is used, and then heat transfer from the cavity bottom is severely reduced. Aung [6] investigated the laminar heat transfer characteristics behind a backward-facing step and reported the heat transfer reduction occurs in a recirculating region formed there. For improving such heat transfer reduction in a recirculating region, some techniques as using flow resonance [7], the flow pulsation [8] and the insertion of an immersed body [9] were suggested.

Suzuki et al. [10] suggested a technique using the Barus effect of a viscoelastic fluid in order to enhance the heat transfer from the cavity bottom. Viscoelastic fluids show a flow expansion at a sudden expanded flow path and sweep the cavity bottom. This phenomenon is called Barus effect. In the previous studies [11,12], flow and heat transfer characteristics in a cavity were investigated experimentally and numerically. From the results, it was found that the heat transfer from the cavity bottom is effectively enhanced by the Barus effect though its characteristics severely depend on the geometric parameters, and Reynolds and Weissenberg numbers.

*Corresponding author: H Suzuki
Phone: +81-78-803-6490, Fax: +81-78-803-6490
E-mail address: hero@kobe-u.ac.jp
In the previous report [13], a strange fluid motion was found in a cavity in a mid-range of the Reynolds number around 2,500. There, the flow penetrates into the cavity turns back toward the upstream backward-facing side wall of the cavity, and after this, the flow turns again toward the downstream forward facing side wall in the deeper region of the cavity and sweeps the fluid near the cavity bottom. Thus, a bulge-like structure is formed as attached to the upstream backward-facing side wall of the cavity. This fluid motion can be expected to enhance the heat transfer from the cavity bottom because the velocity gradient on the bottom wall is kept high and the high temperature fluid heated by the cavity walls is swept out of the cavity.

In this paper, such bulge like motions observed in the cavity by use of a viscoelastic fluid will be focused on. It affects the fluid motion of the separation bubbles formed in the downstream region in the cavity, where the heat transfer is reduced as reported in the previous study [10]. Flow visualization experiments and velocity field measurements by a particle tracking velocimetry have been performed. The solvent Reynolds number is changed from 680 to 4,200 while the geometry of the cavity is fixed. The Reynolds number range of the appearance of the bulge flow structures and the instability of the separation bubbles will be discussed.

2. Experimental procedures

2.1. Materials
A cationic surfactant (oleylbishydroxyethylmethylammonium chloride: C_{18}H_{35}N(C_{2}H_{4}OH)_{2}CH_{3}Cl) was used for adding viscoelasticity to the fluid. The surfactant was dissolved in ion-exchanged water at a concentration of 2,000 ppm. Sodium salicylate (C_{6}H_{4}(OH)COONa), as a counter-ion supplier for rod-like micelle formation, was also added to the solution. The molar ratio of the counter-ions to the surfactants was set at 1.5. The solution was allowed to equilibrate for at least one day prior to any experiments.

2.2. Rheological features
The apparent viscosity and the first normal stress difference of the fluid were measured by use of a shear-control rheometer (Rheometric Scientific, ARES) with a cone-and-plate device with the diameter of 50 mm. Figures 1 and 2 show the apparent viscosity and the first normal stress difference of the present system, respectively. The present system has high viscosity in the region of low shear rates, but it shows a steep shear thinning behaviour with shear rates. In the range of high shear rates, the first normal stress shows very high values. Thus, this system has high viscoelasticity.

![Figure 1. Apparent shear viscosity.](image1)

![Figure 2. The first normal stress difference.](image2)
Suzuki et al. [14] measured the relaxation behaviour of the surfactant system with a triple exponential Maxwell model as follows.

$$\tau = \tau_1 e^{-t/\tau_1} + \tau_2 e^{-t/\tau_2} + \tau_3 e^{-t/\tau_3}$$  \hspace{1cm} (1)

Here, $\tau$ Pa is the total stress and $\tau_1$ Pa, $\tau_2$ Pa and $\tau_3$ Pa are the contributions from the respective relaxation behaviours to the total stress. $t$ s is time and $t_{\tau_1}$ s, $t_{\tau_2}$ s and $t_{\tau_3}$ s are the relaxation times for the respective relaxation behaviours defined as $t_{\tau_1} < t_{\tau_2} < t_{\tau_3}$. The three relaxation times of the present system is tabulated in table 1.

|   | $t_{\tau_1}$ | $t_{\tau_2}$ | $t_{\tau_3}$ |
|---|-------------|-------------|-------------|
|   | 9.96x10^{-2} s | 7.77x10^{-1} s | 9.94 s |

2.3. Flow visualization experiments

Figure 3 shows the experimental apparatus for flow visualization experiments and velocity measurements. The viscoelastic fluids flow into a test duct with the height, $W$ m, of 40 mm and the spanwise width of 75 mm, made of transparent acrylic resin, by a pump from a reservoir tank. Five ribs with the height, $H$ m, of 20 mm and the length of 100 mm were mounted on the bottom of the test section with the length of 1,100 mm. Each distance between ribs, which is the cavity length, $L$ m, was set at 100 mm. Flow visualization was performed with tracer particles of ion-exchange resin with 0.1 mm of the diameter and 850 kg m^{-3} of the density. The fourth cavity was tested in the present study in order to eliminate the effects of inlet flow fluctuation and of flow development. The instantaneous velocity field in the cavity was measured by use of a particle tracking method, where particle movement in the period of 0.1 s was measured by an image processing. The accuracy of the present velocity measurement is within ±3 % on the mean velocity in the narrow flow path.

2.4. Definition of Reynolds and Weissenberg numbers

The solvent Reynolds number, $Re$, was defined with water viscosity, $\mu$ Pa s as follows.

$$Re = \frac{\rho U_w H}{\mu}$$  \hspace{1cm} (2)
Here, $U_m \text{ m} \cdot \text{s}^{-1}$ and $\rho \text{ kg} \cdot \text{m}^{-3}$ are the mean velocity in a narrow flow path between the rib top and the upper wall and the density of the fluid. The Reynolds number was changed from 680 to 4,200 in this study.

The Weissenberg number, $We$, was also defined as follows at the narrow flow path.

$$We = t_r \frac{U_m}{W - H} \quad (3)$$

Here, $t_r \text{ s}$ is a relaxation time. Suzuki et al. [14] reported the third relaxation time corresponds to the formation of besicles. The first relaxation time is deeply related to the drag reduction effect of the present surfactant system, but the flow separation characteristics observed in a cavity were well expressed by the Weissenberg number based on the second relaxation time in the cases when the molar ratio is set at 1.5 [13]. Here, the Weissenberg number was defined with the second relaxation time. With this definition, the Weissenberg number ranged from 1.32 to 8.16 in this study. The temperature was set at the room temperature of 25°C during the experiments.

3. Results and discussions

3.1. Flow behaviors

Figure 4 shows the photos in the cases of water and of the present viscoelastic fluid, respectively, when the Reynolds number is 1,000. In the figure, a white arrow designates the boundary between the recirculating region formed in the cavity and the main flow. In the case of water, the flow separated from the upstream top of the cavity reaches directly the downstream top, and then the recirculating region covers the cavity. Thus, the flow velocity is very small near the cavity bottom. On the other hand, the flow separated from the upstream top of the cavity in the case of the viscoelastic fluid penetrates deeply into the cavity. The flow sweeps the cavity with high velocity due to the Barus effect of the viscoelastic fluid. This causes the heat transfer enhancement from the cavity bottom as reported in the previous study [10].

Figure 5 shows the effects of the Reynolds number on the flow behaviours when the Reynolds numbers were 1,000, 1,700, 2,800 and 4,200, respectively. When the Reynolds number is 1,700, the flow separated from the upstream top of the cavity also penetrates into the cavity but it turns back toward the upstream side wall of the cavity without reattachment on the cavity bottom. After this, the flow sweeps the fluid near the cavity bottom with very high velocity. Thus, a bulge-like fluid structure is formed on the upstream side wall of the cavity. In this case, it is also found that the tip of the separation bubble formed in the downstream region of the cavity fluctuates slowly. As discussed later, it is found that the tonguing motion occurs significantly related to the bulge structure fluctuation. In the present conditions, these fluid motions are found to appear in a range over $Re = 1,300$. In the
case of higher Reynolds number of 2,800, the flow more highly fluctuates and some vortices can be observed both in the cavity and in the main flow. On the other hand, the flow fluctuation near the bottom of the cavity decreases in the case when the Reynolds number of 4,200, though the main flow shows high-level turbulence. Thus, the bulge-like structure disappears and the rather stable flow covers the cavity bottom at $Re = 4,200$.

![Figure 5. Effect of the Reynolds number on the flow behaviours.](image)

### 3.2. Time variation characteristics

Figure 6 shows the time variation of the flow behaviours when the Reynolds number is 1,700. In order to discuss the velocity field, the respective instantaneous velocity vectors in the cavity is also shown in the figure. At 0 s, a small bulge structure in the upstream region of the cavity is observed. In the downstream region, a large separation bubble is formed at that time. From the velocity vectors, it is found that there exist high velocity regions upon the bulge structure and upon the separation bubble. Especially, the velocity over the separation bubble is very high and it is accelerated during sweeping the cavity bottom by the high velocity flow penetration into the cavity. The turning-back flow velocity is not high, but contributes the flow acceleration of that high-velocity sweeping flow. At 15 s, the flow from the upstream region into the cavity moves toward the downstream region. Then, the bulge structure is expanded toward the downstream region of the cavity. This causes the depression of the separation bubble formed in the downstream region of the cavity. This motion decelerates the flow over the separation bubble, and then the sweeping flow is weakened.

Figure 7 shows the time variations of the penetration point of the high velocity flow, $x_p$, and of the separation point from the cavity bottom, $x_s$. From the figure, it is found that both points fluctuate slowly and widely. The separation point takes a minimum around 20 s and a maximum around 60 s. Thus, the tip of the separation bubble moves widely as a tonguing motion. On the contrary, the penetration point takes a peak and a minimum at the corresponding instants. This indicates the tonguing motion of the separation bubble tip occurs due to this flip-flap motion of the penetration of the high velocity flow supplied from the upstream region of the cavity.

When the Reynolds number is larger than 1,300, three-dimensional flow fluctuation significantly appears in the present conditions. Thus, it is thought that the present flow fluctuation is related to the spanwise movement of the flow. In this paper, the effect of three-dimensionality of the flow cannot
be treated due to the measurement limitation. Such three-dimensionality should be discussed in order to clarify the formation and the fluctuation mechanism of these flow structures.

![Figure 6](image1.png)

**Figure 6.** Time variation of the flow behaviours in the cavity.

![Figure 7](image2.png)

**Figure 7.** Time variations of the penetration and the separation points.

3.3. **Reattachment and Separation characteristics**

In this section, the reattachment and separation characteristics in the cavity are discussed. Figures 8 and 9 show the reattachment length, $x_r$, and the separation length, $x_s$, on and from the cavity bottom, respectively. In the figures, the fluctuation ranges are designated by bars and the most frequent points are plotted by symbols. The solid line in figure 8 shows the reattachment points reported by Armaly *et al.* [15] observed in the downstream region of a backward-facing step. In the figure, the present results on the case of water are also plotted.

From figure 8, it is found that the reattachment point takes a larger value than the cavity length when the Reynolds number is larger than 200 in the cases of water. The present results agree with ones by Armaly *et al.* Thus, the cavity is completely covered by a recirculating region in a high range of the Reynolds number for water cases. On the other hand, the flow penetrates into the cavity due to the Barus effect when the Reynolds number is lower than 1,000 in the cases of the present viscoelastic
fluid. The reattachment point moves toward the downstream in the cavity with increase of the Reynolds number, but it moves toward the upstream due to the bulge structure formation at $Re = 1,300$. The fluctuation of the bulge structure causes the fluctuation of the reattachment point and the fluctuation abruptly increases when the Reynolds number is larger than 2,800. Finally, the cavity is covered by a recirculating region when the Reynolds number is 4,200. Corresponding to this, the length of separation bubble fluctuates from $Re = 1,300$ as shown in figure 9. The separation point fluctuation increases until $Re = 3,500$ and the separation disappears at $Re = 4,200$ corresponding to the disappearance of the reattachment.

Figure 8. Reattachment length.

Figure 9. Separation length.

Figure 10. Correlation of the separation length.

It was reported in the previous study [11] that the length of the separation bubble is correlated by a function of the expansion ratio, $\beta = (W-H)/W$ and of the Weissenberg number as follows.

$$\frac{x_s}{H} \propto 2 \frac{We}{\beta^2 + \beta + 1}$$  \hspace{1cm} (4)
Figure 10 shows the correlation of the present separation points with Equ. (4). In the figure, the numerical result reported in the previous study [12] is also plotted. From the figure, it is found that the results in the cases when the Reynolds number is lower than 1,000 agree well with the correlation of Equ. (4). On the other hand, the results over Re = 1,300 depart from the correlation. Thus, when the Reynolds number is in a mid-range and flow fluctuation appears, the separation length shows the smaller values than the correlation. On the other hand, the separation length reaches the upstream side wall of the cavity when the Reynolds number is 4,200. It is also found that the longest length of the separation bubble agrees with the correlation even when \( Re \) is larger than 1,300. The correlation was obtained from the assumption that the upstream flow is developed. This indicates the upstream velocity profile becomes one of pseudo-developed flows when the longest separation appears.

4. Conclusions

In order to investigate the bulge structure formed behind a backward-facing step of the cavity and the tonguing motion of the tip of the separation bubble formed in the downstream region of the cavity, flow visualization experiments have been performed for viscoelastic fluid. The cavity depth, the cavity length and the width of the flow path were fixed, while the water Reynolds number based on the narrow flow path was changed from 680 to 4,200. From the results, it was found that the flow separated from the upstream top of the cavity penetrates into the cavity and turn back toward the upstream side wall of the cavity at the mid-position of the cavity in a mid-range of the Reynolds number. The flow sweeps the fluid near the cavity bottom wall after this and forms a very high flow stream on the separation bubble. Thus, the bulge-like structure is formed behind a backward facing step of the cavity and can be expected to lead a fresh fluid into the cavity. The bulge structure was formed in a range from 1,300 to 3,500 in the present condition. The tonguing motion of the tip of the separation bubble occurs with the flip-flap motion of the high velocity flow upon such a bulge structure. However, these flow structures disappear in the cavity when the Reynolds number is larger than 4,200, in spite of the fact that the main flow has high turbulent intensity. In this case, the cavity is covered by a recirculating flow. These flow fluctuations observed in the mid-range of the Reynolds number can be expected to enhance the heat transfer from the cavity wall. In the near future, heat transfer experiments will be performed.

5. References

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