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

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## ABSTRACT

Viscoelastic fluid produces normal stresses in a flow which generate secondary and unsteady flows. These flow can enhance the fluid mixing and heat transfer performances compared with Newtonian fluid flow even under low Reynolds number conditions. In the present study, measurements and numerical computations on the heat transfer and the flow characteristics of viscoelastic fluid in a serpentine channel were conducted. The channel curvature changes its direction periodically in the streamwise direction which generates radial forces and vortices at the curve and produces unsteady flows at the inflection point. I will introduce the measurement results of the heat transfer characteristics of the channel walls in the streamwise direction for the fluid flow of polyacrylamide and sucrose water solution. The vortex structure and unsteady behavior of the flow investigated by the particle image velocimetry, streakline visualization, and pressure loss measurements will also be shown together with some numerical results. From these works, we found several types of vortices generated in the flow, with typical ones forming a pair of vortices and single vortices rotating in the clockwise and counter-clockwise directions. These vortices enhanced the heat transfer at the walls in different forms. Because the vortices relied on normal stresses and significantly affected the enhancement of the local Nusselt number, the vortex structure, and the Nusselt number distributions showed a good correlation with the Weissenberg number.

Viscoelastic fluid is a non-Newtonian fluid that exhibits elastic properties in addition to viscosity. The elasticity will produce additional normal stresses in the flow, when shear and shear stress are applied to the fluid. This force changes the main flow structure, generates secondary flows, and increases the flow instability. The secondary flow and unsteady flow enhance fluid mixing between the channel core region and wall, and increase the wall heat transfer compared with Newtonian fluid for low Reynolds number flows. Therefore, heat transfer can be enhanced if the normal stress can be effectively controlled by efficiently designing the channel geometry and viscoelasticity of the fluid. On this background, heat transfer characteristics of viscoelastic fluid flow under low Reynolds number conditions have been investigated keenly in the past for Couette flows, parallel-plates, straight channels, curved channels, and corrugated channels. Among these, the corrugated channels (or serpentine channels) provide the curve part in which the normal stress differences of the viscoelastic fluid and the hoop-stresses generate stresses to produce secondary flows effectively in the channel. In addition to this, the inflection point of the curvature changes the directions of the stress, streamlines, and vortices which can increase the flow instability and change the flow structure to further enhance the fluid mixing and heat transfer [1-6].

In this study, we investigate the flow and heat transfer characteristics of viscoelastic fluid flow in serpentine channel under low Reynolds number condition [2,4,6]. We show that the heat transfer enhancement can be achieved by a factor of three compared with Newtonian fluids owing to the generation of strong secondary flow and unsteady flow. The serpentine channel used in this study had a square cross section of 5 mm on side, and consisted of semicircle parts connected periodically in the streamwise direction. The inner and outer radii of the semicircle part were 5 and 10 mm, respectively. The number of periodic curve units $N$ was 30. Local heat transfer measurements at the top-bottom and sidewalls of the channel were conducted simultaneously with the flow visualization. PIV and pressure loss measurements were also conducted. We also carried out numerical simulation to understand the relationship between the flow and heat transfer characteristics, and the normal stress distribution generating the vortices. An aqueous solution of 500 ppm polyacrylamide (PAM, molecular weight 1.8×107: Polyscience Inc.), 1 wt% NaCl, and sucrose was used as the viscoelastic fluid. The flow Reynolds number investigated was in the range of 0.1-8.8, and for the Weissenberg number it was 8-220.

To demonstrate the revealed characteristics and the performance for heat transfer enhancement, several results will be shown here. Figure 1 shows the average Nusselt number distribution and the friction factor for the sucrose and viscoelastic fluids in relation to the Weissenberg number. Compared with the sucrose solution case (Newtonian fluid), $Nu$ shows larger value by a factor of three for $Wi > 100$. Further, a good correlation is obtained between the values and the Weissenberg number over solutions of different relaxation times.

Figure 2 shows the representative vortices generated in the channel cross-section for $Wi \sim 70$. Figure 3 shows the local Nusselt number distribution in the streamwise direction measured at the top-bottom walls and sidewalls. The Nusselt

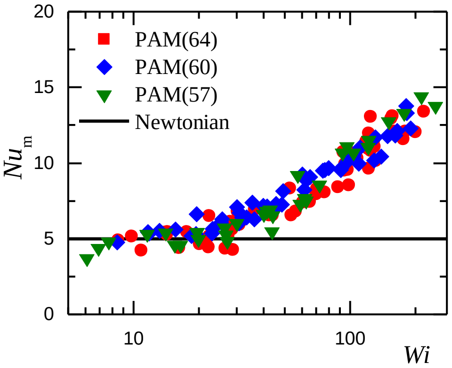


Fig. 1 Average Nusselt number in relation to Weissenberg number.

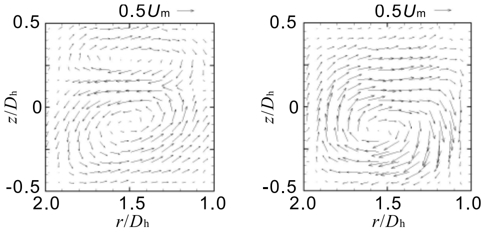
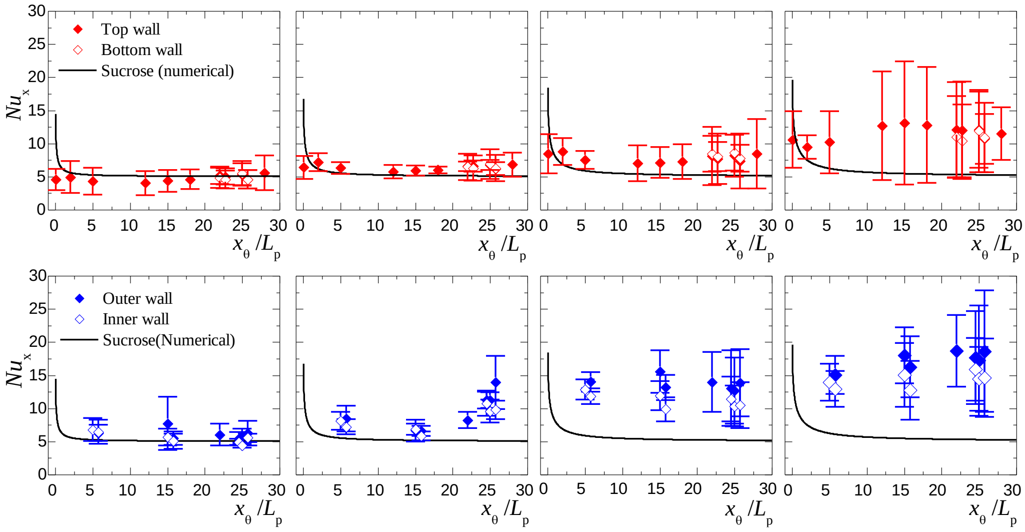


Fig. 2 Velocity vectors of the pair of vortices and the single vortex.



(a) $Wi$ = 7–29 (b) $Wi$=29–45 (c) $Wi$ = 50–85 (d) $Wi$ = 100–150

Figure 3 Local Nusselt number distribution in the streamwise direction for the top-bottom walls and sidewalls in relation to the Weissenberg number.

number varies with channel walls, streamwise locations, and *Wi*. This was mainly attributed to the structure of the vortices generated in the cannel. As shown in Fig. 2, the vortices appeared in the forms of a pair of vortices, and single vortex with clockwise and anti-clockwise rotation. In small *Wi* conditions, the stress is relatively small and the vortex forms a single vortex with the rotation direction depending on the position of the main flow (high velocity region) in the cross-section. As the *Wi* increases, the increase of the stress makes the vortex formation more stable resulting in the generation of the pair of vortices. The single vortex increase the heat transfer at the top and bottom walls, and the pair of vortices increase the heat transfer at the outer wall of the curved channel as shown in Fig. 2.

The results and discussion on the effects of the normal stresses on the flow instability, the relationship between the local heat transfer and vortex structure, and the correlation between the non-dimensional variable of flow and heat transfer will be introduced in my talk.

## ACKNOWLEDGMENTS

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