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RESEARCH PAPER

Multiplexed microfluidic viscometer for high-throughput complex fluid rheology

Deepak E. Solomon · Siva A. Vanapalli

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Abstract We report the first multiplexed microfluidic viscometer capable of measuring simultaneously the viscosity as a function of shear rate for multiple samples. The viscometer is based on a flow-comparator technique where the interface location between co-flowing streams of test and reference fluids is a sensitive function of the viscosity mismatch between the two fluids. We initially design a single microfluidic viscometer and study two different modes of comparator operation—the interface displacement (ID) mode and the interface compensation mode (IC). We find that both modes yield viscosity curves for Newtonian and polymeric fluids that are consistent with a conventional rheometer. Based on the results from the single microfluidic viscometer, we present an operating window that serves as a guide to assess accessible viscosities and shear rates. We then design a 4-plex and 8-plex viscometer based on the ID mode and show that it is capable of reliably measuring viscosity curves for Newtonian fluids, polymeric solutions and consumer products. Collectively, our results demonstrate that the multiplexed viscometer is capable of measuring in a parallel format, viscosities of fluids spanning nearly three orders of magnitude ($\approx 10^{-3}$–1 Pa s) across a shear rate range of $\approx$1–1,000 s^{-1}. We believe our multiplexed viscometer is a low cost and high-throughput alternative to conventional rheometers that analyze samples serially using expensive robotic liquid-handling systems. The multiplexed viscometer could be useful for rapidly analyzing a wide selection of complex fluids on-site during product formulation and quality control.

D. E. Solomon · S. A. Vanapalli (✉)
Department of Chemical Engineering, Texas Tech University,
Lubbock, TX 79409-3121, USA
e-mail: siva.vanapalli@ttu.edu

1 Introduction

The rheological properties of complex fluids are of prime importance in various industries such as paints, petroleum and foods (Pal et al. 1992; Larson 1999; Rao 2006; Tadros 2010). Properties such as shear viscosity impact the ability to effectively process and transport complex fluids. Conventional viscosity measurement devices such as rotational rheometers and capillary viscometers are often used to characterize the viscosity of complex fluids in industrial settings. In recent years due to advances in materials and microfabrication technology, several microscale viscometers as well as microfluidic rheometers have been developed. These miniaturized devices have significant potential to be used in various industrial applications because of their small size, cost-effectiveness, ease of use and small sample volume requirements compared to their macroscale counterparts (Pipe and McKinley 2009). The microfluidic viscometers also offer the possibility of point-of-care diagnosis of various medical disorders (Ong et al. 2010).

Microfluidic viscometers developed to date exploit different operating principles to measure viscosity across various regimes of shear rates. Three main operating principles currently exist depending upon how fluids are driven into the microchannels and the means by which pressure drop or flow rate is measured. In one approach, microfabricated pressure transducers (Pipe et al. 2008; Pan and Arratia 2012) or drag force sensors (Noel et al. 2011) are integrated into a microfluidic channel to record directly the pressure drop as a function of imposed flow rate. Flow rates are varied using syringe pumps, and sample viscosity as a function of shear rate is subsequently computed from equations developed for a slit rheometer (Macosko 1994). A significant advantage of this approach is the ability to measure viscosity of complex fluids at very high shear rates