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Viscoelastic responses of flow driven by a permeable disk investigated by ultrasound velocity profiling

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ABSTRACT

Ultrasound velocity profiling was applied to viscoelastic flow induced around a moving permeable disk. There were two objectives to this measurement. The first was to find technical advantages and restrictions when applying ultrasonic Doppler velocimetry to a viscoelastic liquid. This issue has not been clarified even though ultrasonic pulses may interact with an elastic medium in the monitoring of the Doppler shift frequency. The second objective was to determine the fluid physics of a viscoelastic liquid around a permeable object, which will help in designing mixing process for materials subject to strong rheological resistance. In this paper, we report a representative response of a viscoelastic liquid in terms of its spatiotemporal velocity distribution. The response highlighted is cyclic lateral waves that form behind the disk, which were hardly detectable by particle image velocimetry. We discuss multiple reasons for this phenomenon considering not only fluid properties but also the measurement principle of ultrasound velocity profiling as applied to viscoelastic liquid.

1. Introduction

Mixing is one of the greatest concerns in polymer processing since viscoelasticity resists local material displacement [1]. Similar issues are faced for heat transfer and chemical reactions when handling non-Newtonian fluids. To understand such behavior, scientists in the field of fluid mechanics have investigated particular events arising for various configurations of internal flows [2–10] and external flows [11–13]. It is known that a general way of enhancing mixing is to provide multiple streamlines that tangle complicatedly in the system [14]. Pellets or porous cells having complex shape in chemical facilities are placed in a reactor to control non-Newtonian flow by combining local external flows. Here we focus on a permeable disk as one such cell structure. The disk allows ambient fluid to penetrate through many small holes. Although the disk shape itself is simple to manufacture, the flow characteristics of the disk are difficult to predict theoretically, particularly in the case of viscoelastic fluids.

Fig. 1 illustrates streamline patterns of three different disks. In the case of a solid disk (a), upstream fluid totally turns aside the disk. For Newtonian fluids having a range of Reynolds numbers, backward flow takes place behind the disk. For viscoelastic fluids, there is forward flow faster than the inflow velocity behind the disk, which is called negative wake [11]. No matter the fluid property, the backward and forward flow calms down as a hole is provided at the center of the disk as shown in (b). The rate of flow penetrating the hole depends on the flow resistance relative to the resistance of the external flow. The ratio of the flow rate is estimated analogously to parallel resistance. By increasing the number of holes, the flow behavior is governed by a doubled parallel resistance as shown in (c). For Newtonian fluids, such a permeable disk experiences drag stronger than that experienced by a solid disk because of viscous friction dominating the total drag [15–17]. For shear-thinning fluids, through-flows of the permeable disk are rather accelerated. For fluids with yield stress, the through-flow completely stops when the differential pressure acting on the disk surfaces is lower than the yield stress. For viscoelastic fluids, it becomes more difficult to predict the fluid behavior since viscoelasticity interacts among the many stream tubes that are provided by the through-flows. Additionally, the elasticity results in a resonance frequency along each streamline, which affects the global flow structure via the complexity of the doubled parallel resistance. Summarizing these issues, it is noted that the measurement of viscoelastic flows around a permeable disk requires careful consideration of multi-scale events emerging in both space and time.

Against the background described above, ultrasound velocity

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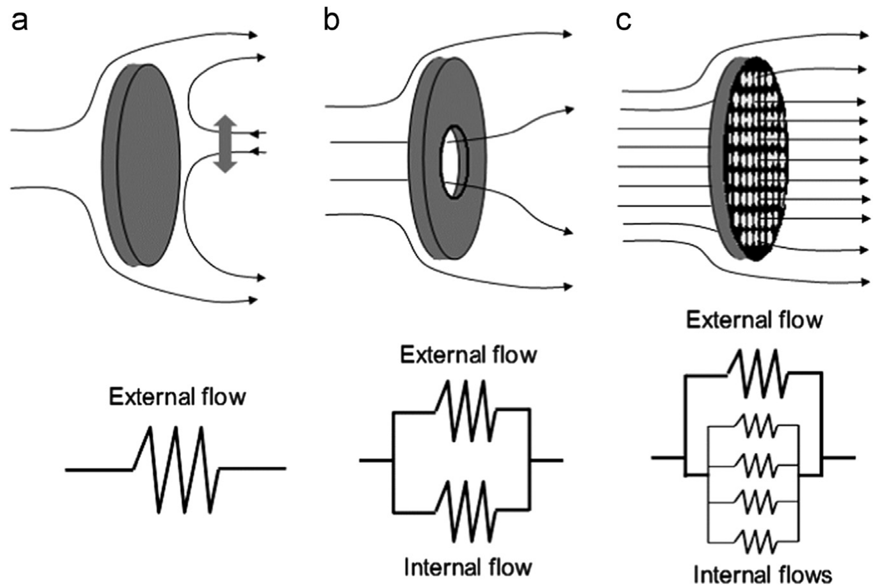

Fig. 1. Flow streams allowed by an opening(s) in a disk and their conceptual description in terms of flow resistance. (a) Solid disk (b) Hollow disk (c) Permeable disk.

profiling (UVP) is regarded as a convenient technique of quantitatively visualizing viscoelastic responses. This is because UVP reveals particular events that take place within the two-dimensional space–time velocity distribution. For bubbly liquid that is categorized as a shear-thinning fluid, UVP has been successfully applied in a viscometric study [18]. However, there have been few reports on the application of UVP to viscoelastic fluids, other than our previous studies on simpler geometries such as a cylindrical container [19,20]. In the present study for the permeable disk, the most representative result is the occurrence of lateral waves in the wake region of the disk. The waves have a Strouhal number higher than 2, which is attributed to the property of viscoelastic fluid penetrating the permeable disk. This event can be identified as a viscoelastic version of flow-induced vibration. A more important finding is that lateral waves are mostly unseen in particle image velocimetry (PIV) data but they appear clearly in UVP data. The reason for this was discussed among experts in the field of UVP at the 9th International Symposium on Ultrasound Doppler Method (ISUD, Strasbourg, France, 2014), where we noted several ideas from participants. It was suggested to us to publish our finding so as to present the discrepancy to general readers. To this end, we here leave our results emphasizing the difference between PIV and UVP, and discuss all possible factors that contribute to the differences. We believe that the paper provides both PIV and UVP developers with suggestions for future improvement of the respective techniques when applied to viscoelastic fluids.

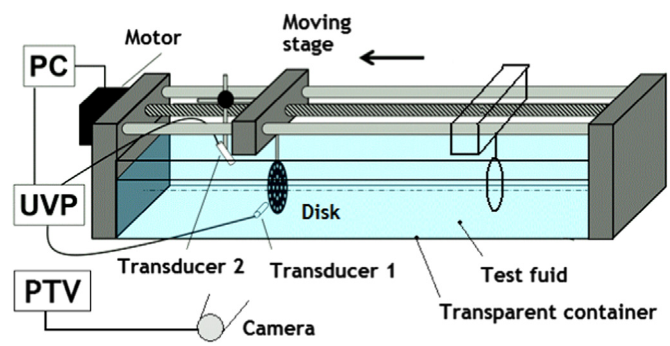

Fig. 2. Overview of the experimental setup for measuring the velocity distribution around a moving disk.

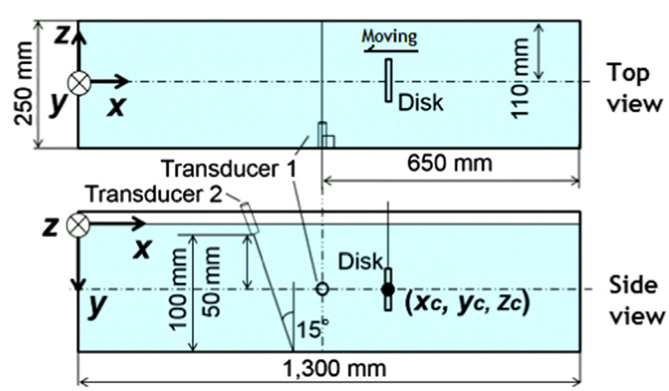

Fig. 3. Dimensions of the container and locations of ultrasound transducers for UVP measurement.

2. Experimental method

2.1. Experimental apparatus

A towing tank was used to measure the flow field induced by a moving object. The overall view of the tank is shown in Fig. 2. Detailed dimensions of the tanks as seen from the top and side are presented in Fig. 3.

A moving stage to tow a test object in liquid could slide smoothly along two parallel cylindrical rails mounted on top of the tank. A low-friction screw was rotated by a motor to drive the moving stage at a constant speed controlled using a personal computer. The speed was fixed to 20 mm/s in this work. The moving test object was a single disk; i.e., a thin circular plate. The disk was connected to the moving stage via a thin rod. Before performing the main experiments, we tested four types of disks in preliminarily experiments to clarify the flow behavior. The four disks are shown in Fig. 4. All the disks had the same outline diameter of $D=50$ mm and thickness of 2.0 mm. Flow could permeate through the disk because of the presence of holes. The