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Interaction effects in multi-outlet viscoelastic contraction flow

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ABSTRACT

This paper describes an experimental study of interaction effects in viscoelastic contraction flows with an array of multiple, parallel outlets. The study focuses on edge effects, that is, effects of the finite size of an array, on flow rate distribution and flow stability. The experiments were carried out with a PEG-PEO Boger fluid in glass microfluidic chips with three parallel, abrupt contractions, variable outlet spacing, and free outflow. We used micro-Particle Image Velocimetry (μ-PIV) to measure the velocity field, and particle streak imaging to visualise the flow. The two most important conclusions of our study are: 1. the flow in the three outlet case is more unsteady than in the single outlet case, which possibly leads to flow rate fluctuations in the individual outlets, and 2. if the distance between the outlets is smaller than the distance between the outer outlets and the side walls of the upstream channel, the flow rate in the central outflow channel is lower than that in the outer two channels. The difference in flow rate reduces with increasing vortex size; at the highest tested flow rates the flow rate in the middle channel is even higher than that in the outer channels. These results are relevant for industrial production processes involving multi-outlet viscoelastic extrusion flow, such as fibre spinning.

1. Introduction

Processing conditions in many practical applications are limited by viscoelastic contraction flow instabilities. Therefore, viscoelastic contraction flows are extensively studied. Comprehensive reviews of the work in this field are given by Boger [3], White et al. [19], and, more recently, by Owens and Phillips in their book on computational rheology [13].

Some practical applications, such as fibre spinning, feature multi-outlet contraction flow. As the spacing between the outlets in these applications tends to be relatively small – in the order of a few outlet diameters – interaction between the different contractions can be expected. Understanding of the influence of interactions on, for example, flow stability and distribution of flow rate over the outlets, is of great importance for the performance of an industrial process. However, research on this topic seems to be rather limited.

To the knowledge of the authors, two papers were published on the subject of multi-outlet contraction flow. The first one is by Koelling and Prud'homme, [9], and describes experimental work with a poly-butene-poly-isobutylene (PB-PIB) Boger fluid in a set-up with nine outlets in a square array. Three different contraction ratios are used, where the contraction ratio is defined as the ratio of the distance between the outlets and the outlet diameter. The second paper is by Naka et al. [10] (in Japanese). In this paper aqueous solutions of poly-acrylamide (PAA) in two different concentrations are used. The experimental set-up is a contraction–expansion geometry, with either nine or twenty-five holes in a square array and with variable spacing.

Both papers report instabilities that are not observed in single outlet contraction flow. Also the vortex height in multi-outlet flow is smaller than in single-outlet flow. Moreover, particle streak images presented in both papers show that the flow towards outlets at the edge of an array is highly skewed in most cases. Remarkably, neither of the papers discuss this skewness. Naka et al. do discuss measurements of the distribution of flow rate over the outlets, but find that the velocity into each outlet is practically equal and – consequently – do not go into much detail.

We believe that under free outflow conditions, the skewed flow at the edges of an array of outlets could possibly influence the flow rate distribution. Free outflow conditions occur in many industrial applications, and flow rate distribution is an important factor in such applications. Therefore, the focus of our study is on the influence on the flow rate distribution, of asymmetry and instability in the flow towards the contraction.

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The character of our study is mainly exploratory; we observe effects and try to explain them, while a more comprehensive investigation is left for a future study.

From the literature on single-outlet viscoelastic contraction flow, it is known that most phenomena seen in axisymmetric contraction flow are known to occur in planar flow as well, or at least to have a planar counterpart (e.g. [17,16,11]). Therefore, we chose to use microfluidic flow cells for our experiments, with either one or three contractions.

Nowadays, microfluidic flow cells are widely used in the study of (single-outlet) viscoelastic contraction flow (e.g. [14,15]). Such flow cells offer several advantages, such as low sample volume, easy optical access, and high deformation rates at low Reynolds numbers. The latter enables studying effects of fluid elasticity without interference of inertia.

For most practical applications, the behaviour of the extrudate is more important than the behaviour of the flow upstream of the contractions. Unfortunately, at the flow rates used in this study, our PEG-PEO Boger fluid does not form coherent jets upon leaving the flow cell. Therefore, in this study we do not consider the behaviour of the extrudate.

In Section 2, we discuss the preparation and rheology of the test fluid, the experimental set-up, and the measurement methods we used. The experimental results are discussed in Section 3. Finally, conclusions and recommendations for further research are summarised in Section 4.

2. Experimental

2.1. Test fluid

As a viscoelastic test fluid, we used a poly-ethyleneglycol-poly-ethyleneoxide (PEG-PEO) Boger fluid. This is a solution of 30 wt% poly-ethyleneglycol (PEG), 8000 g/mol, and 0.06 wt% poly-ethyleneoxide (PEO), 4×10^6 g/mol (both from Sigma-Aldrich) in water, with a density of $\rho \approx 1040$ kg/m^3. The rheological properties of the solution were measured on a TA Ares-G2 rheometer with a Couette geometry and a gap width of 5 mm. Oscillatory as well as steady measurements were performed (see also [5]).

The results are shown in Fig. 1. The Boger fluid has a practically constant viscosity of 0.08 Pa·s over the measured range of shear rates. The measured storage modulus values agree satisfactorily with those measured by Dontula et al. [4]. Fitting a single-mode linear viscoelastic model to the oscillatory shear data yields a relaxation time of 17 ms. However, because of the rather poor quality of this fit, we decided to use the Zimm relaxation time [20] instead. For our Boger fluid, this was calculated to be 4.2 ms, by Sankaran et al. [15].

The extensional viscosity was measured using a Cambridge Trimaster Extensional Rheometer (courtesy of Dmitri Tsentalovich, Rice University). Four different plate distances were used, all resulting in virtually the same behaviour (Fig. 2). The Boger fluid is extension thickening, with a Trouton ratio of $\mathcal{O}(10^4)$.

2.2. Experimental set-up

All experiments were performed in glass microfluidic chips (Micronit Microfluidics) with either one or three abrupt contractions of 100 μm wide, an upstream channel width of 10 mm, and a depth of 100 μm. The contractions have a length of 1 mm, with free outflow at the end (Fig. 3). In the three-outlet chips the centre-to-centre distance between the outlets is either 0.5 mm or 2.5 mm. In the remainder of this paper, these geometries are referred to as SS3 (small spacing, three outlets) and LS3 (large spacing, three outlets), respectively.

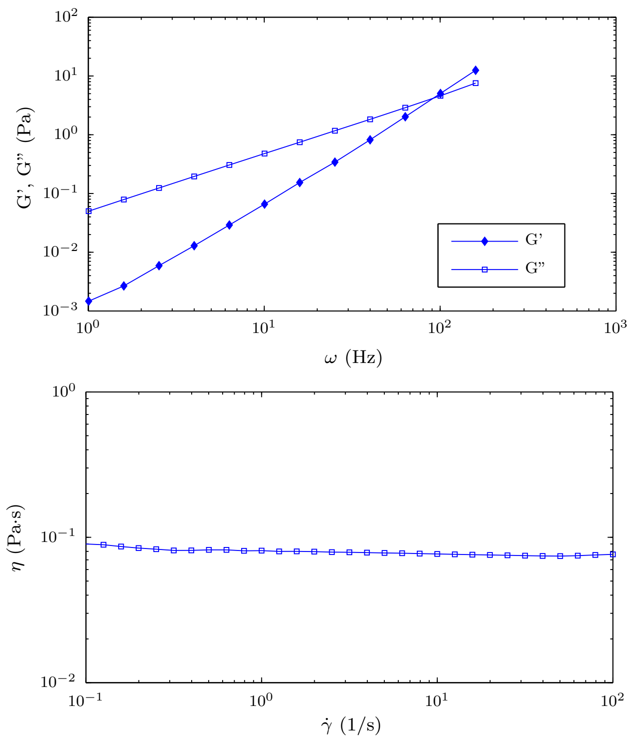

Fig. 1. Rheological behaviour of the PEG-PEO solution used as test fluid. Top: Loss modulus, G" (open symbols), and storage modulus, G' (filled symbols), in an oscillatory frequency sweep (measured at 25% strain), bottom: viscosity in steady shear. Measurements performed at 25 °C.

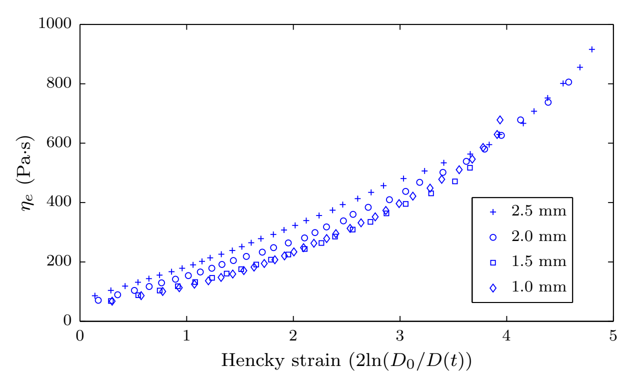

Fig. 2. Extensional viscosity as a function of Hencky strain, measured using a Cambridge Trimaster Extensional Rheometer at four different plate distances (courtesy of Dmitri Tsentalovich, Rice University).

The length of the upstream channel is 15 mm. Because the depth of the flow cells is much smaller than the length and width of the upstream channel, the Hele-Shaw approximation holds for the flow in the upstream channel, meaning that the velocity profile immediately downstream of the channel entrance is uniform (this was checked with a PIV measurement, see also Drost and Westerweel [5]).

The dimensions of the chips were chosen to be representative for a dry jet wet spinning process (see e.g. US Patent 3,767,756 [2]). The small depth also enables the study of other, less transparent fluids.

Effects of skewed flow towards the edge outlets are expected to be most distinct in the SS3 geometry, because of the large difference between the outlet-to-outlet and the outlet-to-wall distance. This difference was deliberately chosen to be extremely large, to exaggerate any effects of it.