Measurement on Flow and Heat Transfer Characteristics of Viscoelastic Fluid Flow in a Serpentine Channel

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Abstract: Flow and heat transfer characteristics of diluted viscoelastic fluid flow in a serpentine-curved cha nnel are described in this study. Measurement of two dimensional velocity field using the particle image ve locimetry (PIV) and flow visualization was conducted in order to understand unsteady flow characteristics a nd the vortex structure. In addition to this measurement, average heat transfer coefficient was measured und er isothermal heated wall condition. The viscoelastic fluid was 64wt% sucrose water solution to which poly acrylamide of 500ppm was mixed. The results showed that in the viscoelastic fluid case, large fluctuations were produced in the flow and their intensities increased markedly against the Reynolds number in the stre amwise and spanwise directions even at *Re* =1.0~3.0. Larger fluctuation intensities were observed particularl y at the inflection point of the channel curvature. These fluctuations were produced mainly due to the gene ration of the longitudinal vortices which was not observed in the Newtonian fluid case. By these flow fluct uations and secondary flows, the heat transfer coefficient increased dramatically.

1. Introduction

The influences of the rheological properties of the viscoelastic fluid on laminar heat transfer, particularly in the case of straight channel, have been keenly studied in the past several decades. Hartnett et al. (1985) and Chunbo & Hartnet (1992) have reported from their experiment that the heat transfer coefficient in the case of viscoelastic fluid flow increases markedly compared with the Newtonian fluid flow case. The main cause was believed to be attributed to the secondary flow which was generated and enhanced by the normal force difference. Flow instability of viscoelastic fluid flow has also been studied with great deal of interest. Larson et al. (1990) studied the flow instability of Taylor-Cuette flows in rotating coaxial cylinders. Joo & Shaqfeh (1994) investigated the mechanism of the increase in the flow instability of Taylor-Dean flows in coaxial cylinder. It is known from these studies that the flow instability is enhanced due to the fluid elasticity, and that Taylor vortices can be generated even under very low Dean number flows.

Recently, several studies on the mixing characteristics of viscoelastic fluid in a serpentine-curved channel under low Reynolds number condition have been published in the literatures. Groisman & Steinberg (2001) showed in their measurement that flow fluctuation can be observed even in the order of *Re* ~ 10. Tamano et al. (2009) reported that a pair of vortices was generated in the time-mean velocity fields at the outlet of the serpentine channel with circular cross-section. All these results indicate the possibility of effectively enhancing the mixing performance or moreover mass and heat transfer at the channel wall. To the knowledge of the authors, however, there are no experiments conducted to link such unsteady flow and the fluid mixing with the heat/mass transfer performance. Moreover, the characteristics of the flow fluctuation and vortices have not been understood yet. It is essential to study these characteristics of viscoelastic fluid flows in serpentine channels in order to provide an insight for the feasibility of using the viscoelastic fluids as working fluids, and to aid the designing of an effective channel shape and conditions in order to apply this technique to the fields of thermal engineering, chemical engineering and medicine. In this study, measurements of the heat transfer coefficient and velocity field of the viscoelastic fluid flow in a serpentine channel with a square cross-section are described.

2. Experimental method

2.1. Experimental apparatus

Figure 1 shows the schematic diagram of the experimental apparatus applied to the present measurements. The channel consists of three parts: the inlet and outlet straight channels, and the serpentine channel. The serpentine channel used for the heat transfer measurement was made of copper in order to apply an isothermal condition to the wall. Constant temperature water was supplied from the thermostat bath to the circular cross-channels installed in the wall. On the other hand, PIV measurements were carried out using transparent acrylic channels. The channel had a square cross-section of 5mm in width and height. The serpentine channel had a periodical shape, which consisted of 10 repeating units of circular curved parts.

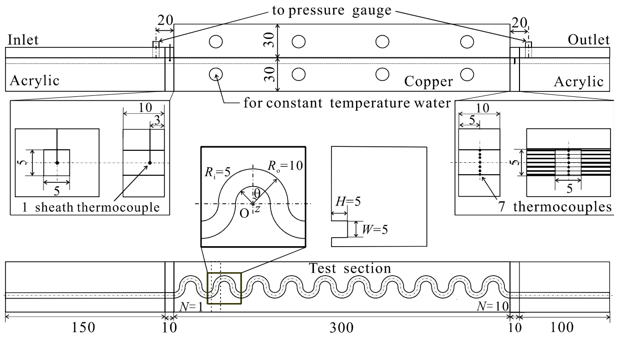


Fig. 1 Experimental apparatus and channel shape.

The inner and outer radii were 5 and 10mm, respectively.

The working fluid was supplied to the channel by a pump driven by pressurized air. The mass flow rate was measured by measuring the mass of the fluid flowing out from the outlet of the channel using an electronic weighing machine and data logger.

2.2. Heat transfer measurement

In order to measure the fluid temperature for bulk mean temperature calculations, temperature measurement units were placed at the inlet and outlet of the copper test section. The fluid temperature at the inlet was measured by a sheath K-type thermocouple of 0.5mm in diameter having its end point positioned at the center of the channel cross section. Temperature at a single point only was measured since a uniform temperature distribution was expected for the inlet flow. The fluid temperature at the outlet was measured by 7 K-type thermocouples located evenly in the height direction in the middle of the channel width. Since the available temperature distributions obtained from this measurement were only in one-dimensional form, expansion of the temperature distribution from one- to two-dimension was necessary. Thus, in this study, the fluid temperature was assumed to have a similar distribution to the measured one at $r = R_{in}$ in the r and z directions. The temperature of the heated cupper part was also measured by K-type thermocouples, the variation of which was 0.5 °C. Streamwise velocity distributions of laminar flow in a square duct (Shah, 1978) were used in the sucrose solution case. We have assumed that the velocity distribution in the PAAm solution case is similar to the laminar flow of Newtonian fluid case based on the discussion on the friction factor. The temperatures and velocities obtained from these processes were employed to calculate the bulk mean temperatures, and the average heat transfer coefficient of the serpentine channel..

2.3. PIV measurement

The PIV system was composed of a double pulse Nd:YAG laser (New Wave Solo3: wave length 532nm) and high resolution CCD camera (TSI, Powerview Plus 4MP: 12-bit monochrome, 4-Mpixels). A laser sheet was irradiated to the channel in the direction from the sidewall to illuminate the particles in that plane. The height position of the laser sheet was located at the center (z/H=0.5) of the channel. The spatial resolution of the image obtained by the camera was 15μm/pixels, and the frame rate was 5fps. The total number of images and the corresponding time period were 600 and 120s. This condition was sufficient to calculate the statistics values of the flow fluctuation. PIV analysis software (TSI, Insight 6.0) was used to obtain the flow velocity from the recorded images. Glass beads (LaVision, glass hollow sphere: nominal diameter=10μm, relative density=1.1) were mixed in the fluid as tracer particles.

Table 1 Flow conditions in the experiment.

Fluid	*Re*	*De*	*Wi*
Sucrose	1.01 – 4.29	0.59 – 2.48	–
PAAm	0.33 – 1.92	0.19 – 1.11	7.0 – 50

2.4. Experimental conditions

Two kinds of working fluids were prepared for the experiment. One was a sucrose water solution (sucrose 64.4wt%), which was a Newtonian fluid. The other was polyacrylamide (PAAm) water solution (sucrose 64,4wt%, NaCl 1wt%, PAAm 500ppm), which was a viscoelastic fluid. The fluids were prepared mixing the solute to water using a pot rotating mill. NaCl was mixed in the fluid to keep the polymer structure and fluid properties stable.

The fluid viscosity μ, density ρ and relaxation time γ of PAAm solution were measured prior to the experiment. μ measured by the rheometer (Anton paar, MCR-301) were 123mPa·s and 359mPa·s for the sucrose and PAAm solutions, respectively. The relaxation time was 2~3s which was calculated by appying the Powell-Eyring (Hartnetl et al., 1985) model to the measured results using the rheometer. The heat capacity C_p and thermal conductivity λ, were derived from the empirical equation shown in the references of Gucker and Ayers (1937) and Werner et al. (2007) for the fluid temperature of 25°C.

The flow conditions considered in this study are summarized in Table 1. *Re* is the Reynolds number defined as $Re = \rho U_m D_h / \mu$, where U_m and D_h are the average velocity and hydraulic diameter, respectively. *De* is the Dean number, which is defined as De $= Re(2W/(R_i+R_o))^{0.5}$. W is the channel width, and R_i and R_o are the inner and outer radii of the curved channel. *Wi* is the Weissenberg number and is defined as $W_i = \gamma (U_m/D_h)$. γ is the relaxation time of the solution.

3. Results and discussion

3.1. Heat transfer performance

Figure 5 shows the relationship between the average Nusselt number, Nu_m, and the Reynolds number, *Re*, for the cases of sucrose and PAAm solutions. The analytical results for the Nusselt number of laminar flow in a straight channel with square cross-section is depicted in the figure for comparison. This analysis

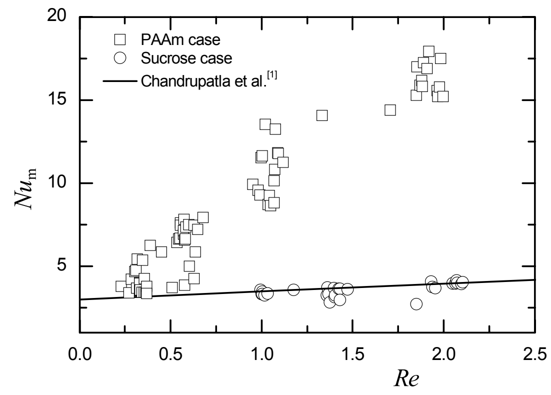


Fig. 2 Relationship between average Nusselt number and Reynolds number.

considers the entrance region effect, and is derived by Chandrupatla & Sastri (1977).

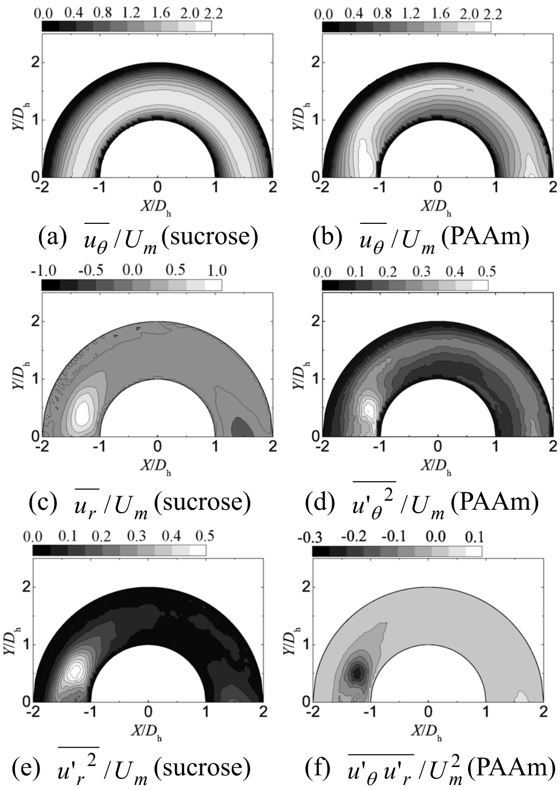
The Nusselt number Nu_m of the sucrose solution case slightly increases with Re due to the development of the thermal boundary layer at the inlet. Further, the result agrees well with the analytical one showing the validation of the measurement. Therefore, the flow in the serpentine channel is flowing along the curved channel without accompanying any secondary flows, which is consistent with the small De shown in Table 1.

In the PAAm solution case, Nu_m increases markedly as Re increases, and shows a considerable heat transfer enhancement compared to the sucrose solution case. Nu_m appears to approach to the value of sucrose solution case as Re decreases. Therefore, it is expected that the increase of Nu_m is related more to the production of secondary flow rather than the change in the velocity distribution due to the non-Newtonian behavior such as shear thinning.

3.2. PIV measurement

Figures 3 (a)–(c) show the velocity distributions of the streamwise (circumferential) and spanwise (radial) components of the flow velocity measured at the 2nd curve of the serpentine channel. The results are for the sucrose (Re=3.3) and PAAm solutions (Re=2.1). Figures 3 (d)–(f) show the fluctuation intensities and Reynolds stress in the case of PAAm (Re =2.1).

As shown in Fig. 3 (a), in the sucrose solution case, which is a Newtonian fluid, a symmetric velocity profile is observed along the streamwise direction of the curved channel. On the contrary, in the PAAm solution case, spanwise flow is generated at the inflection point of the serpentine channel ($X/D_h \cong \pm 1.5$), and an outward deviation of the position where the streamwise velocity becomes maximum can be observed. These results indicate that the flow flows from the outside of a curve to the outside of the next curve. Although not shown here, this secondary flow was also observed in the streamline structure visualized by the dye. This flow is one of the reasons why the heat transfer enhancement is obtained.



(a) $\overline{u_\theta}/U_m$ (sucrose) (b) $\overline{u_\theta}/U_m$ (PAAm)

(c) $\overline{u_r}/U_m$ (sucrose) (d) $\overline{u'^2_\theta}/U_m$ (PAAm)

(e) $\overline{u'^2_r}/U_m$ (sucrose) (f) $\overline{u'_\theta u'_r}/U_m^2$ (PAAm)

Fig. 3 Time-mean velocities and fluctuation intensities contours at the 2nd curve.

In Figs. 3 (d), $\overline{u'^2_\theta}/U_m$ shows a large value along the channel curve near the channel centerline. The streamwise fluctuation, therefore, exists through the channel streamwise direction. On the other hand, $\overline{u'^2_r}/U_m$ is nearly zero in the curve area, and increase in the area located slightly downstream of each inflection point of the serpentine channel. As shown in Fig. 3(f), the Reynolds stress $\overline{u'_\theta u'_r}/U_m^2$ also increases in the area adjacent to the inflection point. The increase of these values is believed to be attributed to threefold. One is the fluctuation produced along the streamline as observed in the curved area shown in Fig. 3(b). Since the flow crosses the channel near the inflection point, the fluctuation along the streamline will accompany an apparent spanwise fluctuation. The second one is the fluctuation due to the variation of the streamwise position at which the spanwise flow is located. Namely, the maximum peak of $\overline{u_r}/U_m$ changed its streamwise position, and increased the apparent spanwise fluctuation. The third one is the additional fluctuation generated by the secondary flow and increase of the flow instability. This spanwise fluctuation enhances the heat transfer performance in addition to the secondary flow (longitudinal vortex) generated in the channel.

In order to evaluate the influence of the fluctuation mentioned above on the heat transfer performance, the fluctuation energy k_m (=($\overline{u'_x u'_x}$ + $\overline{u'_y u'_y}$)/2) is calculated and depicted against the Reynolds number in Fig. 4. Note that, k_m is the value of the fluctuation energy spatially averaged in the half-curve area of N=2;

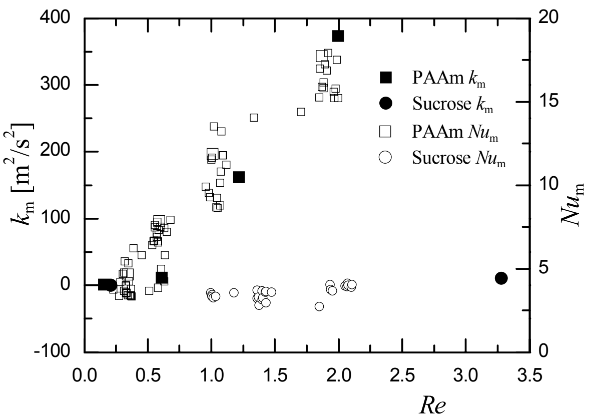


Fig. 4 Relationship between *Re* and average fluctu ation energy, *k*, at the 2nd curve.

i.e. the area shown in Fig. 3. For comparison, the relationship between Nu_m and *Re* shown in Fig. 2 is superimposed on the figure. In this case, the vertical range is adjusted in the following way. First, the scale of Nu_m and k_m are adjusted so that Nu_m of the sucrose solution case and k_m=0 are located at the same level. Then, the levels of the maximum values of Nu_m and k_m are roughly matched.

In the figure, k_m in the sucrose solution case remains constant showing that now fluctuation occurs. This is reasonable since the working fluid is Newtonian fluid and *Re* is completely in the range of steady laminar flow condition. In the PAAm solution case, k_m is also zero at Re <0.5. However, k_m increases as *Re* increases indicating the production of the flow fluctuation in the channel. Furthermore, the increase rate of k_m agrees fairly well with that of Nu_m showing that a considerable correlation exists between the two values.

We believe that the fluctuation flow observed in this study is more likely to be an unsteady laminar flow fluctuation rather than the "viscoelastic turbulence" called in the studies of Groisman and Steinberg. The heat transfer enhancement is, therefore, attributed to not only the flow fluctuation mentioned above, but also by the longitudinal vortex like secondary flow generated at the inflection point and the channel curve. From Fig. 4, a correlation should exist between the magnitude of the secondary flow and fluctuation intensity, and thus the Reynolds number. Further measurement and discussion on the three-dimensional structure will be made in the future work.

4. Conclusion

Measurements on the heat transfer coefficient and flow velocity were carried out for the viscoelastic fluid flow in the square serpentine channel. The conclusions obtained from the measurements are summarized as follows:

Enhancement of heat transfer performance was observed in the PAAm solution (viscoelastic fluid) case compared with the sucrose solution (Newtonian fluid) case. The average Nusselt number Nu_m in the PAAM case increased markedly as the Reynolds number *Re* increased.

Streamwise fluctuation was observed along the serpentine channel in the PAAm solution case. Spanwise fluctuation, and also spanwise flows was, however, only observed in the area located downstream of the inflection point of the channel curvature. In addition to these, a secondary flow flowing from the outside of one curve to the outside of the next curve. A reasonable correlation between the increase of Nu_m and the fluctuation energy against *Re* was observed.

Therefore, the increase of Nu_m is mainly attributed to the flow fluctuation and secondary flow generated in the channel which is obtained only by the combination of viscoelastic fluid and the serpentine channel.

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