In order to clarify the mechanism of the bulge structure appearance observed in a cavity swept by a visco-elastic fluid, velocity fields were measured by a two-dimensional particle image velocimetry (PIV). The rib height, the cavity length, the flow path height and the flow path width were fixed at 20 mm, 100 mm, 40 mm and 75 mm, respectively. The Reynolds number was also fixed at 1,700 where the bulge structure appeared as reported by the previous study. The spanwise positions of the two-dimensional PIV were changed in 6 steps from the center plane to the outer region. From the results, it was found that the bulge structure has high-level fluctuation and its intermittency is related to the longest relaxation time. The bulge structure appears when the main flow separated from the upstream top corner of the cavity is intensified. The separated main flow contracted in the former cavity region expands not only toward the cavity bottom but also toward the outside walls of the flow path. In order to supply the fluid in the center plane, the backward flow occurs in the cavity. This flow motion was concluded to be a basic mechanism of the bulge structure appearance.

**Key Words:** Viscoelastic fluid / Particle image velocimetry / Cavity / Bulge structure / Barus effect

1. INTRODUCTION

In order to expand the heat transfer surface in a heat exchanger, rib-like promoters are often mounted on a heat transfer wall. However, thermal accumulation occurs in a cavity between such ribs because of the recirculating flow formation when a Newtonian fluid is used, and then heat transfer from the cavity bottom is severely reduced as reported by Aung et al.\(^1\) In such a recirculating region, the heat transfer cannot be enhanced only by increase of the flow rate. Thus, some heat devices having complex geometries are used for enhancement of the heat transfer in such recirculating regions\(^2\text{-}^4\). We suggested to use viscoelastic fluids instead of Newtonian fluids. Some kinds of viscoelastic fluids show a flow expansion at a sudden expanded flow path and sweep the cavity bottom. Then, the recirculation region can be depressed in the cavity. This phenomenon is called Barus effect.

Suzuki et al.\(^5\text{-}^{10}\) suggested a technique using this Barus effect of a visco-elastic fluid for augmentation of heat transfer in a cavity bottom between ribs. In addition, for improvement of the total heat transfer in a cavity by using the Barus effect, the effect of geometric parameters of the rib height and width and of the cavity length were experimentally investigated focusing on such separation region using a open channel\(^1\). In the previous study\(^11\text{-}^{12}\), a unique flow structure was confirmed in a cavity in a mid-range of the Reynolds number around 1,500. The main flow separated from the upstream top corner of the cavity penetrates into the cavity, reverses at the middle position, sweeps the cavity bottom, separates from the bottom again and goes away from the cavity as shown in Fig. 1, where a path line was schematically drawn from the movie observation. The separated flow forms bulge-like structure, and then it is was called a bulge structure. This structure causes the effective sweep in the cavity and de-presses the separated bubble\(^9\), which is the recirculation flow region observed in the downstream region of the cavity. Then, it can be expected to cause the effective heat transfer augmentation from the cavity bottom. However, the

\[\text{Fig. 1. Bulge structure observed in a cavity at } Re = 1700\]
mechanism of the bulge structure appearance has not yet been clarified.

In this study, two-dimensional velocity fields are measured in order to clarify the mechanism of the bulge structure appearance. Two-dimensional measurements of the velocity characteristics are taken in several spanwise positions. With this, three-dimensional velocity fields around the bulge structure will be discussed in the mean velocity structures. The fluctuation characteristics of the bulge structure are also discussed. From this, a schematic model will be suggested for the bulge structure formation in a cavity swept by a visco-elastic fluid.

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 visco-elasticity 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.

This surfactant system is famous to cause the effective the drag reduction in a pipe flow\(^{13-16}\). However, such a drag-reducing system reduces heat transfer\(^{17}\). The present technique of using Barus effects is also useful for the heat transfer recovery.

2.2 Rheological Characteristics

The apparent viscosity, \(\eta\) [Pa·s], and the first normal stress difference, \(N_1\) [Pa], of the fluid were reported in the previous study\(^{11, 18}\), where they 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 2 and 3 show the apparent viscosity and the first normal stress difference of the present system at a steady state, respectively. The present system has high viscosity in the region of low shear rates, but it shows a significant 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 significant viscoelasticity.

Suzuki et al.\(^{19}\) investigated the relaxation behaviour of the surfactant system and analyzed with a triple exponential Maxwell model as follows.

\[
\tau = \tau_1 e^{-t/\tau_1} + \tau_2 e^{-t/\tau_2} + \tau_3 e^{-t/\tau_3}
\]

(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 \(t_1\) [s], \(t_2\) [s] and \(t_3\) [s] are the relaxation times for the respective relaxation behaviours defined as \(t_1 < t_2 < t_3\). The three relaxation times obtained by a least squares method in the previous study are tabulated in Table I.

| \(t_1\)     | \(t_2\)     | \(t_3\)     |
|-------------|-------------|-------------|
| 9.96 \times 10^{-2} s | 7.77 \times 10^{-1} s | 9.94 s |

2.3 Velocity Measurements

Figure 4 shows the experimental apparatus for the velocity field measurements. The visco-elastic fluids flow

Fig. 2. Apparent viscosity of the present surfactant solution at 2,000 ppm\(^{11}\).

Fig. 3. Apparent viscosity of the present surfactant solution at 2,000 ppm\(^{11}\).

Table I. Relaxation times\(^{19}\).
through an entry duct with the height of 20 mm, the spanwise width of 50 mm and the length of 2.4 m into a test duct with the height, \(B\) [m], of 40 mm and the spanwise width, \(D\) [m], of 75 mm, which was 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. Figure 5 shows the test section. The origin of the coordinates was set at the top corner of the cavity and at the center of the spanwise direction as shown in the figure. \(x\) [m], \(y\) [m] and \(z\) [m] was assigned to the streamwise, the normal and the spanwise coordinates, respectively. \(U\) [m·s\(^{-1}\)], \(V\) [m·s\(^{-1}\)] and \(W\) [m·s\(^{-1}\)] were defined as the velocity components corresponding to each coordinate in this study.

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. A streamwise slit light with the spanwise width of 3 mm was exposed in the streamwise direction from the bottom of the cavity to the top surface. In order to measure the three-dimensional structure, the spanwise positions of the slit light were changed in five steps; \(z = 0, 7.5, 15, 20, 32.5\) mm from the center plane. In order to clarify the symmetricity of the flow system, the slit light was also set at \(z = -7.5\) and \(-15\) mm.

The two dimensional velocity fields at each spanwise section was taken through the side wall of the cavity by a high-speed camera (Photoron, FASTCAM SA3), which has the resolution of 1,024 × 1,024 pixels. The shutter speed was set at 1/10,000 s, and the time interval was adjusted at 1/250 s. The tracer particles of ion-exchange resin with 0.1 mm of the diameter and 850 kg·m\(^{-3}\) of the density was used for flow visualization. A commercial software (LaVision 8) was used to calculate velocity fields from the series of the images, where the scanning image size was set at 24 × 24 pixels. In each experiment, time-series of 30 s was taken and analyzed.

In this study, the velocity measurements were performed in the 3\(^{\text{rd}}\) cavity in order to eliminate the effects of inlet and outlet. As pointed out in the previous study\(^{(16)}\), the surfactant solution flow requires very long entry length of more than 1,000 times of the hydraulic diameter. In the present case, 28.5 m of the entry duct is required for flow fully developing. This is related to the fact that the present fluid has a very long induction time, which is about 200 s at the shear rate of 10 s\(^{-1}\) as reported in that previous study. Thus, the flow inserted into the test section is not fully developed. However, the flow and the heat transfer characteristics in the 3\(^{\text{rd}}\) cavity were reported to be almost the same as those in the 4\(^{\text{th}}\) cavity in the previous experimental\(^{(5,9,12)}\) and numerical studies\(^{(20)}\).

The solvent Reynolds number, \(Re [-]\), was defined with water viscosity, \(\mu\) [Pa·s] as follows
\[
Re = \frac{\rho \, U_m \, H}{\mu}
\]  
(2)

Here, \(U_m\) [m·s\(^{-1}\)] and \(\rho\) [kg·m\(^{-3}\)] are the mean velocity in the narrow flow path between the rib top and the upper wall and the density of the fluid. The solvent Reynolds number is fixed at 1,700 within ± 1 % in this study. The mean flow velocity in the narrow flow path was 0.0819 m·s\(^{-1}\) at the room temperature of 22 °C (\(\mu = 9.61 \times 10^{-4}\) Pa·s and \(\rho = 9.98\) kg·m\(^{-3}\)).

The zero-shear Reynolds number, \(Re_0[-]\) in the followings is often used in the discussions on inertio-elastic instability.
\[
Re_0 = \frac{\rho U_m H}{\eta_0} = 34.1
\]  
(3)

Here, \(\eta_0\) [Pa·s] is the zero-shear viscosity. It is \(4.99 \times 10^{-2}\) Pa·s as determined from Fig. 2.

The visco-elastic fluid is also dominated by the shear rate and the relaxation time. The Weissenberg number, \(Wi [-]\) and the Deborah number, \(De [-]\) defined in the followings are calculated as follows.
\[
Wi = \frac{t_r \, U_m}{(B - H)} = 3.30
\]  
(4)
Here, the second long relaxation time is used as the representative relaxation time, because the flow pattern depends on Wi based on the second relaxation time as reported in the previous study. When the Deborah number defined with the mean velocity in the wide flow path, \( U_m/2 \), is larger than about 1, the separated flow from the upstream top corner directly reaches the downstream top corner of the cavity because the fluid relaxation does not enough occur until the flow approaches to the cavity end. In that case, the flow does not penetrate into the cavity, and then the bulge structure is not formed as previously discussed. The Mach number, \( Ma \) [-], and the elasticity number, \( El \) [-] in this study is as follows.

\[
Ma = \sqrt{WiRe_0} = 10.6 \tag{6}
\]

\[
El = \frac{Wi}{Re_0} = 10.3 \tag{7}
\]

When the Mach number is higher than 10, flow fluctuates due to the inertio-elastic instability.

### 3. RESULTS AND DISCUSSION

#### 3.1 Time-Variations of the Bulge Structure

Figure 6 shows the time-variations of the velocity vectors at \( z/H = 0 \) in the cavity. At \( t = 0 \) s in Fig. 6(a), the flow separated from the top corner of the cavity reattaches on the cavity bottom. However, as shown at \( t = 1 \) s in Fig. 6(b), the separated main flow turns back toward the upstream wall of the cavity without reattachment on the cavity bottom. After that, the flow sweeps the cavity bottom, separates from the bottom again and goes away from the cavity. Thus the flow forms the bulge structure on the upstream cavity wall. In Fig. 6(b), the negative velocity region can be clearly observed where \( x/H = 1.5 \) and \( y/H = -0.5 \). However, this bulge structure shrinks with the time of 2 s in Fig. 6(c) to 3 s in Fig. 6(d). Thus, the bulge structure is found to fluctuate in time. In order to understand the fluctuation characteristics of the bulge structure, the time-variations of the streamwise velocity components at \( y/H = -0.5 \) and 0.5 where \( x/H = 1.5 \) at \( z/H = 0 \) in Fig. 7. From this figure, the negative values can be observed intermittently at \( y/H = -0.5 \). The time interval of the appearance of the negative values is about 5 s. From this figure, it is also found that the flow fluctuation synchronizes with the fluctuation of the main flow at \( y/H = 0.5 \) in an inverse phase. Thus, the bulge structure is indicated to appear when the main flow velocity is high. In order to investigate the time characteristics of the bulge structure, the power spectra of the streamwise velocity component at \( y/H = -0.5 \) and 0.5 shows in Fig. 8. Due to the limitation of the high-speed camera memory, the sampling time is not enough. Then, we cannot discuss the time characteristics precisely. However, it is found from the figure that the peaks of the spectra locates around 0.1 Hz and 0.2 Hz in the case of \( y/H = -0.5 \) and around 0.3 Hz in the case of \( y/H = 0.5 \). These peaks correspond to the longest relaxation time tabulated in Table I or to one third of it. This indicates that the longest relaxation time dominates the bulge structure formation.
Figures 9(a) and (b) show the fluctuation intensity of streamwise and normal velocity components, $u'$ [m·s$^{-1}$] and $v'$ [m·s$^{-1}$] at $z/H = 0$, respectively. The fluctuation intensities are defined as follows.

$$
\text{(8)}
$$

Here, the over-line, “$\overline{}$”, designates the time mean.

From this figure, it is found that the streamwise velocity of the main flow separated from the upstream top corner of the cavity fluctuates strongly in time. This fluctuation causes the high-level fluctuation around the bulge structure and corresponds to the appearance and disappearance of the structure. On the other hand, the normal velocity component fluctuation is not so high around the bulge structure. Its intensity is large in the downstream region of the cavity. This fluctuation corresponds to the tonguing motion of the separated bubble near the downstream bottom corner of the cavity, which was observed in the previous study. In the previous study, we indicated that the tonguing motion significantly relates to the fluctuation of the bulge structure. Thus, that is ensured in the velocity field measurements.

3.2 Mean Velocity Structures

In order to clarify the mechanism of the bulge structure formation, the mean velocity fields will be discussed.

Figure 10 shows the mean velocity vectors at $z/H = 0$ to 1.625. In the figure, $\overline{U}$ [m/s] is the time-averaged streamwise velocity component. From Fig. 10(a) at $z/H = 0$, it is found that the bulge structure is very small in the mean velocity fields. It means the bulge structure appears intermittently in the cavity and is highly fluctuating. From Fig. 10(a), high velocity regions at $z/H = 0$ are also observed at the inlet of the cavity, near the cavity bottom in the middle position and at the outlet of the cavity. The high velocity region at the inlet becomes weaken and disappears in the outside of the flow path at $z/H = 1.625$ shown in Fig. 10(d). The high velocity region near the cavity bottom is expanded in $y$ direction with $z/H$, instead of the velocity decreasing at the inlet. At $z/H = 1.625$, the high velocity region near the cavity bottom expands until $y/H = 0$. On the outlet high velocity region observed at $z/H = 0$, it is intensified at $z/H = 0.75$, expanded at $z/H = 1.25$ and weakened at $z/H = 1.625$. This indicates that the mean spanwise flow exists in the cavity. Namely, it indicates the flow spanwise expands toward the outside sidewalls at the inlet of the cavity, this expansion accelerates the flow in the outside and the flow contracts at the outlet of the cavity.

In order to ensure this, the estimation of the spanwise mean velocity components, $\overline{W}$ [m/s], has been performed. In this study, the two-dimensional velocity measurements were conducted at each spanwise position. Then, the instantaneous spanwise velocity component, $W$ [m/s] cannot be obtained, but mean value of the spanwise velocity component can be calculated with the following method. From the mass continuity equation, the $z$-direction gradient of mean spanwise component can be calculated as follows.

$$
\text{(9)}
$$

Here, $\overline{V}$ [m/s] is the normal mean velocity component. From the two-dimensional PIV measurements, each velocity gradient in the right side of the equation can be calculated. However, we took a few spanwise points and the sampling time was not enough in this study. Then, we have applied the least-squares method on the measured values on $\partial \overline{W}/\partial z$.

First we assumed the flow is symmetry on the center plane at $z/H = 0$. Figure 11 shows the symmetricity of the flow. From the comparison of Fig. 11(a) with Fig. 11(b), and of Fig. 11(c) with Fig. 11(d), it is found that the flow has enough symmetricity on the center plane. Thus, the spanwise...
velocity component, $\bar{W}$, can be assumed to be a 7th polynomial function of $z$ as follows under the assumptions of $\bar{W} = 0$ m/s and $\partial \bar{W} / \partial z = 0$ s$^{-1}$ at $z/H = 0$.

$$\bar{W} = a_1 z^7 + a_2 z^5 + a_3 z^3$$

(10)

Then, $\partial \bar{W} / \partial z$ becomes as follows

$$\frac{\partial \bar{W}}{\partial z} = 7a_1 z^6 + 5a_2 z^4 + 3a_3 z^2$$

(11)

Here, $\bar{W}$ and $\partial \bar{W} / \partial z$ becomes zero at the side wall of $z = D/2$ ($z/H = 1.875$). Then,

$$a_2 = -2 \left( \frac{D}{2} \right)^2 a_1$$

(12)

$$a_3 = \left( \frac{D}{2} \right)^4 a_1$$

(13)

Thus, only the coefficient $a_1$ [m$^{-6}$·s$^{-1}$] should be determined by the least-squares method with values in $z$-direction in this study.

Figure 12 is an example of the correlation curve obtained by the present least-squares method. This shows the validation of the present method. In this case, the correlation factor is 0.86, but the average correlation factor in the whole domain was not so high at 0.65 because the sampling time was not enough. However, the streamwise velocity component can be qualitatively discussed.

Figure 13 shows the three-dimensional features of the mean velocity fields in the cavity. This figure shows the results only in the half of the flow path when $z/H \geq 0$ and the velocities on the wall were also plotted as zero. From Fig. 13(a), it is found that the inlet velocity is contracted in the former cavity mounted in the test cavity, and then the velocity is higher than twice of the cross-sectional mean velocity, $U_{m1}$. However, the streamwise velocity at the center
plane of \( z/H = 0 \) decreases in the middle position of the cavity. On the other hand, the velocity near the side-wall in the middle position of the cavity increases, especially near the cavity bottom. After that, the streamwise velocity near the sidewall decreased and it increases near the center plane. The normal velocity takes negative values at the center plane near the inlet of the cavity as shown in Fig. 13(b). This corresponds to the flow penetration into the cavity and the formation of the bulge structure. It is also found that the normal velocities slightly become large near the outside wall in the middle position of \( x/H = 3.0 \) and show high values at the outlet especially around \( y/H = 0 \) at \( x/H = 4.5 \), where the normal velocity decreases near the outside wall. These features of streamwise and normal components of velocities correspond to the former discussions on the results shown in Fig. 10. In Fig. 13(c), the calculated spanwise mean velocities are plotted. From this, it can be confirmed that the flow directs to the outside walls in the upstream region of the cavity at \( x/H = 1.5 \). Especially, the spanwise velocity becomes large near the cavity bottom. On the other hand, the spanwise velocities turns negative at \( x/H = 4.5 \). Then, the flow is contracted into the center plane at the outlet of the cavity.

From these results, it is found that the contracted flow at the inlet of the cavity expands not only toward the cavity bottom but also toward the outside wall by Barus effects. Then, the flow near the outside wall was accelerated especially in the middle position of the cavity bottom. In order to supply the fluid to the center plane, the main flow separated at the top corner should direct toward the cavity bottom. When the inertia of the main flow becomes large, it cannot supply the fluid into the cavity, the fluid should be supplied from the downstream region of the cavity. Thus, the high velocity of the main flow induces the backward flow in the cavity. Then, the bulge structure appears in the cavity. When the backward flow occurs, the fluid should be supplied from the region near the outside. Then, the main flow in the center plane contracted at the outlet of the cavity. A schematic flow structure shows in Fig. 14 when the bulge structure appears. From the present results, a flow model on the bulge structure appearance can be suggested. From this model, it is found the aspect ratio of the flow path, which was fixed at 0.27 in the present cases, could significantly affect the bulge structures. We reported the bulge structure becomes small in a micro-channel\(^{(23)}\). This could be caused not only due to the low Reynolds number but also the high aspect ratio of 1.25 in the micro-channel. The effects of the aspect ratios should be clarified for the bulge structure formation. In that previous study, we reported that the Mach number which is frequently used for the inertio-elastic instability\(^{(23, 24)}\) could not enough explain the bulge structure appearance in a micro-cavity. The bulge structure in a micro-cavity appears when \( Ma \) is larger than 25. However, the structure does not appear in the micro-cavity even in high Mach number when the fluid elasticity number is lower than 5. These criteria do not agree with the results of the present macro-cavity, either. Thus, the effects not only of the geometric parameters but also of the fluid properties should be investigated in order to clarify the bulge structure appearance.

### 4. CONCLUSION

In this study, two-dimensional velocity measurements
have been performed in the cavity swept by a viscoelastic fluid. Especially, the bulge structure observed when the Reynolds number was set at 1700 was focused on. The two dimensional velocity fields were measured by a PIV system in the several spanwise positions.

From the results, it was found that the bulge structure appears intermittently and that the time characteristics relate to the longest relaxation time. It was also found that the flow fluctuation of the negative streamwise velocity around the lower region of the bulge structure synchronizes with the fluctuation of the main flow in an inverse phase.

From the mean flow analyses, it is found that the contracted flow formed in the former cavity expands not only toward the cavity bottom but also toward the outside walls of the flow path by Barus effects. Then, the flow is accelerated near the cavity bottom and near the outside wall. In order to supply the fluid in the center plane, the main flow separated from the upstream top corner of the cavity penetrates into the cavity. When the main flow is intensified, the fluid should be supplied from the downstream region, and then the backward flow occurs in the cavity. This causes the synchronization between the negative velocity appearance under the bulge structure and the main flow in an inverse phase. This also causes the contraction of the main flow at the outlet of the cavity. There flow structures were concluded to be a mechanism of the bulge structure formation in the cavity swept by a viscoelastic fluid.

In this study, a basic mechanism of the bulge structure formation was clarified. From this, the bulge structure formation was significantly affected by the flow path aspect ratio. The bulge structure is also affected by the fluid properties and by the other geometric parameter. In the near feature, the effects of the geometric parameters and of the fluid properties on the bulge structure appearance should be investigated.

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