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Communication

Imaging the velocity profiles in tubeless siphon flow by NMR microscopy

Y. Xia[a,*] and P.T. Callaghan[b]

[a] Department of Physics, Oakland University, 190 Science and Engineering Building, Rochester, MI 48309, USA
[b] MacDiarmid Institute for Advanced Materials and Nanotechnology, School of Chemical and Physical Sciences, Victoria University of Wellington, Wellington, New Zealand

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Abstract

We report on the use of NMR micro-imaging to observe flow within a tubeless siphon. The flow is maintained in a visco-elastic liquid of high extensional viscosity, namely 0.5% w/v 8 million Dalton polyethylene oxide in water. The velocity profiles reveal a significant velocity gradient in the vertical direction as well as a transition from near-Poiseuille flow at the pipe entrance to plug flow far from the pipe entrance towards the base of the tubeless siphon.

1. Introduction

The tubeless siphon flow was first observed by Fano [1]. In this flow a pipe attached to a vacuum source or pump is first dipped below the surface of a reservoir of fluid, thus drawing fluid up the pipe. Subsequently the pipe entrance is elevated above the fluid surface while a free column of fluid is drawn from the reservoir to the pipe, allowing steady state flow up the column. The column is balanced by the extensional stress difference [2] $\sigma_{zz} - \sigma_{xx}$ associated with the vertical velocity gradient $\partial v_z/\partial z$ i.e.,

$$\sigma_{zz} - \sigma_{xx} = \overline{\eta}_e \frac{\partial v_z}{\partial z}, \qquad (1)$$

where $\overline{\eta}_e$ is the extensional viscosity of the fluid. Fano columns are most easily formed in viscoelastic solutions where extensional viscosities often exceed shear viscosities by several orders of magnitude. The ratio of extensional viscosity $\overline{\eta}_e$ to shear viscosity η is known as the Trouton ratio [2]. An example of a highly elastic fluid with large Trouton ratio is provided by dissolving high molecular weight random coil polymers at concentrations sufficient for the formation for entanglements. Using such fluids, Fano columns of up to 20 cm length have been reported [3,4].

The physics of the Fano column is commonly represented by assuming that the vertical flow velocity v_z is homogeneous across any cross-section, but that its magnitude decreases below the pipe entrance so as to maintain the necessary gradient according to Eq. (1). The effect of this is that the column diameter must increase with distance below the pipe entrance in order to conserve the volume flow rate. In consequence, much research work on Fano flow has involved careful measurements of column diameters.

In 1988, Matthys [5] reported on the first velocimetry measurement of tubeless siphon flow. Using a photochromic dye and time-lapse photography he was able to measure a projection of the flow field onto a plane. These measurements revealed for the first time that the velocity was far from homogeneous and that shear effects were therefore important. However, these measurements did not reveal the local Eulerian velocity field $v_z(\mathbf{r}, t)$ at all points in the siphon flow. In this communication, we report on the use of NMR microscopy to measure this velocity field, directly, for the first time. A quantitative analysis of this field that accounts for the balance of shear, gravitational, and extensional forces, will be presented elsewhere.

* Corresponding author. Fax: 1-248-370-3408.
E-mail address: xia@oakland.edu (Y. Xia).

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The arrangement of the siphon and pump is shown in Fig. 1. A 0.5% w/v solution of 8×10^6 Da polyethylene oxide (Aldrich 37-283-8) in water was used, the water having been doped with 0.1% w/v $CuSO_4$ in order to reduce the water T_1 to around 300 ms. The glass pipette used to draw the fluid up from the reservoir has an internal diameter of 1.2 mm and external diameter of 1.7 mm. The reservoir container, which fits inside the 15 mm diameter RF resonator of the microimaging probe, has an internal diameter of 12.5 mm and length of 600 mm. Both the pipette and the reservoir are connected via 6 m of 4 mm diameter plastic tubing to a pump (Cole-Parmer 72511-35) which is used to maintain a constant flow, the total fluid volume of the system is about 600 ml.

Before flow starts, the tip of the glass siphon pipe is lowered into the polymer fluid in the reservoir and the pump turned on. Once steady state flow is established, the tip of the pipe is gradually lifted to a distance of several millimetres above the surface of the reservoir fluid, thus creating the tubeless flow. The flow rate was adjusted to 90 ml/h using the pump setting, a convenient rate for establishing a tubeless flow. Repeated experiments showed that it was possible to establish a column height of up to 6 mm while retaining stable flow, as shown in the photograph of Fig. 2a. (The column height was about 6 mm for the data set shown here.) Note the slight lean in the column and the strong curvature of the fluid surface near the base, consistent features in our system associated with the size of the reservoir and surface tension effects at the top of the reservoir fluid. Also shown in Fig. 2b is a 128×128 pixel NMR micrograph, acquired as a 1 mm thick longitudinal slice.

Microimaging experiments were carried out at Victoria University of Wellington using a Bruker AMX300 system equipped with a 25 mm-diameter 3-axis gradient set. The 300 MHz proton NMR signal derived from the water molecules of the water solvent and velocity mapped were obtained using a standard Pulsed Gradient Spin Echo sequence [6] combined with Spin Warp imaging. A series of 8 separate 128×128 pixel images were obtained for eight different values of the PGSE encoding ("q") gradient, and this set inverse Fourier Transformed along the q-dimension to obtain displacement propagators for each pixel [7]. Velocity images were obtained, over a period of several hours, at various heights along the column, using slices transverse to the column axis and with thickness 1 mm. The in-plane resolution was 31.25 μm. Fig. 2c shows samples of of 16 velocity maps taken at 0.5 mm intervals of different vertical displacements with respect to the pipe entrance at $z = 0$, negative distances referring to levels below the pipe entrance and within the Fano column. Note that noisy pixels

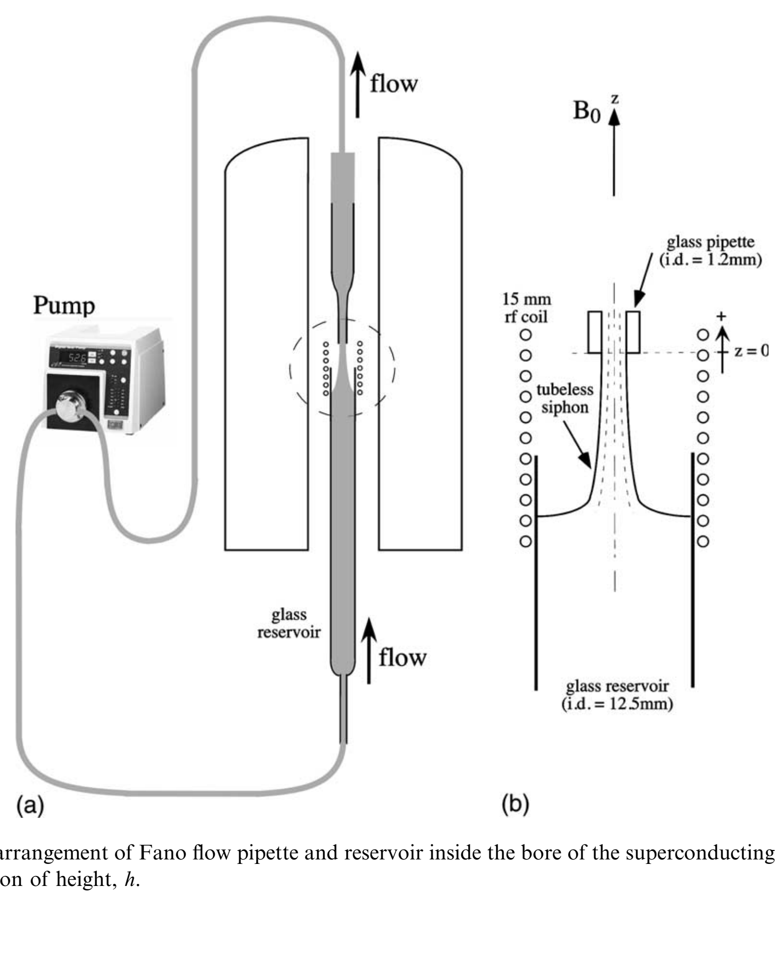

Fig. 1. (a) Schematic showing arrangement of Fano flow pipette and reservoir inside the bore of the superconducting magnet. (b) Geometry of Fano flow showing the tubeless siphon of height, h.

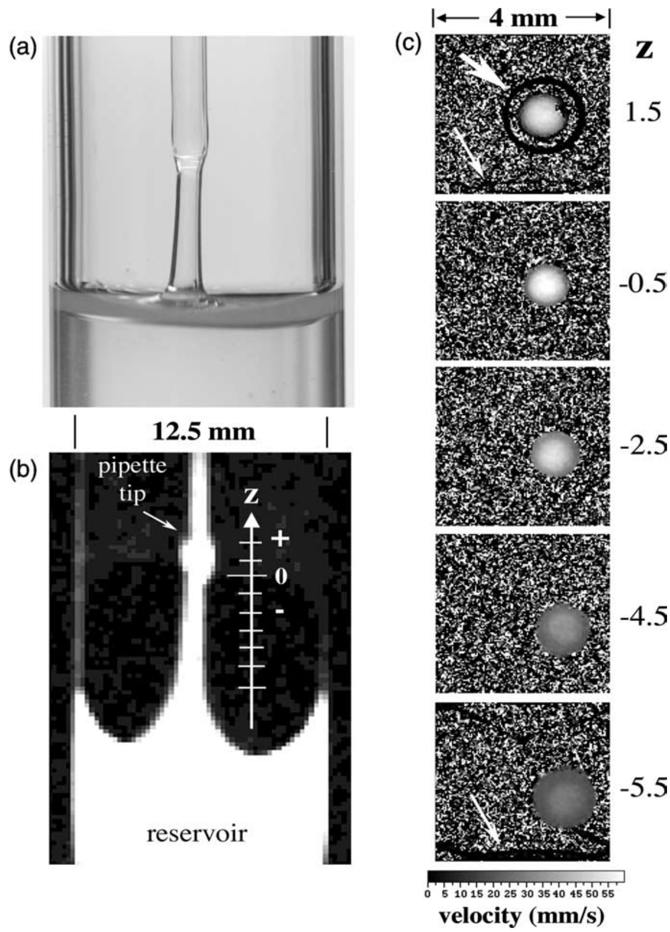

Fig. 2. (a) Photograph of Fano column formed with 0.5% w/v 8×10^6 Da polyethylene oxide in water. (b) NMR micrograph of Fano column taken using a 1 mm slice thickness. Note the wetting layer fluid around the pipette entrance resulting from prior insertion in the reservoir fluid. (c) Grey scale velocity maps at different displacements with respect to the pipette entrance. The dark ring at $z = 1.5$ mm (big arrow) is due to the stationary fluid wetting on the outside of the pipette. The small arrow indicates 'foldbacks' from the stationary fluid wetting the inner surface of the reservoir tube.

represent locations where there is no detected signal from the liquid. The images show successive changes in velocity patterns with vertical displacement, a tendency towards plug flow being apparent at increasing distance below the pipe entrance. As expected the radius of the column increases down the column. Furthermore an obvious asymmetry of the velocity profile in the flow becomes apparent down the column, due to the slight tilt of the vertical siphon column as evidently in Fig. 2b. Note the dark ring surrounding the pipe at $z = 1.5$ mm. This is due to a layer of stationary fluid adhering to the pipe exterior subsequent to dipping the pipe into the reservoir at the start of the experiment.

Fig. 3 shows a sample of velocity profiles taken at displacements of +1 mm (inside the pipe), −1.5, −3.5, and −5.5 mm with respect to the piper entrance. Just inside the pipe a non-slip boundary condition is nearly achieved. Outside the pipe, in the column, a finite velocity is seen at the free surface, with a tendency towards a low outer surface shear rate becoming more apparent. Of course, a finite shear rate at the outer surface is possible if surface

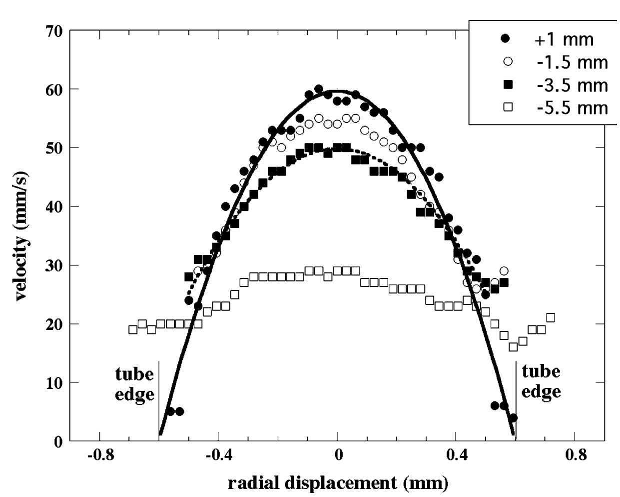

Fig. 3. Velocity profiles, $v_z(r, z)$, obtained in transverse sections across the Fano column at vertical displacements of $z = 1$ mm (inside the pipette) solid circles, −1.5 mm open circles, −3.5 mm solid squares, and −5.5 mm open squares. Note the gradual reduction in the shear and the gradient in the z-component of velocity with displacement down the column.

tension effects are accounted for. At −5.5 mm, significant broadening of the column is seen, along with a nearly plug-flow profile. Note the gradual decrease in mean velocity component v_z down the column, as required by the need to balance gravitational stress.

A remarkable feature of the present study is the high degree of shear that exists at within the free column. Of course strong shearing is a feature of flow within the pipe and the appearance of shear within the column must reflect the conditions prevailing downstream in the approach to pipe flow. A detailed quantitative analysis of these effects will be presented elsewhere.

To our knowledge the results reported here constitute the first NMR velocimetry study of Fano flow, as well as the first direct measurement of radial profiles of axial velocity in such a flow. The facility to make such measurements holds out the possibility that NMR microscopy can be used to measure extensional viscosities in elastic liquids.

Acknowledgments

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