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Stagnation Flow Extensional Viscosity Measurement Using Inverse Methods

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Abstract

This paper presents a novel approach to extensional viscosity measurement. A pressure drop technique in using stagnation point flow in a T- junction was implemented to obtain viscoelastic characteristics of a complex fluid. The stagnation point flow generates a non-homogeneous flow field which induces a range of extensional rates along the back wall of the channel. This geometry creates an information rich flow field that yields the whole extensional viscosity response curve in one experiment. A CFD model was created to predict flow field statistics of the flow. An inverse method was tested in order to assess constitutive parameters of a fluid of interest. Potentially this method could be used in development of a new extensional rheometer as an on-line and in-line controlling device in many industrial processes.

Keywords Extensional viscosity; Inverse method; Non-newtonian fluids; Rheology; Stagnation point flow.

1. Introduction

Extensional phenomena manifest in many industrial and everyday living processes. Non-Newtonian (or complex) fluids such as polymer melts and solutions, gels, emulsions exhibit both viscous and extensional properties. Extensional rheometry plays a key role in many industrial processes and is therefore central to a processing operation design for a wide range of polymer materials, food and medicine technologies. Complete understanding of a complex fluids behavior is difficult due to the existence of both shear and elastic effects in all processes when viscoelastic fluids are subjected to deformation.

Usually determination of constitutive parameters of complex fluids requires samples to be taken manually and put into conventional rheometers. Generally, conventional rheometers (filament stretching, capillary break-up, four mills and other types) are bulky and use optical means of measurements, which is not suitable for a wide range of opaque liquids, such as paints, food and cosmetics.

Characterization of extensional properties of non-Newtonian liquids is still a complicated problem due to difficulties in separation of viscous and elastic components of flow behavior. The general approach to this problem is discussed in many articles [1-3]. A significant amount of the literature is devoted to the measurement of elastic characteristics of particular materials and liquids [4, 5].

The evolution of scientific equipment and mathematical algorithms means that it is now possible to solve complicated problems pertaining to complex fluids that are of major importance to the further development of elongational flow engineering. The flow field within T-junction geometry of a device for fluids that exhibit elongational rheometry is non-homogeneous due to the stagnation point. In contrast with the operation of conventional rheometers, data processing from the prototype rheometer involves modelling of the flow field and the construction of the mapping algorithm to connect data obtained from the device with the underlying constitutive parameters of the fluid.

2. Stagnation point T-shaped flow rheometer

Conventional rheometers widely used for these purposes usually provide constitutive parameters of fluids for a *single* flow rate. This means that several experiments must be performed in order to obtain the viscosity constitutive equation. A device that generates a range of viscoelastic responses within a single experiment must incorporate a non-homogeneous flow. This device has to be capable of producing accurate rheological data for viscoelastic fluids that arise in industrial applications, work with opaque liquids and liquids with high viscosity (such as gels, pastes and emulsions). The specific T-shaped channel permits the generation of a large range of extensional rates in the vicinity of the stagnation point, which is situated at the back wall of the channel.

The sensing system was developed to permit an analysis of a broad range of viscosities and to function without the need for optical measurements. The latter means of viscosity investigation, such as break up capillary and particle based velocimetry techniques, are precise and reliable, but bulky, expensive, involve manual manipulation and analyze only visual zone of a flow [6, 7]. Oh the other hand, pressure drop measurements permit the development of a robust, flow-through device which could be used as a by-pass or in-line tool in industrial processes [10].

The novel rheometer combines a T-shaped slot channel with four flush mounted pressure transducers installed at the inlet, two outlets and the stagnation point zone of the channel. Additionally, three capacitance sensors are deployed in the vicinity of the stagnation point. This system of sensors permits measurement of the pressure drop along the channel and the flow field velocity. A computer-controlled syringe pump is used to generate a pressure driven flow through the channel of the rheometer, thus controlling shear and normal stresses [8, 9].

3. Inverse method

An inverse methodology could work in the case when it is not possible to measure parameters of interest directly, but when it is possible to collect alternative data and map them onto the required parameters using models of the physical processes involved [11]. A numerical algorithm was developed for the inverse problem that permits the derivation of the constitutive parameters of non-Newtonian fluids from an information rich data set of measurable flow parameters, such as pressure and velocity fields.

The Phan-Thien-Tanner model was realized in COMSOL finite element analysis software package to provide a good representation of the common properties of viscoelastic non-Newtonian fluids [12]. This model allows the investigation of both shear-thinning and elastic effects in a flow.

The viscoelastic CFD model based on Phan-Tien-Tanner model was validated with bench-marking data, obtained from a conventional cone-and-plate rheometer (Fig. 1).

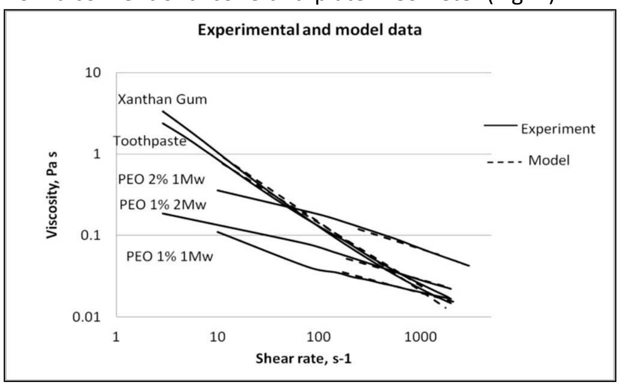

Figure 1. Validation of the viscoelastic CFD model.

Good agreement was obtained, as could be seen on the figure 1. The difference between experimental data and model results do not exceed 5 %, but the model is valid not on full range of shear rates and is restricted by 1000 s^{-1}.

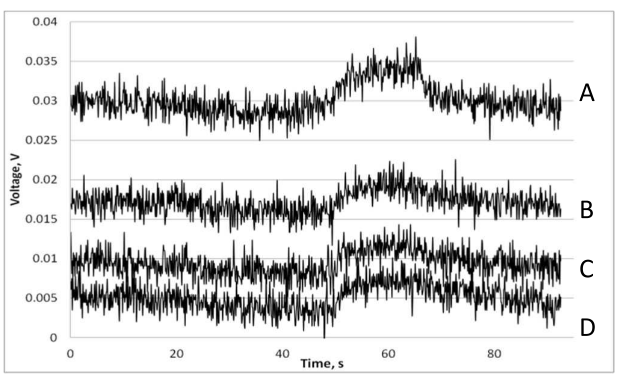

Figure 2. Sensors reading for steady state flow of glycerol (A - inlet, B - T-junction, C, D - outlets).

In order to infer constitutive parameters for the shear viscosity from global statistics of the model, the ratio of the pressure differences over the areas of the three pressure sensors were calculated. Further investigations showed that constitutive parameters of a non-Newtonian liquid could be uniquely converted from the pressure field measurements, which confirms the concept of using this novel method of viscosity measurement which involves combining stagnation point flow and inverse method.

The device has shown the sensitivity in measuring a pressure drop in wide range of pressure driven flows. The example for glycerol at flow rate of 5 ml/min is presented on fig. 2.

4. Conclusions

The preliminary investigation revealed promise for the inverse function with potential one-to-one mapping of flow field data to extensional constitutive parameters. Future investigation will be devoted to developing the CFD code for modeling liquids with a wider range viscoelastic characteristics. The goal is to generate a parametric map in the form of a "look-up table" for in-situ characterization of non-Newtonian liquids.

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