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SHORT PAPER

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# Vortex formation in a viscoelastic entry flow of asymmetric planar contraction

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## 1 Introduction

Manufacturing a uniform liquid film is a key technology in the slot die coating. Therefore, an attention has been paid to the flow structure in the entry flow of a slot die having asymmetrical planar contraction. It is known that the flow computation of the entry flow is notoriously difficult in solving the governing equations due to the geometrical singularity and the non-Newtonian properties of the fluid (Baaijens 1998). Therefore, there is only an experimental approach, which provides reliable results of non-Newtonian flow phenomena occurring in the slot die (Schweizer 1988; Clarke 1995). However, there are very few quantitative measurements of velocity field in the viscoelastic fluid flow (Rodd et al. 2007).

The purpose of this paper is to visualize the entry flow structure of asymmetric planar contraction of viscoelastic fluid flow by measuring the velocity field of Newtonian and viscoelastic fluids using the particle-image velocimetry. An attention is placed on the vortex formation in the entry flow, which is a crucial topic in the production of uniform liquid film.

## 2 Experimental methods

The geometrical configuration of the test channel is shown in Fig. 1, which is similar to the actual slot die geometry for the production of optical and polymer films. The channel is fabricated by acrylic resin material to visualize the internal flow through the channel. The entry channel has a square cross section of $5 \times 5$ mm with the contraction channel section of $0.54 \times 5$ mm, which provides the asymmetric planar contraction. The origin of the coordinate $x$, $y$ is set to the entrance of the contraction.

The velocity fields in the entry flow of the asymmetric planar contraction were measured by a standard particle-image velocimetry (PIV) system. Note that the flow visualization was carried out using tracer particles of acrylic resin material having a diameter of 10 μm. The plane of measurement was set to the channel center ($x$–$y$ plane) of the contraction. The illumination of laser light sheet of 1 mm in thickness was provided from the double-pulsed Nd:YAG laser of 532 nm in wavelength. The flow observation was made

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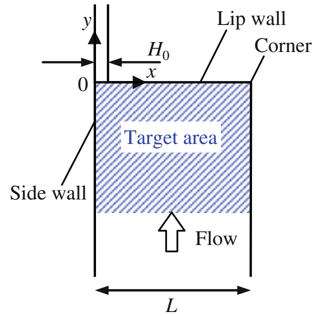


**Fig. 1** Schematic of asymmetric planar contraction

by a monochrome CCD camera (1,018 × 1,008 pixels, 8 bit) with a microscope having a magnification of 2.7. The PIV analysis and the error analysis have been reported by Fujisawa et al. (2005).

The experiments were carried out using Newtonian fluid (DI water) and viscoelastic fluid (polymer solutions). The viscoelastic fluid contains 34.0 wt% polyethylene glycol ($8 \times 10^3$ g/mol) and 0.01 wt% polyethylene oxide ($4 \times 10^6$ g/mol). Note that the relaxation time of the viscoelastic fluid was estimated as $\lambda = 0.0272$ s (Tirtaatmadja et al. 2006).

## 3 Results and discussions

Figures 2 and 3 show statistical properties of velocity field in the asymmetric planar contraction flow of Newtonian and viscoelastic fluids, respectively, which are obtained from the PIV measurements of 300 velocity fields. Each figure consists of velocity vector map, contour plots of the velocity magnitude and streamlines. Note that the streamlines obtained from the PIV measurement are piled up over the experimental observation of streak lines in Figs. 2 and 3. The Reynolds number is set to $Re$ (=$H_0V_0/\upsilon$) = 3.2 in both cases, and the Weissenberg number of the viscoelastic fluid is $W_i$ (=$2\lambda V_0/H_0$) = 47.3, where $H_0$: inlet width of contraction, $V_0$: mean velocity through the contraction, and $\upsilon$: kinematic viscosity of fluid.

For the Newtonian fluid flow (Fig. 2), the velocity distribution shows the parabolic profile in the inlet of the entry channel, which has a maximum at the center of the channel. As the flow approaches the contraction in the entry channel, the flow gradually directs to the contraction and the velocity magnitude increases.

The velocity field of the viscoelastic fluid flow (Fig. 3) greatly changes from that of the Newtonian fluid flow (Fig. 2). The entry flow of viscoelastic fluid attaches to the inlet side wall, and the velocity distribution in the channel inclines to the contraction flow side. The inclination of the entry flow to the channel wall is due to the elongational viscosity of the viscoelastic fluid. On the other hand, the low velocity region over the contraction lip grows in size and the recirculating flow is formed around the channel corner. The recirculating flow is rotating in clockwise direction induced by the main flow toward the contraction. The presence of the recirculating entry flow is expected to deteriorate the spanwise uniformity of the contraction flow, so that it is not favorable in the production of film coating (Nam et al. 2009). The formation of recirculating flow of viscoelastic fluid in the asymmetric planar contraction flow has not been observed in literature. The present results clearly indicate that the vortex formation occurs in the asymmetric planar contraction flow of

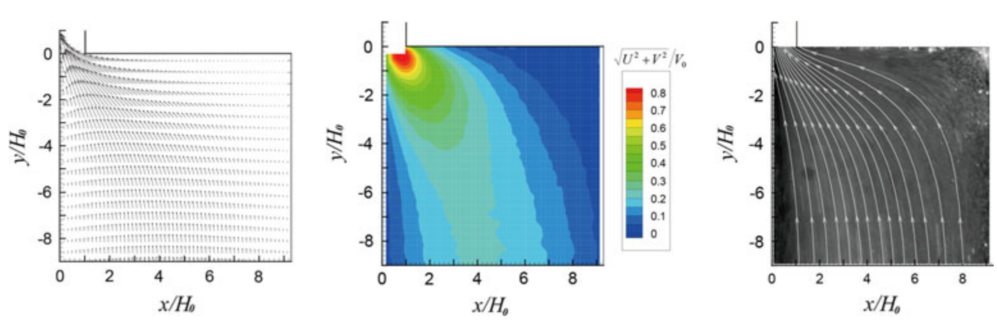


**Fig. 2** Velocity field of Newtonian entry flow through asymmetric planar contraction

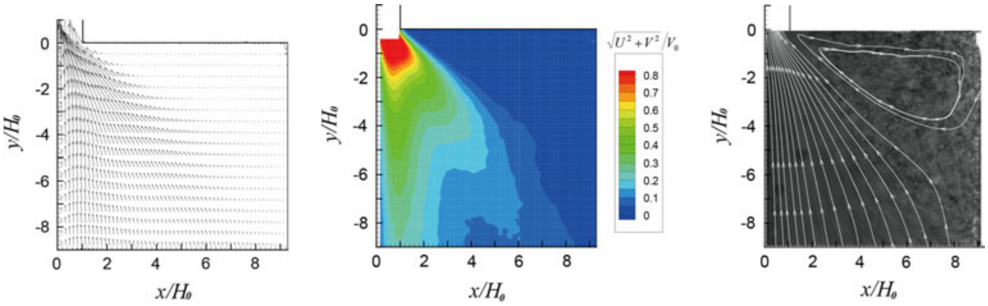


**Fig. 3** Velocity field of viscoelastic entry flow through asymmetric planar contraction ($W_i = 47.3$)

viscoelastic fluid at Reynolds number $Re = 3.2$, which corresponds to the actual condition of film production ($Re = 1$–$10$). Therefore, the vortex formation is unavoidable in the slot die entry flow of viscoelastic flow in this range of Reynolds number. According to the experiment at various flow rates of viscoelastic fluid flow, the vortex formation condition is observed at $W_i > 30$ in the entry flow of asymmetric planar contraction.

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