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HEAT TRANSFER ENHANCEMENT EFFECTS OF SECONDARY FLOWS OF VISCOELASTIC FLUIDS IN SERPENTINE CHANNEL

Kazuya Tatsumi*, Yousuke Tanaka, Reiko Kuriyama, Kazuyoshi Nakabe

Kyoto University, Kyotodaigaku-katsura, Nishikyo-ku, Kyoto 615-8540, Japan

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1. INTRODUCTION

Viscoelastic fluid is a non-Newtonian fluid that exhibits elastic properties in addition to viscosity. The elasticity will produce normal stresses in the flow, when shear and stress are applied to the fluid. This force changes the main flow structure, generates secondary flows, and increases the flow instability, which enhance the fluid mixing and heat transfer compared to Newtonian fluid. Especially in a channel with curvature, longitudinal vortex-like secondary flow similar to Dean vortex is produced due to the normal stress differences of the viscoelastic fluid. In the serpentine channel, the vortices are generated at the curvature, and the strength of the radial flow and the flow instability are increased by the inflection point of the curvatures [1-3]. The vortices enhance the heat transfer coefficient of the sidewalls, significantly [4,5]. The flow in these channels is a mixture of the viscoelastic fluid flow and the Dean vortices. However, the difference between the contribution of the two flow on the heat transfer characteristics, and moreover, the combined effects of these two flows are not investigated in detail. In this study, flow and heat transfer characteristics of viscoelastic fluid in serpentine channel under low Reynolds number condition are mainly investigated by numerical computation using Oldroyd-B model. Firstly, we introduce a dimensionless normal stress difference, and show that the average Nusselt number can be correlated well with this value for both, the numerical and measurement results. The aspects of the flow structure of the viscoelastic flow and Dean flow are compared and discussed in relation to the Weissenberg number and Dean number. Finally, the temperature field and heat transfer enhancement effect of these flows are evaluated.

2. METHODS

Unsteady and three-dimensional form of the continuous equation, Navier-Stokes equation, and energy conservation equation were solved in the present computation. The viscoelasticity of the fluid was applied to the computation by employing the Oldroyd-B model as the constitutive equation and adding the additional stress term to the Navier-Stokes equation. Oldroyd-B model is a fundamental model derived by also considering the behaviour of the viscoelasticity in molecular level. We used this model to simplify the problem for comparing the stress and flow structure with the measurements. Non-slip and constant temperature conditions were applied to the channel walls, and periodic boundary condition was applied to the streamwise boundaries.

Heat transfer measurement was conducted under isothermal wall condition for serpentine channel. The wall temperature and the bulk mean temperatures of the inlet and outlet flow were measured to obtain the average heat transfer coefficient. Velocity distribution of the cross-sectional planes were measured using the particle image velocimetry (PIV) method.

The serpentine channel consists of two semi-circular parts with curvature of opposite direction (Fig. 1). The channel has a square cross section of 5 mm (=H) on side, and the inner and outer radii of the semicircle part are

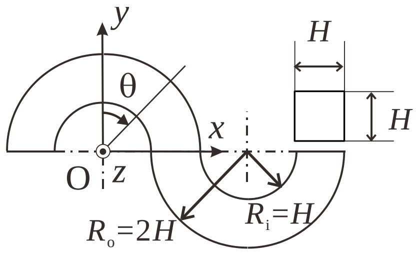

Fig. 1 Periodic region of serpentine channel.

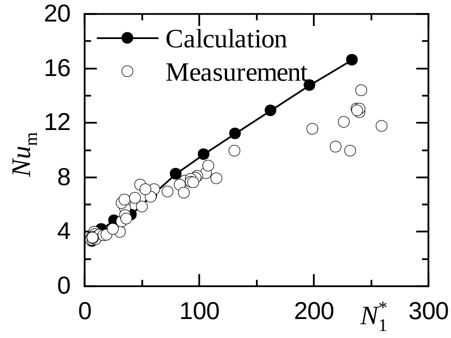

Fig. 2 Nu_m and dimensionless normal stress differences N_1^*.

*Corresponding Author: tatsumi@me.kyoto-u.ac.jp

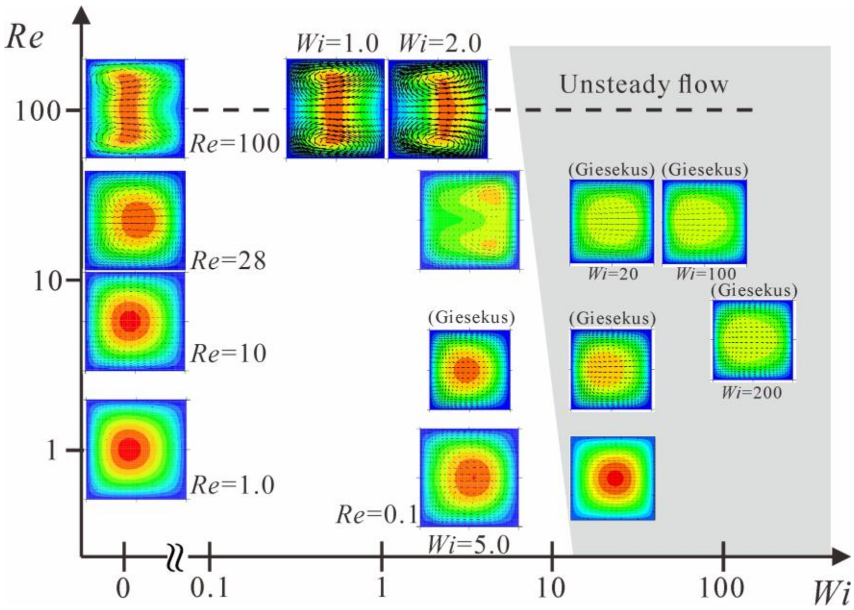

Fig. 3 Mapping of flow structure in relationship to Weissenberg number and Reynolds number.

R_i/H = 1 and R_o/H = 2, respectively. The periodic region with two semicircle curves shown in the figure was set as the domain to be solved in the computation. For the measurement, the number of the periodic region was 10. The range of the Reynolds number *Re*, Dean number N_D, Weissenberg number *Wi* were *Re*=0.5-2.8, N_D=0.28-16, and *Wi*=0.5-6 for the computation, and *Re*=1.0-2.1, N_D=0.57-1.2, and *Wi*=6.0 for the measurement, respectively.

3. RESULTS AND DISCUSSION

The average Nusselt number Nu_m is compared with the measurements for validation. We will introduce a dimensionless parameter related to the normal stress to compare these results. The term expressed as $(\tau_{\theta\theta} - \tau_{rr})/r$, which appears in the equation of motion of the radial direction as the normal stress difference N_1, plays an important role in the generation of the secondary flow. We can derive the following dimensionless parameter by normalizing the equation of motion applying *H* and the streamwise mean velocity U_m as the characteristic length and velocity.

$$N_1^* = \frac{\rho H^2}{\mu_0^2} N_1 \tag{1}$$

We rearranged the relationship of the Nu_m with the *Re* and *Wi* to N_1^* and will show it in Fig. 2. The results give a reasonable agreement, showing that N_1^* can be an index to represent the flow and heat transfer characteristics, and the validity of the computation.

To roughly demonstrate the effects of the centrifugal force and viscoelasticity, the secondary flow and streamwise velocity at the cross-section of θ=0 obtained by the computation are plotted against *Re* and *Wi* which is shown in Fig. 3. Secondary flow increases as *Re* and *Wi* increases, and by these flows, the flow core region of low temperature is carried toward the outer sidewall and enhance the heat transfer of the outer and top-bottom walls. The Dean vortex and the viscoelastic fluid show similar flow structure. However, the Dean flow fully developed in the curved channel, while in the viscoelastic fluid case, flow structure changed as the normal stress distribution changed depending of the position of the flow core region. The results showed that this viscoelastic effect can increase the strength of the secondary flow, give larger movement of the flow core region leading to the redevelopment of the thermal boundary layer, and further increase of the overall heat transfer coefficient. These discussions will be extended more in the presentation.

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