Flow-Induced Orientation of a Polymer Solution in a Planar Channel with Abrupt Contraction and Expansion

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The flow-induced orientational changes of 0.5-wt% xanthan gum solution in a planar channel with an abrupt contraction followed by an abrupt expansion were examined by measuring the flow-induced birefringence and velocity fields. Four 4:1:4 abrupt-contraction-and-expansion channels with middle slit lengths of 1 mm, 2 mm, 3 mm, and 10 mm were tested in the experiments. How the flow-induced orientation developed near the centerline after the abrupt expansion was found to differ remarkably with the slit length. For slit lengths of 3 mm and 10 mm, the polymer molecules were temporarily aligned perpendicular to the flow direction by negative elongational flows generated after the abrupt expansion. By contrast, no similar phenomenon was observed for the slit lengths of 1 mm and 2 mm. These results show that the typical flow-induced orientational changes in a polymer in a planar channel just after an abrupt expansion are affected substantially by the length of the middle slit.

Key Words: Abrupt contraction-expansion flow / Flow-induced birefringence / Planar channel / Polymer solution / Velocity profile

1. INTRODUCTION

In recent years, items molded from plastic and specifically polymer materials have become key components in support of advanced technology in a wide range of fields. In addition, with advances in chemical synthesis and molding processing technologies, the development of plastic molded items serving various functions is continuing, and plastic products are becoming increasingly important. A complex flow geometry that exists in many engineering applications such as molding processes, inkjet printing, elastic instabilities, and so on has been used extensively to study the viscoelastic flow. Many researchers have reported the flow behavior such as flow patterns1-12), pressure drop4, 6-11, 14), velocity profiles4, 7, 9-14) and so on using a contraction flow and expansion flow.

To improve the quality of molded items, it is crucial to understand how flow influences both the direction and degree of orientation of polymers. Because the molecular orientation induced by flow in the molding process affects the properties of molded items, there have been many experimental and numerical studies of the flow-induced orientation of polymeric liquids15-23). Most of the experimental studies relied on optical measurements such as small-angle light scattering15, 16) or flow-induced birefringence (FIB)17-19, 22) to examine the flow-induced orientation of the polymers.

Contraction flows15-21) have attracted the attention of researchers studying complex flow fields because the viscoelastic properties of the fluid are strongly affected in the flow field. Quinzani et al.17) used FIB to measure the distribution of birefringence in a viscoelastic planar flow with an abrupt contraction and analyzed the stress fields. Azaiez et al.20) and Favero et al.21) analyzed numerically the velocity profiles, shear stresses, and normal stress differences in an abrupt contraction, and the results agreed qualitatively with the experimental data obtained by Quinzani et al.17). Martyn et al.18) investigated the relationship between the birefringence and stress fields in a viscoelastic melt flow in a planar channel with an abrupt contraction.

Flows with abrupt expansions occur often during polymer processing. Although the channel geometry of an abrupt expansion is symmetrical to that of an abrupt contraction, the flow in the former case is deemed to be more complex because the upstream flow conditions affect the flow...
structure of the polymer. In flows with an abrupt expansion, it has been reported that the degree of molecular orientation changes dramatically because the fluid flows preferentially toward the outer wall after the abrupt expansion\cite{15, 16, 22, 23}. However, most of those studies considered only cases in which the flow entering the expansion section was fully developed. In the molding process, one observes not only developed flow but also flow into the abrupt expansion that is still influenced by the contraction flow. However, to date only a few reports have focused on the flow-induced structure of complex fluids through a channel with an abrupt contraction and expansion\cite{16, 23}. Thus, the flow-induced orientation of polymers in these complex flow fields is yet to be elucidated.

The aim of this study was to analyze the flow-induced orientation of polymers and the velocity field in a planar channel with an abrupt contraction followed by an abrupt expansion. To achieve this, FIB and particle-tracking velocimetry were used. Furthermore, how the slit length influenced the flow-induced orientation of the polymers was investigated.

2. EXPERIMENTS

2.1 Test fluid

The test fluid used in this work has been described previously\cite{22}. Briefly, it was an aqueous solution of xanthan gum (XG400; Mitsubishi-Kagaku Food Corp., Japan), which exhibits non-Newtonian and viscoelastic properties due to the network structures that are present in the polymer\cite{24-28}. The polymer was dissolved in deionized water to a concentration of 0.5-wt%, and the test fluid was left at 4 ± 1 ºC for at least 24 h. For the flow velocimetry measurements, the test fluid was seeded with 10-µm-diameter polymeric particles (EPOSTAR GP-HC109; Nippon Shokubai Co., Ltd., Japan) at a weight ratio of 6000:1.

Figure 1 shows the shear viscosity of the 0.5-wt% solution of xanthan gum as measured using a rotational rheometer (HAAKE MARS III; Thermo Fisher Scientific Inc., Germany) with a cone-and-plate configuration. As can be seen, the xanthan gum solution exhibits shear-thinning behavior.

2.2 Test channels

Figure 2 shows the test channel and coordinate system schematically. Four planar abrupt-contraction-and-expansion channels were examined in this study. The channels were formed by sandwiching two machined thin spacers between two glass plates with an area of 40 mm × 100 mm and a thickness of 1.1 mm. The flow area comprises the region between the two spacers as shown in Fig. 2. Table I summarizes the dimensions of the test channels. For convenience, a channel with a slit length of $n$ mm is referred to herein as Channel L$^n$.

![Fig. 1 Shear viscosity of 0.5-wt% solution of xanthan gum measured at 25 ºC.](image)

![Fig. 2 Schematic of the test channel and coordinate system.](image)

| $H_1$ (mm) | $H_2$ (mm) | $H_3$ (mm) | $L$ (mm) |
|------------|------------|------------|----------|
| 1.0        | 4.0        | 0.5        | 1.0      |
| 1.0        | 4.0        | 0.5        | 2.0      |
| 1.0        | 4.0        | 0.5        | 3.0      |
| 1.0        | 4.0        | 0.5        | 10.0     |
The origin of the Cartesian coordinate system is located at the center of the slit entrance in both the width and height directions (Fig. 2). The $x$ axis corresponds to the flow direction, and the $y$ and $z$ axes are perpendicular to it.

### 2.3 Velocity measurement

Velocity profiles were obtained using the following procedure. First, a microscope (BX51; Olympus Optical Co., Ltd., Japan) with a $4 \times$ objective was focused on the particles located near the plane $z = 0$. A high-speed camera (VC-600W; Keyence Corp., Japan) connected to the microscope was then used to monitor the particle motion. Finally, the velocity profiles were obtained by tracking the particles. In this configuration, the depth of field was approximately $\pm 84 \, \mu$m.

### 2.4 Flow-induced birefringence

Figure 3 shows schematically the FIB measurement system used in this study and developed in our previous study. A He–Ne laser (05-LHP-151; Melles Griot Corp., USA; power: 5 mW; beam diameter: 0.81 mm; wavelength: 632.8 nm) was used as the light source, and a rotating half-wave plate was used as a polarization state generator to rotate the polarization plane of the He–Ne laser beam. To increase the spatial resolution, the light was concentrated using a $20 \times$ objective. The concentrated light was then transmitted through the flow channel along the $z$ axis, and the intensity of the transmitted light was measured. The data were recorded using an optical analyzer (OAS Ver. 4.2; Japan High Tech Co., Ltd., Japan) and the birefringence and orientation angle of the test fluid were calculated. Details of the optical system have been reported previously.

Because the light travels through the flow channel along the $z$ axis, the obtained birefringence and orientation angle are average values over the transmission region. The measuring position in the $xy$ plane was adjusted by moving the flow channel using a dual-axis stage and a stepping controller (MMC-2; Chuo Precision Industrial Co., Ltd., Japan). The positioning resolution was determined as being $2 \, \mu$m.

### 2.5 Experimental setup

In this study, the typical shear rate $\dot{\gamma}_{typ}$ is defined as

$$\dot{\gamma}_{typ} = \frac{U_{\text{ave}}}{h_f/2},$$

where $U_{\text{ave}}$ [mm/s] is the mean velocity in the middle slit section. The xanthan gum solution was pumped through the flow channel using a syringe pump (CSP-100S; Daiken Medical Co., Ltd., Japan), and the flow rate was adjusted in the range of 1.8–45 mL/h to generate typical shear rates of 4, 40, and $100 \, s^{-1}$. In addition, the Reynolds number ($Re$) and the Weissenberg number ($Wi$) were defined as

$$Re = \frac{\rho U_{\text{ave}} D_h}{\eta_{typ}},$$

$$Wi = \dot{\gamma}_{typ} \lambda,$$

where $\rho$ is the fluid density, $D_h$ is the hydraulic diameter defined by $D_h = 2H_1H_3/(H_1+H_3)$ and $\lambda$ is the characteristic relaxation time ($\approx 53.2 \, s$). For detail, see our previous study.

Experiments were performed over the range of Reynolds and Weissenberg numbers ($1.35 \times 10^{-3} \leq Re \leq 3.21 \times 10^{-1}$, $2.13 \times 10^{2} \leq Wi \leq 5.32 \times 10^{3}$).

All of the experiments were performed along the centerline ($y = 0$) at room temperature ($24 \pm 1 \, ^\circ C$). Xanthan gum solution is considered to be stable under changes in temperature; for example, its viscometric properties have been reported to remain constant over the approximate range of $5$–$40 \, ^\circ C$.

### 3. RESULTS AND DISCUSSION

#### 3.1 Profiles of velocity and flow-induced orientation along centerline with various slit lengths

Figure 4(a) and (b) show profiles of the axial velocity $v$, along the centerline ($y = 0$) at a typical shear rate of $40 \, s^{-1}$. According to Fig. 4(a), the fully developed upstream flow accelerates rapidly as it enters the slit section and then reaches a constant velocity. Such velocity profiles have also been reported in previous studies. According to Fig. 4(b), the flow then decelerates rapidly after the abrupt expansion. Because the downstream velocity reaches a constant value,
the flow field is considered to develop within this region. Moreover, the axial velocity exhibits similar profiles after the abrupt expansion despite the different slit lengths. These results indicate that the slit length does not affect the flow along the centerline after the abrupt expansion.

Figure 5(a) and (b) show the distributions of the birefringence and orientation angle along the centerline ($y = 0$) at a typical shear rate of $40 \text{ s}^{-1}$. The orientation angle $\theta$ is defined as positive in the counterclockwise direction with respect to the $x$ axis (see Fig. 2). The sign in the birefringence differs depending on the sample. Xanthan gum solution used as the test fluid shows negative value of the birefringence. Because the magnitude of birefringence is correlated with the degree of molecular orientation, high birefringence indicates a highly oriented molecular state. As mentioned above, it is necessary to account for the fact that the birefringence and orientation angle measured in this study are mean values in the channel height direction.

In the upstream region, the birefringence increases dramatically near the contraction [Fig. 5(a)] and the orientation angle is zero [Fig. 5(b)]. This indicates that the molecules are highly stretched in the flow direction, and this molecular orientation is deemed to be induced by the elongational flow generated near the abrupt contraction.

By contrast, the flow-induced orientation differs remarkably after the abrupt contraction. In Channels L3 and L10, the birefringence decreases gradually in the slit section and reaches a constant value prior to the abrupt expansion, as shown in Fig. 5(a). After the abrupt expansion, the birefringence decreases suddenly, followed by a rapid increase and subsequent gradual decrease. In this region, the orientation angle changes to and then remains at $90^\circ$, as shown in Fig. 5(b). These results indicate that after the abrupt expansion, the molecules are aligned perpendicular to the flow direction. This phenomenon was also observed in the abrupt expansion flow reported in previous studies. The
birefringence then increases gradually, and the orientation angle becomes zero in the downstream region, demonstrating that the molecules become realigned in the flow direction. Similarly, in Channels L 1 and L 2, the birefringence also decreases in the slit section. However, the fluid arrives at the abrupt expansion before the birefringence has reached a constant value. The birefringence decreases monotonically after the abrupt expansion and then increases gradually in the downstream region. In addition, Fig. 5(b) shows that the orientation angle remains at approximately zero in all regions. These results show that the flow-induced orientational changes of the polymer after the abrupt expansion depend on the slit length.

3.2 Influence of flow rate on flow-induced orientation in Channels L 1 and L 10

Figures 6 and 7 show the distributions of the birefringence $\Delta n'$ and orientation angle $\theta$ along the centerline ($y = 0$) for all flow rates in Channels L 1 and L 10, respectively.

From Figs. 6 and 7, in neither channel does the flow-induced orientation change qualitatively with the typical shear rate. From Fig. 7(a), it is difficult to conclude that the birefringence in the slit section at a typical shear rate of 100 s$^{-1}$ reaches a constant value prior to the abrupt expansion, but the flow-induced orientational change after the abrupt expansion is qualitatively the same as at the other typical shear rates of 4 and 40 s$^{-1}$. This clarifies the fact that within the range of typical shear rate used in this study, the flow-induced orientational change after the abrupt expansion does not depend on the typical shear rate (flow rate). However, it remains unknown whether flow-induced orientational change is qualitatively the same at the typical shear rates defined in this study (4, 40, and 100 s$^{-1}$) as it is at lower or higher typical shear rates in Channels L 1 and L 10. To examine in more detail how the flow rate influences the flow-induced orientation after the abrupt expansion, an experiment must be conducted in future over a wide range of flow rate.
3.3 Consideration of flow-induced orientation by slit length

In this work, the average values of the birefringence and orientation angle in the $z$ direction were measured. The molecular orientation is deemed to vary continuously in the channel height direction. Although very simple, the contributions of the shear-dominated region near the walls and the elongation-dominated region in the center of the channel height direction are evaluated.

Figure 8 shows the orientational changes of the polymer as represented by average orientation ellipses. In Channels $L_3$ and $L_{10}$, the birefringence is constant in the slit section, as shown in Fig. 5(a). Thus, because of the relaxed molecular orientation as shown in Fig. 8(a), the molecular orientation in the center of the channel height direction is deemed to be random prior to the abrupt expansion. After the abrupt expansion, the contribution of the negative elongational effect near the center plane in the channel height direction is strong, such that the molecules become aligned perpendicular to the flow direction. This is deemed to explain the rapid increase in the birefringence and the change in the orientation angle to 90° after the abrupt expansion. In Channels $L_1$ and $L_2$, the molecular orientation in the center of the channel height direction is deemed to be still aligned in the flow direction at the abrupt expansion because the birefringence does not become constant. Following the abrupt expansion, the molecules experience transverse extension similar to that in Channels $L_3$ and $L_{10}$. Although the effect on molecular orientation is similar, the molecules are deemed to be not oriented in the transverse direction because they are oriented in the flow direction at the abrupt expansion, as shown in Fig. 8(b). Thus, no rapid increase in birefringence or change in the orientation angle is observed in Channels $L_1$ and $L_2$.

To quantitatively discussed on the mechanism, Deborah number in the narrow space was defined as

$$De = \frac{\mu_{an}}{L},$$

where $L$ is slit length. In the cases of Channels $L_1$ and $L_2$, no rapid increase in birefringence is observed in a range of Deborah numbers $26.6 \leq De \leq 1330$. In the others case, rapid increase in birefringence is observe in a range of Deborah numbers $5.32 \leq De \leq 443$. Deborah number was higher than unity for all test cases, and a critical Deborah number did not find in this study. The quantitatively mechanism of two phenomena will be the subject of future experiments.

The results show that the typical flow-induced orientational changes of a polymer in a planar channel just after an abrupt expansion are affected by the upstream flow conditions.

4. CONCLUSIONS

Flow-induced orientational changes were measured for solutions of 0.5-wt% xanthan gum pumped through four 4:1:4 abrupt-contraction-and-expansion planar channels with different middle slit lengths of 1 mm, 2 mm, 3 mm, and 10 mm. Remarkable differences in the flow-induced orientational changes were observed after the abrupt expansion depending on the slit length. In Channels $L_3$ and $L_{10}$, the birefringence decreased gradually after the abrupt contraction and reached a constant value prior to the abrupt expansion. A sudden decrease and rapid increase in the birefringence occurred immediately after the abrupt expansion. The orientation angle changed to become perpendicular to the flow direction. In the two channels with shorter slits, the birefringence decreased after the abrupt contraction, similar to the behavior in Channels $L_3$ and $L_{10}$; however, the fluid arrived at the abrupt expansion before the birefringence had reached a constant value. The birefringence decreased monotonically after the abrupt expansion and subsequently increased gradually toward an equilibrium value in the downstream region. The orientation angle remained at approximately zero.

The results of this study show that the flow-induced orientational changes that take place in a polymer solution...
flowing through a planar channel with an abrupt contraction and expansion along its centerline are strongly affected by the slit length.

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