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Effects of the extensional rheological properties of polymer solutions on vortex shedding and turbulence characteristics in a two-dimensional turbulent flow

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ABSTRACT

An experimental study was performed to investigate the relationship between the extensional rheological properties of polymer solutions and vortex deformation in turbulent flow. Polyethyleneoxide as a flexible polymer and hydroxypropyl cellulose as a rigid polymer are added to two-dimensional (2D) turbulent flow. Specifically, 2D flow is advantageous as it examines the effect of the extensional rheological properties of polymers on the flow. In the study, 2D turbulent flow and vortex shedding in 2D turbulent flow were observed using interference patterns and particle image velocimetry (PIV). Power spectrum of the 2D flow images and 2D turbulence statistics calculated by PIV analysis indicated that there are three flow regimes of vortex shedding in the 2D turbulent flow of the polymer solution. The vortex shedding in the 2D flow was categorized into three types, and this was affected by the relaxation time of the polymer solutions.

1. Introduction

Research attention has focused on polymer drag reduction for more than half a century. During the period, a large number of experimental studies were conducted [1–9]. Turbulence statistics of a flexible polymer solution and a rigid polymer solution were compared, and subsequently type A and B drag reduction, and low and high drag reduction were suggested [10–16]. The most important feature of drag reduction is that the polymer additives do not simply suppress turbulent motion: the turbulent fluctuation in the streamwise direction increases while the normal turbulent intensity decreases. The effect is anisotropic [6–8,17–23]. Vortices that are generated at the wall in a flow undergo deformation when drag reduction occurs [7,8,21–23]. The anisotropy of turbulence is due to the deformation of vortices. Motozawa et al. [8] proposed a model for vortex variation near a wall with polymer additives. However, the background mechanism of drag reduction is not completely clarified to date.

The complexity of the phenomenon stems from interactions between vortices and polymers in the turbulent flow. Polymer molecules are larger than solvent molecules although the polymer molecules are significantly smaller than the smallest vortex sizes in the flow. It is considered that stretched polymers play a role in the phenomena. The main questions on the phenomenon are related to the manner in which the polymers interact with vortices, namely polymer characteristics that affect turbulence.

Many numerical studies were performed to clarify the anisotropic effect of polymers on drag reduction. den Toonder et al. [4] proposed an extensional viscosity model—viscous anisotropic effects of extended polymers—that is essential for turbulent drag reduction. However, the extensional viscosity model is unable to predict the onset of drag reduction. Therefore, Min et al. [17] adopted the elastic theory wherein the study derived transport equations for kinetic energy and elastic energy. Kinetic energy is transported through the elastic energy of polymers in a turbulent flow. To achieve energy transportation, a time criterion is important. Min et al. [17] suggested that the relaxation time of a polymer should be sufficiently long to transport elastic energy from the near-wall region to the buffer or log layer. In the study, the time criterion was defined based on wall shear velocity.

Both experimental [6–8] and numerical [17–23] studies captured vortex deformations. However, the index or criteria proposed in these studies was derived based on shear stress: the time criterion or rheological properties were defined by physical properties based on shear stress. While these studies discussed extensional viscosity or extensional rheological properties, it is not possible to separate the effects of extensional stress on polymers from the effects of shear stress. Therefore, the effects of extensional rheological properties of polymers will be clearer if we observe a turbulent flow that is mainly affected by extensional stresses.

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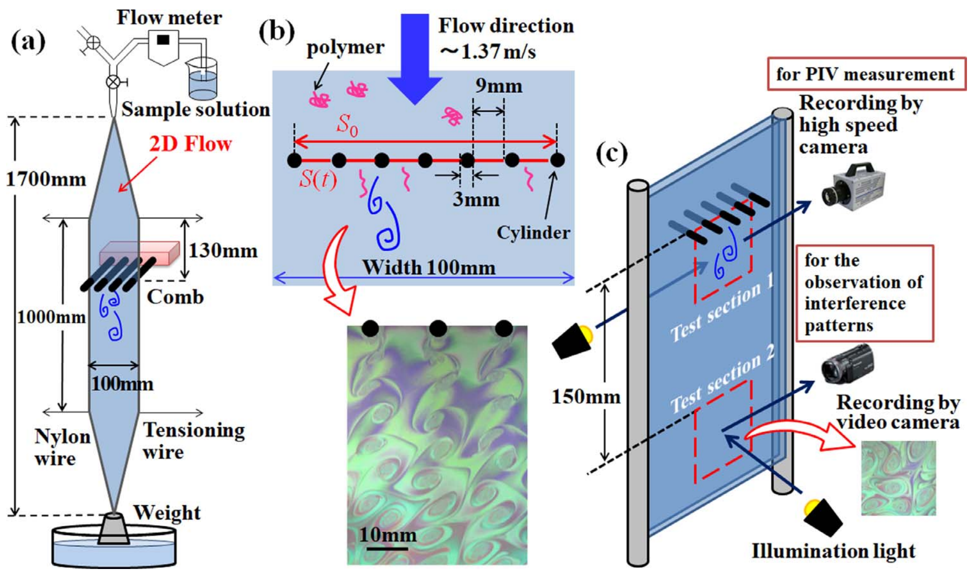

Fig. 1. Schematic of the experimental apparatus.

To focus on extensional rheological properties of a polymer solution in a flow, we used a flowing soap film, namely a quasi-two-dimensional (2D) flow, to realize a turbulent flow that was mainly affected by extensional stresses [24–26]. The flowing soap film is surrounded by air, and therefore the 2D flow is free from shear stresses that are due to the existence of solid walls. Additionally, an extensional flow occurs at the comb when a comb that consists of equally spaced cylinders is inserted into the 2D flow. The comb generates vortices that merge into others. The 2D turbulent flow is the result of merger of several vortices in which vortices that are generated in the flow characterize the turbulence. Thus, for the case in which polymers are added to the flow, polymers affect the 2D turbulence. Therefore, we focus on the effects of the extensional properties of polymer solutions on the 2D turbulence where it is possible to almost neglect the effects of shear stress.

Variation in the 2D turbulence that was caused by polymers was reported in previous studies [27,28]. Flowing soap films were used as a test field of the 2D turbulence. The studies reported that the polymers suppress large scale fluctuation of thickness fluctuation in the flowing soap films, and this is because energy transfer is prevented due to the polymers [28]. In our previous studies [29–31], we compared the effects of a flexible and a rigid polymer on 2D flow. Vortices in 2D turbulent flow exhibited deformation with polymers. It is suggested that the prohibition of energy transfer in the flow varied due to the rigidity of polymers [31].

The vortices in 2D turbulent flow were generated at the comb in the flow, and thus the present study involved an experimental investigation that focuses on vortex shedding characteristics at cylinders in 2D flow. The 2D turbulent flow system allows us to consider vortex characteristics affected by extensional rheological properties under extensional stress. In a previous study, Cressman et al. [32] studied the effect of polymers on vortex shedding in a 2D flow. The vortex was deformed with polymer additives. Cressman et al. discussed the effect of the extensional viscosity of polymer solution on the vortex deformation although they did not quantify extensional rheological properties. We conducted a more precise study on the vortex deformation, and we also mention the connection between the deformation of vortices and turbulent drag reduction.

Specifically, 2D turbulent flow and vortex shedding are visualized using interference patterns of the film. The velocity fields close to the cylinders are captured by particle image velocimetry (PIV), and the flow statistics are discussed. The extensional rheological properties of flexible and rigid polymer solutions are measured, and the effect of extensional rheological property on vortex shedding is clarified in terms of relaxation time and vortex shedding time.

2. Experimental procedures

2.1. Materials

Sodium dodecylbenzenesulfonate (SDBS) was dissolved in pure water at a concentration of 2 wt%. Polyethyleneoxide (PEO, molecular weight: 3.5×10^6) was used as a flexible polymer wherein concentrations were varied as 0.25, 0.5, 0.75, 1.0, 1.25 and 1.5×10^{-3} wt%. As rigid polymers, hydroxypropylcellulose (HPC, molecular weight: $>1.0 \times 10^6$) was used at concentrations of 0.01, 0.02, and 0.05 wt%. The overlap concentration of PEO is approximately 1.2×10^{-2} wt%, and that of HPC is approximately 0.15 wt%.

2.2. Viscosity and relaxation time measurements

The viscosity of the sample solutions was measured by using a rheometer (MCR301: Anton Paar) with a cone-plate device at shear rates from 1 to 1000 s^{-1}. The relaxation time of the sample solutions under extensional stress was measured by a capillary break up extensional rheometer (CaBER, Thermo scientific). The diameter of the end plate of CaBER was 6 mm, the initial distance between two end plates was set as 3 mm, and the final distance between two plates was adjusted as 8 mm. The diameter of the neck of the fluid, D [mm], was plotted relative to time, t [s]. The diameter was fitted using the fitting function, $D = A\exp(-t/3\lambda)$ to calculate each relaxation time under extensional stress, λ [s], of each sample solution. Here, A [m] is a constant that was determined by the experiment. The extensional property of sample solutions was evaluated by the relaxation time in this study because the absolute value of the dilute solution extensional viscosity is not completely reliable.

2.3. Experimental apparatus used to create flowing soap films

The experiments were performed using the apparatus shown in Fig. 1. The complete image of the apparatus is shown in Fig. 1(a). The outline of our apparatus follows that in previous studies [29–31] as originally proposed by Rutgers et al. [33]. The channel was composed of two nylon wires tightened by a weight. Gravity-driven sample solutions flew between the two wires to create flowing soap films. The flow rate, Q [L/s], was controlled by a valve connected to an injection nozzle. The flow rate was measured by a flow meter (KEYENCE, FD-