# START-UP BEHAVIOR OF VISCOELASTIC FLUID FLOW NEAR A CAPILLARY ENTRY

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## INTRODUCTION

The flow near a die entry or in an abruptly contracting pipe flow is one where the elasticity of the fluid can have a dominant effect because the fluid element is elongated unsteadily even when the flow field itself is steady. Due to its practical importance, many studies have been carried out on viscoelastic fluid flows contracting channels, mainly on steady flows. This investigation is focused on the effect of elasticity on the development process of a capillary entry flow where the influence of side-walls of the large channel upstream is negligible.

## EXPERIMENTAL

Figure 1 shows the geometry of the test section channel and the coordinate system used in this paper. A capillary with a diameter $d$=2mm and a length $L$=157mm is attached flush to the bottom of the upstream large reservoir. Since the contraction ratio is virtually infinite, influence of the side-walls of the upstream reservoir can be taken to be negligible.

An aqueous solution of 0.2 wt% polyacrylamide (PAA-solution) is used as the test fluid. A rice-syrup/water mixture is used as a Newtonian fluid for comparison. A cone-plate type rheometer is applied to obtain the material functions in the steady simple shear flow. The shear viscosity and the first normal stress difference of the PAA-solution thus obtained are shown in Fig. 2. Since the viscosity is well represented by the power-law model, the generalized Reynolds number $Re^*$ is estimated for the developed capillary flow by applying the power-law for the viscosity. The range of $Re^*$ in this experiment is 0.8 - 90.

In an experimental run, the fluid filling the test section was kept at rest for a while under the pressure of compressed air, or a natural head, and then the valve below the capillary was quickly opened to start the flow. The driving pressure was kept constant during a test run.

The tracer-particle and light-sheet technique was applied to visualize the flow. A two-component LDV was used for velocity measurement in the x-z plane. The flow rate $Q$ and the pressure drop through the capillary were measured simultaneously.

## RESULTS AND DISCUSSION

The flow pattern of the Newtonian rice-syrup/water mixture is shown in Fig. 3, compared with the velocity vectors obtained by the LDV measurement. The exposure time for the photograph is from $t = 0$ to $t = 9$s. Results as shown in this figure and measurements on the flow rate and pressure drop show that the development of the flow field of a Newtonian fluid upstream the capillary entry is virtually quasi-steady at a Reynolds number in the range of this experiment, i.e. the flow pattern with radial streamlines as shown in Fig. 3 develops immediately after the flow starts and the absolute values of velocities increase proportionally with the flow rate $Q$ till it attains its terminal value $Q_\infty$. The flow rate $Q$ increases monotonously and the transient time $t_{tr}$ for $Q$ is very short, say less than 0.5 s, in contrast with the case of the PAA-solution as described in the following sections.

The normalized flow rate $Q/Q_\infty$ of the PAA-solution is plotted against the non-dimensional time $t/\lambda$ in Fig. 4. The relaxation time $\lambda$ and the Weissenberg number *We* are calculated by applying the Denn model for the developed capillary flow based on the material functions in Fig. 2 [1]. The transient time $t_{tr}$ for the PAA-solution is quite long, e.g. $t_{tr}$ =7s at *We*=4.1, and $t_{tr}/\lambda$ is almost independent of *We*. A very large over-shoot of the flow rate is observed and the maximum value of $Q/Q_\infty$ is seen to increase with *We* in the experimental range of this work.

The axial and radial components of velocity, $v_z$ and $v_r$, on the centerline upstream the capillary entry is shown in Fig. 5. The measurement is carried out simultaneously with the *Q* for *We*= 4.1 in Fig. 4. The delayed development and the overshoot behaviors are observed in $v_z$ corresponding with *Q*. However, the relative value of maximum overshoot is considerably lower than that of *Q*, meaning that the pattern of streamlines changes during the transient stage.

Instantaneous flow patterns and velocity fields in the transient stage are compared in Fig. 6. The flow pattern just after the start of flow is similar to that of a Newtonian, and then the angle of the flowing region where the velocity vector is pointing towards the entry decreases with time. The size of the vortex surrounding the flowing region grows gradually till the terminal developed flow field is established. The transient behavior of the flow rate is considered to be caused by the entry pressure loss that depends on the flow pattern upstream the entry.

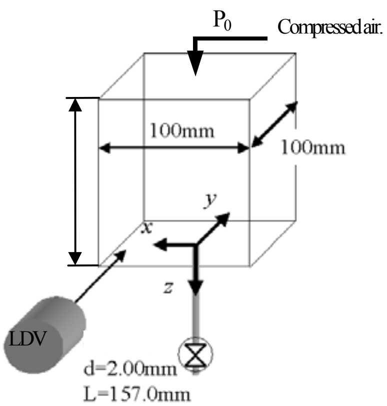
## CONCLUSIONS

While the developing process of capillary entry flow of a Newtonian fluid is virtually quasi-steady, it takes a considerable time for a viscoelastic fluid to attain its terminal regime. The transient time for the PAA-solution, non-dimensionalized by the fluid relaxation time, is independent of the *We* number, but the flow rate overshoot ratio is seen to increase with *We*.

The flow pattern upstream the capillary entry determines the elongation rate, which governs the elongation stress at the entry, and the entry pressure loss in turn. Hence, the transient behavior of the flow rate is attributed to the gradual development process of the flow field upstream entry.

## REFERENCES

[1] D.V. Boger and K. Walters, Rheological Phenomena in Focus, p.7, Elsevier, 1993.



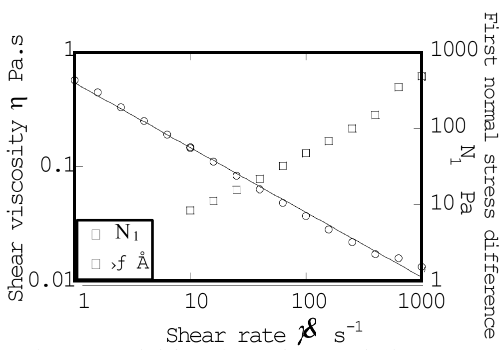



Fig.2 Material functions of PAA-solution at 20□ ž

Figure 1 Flow channel and the coordinate system

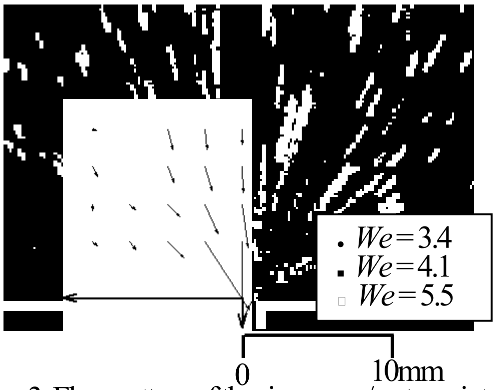



Figure 3 Flow pattern of the rice-syrup/water mixture ($Re=0.8$)

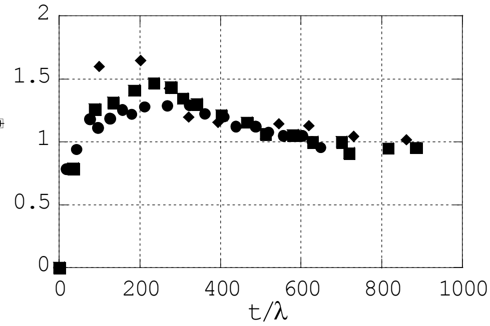



Figure 4 Transient behavior of flow-rate of the PAA-solution

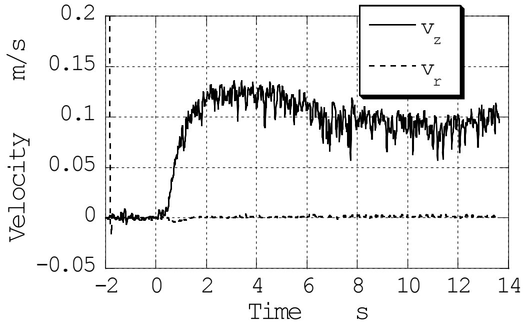



Figure 5 Transient behavior of velocity of the PAA-solution ($We=4.1$, $z/d=-5$, $x=y=0$)

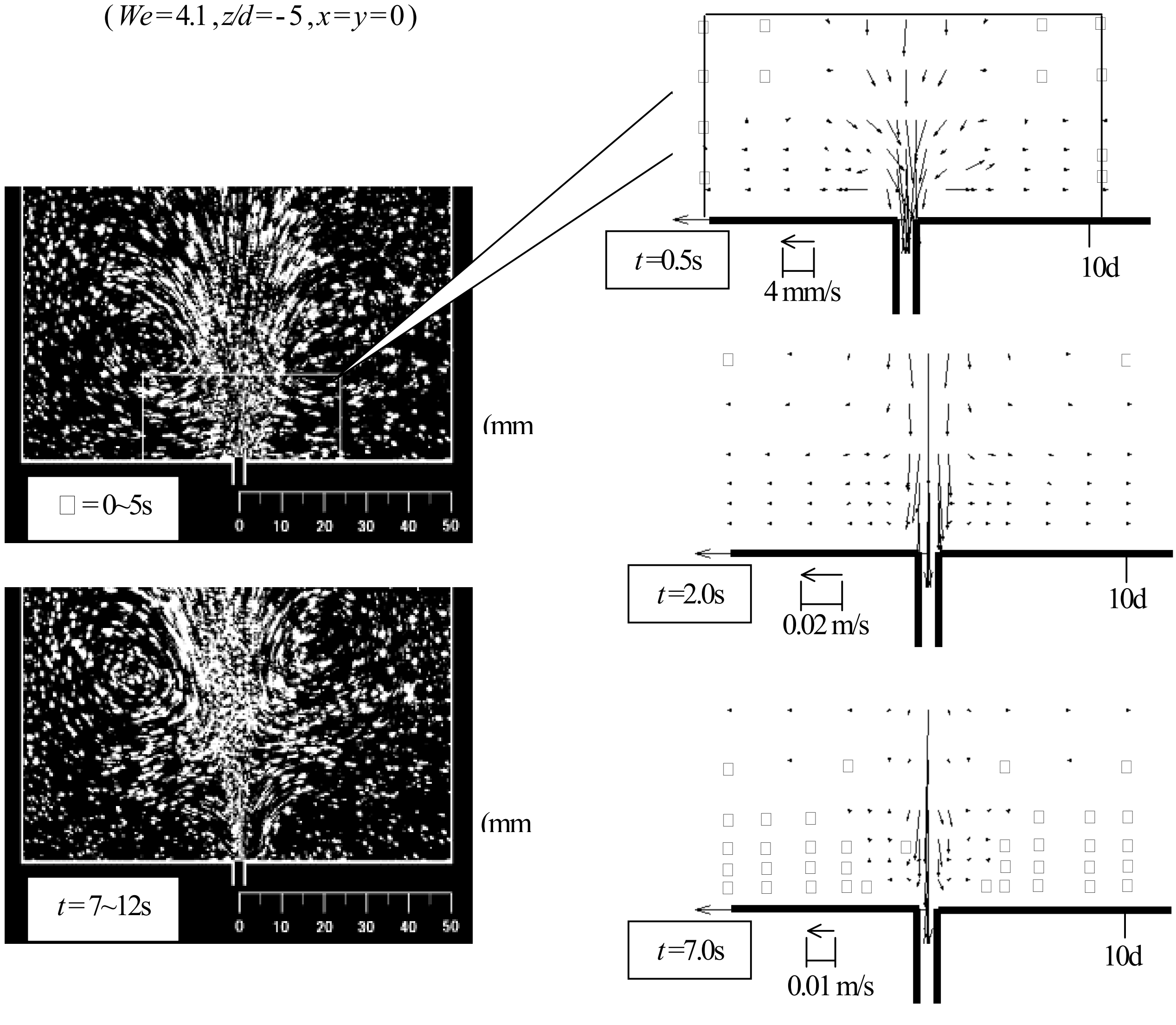



Figure 6 Development of flow field of the PAA-solution ($We=4.1$)