Viscoelastic Flow in Two Cycle Converging—Diverging Channel; Experimental Study for Pressure Characteristics and Flow State Classification

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Pressure characteristics were studied experimentally for a two cycle converging—diverging channel (a type of corrugated tube), using polyacrylamide water solutions as working fluids. Effects of the viscoelasticity on the pressure distribution along the channel wall were examined by comparing the data for polymer solutions with a Newtonian fluid. The experimental results for the two cycle channel were also compared with the data for one cycle channel having the same dimension. The total pressure drop for the two cycle channel with a dilute polymer solution was smaller than that of the Newtonian fluid in a region of lower Reynolds number, whereas no such a symptom was observed in the case of the one cycle channel.

From the observation by a flow visualization technique in the laminar flow regime, there were found to exist five and four major flow modes in the converging and diverging parts of the channels, respectively, and hence there appeared, in total, thirteen flow states in the channels. Based on the flow modes, flow state maps are presented in the present study.

Key Words : Viscoelastic fluids/Pressure characteristics/Flow visualization/Two cycle converging—diverging channel/Flow state classification

1. INTRODUCTION

Non-Newtonian fluids with the viscoelasticity show various behaviors, depending on patterns of flow channel. To date, major works are focused on flow characteristics of the entry flow^{1,2)} or the exit flow³⁾ (including dieswell problem) in channel geometry of sudden contraction or expansion for polymer concentrated solutions or melt in very low Reynolds numbers. However, a smoothly varying flow channel such as a Venturi type tube, where a fluid enters at the converging channel and after passing the nozzle part the fluid leaves through the diverging channel, is often encountered in an installation of fluid transporting line or in an actual measurement device of the flow rate. In relation to a study for the axially varying flow channel, James *et al.*⁴⁾ studied the pressure loss characteristics in a packed bed for dilute polymer solutions and reported the substantial loss could be caused by the viscoelastic effect of the solutions. It is now widely understood that a representative model geometry for a packed bed or a porous medium would be a channel with alternate converging and diverging sections. Huzarewicz⁵⁾ has measured

the total pressure drop for a variety of extremely viscoelastic fluids flowing through channels having a sinusously varying channel wall and showed the conditions for appearance in the viscoelastic effect on the pressure drop in the geometry. Most of the works concerning such flow behaviors of non-Newtonian fluids are focused on a single cycle channel with alternate converging and diverging sections. Davidson *et al.*^{6,7)}, among the limited works for the higher cycle of the diverging-converging channel, reported some results on velocity and stress distributions for very slow flows (creeping flow) in two-dimensional sinusously varying channel using a highly viscoelastic polymer solution. The studies on flow characteristics in a higher cycle of the channel with alternate converging and diverging sections are, however, not fully accomplished, particularly for the flow states and pressure characteristic in relatively high Reynolds numbers, despite of its physical significance in an engineering application. It is expected, moreover, that the experimentally observed flow states appearing in these channels and pressure characteristics would give better understanding of the complicated flow behavior in the viscoelastic flow dynamics, and provide

basic data to be utilized in a numerical computation.

In the present study, an investigation is carried out for viscoelastic fluids through a periodically varying wall geometry of the 2 cycle converging-diverging channel with a circular cross section. Experiments are conducted using polyacrylamide water solutions of 500, 1000 and 2000 ppm together with glycerin water solution as the Newtonian fluid. The objectives of the present investigation are to give a detailed pressure characteristic associated with the flow states in the laminar flow regime, including the appearance of normal stress by the elastic effect along the flow channel and the pressure drop of the total flow channel for relatively high Reynolds number region. Experimental results for the 2 cycle channel are compared with those for the 1 cycle channel with the same dimension, and the differences are discussed in relation with the Newtonian fluid. Furthermore, flow state maps are presented, based on the observation of the flow modes.

2. EXPERIMENTAL SETUP AND FLOW VISUALIZATION ARRANGEMENT

Fig. 1 shows a schematic diagram of the experimental apparatus. Test fluids are pumped by the piston and cylinder ④ (the bore radius of 100mm and the stroke of 500mm) which is driven by an electric motor ① through the driving mechanism ② and ③. By setting a speed of the electric motor, a constant flow rate of test fluid is obtained, and the flow rate Q in the present experiments ranges from 3.27×10^{-7} to $3.93 \times 10^{-4} \text{ m}^3/\text{s}$. The test section of the 1 cycle channel or the 2 cycle channel is connected to the cylinder by a hydrodynamically smooth plane pipe (made of acrylic resin) ⑤ of 25mm inner radius. The length of the connecting pipe ⑤ is sufficiently long ($L=2000\text{mm}$ length)⁸⁾ with which the flow entering to the test section is fully developed. At the far down stream from the test section (the length of the outlet pipe ⑫ is extended sufficiently long length of 2125mm), the over head tank whose height is 550mm high from the center line of the flow passage is installed in order to avoid the negative reading of the pressure measurement device at nozzle parts of the

Fig. 1 Schematic diagram of experimental apparatus

test section. The flow passage, including the inlet pipe, the test section and the outlet pipe, is set in the horizontal position as shown in Fig. 1. Pressures along the test section are measured by the pressure transducers (strain gauge type) whose signals are amplified, digitized and finally sent to a computer with which data signals are simultaneously processed. The pressure in each pressure transducer is calculated as a mean value of 2000 data after the flow reaches the time independent of the startup. This procedure is repeated 5 times under the same experimental condition. The representative pressure is taken for each pressure transducer as a mean value of 5 pressure data (thus the representative pressure value of one transducer for one experimental condition is the mean value of total 10000 data). Experiments are conducted in the temperature of $22 \pm 0.5^\circ\text{C}$ by controlling the surrounding temperature of the whole experimental apparatus.

Since the static pressure at the channel wall is measured through the static pressure hole (0.5mm diameter), there might be necessity to have the hole pressure correction due to an effect of the cavity flow⁹⁾. The evaluation of the hole pressure correction is achieved along with Higashitani *et al.*¹⁰⁾,

$$P_H = -\frac{1}{6}(\sigma_{11} - \sigma_{22}), \quad (1)$$

where P_H is the hole pressure error and $\sigma_{11} - \sigma_{22}$ is the first normal stress difference of the test fluid. The error in P_H estimated is well below 5% for the maximum flow rate for the most concentrated solutions; with which $\sigma_{11} - \sigma_{22}$ is obtained for the highest possible shear rate¹¹⁾ $\dot{\gamma} = \{(3n+1)/4n\} \cdot \{32Q/\pi L^3\}$ from the rheological data of test fluid in Table I. Thus in the present investigation, the necessity of the hole pressure correction is not found in the experimental range, since the overall accuracy of the pressure measurement is approximately maximum $\pm 5\%$ (instrument error).

Detailed dimensions of the test sections are shown in Fig. 2 (a); the 1 cycle channel and Fig. 2 (b); the 2 cycle channel.

Fig. 2 Details of test section

Fig. 3 Flow visualization arrangement

The 1 cycle converging-diverging channel with a circular cross section is typically used in an actual application for flow measurements as a Venturi pipe, and the 2 cycle channel with a circular cross section is made by simply connecting the 1 cycle channel in series. Pressure taps are located in every 100mm distance from the inlet as shown Figs. 2(a) and (b).

In Fig. 3, a flow visualization arrangement is shown for the 1 cycle channel as an example. The slit light of the argon ion laser is applied at the vertical position of the channel center-line, and the flow mode observations as well as the photograph are achieved on the plane of the laser slit sheet in the channel. The streak line patterns are recognized in prevailing flow states by adding the aluminum oxide powder or micro-polystyrene particles in test fluids.

3. TEST FLUIDS AND RHEOLOGICAL CHARACTERIZATION

Test fluids used in the experiment are polyacrylamide ($M_n \approx 1.2 \times 10^6$, Sun-flock AA-300P, Sanyo Chemical Corp.) water solutions. A Newtonian fluid, a glycerin water solution, is used as standard. The concentrations of the polymer solutions are 500, 1000, 1500 and 2000 ppm. They are abbreviated as PAA500, PAA1000, PAA1500 and PAA2000, respectively. Rheological properties are measured by a cone-and-plate rheometer at 22°C. Representative properties of test fluids are tabulated in Table I (a) and (b). Rheological constants K and n listed in Table I (a) are obtained by fitting the shear stress σ_{12} with the following power law model,

$$\sigma_{12} = K\dot{\gamma}^n. \quad (2)$$

The constants m and v tabulated in Table I (b) are obtained by fitting the first normal stress difference N_1 with the following power law model,

$$N_1 = \sigma_{11} - \sigma_{22} = m\dot{\gamma}^v. \quad (3)$$

The rheological constants listed in Table I are taken for the shear rate range of $1 \leq \dot{\gamma} \leq 240$ 1/s. The relaxation times tabulated in Table II are obtained by fitting σ_{12} and N_1 data with the Giesekus model.¹²⁾ Giesekus model is well defined model for polymer melts or high concentrated polymer solutions, but it is known⁹⁾ that the model can be sufficiently applied for dilute polymer solutions as well. In Fig. 4, the fitting σ_{12} and N_1 by the Giesekus model¹²⁾ and the power law model

Fig. 4 Rheological characterization

Table I (a) Rheological properties of test fluids
(for Shear viscosity $\sigma_{12} = K \dot{\gamma}^n$)

Test fluid	concentration	Density (kg/m ³)	K (mPa·s ⁿ)	n	range of shear rate $\dot{\gamma}$ (1/s)
Glycerine	50(wt%)	1.125	6.2	1	
PAA	500(ppm)	1.004	67.9	0.573	1~240
PAA	1000(ppm)	1.005	253.4	0.439	1~240
PAA	1500(ppm)	1.006	517.5	0.387	1~240
PAA	2000(ppm)	1.007	834.0	0.351	1~240

Table I (b) Rheological properties of test fluids
(for First normal stress difference $N_1 = m \dot{\gamma}^u$)

Test fluid	concentration	Density (kg/m ³)	m (mPa·s ^u)	u	range of shear rate $\dot{\gamma}$ (1/s)
PAA	500(ppm)	1.004	341.0	0.736	1~240
PAA	1000(ppm)	1.005	1300.0	0.709	1~240
PAA	1500(ppm)	1.006	3194.4	0.675	1~240
PAA	2000(ppm)	1.007	5536.0	0.652	1~240

Table II Relaxation times of PAA solutions

Test fluid	Relaxation time λ_G (s)
PAA500	0.4
PAA1000	0.6
PAA1500	0.7
PAA2000	0.8

are depicted for the test fluids.

4. RESULTS AND DISCUSSIONS

Typical measured pressure distributions in flow channels are presented in Fig. 5, and pressure drop characteristics are summarized in Figs. 6 and 7. Representative flow modes observed in the test sections are presented in Fig. 8 with typical flow patterns (Fig. 9). In Fig. 10 and Fig. 11, flow state maps are presented, based on the flow state classification (Table III).

In Fig. 5-1, the pressure distributions along the 1 cycle channel wall at pressure tap positions (as indicated in Fig. 2 (a)) are shown for representative Reynolds numbers; (a) $Re^* = 100$, (b) $Re^* = 200$, (c) $Re^* = 300$. It is noted here that for the data presented in Fig. 5 the flow state in $Re^* \geq 100$ is uniformly chosen as the spiraling flow state (as shown in C-⑤ and D-④ of Fig. 8, and Fig. 9 (c) which are to be discussed later in details) so that the direct comparison of PAA water solutions is possible in the fixed flow state for a given Reynolds number (where the reference Newtonian flow state is the smooth converging-the vortex flow II in Table III). In

Fig. 5-1 Pressure distribution of 1 cycle channel

Fig. 5-2 Pressure distribution of 2 cycle channel

each diagram of Fig. 5-1, the pressure is nondimensionalized by $1/2 \rho U_m^2$ where U_m is the mean velocity obtained from the flow rate Q at representative points, i.e. $U_m = Q / (\text{cross section area})$, and the inlet pressure at the tap position $z=0$ is set to zero so that the negative sign of the downstream pressures is showing the pressure drop referring to the inlet pressure. The Reynolds number in the present study is defined by the power law model as follows,

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

where D is the diameter of the inlet pipe. The horizontal axis z of each diagram in Fig. 5-1 is the axial distance from the inlet pressure tap. The pressure at $z=0$ (inlet reference pressure) is denoted as P_1 and the pressures at $z=100, 200, 300$ and 400 are denoted as P_2, P_3, P_4 and P_5 , respectively, where P_2 is, for example, the pressure at the throat in the 1 cycle converging-diverging nozzle as indicated in Fig. 2 (a). As shown in Fig. 5-1, a large pressure drop occurs at throat position (P_2) in the case of the Newtonian fluid since at the throat the velocity head increases while the pressure head decreases. In the downstream for the Newtonian fluid, the pressures P_3 and P_4 gradually increases and the pressure P_4 and P_5 become almost the plateau (there observed still slight increase of pressure between P_4 and P_5 due to the extension of the

vortex region to the further down stream region), indicating the pressure drop recovery of the channel. It is mentioned that this pressure recovery is owing to the fact that at the down stream from the diverging section, where the secondary flow exists, the flow state becomes the smooth pipe flow like-wise observed at the inlet section. However in the viscoelastic fluids, the pressure drops (P2) at the throat are much smaller than that of Newtonian fluid, even for lowest concentration solution of PAA500. This unique character of the pressure behavior at throat is due to appearance of normal stress component ρ_{rr} , which is included in the actual pressure measurement, since in the converging nozzle part (from the inlet to the throat) the elongational flow field appears leading the increase⁽¹³⁾ of elongational viscosity as well as the increase of the first normal stress difference in the high shear rate near the throat region. The increase of P2 is maximum for PAA2000 while the other fluids do not have much dependency on the concentrations for lower Reynolds number. However some noticeable differences of P2 on the solution concentrations are tended to appear for high Reynolds numbers as shown in Fig. 5-1(b) and (c). Similar pressure characteristics are observed in the case of the sudden contraction flow passage examined by Shirakashi *et al.*⁽¹⁴⁾, who have similarly used PAA water solutions. They showed a large pressure rise at the inlet section of the channel and discussed that this pressure rise is due to an appearance of the normal stress component σ_{rr} . The pressure characteristics obtained in the present study have shown some common aspects with those obtained by Shirakashi *et al.*⁽¹⁴⁾. Pressures at down stream P3, P4 and P5, however, show quite different features compared with the Newtonian fluid. No pressure recovery from the P2 is observed, and it is found that the pressure is kept dropping from P2 toward P3, and finally becomes plateau at P4 and P5. Large dependence on the solution concentration is obtained for the pressures at down stream P3 to P5; the higher concentrations, the higher pressure drop appears. This trend becomes more significant for lower Reynolds number (Fig. 5-1(a)) than for higher Reynolds numbers (Figs. 5-1(b), (c)). This trend is speculated probably to be due to the elastic effect derived from the different relaxation time constants as shown in Table II. The longer relaxation time delays the stress relaxation, increasing the elastic effect on the flow at the down stream where the effect of the elongational flow at the converging part remains, resulting in the change of flow modes appearing at down stream. The pressure characteristics are largely affected by the flow states, particularly a change of the flow state occurred in the converging part influences the down stream flow state and causes substantial influence on the prevailing pressure. It is observed that prevailing flow states are quite different from those of the Newtonian fluid as it is examined in details in the proceeding part of the present work; a strong and large circulation zone (secondary

flow associated with the eddy motion) followed with an oscillatory motion appears at the down stream from the throat part; flow state V and VI for PAA500, and flow state XIII for PAA1000, PAA1500 and PAA2000. And it is thought that these unique flow states might have caused those high pressure drops in case of the concentrated elastic fluids, while the relatively higher pressure recovery (P3, P4 and P5) for PAA500 is probably due to the flow state in the diverging part where the reflecting or the spiraling motion of the secondary flow is found to be weak and resultantly the prevailing flow state becomes very close to the Newtonian flow state II.

In Figs. 5-2(a), (b) and (c), the pressure distribution for the 2 cycle channel are depicted with the same manner as Fig. 5-1. It is noted here again for the 2 cycle channel that the pressures at each tap position are denoted as P1($z=0$), P2($z=100$), P3($z=200$), P4($z=300$), P5($z=400$), P6($z=500$) and P7($z=600$), where the first throat pressure is P2 and the second throat pressure is P4 as indicated in Fig. 2(b). The pressure characteristics in the first cycle (converging-diverging channel) are similar to those obtained in Fig. 5-1 for both Newtonian fluid and PAA solutions. As shown in Figs. 5-2(a), (b) and (c) for the representative Reynolds numbers, the second pressure drop due to increase of the velocity head appears for P4 and then the pressure recovers proceeding at the down stream for P5, P6 and P7 in the case of the Newtonian fluid. On the contrary, with PAA solutions the pressure drop is proceeded in the down stream from the first throat pressure P2 through the second throat pressure P4 as shown in Figs. 5-2(a), (b) and (c) for all representative Reynolds numbers, except for PAA500. The pressure behavior for higher concentration solutions (PAA1000, PAA1500 and PAA2000) shows that the pressure is kept dropping through the channel as if there would be no major influence of the second cycle and the pressure distribution along the channel wall has some similarity and common feature for that in a packed bed or porous body of small particles, where the pressure decreases against flow direction continuously. This trend (continuous pressure drop) and linearity (linearly decrease of pressure along the channel flow direction) become more noticeable for lower Reynolds numbers as shown in Fig. 5-2(a). This phenomena are probably, as described previously, due to the high elasticity (high relaxation time constant) so that the elastic effect dominates the flow state where the time for fluids undergoing the hydrodynamic change becomes insensitive against the stress relaxation in the channel. The flow states which imply to the pressure profiles in the Figs. 5-2(a), (b) and (c) for PAA1000, PAA1500, and PAA2000 are both XIII in the 1st section and the 2nd section where the spiraling flow appears and with the high elasticity strong normal stress components persist. However, with PAA500 the flow state in the 1st section is VI (divergent-spiraling), although the flow state in the 2nd section is XIII .

Hence it is thought that the existence of the flow state VI in the 1st section may cause the relatively high pressure recovery, as stated previously for the 1 cycle channel, with weak elasticity (shorter relaxation time), yielding small normal stress components. Furthermore, it is speculated that the divergent flow in the channel (no matter where it appears in the diverging section of higher cycle channel) has a nature of reduction for the elongational rate at the center of the flow channel, suppressing normal stress components (elongational stress), while near the channel wall region the shear rate is increased due to squeezed and confined space of the divergent flow configuration, causing the drop of normal stress components (first normal stress difference) by the effect of the shear thinning. Thus by the combination of these reduction mechanism for normal stress components in the divergent flow, the prevailing pressure loss will be substantially reduced.

In order to see the quantitative relations for pressure behavior, a representative pressure of P2 (the first throat pressure) is plotted against Deborah number De , which is a measure of the elasticity against the representative time for the hydrodynamic change, defined as follows,

$$De = \lambda_G \frac{U_m}{L}, \quad (5)$$

where λ_G is the relaxation time constant of the Giesekus model as shown in Table II. In Fig. 6, the relationship between P2 and De is displayed for all pressure measurements within the range of Reynolds number ($Re^* = 25 \sim 300$). It is noted that the data of $De=0$ (in Fig. 6) are the case of Newtonian fluid. As seen in Fig. 6, the maximum effect for P2 is occurred at De approximately 3, and P2 becomes nearly plateau for further increase of De number, where the range of De greater than 3 implies the pressure behavior of these continuous pressure drop for PAA1000, 1500 and 2000 with all Reynolds numbers. However, for the dilute solution of PAA500, the pressure distribution becomes quite different compared with those in high concentration solutions as shown in Fig. 5-2. The pressure behaviors for PAA500 shown in Fig. 5-2 (a), (b) and (c) are implied in the range of De less than 3 in Fig. 6 (data for PAA500 are distinguished by a circle-plus symbol in Fig. 6), where the hydrodynamic effect is compatible against the elastic effect. Particularly with $Re^* = 100$ (as shown in Fig. 5-2(a); PAA500), significant pressure rise (recovery) has been obtained in the down stream after P3. The measured pressure rise becomes even greater than that of Newtonian fluid, although for higher Reynolds numbers the pressure characteristic tends to approach the higher concentration solutions (Fig. 3-2 (b) and (c)) due to increase of De number approaching 3.

Based on the measured pressure distribution, the total pressure losses (the difference between the inlet pressure and the

Fig. 6 Pressure drop in first throat section vs. Deborah number De

outlet pressure) for the both channels (the 1 cycle channel and the 2 cycle channel) are examined and are depicted in Fig. 7 for the range of Reynolds numbers, $25 \leq Re^* \leq 300$. The results obtained with 1 cycle and 2 cycle channels are shown in Figs. 7-1 and 7-2, respectively. The Newtonian case is referred in both the diagrams. As seen in Fig. 7-1, for every concentration, the total pressure losses are greater than that of Newtonian case and the higher concentrations the larger losses appear. The total pressure loss is greater in lower Reynolds numbers, since the elastic effect comes to be noticeable against hydrodynamics effect on the pressure in lower Reynolds numbers. However, in the 2 cycle channel there exists a range of Reynolds number, where the total pressure loss is smaller than that of Newtonian fluid, for PAA500 in $25 \leq Re^* \leq 100$ as shown in Fig. 7-2. About 25% loss reduction is obtained at $Re^* = 50$ for PAA500. This loss reduction is due to a unique flow mode (as stated previously) where the diverging flow^{15)~17)} is appearing in the converging section and at the same time a reflecting flow is appearing in the diverging section (this phenomenon would be discussed in details later in this section). This unique mode for PAA500 (the flow states III, IV, V, VI in Table III) occurs at Reynolds number $25 \leq Re^* \leq 100$ where the hydrodynamics effect and the elastic effect have almost evenly contribute to the flow characteristics when De is nearly unity. However, when the Reynolds number is increased (with PAA500) beyond 100, the total pressure drop increases as shown in Fig. 7-2. This would be due to the reason that the new flow state of VIII, which is observed in the higher concentrated solutions (e.g. Fig. 11(b)), begins to appear yielding large pressure loss caused by the spiraling motion of the secondary flow. For higher concentrated solutions the strength of the spiraling motion (represented as VIII) becomes substantial, yielding large pressure losses as shown in Fig. 7-2. It is of interest to note that the differences between the higher concentration

Fig. 7-1 Total pressure drop of 1 cycle channel

Fig. 7-2 Total pressure drop of 2 cycle channel

solutions are small. This would be probably due to the firmly established common flow state (XI and XII) as observed in Figs. 11 (a) and (b) for $Re^* \geq 50$.

From all results of the flow visualization with both PAA solutions and the Newtonian fluid in the range of Reynolds number $Re^* \leq 300$, we have obtained five major flow modes in the converging part of the channels as; C-① smooth converging flow, C-② divergent flow, C-③ vortex flow, C-④ deflecting flow and C-⑤ spiraling flow. C-① the smooth converging flow is a steady symmetric flow that enters from the inlet section toward nozzle throat, flowing smoothly along the converging channel geometry with the laminar state. C-② the divergent flow is a steady symmetric flow having a strong radial positive velocity component so that the flow expands in the mid region of the converging channel. The similar flow mode is reported by Cable *et al.*^{15),16)}, and Mori *et al.*¹⁷⁾ for a viscoelastic fluid in entry flows. C-③ the vortex flow is a steady symmetric flow that has the eddy circulation zone existing close to the channel wall. It is thought that this secondary flow accompanying the eddy circulation zone is generated by the adverse pressure gradient against the driving flow pressure due to an addition of the normal stress

component to the isotropic pressure in the elongational flow field of the converging channel. C-④ the deflecting flow is a steady asymmetric flow where the eddy circulation zone becomes asymmetric to the axis of the channel so that the main flow deflects from the mode C-③. C-⑤ the spiraling flow is a time dependent asymmetric flow where the deflected main flow of the mode C-④ has a periodic swirling motion to the axis of channel. It is observed that in the mode C-⑤ the rotating direction of the main flow to the axis of the channel is arbitrary in each experiment where as once the direction is set at beginning of the mode C-⑤ the rotating direction is kept and a constant periodicity is persisted.

In the diverging part of the channels the following four major flow modes are obtained; D-① smooth diverging flow, D-② vortex flow, D-③ deflecting flow and D-④ spiraling flow. There is no divergent flow appearing likewise in the converging part, and the flow states associated with those four major flow modes are similar to those in the converging part beside the flow has the diverging nature in the diverging part of the channels. In Fig. 8 the schematics of these modes are depicted. In Table III, the total thirteen flow states are classified for both the 1 cycle channel and the 2 cycle channel by the combination of five (C-①~⑤) flow modes in the converging part and four (D-①~④) flow modes in the diverging part. In Fig. 9, representative flow patterns are displayed as results of the flow visualization with PAA1000. In Fig. 9, each photographs (a) ~ (c) are the typical flow states appearing in the 1 cycle channel or in the 2 cycle channel (the first section or the sec-

Fig. 8 Schematic diagram of flow modes

ond section) where the flow enters from the left hand side toward the converging part and through the throat the flow leaves from the right hand side after passing the diverging part of the channel. As shown in Fig. 9(a), the flow state is III where at the converging part the flow mode is C-② while at the diverging part the flow mode is D-①. Likewise in Fig. 9 (b), the flow state is VIII where C-④ and D-① modes are prevailed in the converging part and the diverging part of the channel respectively, and in Fig. 9 (c) the flow state is XIII where the observed mode in the converging part is C-⑤ and D-④ in the diverging part.

In Fig. 10, a detailed flow state diagram is shown for the 1 cycle channel, where the classified flow states in Table III are plotted against log scaled Reynolds number. As shown in Fig. 10, in the case of the Newtonian fluid the mode D-② in the di-

Table III Flow state classification

State	Convergence section	Divergence section
I	Smooth converging	Smooth diverging
II	Smooth converging	Vortex
III	Divergent	Smooth diverging
IV	Divergent	Vortex
V	Divergent	Deflecting
VI	Divergent	Spiraling
VII	Vortex	Smooth diverging
VIII	Deflecting	Smooth diverging
IX	Deflecting	Vortex
X	Deflecting	Deflecting
XI	Deflecting	Spiraling
XII	Spiraling	Deflecting
XIII	Spiraling	Spiraling

(a) Divergent and smooth diverging flow
Flow state III ($Re^* = 11$)

(b) Deflecting and smooth diverging flow
Flow state VIII ($Re^* = 25$)

(c) Spiraling and Spiraling flow
Flow state XIII ($Re^* = 138$)

Fig. 9 Flow patterns of PAA1000

verging part of the channel occurs at $Re^* = 68$ and resultantly prevailing state becomes II. Further increase of Reynolds number does not alter the flow state II in the range of Reynolds numbers. Thus in the 1 cycle channel used in the present study only two different flow states are possible, i.e., state I and II, in case of the Newtonian fluid. On the other hand, with PAA500 the flow state II does not appear, and instead the flow state III appears at $Re^* = 16.5$ and the flow state III persists until $Re^* = 50.1$. At $Re^* = 50.1$ the flow mode D-② occurs in the diverging part while in the converging part the flow mode C-② is kept resulting in the flow state VI ($50.1 \leq Re^* \leq 109$). Further increases of Reynolds number leading the flow state V ($109 \leq Re^* \leq 127$) and finally the flow state VI ($Re^* \geq 127$) appears in the limit of Reynolds numbers. It is noted that with PAA500 at the converging part only two basic modes (C-① and C-②) appear while at the diverging part the mode transition from D-① to D-④ occurs. With PAA1000 the state III ($0.64 \leq Re^* \leq 15.7$) is followed by the state VII ($15.7 \leq Re^* \leq 17.3$), VIII ($17.3 \leq Re^* \leq 38.4$), IX ($38.4 \leq Re^* \leq 56$), X ($56 \leq Re^* \leq 75.7$), XII ($75.7 \leq Re^* \leq 78.5$) and finally the state XIII ($Re^* \geq 78.5$) appears in the limit of Reynolds numbers. For the higher concentration solutions of PAA1500 and PAA2000, as shown in Fig. 10, the similar transition of those flow states as observed in PAA1000 are obtained. However, the trend of the transitions are shifted toward lower Reynolds numbers as the solution concentration becomes higher, indicating the higher solutions have destabilizing effect on the flow state due to high elasticity together with high shear thinning characteristic.

In Fig. 11, the flow states in the case of the 2 cycle channel are depicted, where in Fig. 11 (a) the first section and in Fig. 11 (b) the second section of the channel are considered. As it is seen in Fig. 11 (a), the flow states are the same as those observed in Fig. 10 (the 1 cycle channel) indicating that the flow states in the first section are not largely affected by the existence of the second section in the case of the 2 cycle channel. However, as seen from Fig. 11 (b), the transitions of the flow states in the second section are significantly different

Fig. 10 Flow states vs. Reynolds number (1 cycle channel)

from these of the first section, except for the Newtonian fluid where the transition of the flow state occurs like in the first section although with the Newtonian fluid the transition from the state I to II occurs at lower Reynolds number of $Re^* = 34$ in the second section. Each flow state appearing in the second section for PAA solutions in every concentration are totally shifted toward higher Reynolds numbers compared with that in the first section. This substantial change of the flow states is due to the flow mode difference occurring in the converging part of the second section. The eddy circulation zone (the flow mode D-②) occurred in the diverging part of the first section is extended toward the converging part of the second section, yielding the strong effect on the main flow in the converging part of the second section. Due to the existence of the large eddy circulation zone extended (the flow mode C-②), the region of the main flow is narrowed and straightened at the center line of the converging part in the second section, resulting in an increase of the hydrodynamic effect caused by the high velocity gradient of the flow region. The increase of the hydrodynamic effect results in lower elastic effects which causes the shift of the flow state transitions for higher Reynolds numbers and the appearance of the new flow states. Particularly for PAA500, new flow states of X, XI and XII are observed while the flow state VI is not present in the second section. Furthermore the transition of the flow

state occurs in the very limited range of Reynolds number $25 \leq Re^* \leq 100$ where the flow modes in the converging part are strongly influence by the upstream states. It is noted that the total pressure loss of PAA500 in the 2 cycle channel is less than that of Newtonian fluid in $25 \leq Re^* \leq 100$ as examined previously. This pressure loss reduction is occurred in the range of Reynolds number which corresponds the flow state transition as mentioned above. Thus it is thought the existence of the upstream channel causes flow state change in the second section of the 2 cycle channel leading the total pressure loss reduction, particularly for a dilute viscoelastic fluid such as PAA500.

The pressure loss of the viscoelastic fluid in a packed bed or porous body can be modeled by the converging-diverging nozzle, for which Huzarewicz *et al.*⁽⁵⁾ reported an increase of the pressure loss for the Boger fluid in a sinuous tube (the 1 cycle) by an effect of the elasticity. The gained results in the present investigation give an insight that the 2 cycle channel (or could be higher cycle) might give different results compared to the 1 cycle channel as an extended model for packed bed (or porous medium) in the low Reynolds number region, and would yields a possibility of the further pressure loss reduction for a viscoelastic fluid of the dilute polymer solution in the porous flows or the corrugated flow channel in an actual engineering application.

Further study would be required to examine a mechanism for the flow state transition occurring in these channels with viscoelastic fluids. A numerical analysis together with the stability analysis must be performed in order to verify the phenomena observed in the present study. It is, however, beyond of our present investigation We will reporting the some explanations of flow states appeared with these channel configurations in our future publications.

5. CONCLUSIONS

Data of pressure characteristics and the flow states appearing in the 1 cycle converging-diverging channel and the 2 cycle continuous converging-diverging channel are obtained for various concentration solutions of viscoelastic fluid as well as the Newtonian fluid. From the experimental results, the following conclusions are obtained.

1. The first throat pressure becomes higher than that of Newtonian fluid and at the down stream the pressure is kept dropping continuously passing through the second throat in the case of the 2 cycle channel. This trend becomes significant for higher concentration solutions.
2. With a low concentration solution, in particular for PAA500 in the present study, the pressure loss reduction (in comparison with Newtonian fluid, about 25% reduction is obtained at a low Reynolds number) is

Fig. 11 Flow states vs. Reynolds number (2 cycle channel)

obtained with the 2 cycle channel whereas such a reduction can not be appeared with the 1 cycle channel.

3. The classification of flow states are obtained in the 1 cycle and the 2 cycle channels for viscoelastic fluids as well as the Newtonian fluid. Five basic flow modes are observed at the converging part while four basic flow modes are observed at the diverging part. By combination of these basic flow modes, thirteen flow states are presented in total. It is found that the second section of the 2 cycle channel is strongly affected by the flow state of the first section resulting in new flow states which can not be observed in the case of the 1 cycle channel. Particularly with PAA500, the transition of the flow states are occurring in the very limited range of Reynolds number which corresponds the range of the total pressure loss reduction.

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