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Rheo-optical investigations and near-wall turbulence structure of polymer solutions in turbulent channel flow

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Abstract

In the present study, the turbulence behavior of polymer solutions is investigated using laser-Doppler velocimetry (LDV). At the same time, an attempt is made to determine a possibly occurring extension and orientation of the macromolecules by flow-induced birefringence (FIB). Flow-dynamic and rheo-optical experiments are presented which were performed in a smooth square channel in the area of the fully developed turbulent flow. The turbulent flow properties of aqueous solutions of PAAM and Xanthan Gum were studied. The Reynolds' number was 30.000. The concentration of the polymer solutions was varied between 300 and 800 wppm for Praestol 2300 and between 30 and 120 wppm in the case of Xanthan Gum. The experimental data obtained indicate a significant dependence of the turbulent flow properties on the molecular structure of the polymers used. This could be clearly demonstrated by the values of the root mean square (rms) of the velocity fluctuation. Furthermore, the influence of the extension and orientation of the macromolecules on the turbulent flow properties was investigated.

Keywords: Turbulent channel flow; LDV; Birefringence; Rheo-optic; Polymer; Xanthan Gum; Praestol 2300; PAAM

1. Introduction

In comparison to Newtonian fluids, visco-elastic fluids such as polymer solutions demonstrate clearly different turbulence properties. The results of experiments on visco-elastic fluids in a turbulent fully developed channel flow show that, even for highly diluted polymer solutions, a drastic alteration of the turbulence intensity in comparison to water as a solvent occurs. Explanations for this behavior proceed partly from the assumption that in the near-wall area an orientation and extension of the macromolecules occurs. The elongational flow investigations, for example by Fuller [1], Durst [2], Eich [3] and Zijl [4], showed, that visco-elastic macromolecules are particularly effective when they are aligned. Investigations of the turbulent structure of visco-elastic fluids leads to the assumption that, a minimum stress on the macromolecules is required for a drag-reducing effect to occur (see [5–7]). Can these fluid-dynamic properties be related by the alignment of the macromolecules in dependence on the distance from the wall? What influence on the turbulent properties does in this connection the structure of the macromolecules, rigid or visco-elastic behavior, have.

2. Polymer solvent system

In this study, two different types of polymer solution systems were employed, namely the technical non-ionic polyacrylamide Praestol 2300, supplied by the Stockhausen company (Krefeld) with an averaged molecular weight of $\bar{M}_w = 5–10 \times 10^6$ g/mol and the ionic polymer Xanthan Gum, supplied by the Roeper company (Hamburg) with an averaged molecular weight of $\bar{M}_w = 2 \times 10^6$ g/mol [15]. Ordinary tap water with an averaged conductivity of $\kappa = 550$ μS/cm was used as a solvent. On the basis of structural-rheological considerations, it was possible to determine a concentration of $c^* = 700$ wppm for Praestol 2300 and of $c^* = 100$ wppm for Xanthan Gum for the boundary between the diluted and concentrated solution systems at rest.

The experimental investigations of the polymer flow of Praestol 2300 were carried out over a concentration range

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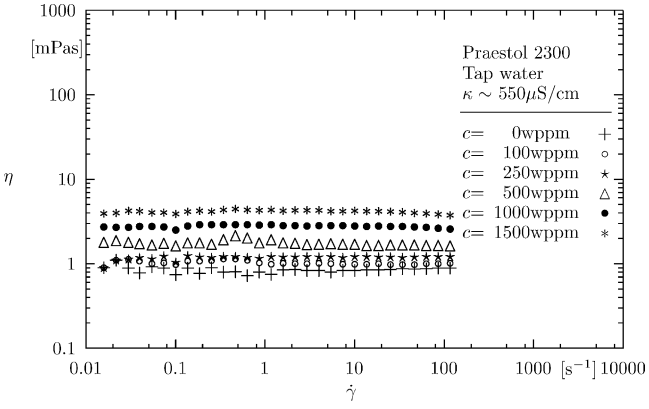

Fig. 1. Shear viscosity of Praestol 2300.

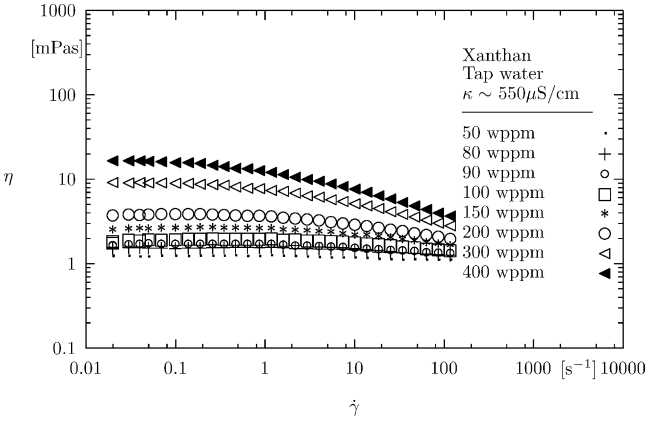

Fig. 2. Shear viscosity of Xanthan Gum.

of 300–800 wppm. For Xanthan Gum, a concentration range of 30–120 wppm was chosen. This means that highly diluted solutions and network solutions were obtained. In Figs. 1 and 2, the shear viscosity versus the shear rate is given for the polymer solutions Praestol 2300 and Xanthan Gum with various concentrations of the additives.

3. Rheo-optical and fluid-dynamic experiments

The investigations of the turbulent structure and the rheo-optical experiments were carried out in a rectangular channel which was part of a circulatory system. The channel consists of optical glass of the type SF57 made by the Schott company (Mainz) and has a hydraulic diameter of $d_h = 19$ mm. The fluid-dynamic and rheo-optical investigations were carried out in the fully developed channel flow at $x/dh = 142$ hydraulic diameters from the channel entrance. A 4-beam, 2-component fiber-flow system with a BSA-processor for signal processing was used as a laser-Doppler velocimeter [16].

The rheo-optical investigations were performed using the technique of crossed polarizers and the "16-intensities" method of an ellipsometer (see Fig. 3). The set-up with a crossed polarizer, in which the polarizer and the analyzer are angled at 90° to each other, measured only the flow-induced alteration in light intensity in a pre-determined preferential direction [13,22,23]. Using this set-up, which operates according to the principle of the 16-intensities method of an ellipsometer, the polarization-optical properties of an optically active medium can be determined via a Mueller matrix, hence giving the intensity as an angular function (see [8]). Signal acquisition was carried out using a photodetector. The emitted light of a He–Ne laser penetrates the channel transversally to the main flow component and is traversed from the center of the channel to the wall area. During the laser-Doppler and rheo-optical measurements, the process data pressure loss, flow rate and temperature were recorded in real time (Fig. 4) [14].

4. Results

In Figs. 5 and 6, the axial turbulence intensity, normalized by the friction velocity, is given as a function of the dimensionless wall distance in the fully developed flow for the Reynolds' number 30.000 and the polymer solutions of Praestol 2300 and Xanthan Gum. For the polymer solutions of Praestol 2300, it can be seen that, compared to the Newtonian profile (tap water), the addition of polymers leads to a marked increase in the fluctuation values. At the same time, the maxima of the curves shift to maxima *urms*-values with a greater wall distance (see [9]). For increasing concentrations the fluctuation values are enhanced in the region of the highly diluted solutions. For the concentration of $c = 800$ wppm, however, the region of network solutions is obtained. Here the fluctuation values are slightly diminished although the concentration is increased. An explanation for this is that the maximum axial velocity fluctuations of the solution change only minimally in comparison to the solvent water. A drastic change in the wall shear stress is, however, already noticeable in the particle area. If the critical concentration is exceeded, the wall shear stress, because of the temporary network, undergoes an increase caused by the increased drag, leading to

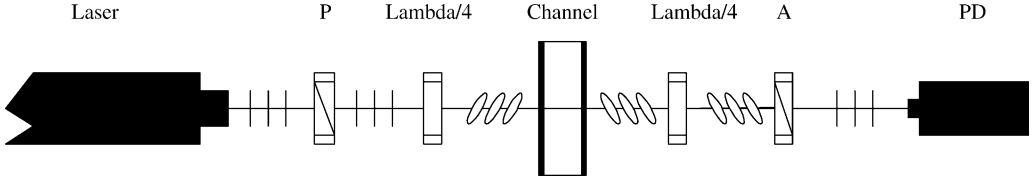

Fig. 3. Rheooptik.