Non-Newtonian fluid flow in elastic tubes

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The knowledge on the non-Newtonian fluid flow behavior in inflatable and collapsible elastic tubes is important to applications such as biofluid mechanics in human body and the transport of food and liquids in pharynx (throat), esophagus and intestines. The ultrasound Doppler based velocity profiles are measured at a fixed position from the outlet of a horizontal collapsible elastic tube immersed in a liquid filled chamber, whose pressure is maintained at a constant value during steady laminar flow of a shear thinning xanthan aqueous solution. For a given volume flow rate and a critical external chamber pressure, the tube is buckled. The shape of the deformed cross section visually observed has two lobes, above and below the horizontal axis through the tube center, with no contact between tube's two vertical planes. As the external chamber pressure increased, the width at the tube center and area of cross section of the two lobed-shaped deformed tube decreased. Consequently, the measured maximum flow velocity at the center of the tube width increased. The shear rate dependent viscosity of xanthan solution was measured using a rheometer.

Keywords: Elastic tube flow, non-Newtonian liquid flow, shear thinning fluids, ultrasound Doppler Velocity profile.

1 INTRODUCTION

The flow of non-Newtonian fluids in elastic inflatable and collapsible tubes is important to biofluid mechanics encountered in human body and other applications; for instance, transport of food and liquids in human throat (pharynx), the tube (esophagus) connecting the throat and stomach, and intestines. The knowledge on the mechanisms of pharyngeal, esophageal and intestinal transport of food and liquids is very useful for the treatment of patients with malfunctioning of these transport processes. The physiology of these applications in human body is very complex, which is not fully understood. The flow behavior (rheology) of the food and liquids through the throat or esophagus or intestines could be broadly characterized in terms of parameters related to: (i) food composition, physico-chemical properties, interaction and microstructure, (ii) mechanical properties (elastic modulus, Poisson ratio, strain and bending stresses) of the elastic tube and its lining (mucus) and (iii) external applied (pressure or compressive) stresses to induce and sustain flow. The food and liquids could have viscous Newtonian or viscous non-Newtonian or viscous and elastic non-Newtonian flow behavior; the latter may be due to the presence of viscoelastic biopolymers.

Although the Stokes laminar flow structure of Newtonian fluids in an elastic tube was numerically investigated [1], there exists no published experimental information on the corresponding velocity distribution in the collapsed tube. Hasegawa et al. [2] experimentally investigated the velocity profiles during swallowing of food in pharynx using ultrasound Doppler velocimetry. In contrast, there are several publications on the velocity profiles measured using this technique during steady and unsteady laminar flow of non-Newtonian fluids and particulate suspensions [see for example reference 3] in non-collapsible pipes. Consequently, the present paper investigates the measurement of the ultrasound Doppler based velocity profiles during steady laminar flow of a non-Newtonian shear thinning xanthan (polysaccharide) solution through a partially collapsed elastic tube immersed in the liquid of a pressure chamber called Starling Resistor [4] set up. The influence of the external chamber pressure on the deformation of the elastic tube and the velocity profiles are also measured.

2 EXPERIMENTAL

2.1 Starling Resistor setup for non-Newtonian fluid flow in elastic tubes

The Starling Resistor setup shown in Figure 1 consists of a cylindrical Plexiglass (PG) pressure chamber (111 mm inner diameter, 5.66 mm thick and 300 mm long) with two side PG flanges through each of which an aluminum pipe is fixed. A 20 mm inner diameter, 1 mm thick and 200 mm long silicone elastic tube (Lindemann GmbH, Germany) is mounted between the two aluminum pipes. The left pipe is connected to a rotor pump and a PVC tank containing the non-Newtonian liquid. Two pressure sensors (Honeywell, Type: 40PC-030G2A) are installed in both the inlet and outlet aluminum pipes to measure the pressures of liquid. Two additional pressure sensors are connected to the pressure chamber to measure the externally applied pressure to deform the elastic tube. The four pressure transducers are connected to a data acquisition board (type USB-6221, National Instruments) with a resolution of 16 bits. Sony DFW-V500 Camera with a resolution of 640X480 is used to obtain images of deformed elastic tube. The Camera is mounted on a aluminum arm, which can be rotated to obtain images of the deformed tube at different angles. The steady flow of a shear thinning non-Newtonian aqueous solution of 0.1 % xanthan (and 0.02 M NaCl) at a constant volume flow rate and different values of the external chamber pressure P_e is carried out at 22°C.

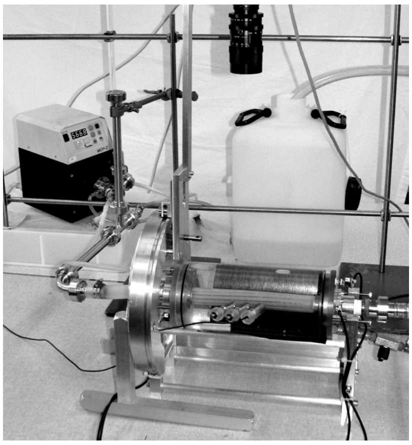


Figure 1: Ultrasound Doppler velocimetry for flow through collapsible silicone elastic tube in Starling resistor setup.

2.2 Ultrasound Doppler based velocity profile measurement in elastic tube

A UVP-Duo (Met-Flow SA, Lausanne, Switzerland) instrument is used to measure the velocity profiles of xanthan solution flowing through the deformed elastic tube in the Starling Resistor setup. A 4 MHz base frequency ultrasound transducer of 5 mm active diameter and 8 mm diameter housing (Met-Flow SA, Lausanne, Switzerland) is used as transmitter and receiver. The Perspex cylindrical pressure chamber is provided with a side tube to house an ultrasound transducer at an angle of 20° with respect to the normal to the horizontal axis. The transducer submerged in water in the pressure chamber is in direct contact with the elastic tube and is positioned at 75 mm from the tube outlet. The transducer is so positioned that it does not contribute to tube deformation. The communication with the UVP-Duo is made with an active X Library from Met-Flow SA. The number of cycles per pulse is 2 and the channel width is 0.37 mm. Each profile is obtained by averaging 100 profiles, which is represented by the full line. The measured velocity of sound in the xanthan solution at 22°C is 1492 m/s.

3 RESULTS AND DISCUSSION

The velocity profiles obtained for undeformed and deformed silicone elastic tube under different external chamber pressures at constant volume flow rate of 33.2 ml/s of xanthan solution are presented below. The corresponding images of the deformed tubes are also shown.

3.1 Velocity profiles in elastic tube

Fig. 2 shows the velocity profile along the tube diameter (expressed as a function of channel number, the channel distance being 0.37 mm) measured during steady flow of xanthan solution in the undeformed silicone elastic tube of circular cross-section when the external chamber pressure P_e is zero and the inlet pressure P_i = 76.6 mbar and P_o = 73.4 mbar. The profile is flat at the center of the tube, indicating shear thinning behavior of xanthan solution.

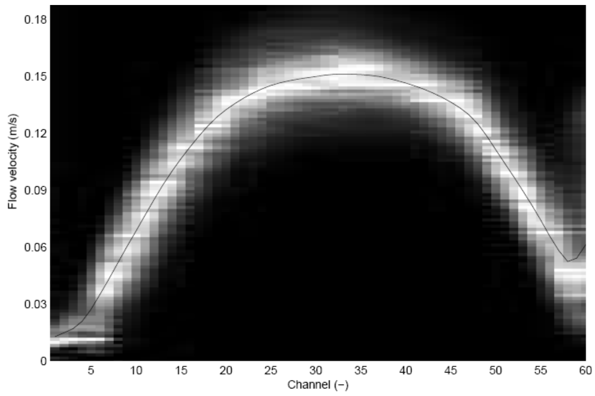


Figure 2: Velocity profile (full line: average profile) in undeformed elastic tube at 0 mbar external chamber pressure.

The profiles in the collapsed tube due to 85 mbar external chamber pressure are shown in Fig.3 (with channel distance of 0.56 mm) for which the inlet pressure is about 73 mbar. The corresponding two images taken from the top and after rotating the camera 110° anticlockwise around cylinder are shown in Fig.4. The length of the deformed tube is 55 mm from the transducer in addition to 20 mm long undeformed tube towards the tube outlet. The shape of the cross section (see Fig.5) along the length of the deformed tube seem to have two lobes above and below the horizontal axis with no contact between the two 39 mm tall vertical planes of the tube. The widths of the deformed tube at the center and top are about 9 mm and 11.4 mm respectively.

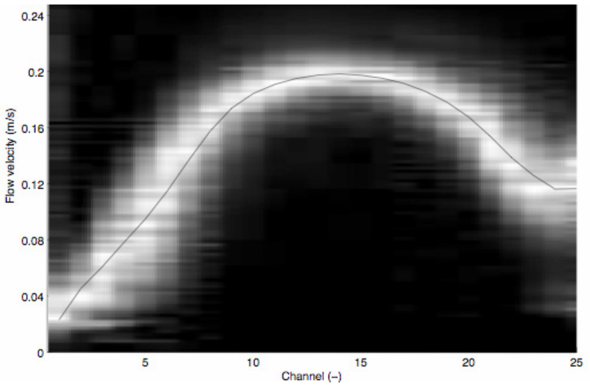
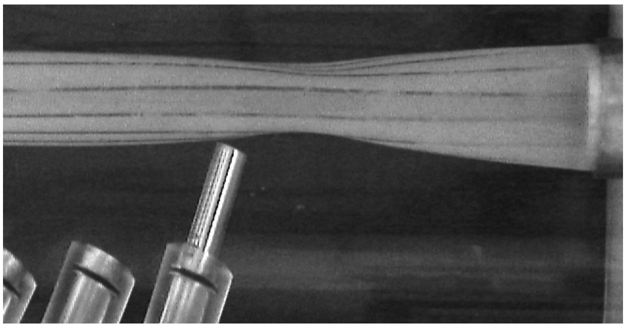
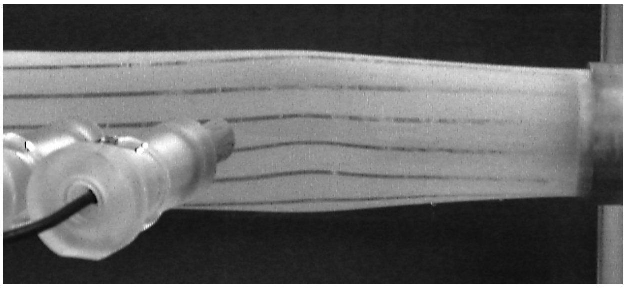


Figure 3: Velocity profile (full line: average profile) in collapsed elastic tube at 85 mbar external chamber pressure.



(a)



(b)

Figure 4: Images of deformed tube at 85 mbar external chamber pressure: (a) top view (b) front view.

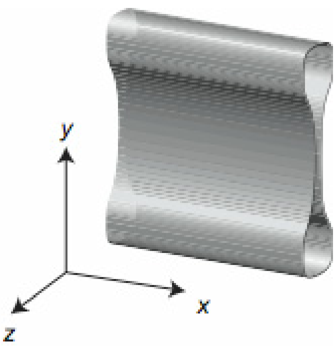


Figure 5: Schematic front view of a partially buckled elastic tube.

Fig.6 shows the velocity profile (with channel distance of 0.56 mm) in the more collapsed flattened silicone tube at 90 mbar external chamber pressure, P_i = 73.1 mbar and P_o = 72.8 mbar. The images of deformed tube from top and after rotating the camera 140° anticlockwise around cylinder are shown in Fig.7.

The deformed tube length from the transducer to the tube outlet is 80 mm. Its shape is the similar to that for 85 mbar external chamber pressure shown above although the dimensions of the cross section are reduced. The deformed tube widths are 5.6 mm and 6.6 mm at the center and top respectively with a height of 18 mm. In contrast, as the chamber pressure increased from 85 mbar to 90 mbar, the area of the two lobed shaped cross section of deformed tube decreased.

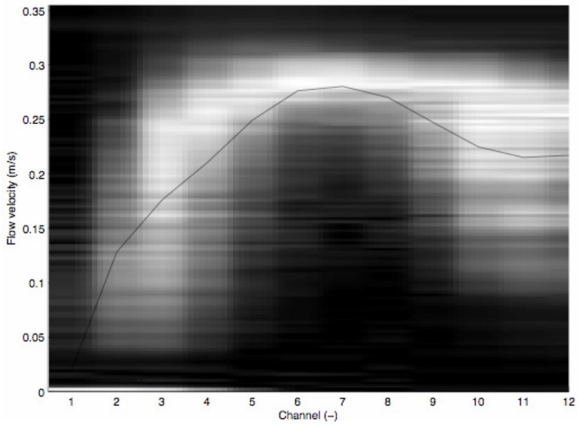
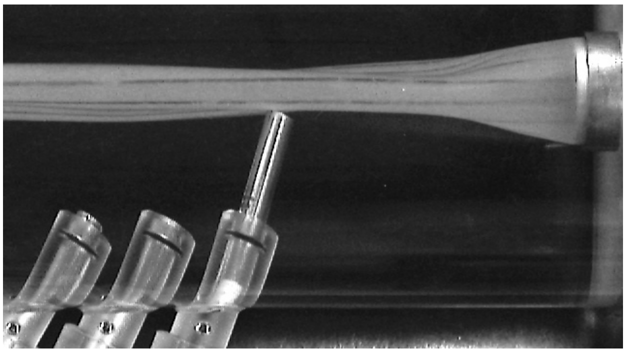
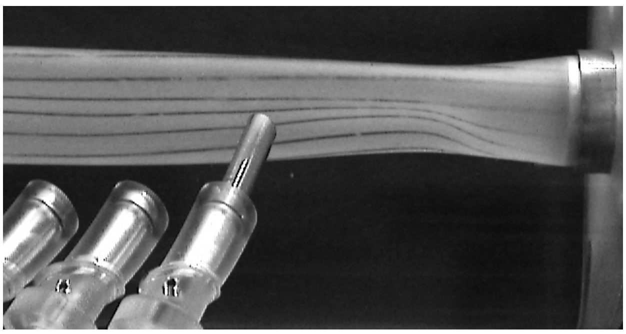


Figure 6: Velocity profile (full line: average profile) in collapsed elastic tube at 90 mbar external chamber pressure.



(a)



(b)

Figure 7: Images of deformed tube at 90 mbar external chamber pressure: (a) top view (b) front view.

Consequently, the corresponding maximum velocity at the center of the tube width can be seen from Figs. 3 and 6 to increase from about 0.2 m/s to 0.28 m/s. The velocity profile in undeformed tube shown in Fig.2 is more symmetric than those at the center of deformed tube width with the two lobed shaped cross section in Figs. 3 and 6. The asymmetry at the center of the tube width could be due to multiple echoes from the tube walls, which are closer to each other. The sensitivity of measured velocity profiles depends on the refraction associated with different sound velocities of the elastic tube, xanthan solution and water in pressure chamber, and the thickness of the tube.

The shear rate, $\dot{\gamma}$ dependent viscosity, η measured using the Physica (MCR300, CC27) rheometer with Couette geometry is shown in Fig.8. It can be seen that the xanthan solution is a shear thinning solution, which is well represented (full line) by the Carreau model:

$$\eta = \eta_0 \left[1 + (\lambda\dot{\gamma})^2\right]^{(m-1)/2} \qquad (1)$$

where η_0 is the viscosity at zero shear rate, λ is the time constant describing the transition from constant shear rate to the shear thinning power law behavior described by the value of m. The values of the constants obtained by fitting the viscosity data are η_0 = 0.063 Pa.s, λ= 1.09 and m = 0.603 (regression coefficient=0.983).

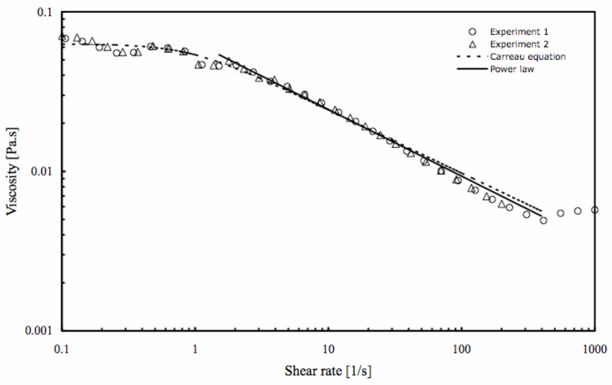


Figure 8: Variation in viscosity with shear rate of xanthan solution measured (symbols) using rheometer at 19°C. Experiments 1 and 2 are replicates carried out for testing reproducibility.

In contrast, the power-law model

$$\eta = K\dot{\gamma}^{n-1} \qquad (2)$$

represented (dashed line) the data well for shear rates higher than 1 1/s in the shear thinning region with the fitted values of K = 0.064 Pa.s^n and n = 0.582 (regression coefficient=0.996). However, this model enables [5] the estimation of maximum velocity:

$$v_m = 4(3n+1)Q / \pi(n+1)d^2 \qquad (3)$$

which agreed reasonably well with the measured value using the ultrasound Doppler method during the flow of shear thinning xanthan solution volume flow rate of Q (Fig.2) through undeformed tube of diameter d. The calculated average shear rate is 6.7 1/s for the velocity profile. The corresponding viscosity is about 0.03 Pa.s so that the Reynolds number is about 70 based on average velocity of 0.11 m/s. Thus the flow of shear thinning xanthan solution in the elastic tube is laminar.

5 CONCLUSIONS

It is demonstrated that the velocity profiles during steady laminar flow of non-Newtonian shear thinning aqueous xanthan solution in undeformed and deformed elastic tube can be measured using ultrasound Doppler velocimetry. A critical external chamber pressure in Starling resistor setup caused the collapse of the elastic tube to form a two lobe-shaped cross-section with a narrow width at the center through which the pulsed ultrasound beam penetrates. The width at the center and area of cross section of the partially collapsed tube decreased with increase in external chamber pressure. Hence the velocity profile is distributed over a narrow width resulting in a higher maximum velocity at a constant volume flow rate. Further investigation of flow field over whole length of the buckled elastic tube for different flow rates, external chamber pressures, non-Newtonian fluids and tube material will enable better understanding of the flow structures relevant to several applications.

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