Modelling the behaviour of Non-Newtonian materials for Capillary Drawing

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ABSTRACT

In this work the original Fitt model is adapted to include Non-Newtonian materials to model the behaviour of polymer tubes during the stretching process in a fibre draw tower. An experimental comparison is then conducted for tubes made of Polycarbonate and Poly(methyl methacrylate), which are both shear thinning materials. Each material is drawn down to three different sizes and the final inner and outer diameter are compared with the calculated final dimensions. The experimental results show both good agreement with the model using Non-Newtonian materials and differences with Newtonian predictions. The model can thus be a helpful tool to aid polymer fibre fabrication for fibres with air gaps.

Keywords: polymer fibres, numerical modelling, hollow fibres

1. INTRODUCTION

In this study the effect of Non-Newtonian materials on fibre drawing is discussed. Hollow core fibres have been increasingly popular due to their properties that simply cannot be achieved using solid-core fibres. Hollow core fibres could potentially reduce transmission loss and have higher damage thresholds, amongst other advantages (Poletti, et al., 2013). The fabrication process of a fibre with airgaps however can be challenging, as the air gaps need to be pressurized and can easily collapse or expand during the drawing process, deviating from the original fibre design (Xue, et al., 2006). As the membrane thickness is a key-feature in the functionality of the fibre, it is crucial to know how the draw process will affect the fibre structure.

Due to increasing interest in holey polymer fibres, where the microstructured cladding avoids the need for any polymer doping to create light guidance, the need has arisen to model the behaviour of polymer fibres during the drawing process. Polymers like PMMA have a relatively low cost and a wider availability compared to the commonly used glasses for fibre fabrication (Argyros & Pla, 2007). For polymer hollow core fibres, the drawing process can be even more challenging due to the effects of the Non-Newtonian fluids in the process (Pone, et al., 2006). To simulate the drawing process for these materials, different approaches can be used. Studies have shown that in some cases, for example where the shear stress is low or in materials where the non-Newtonian effects are minor, Non-Newtonian fluids can be treated as Newtonian materials. A good agreement between this approach and experimental results can be seen in the literature (Xue, et al., 2005). However, for some materials in which the shear stress has a more significant effect on the viscosity this approximation does not work. In this paper we study the effect of the shear-thinning under stress in the drawing of cylindrical capillaries made of Non-Newtonian materials.

2. NUMERICAL MODELLING OF CAPILLARY DRAWS

2.1 Newtonian Materials

The fluid dynamics of the drawing process of capillaries or fibres made of Newtonian materials have been studied extensively (Fitt, et al., 2002) (Jasion, et al., 2015) (Numkam Fokoua, et al., 2013). Fitt et al. have developed a model that can be used to predict the behaviour when drawing capillaries from Newtonian hollow cylinders or preforms (Fitt, et al., 2002). In their model, the gas pressure applied in the preform is taken into account, as well as the temperature profile and viscosity factors influencing the final drawn capillary. The model is compared to the experimental results of drawn silica capillaries, and good agreement is found. More complex models for different fibre structures have since been developed and used successfully for hollow core silica fibre fabrication (Numkam Fokoua, et al., 2013), (Jasion, et al., 2015).

2.2 Non-Newtonian Materials

However, polymers are usually Non-Newtonian, meaning as the name suggests they do not follow Newton’s viscosity law. For these materials, the existing models need to be adapted. In Non-Newtonian materials, the viscosity depends on the shear stress as well as the temperature of the material. They can either

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thin or thicken under stress (shear thinning or shear thickening, respectively). (Scott, et al., 1939). For Non-Newtonian fluids, a power law can be used to determine the viscosity at any point during the capillary drawing process (Rao, 2007). To calculate the effective viscosity μ using this power law, the following equation is used:

$$\mu = K\gamma^{N-1}$$

Where K is the consistency index, defined as the viscosity of the material at the shear rate of $1s^{-1}$, γ the shear rate and N the flow behaviour index.
For N smaller than, equal and larger than 1 the fluid is shear thinning, Newtonian, and shear thickening, respectively.

In this study we work with Polycarbonate (PC) and Poly(methyl methacrylate) (PMMA), which are both shear thinning, with flow consistency indices of 0.8 and 0.25 respectively (Nguyen & Nguyen, 2012). The N numbers for these polymers suggest that PC behaves more like a Newtonian glass fibre than PMMA, which may be beneficial during the drawing process.

3. Experimental results

3.1 Set-up and Tube Drawing

To determine whether the model can accurately predict the drawing of Non-Newtonian capillaries, we compare the results from the model with the results from an experimental capillary draw. Two tubes were drawn to capillary size, one made of PC and the other of PMMA.

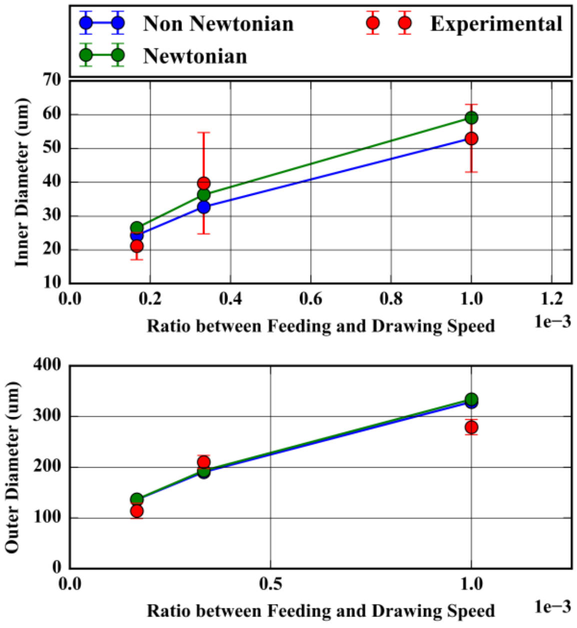

Figure 1 – Experimental results for Polycarbonate compared to simulated results for both Newtonian and Non-Newtonian models

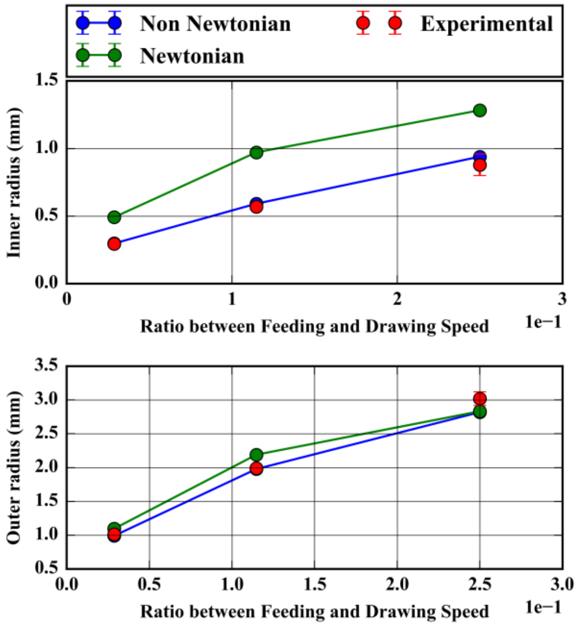

Figure 2 - Experimental results for PMMA compared to simulated results for both Newtonian and Non-Newtonian models

Both were drawn at 3 different speeds while temperature and feed speed was kept constant.
For PMMA we aimed for thicker tubes than for PC, as the viscoelastic effects make drawing thin PMMA capillaries extremely challenging.

3.2 Comparison with Model

In Figure 1 the calculated results for PC are shown for both the Newtonian and Non-Newtonian case and compared to the experimental result. Each drawn tube is cleaved at 3 different positions and an average is used for the measured inner and outer diameter to account for instabilities during the drawing process. The range of measured results is given by the error bars. It can be seen that for PC the difference between the Newtonian and Non-Newtonian case is small as compared to the error in the experimental result. As the flow consistency index for PC is close to 1, it is expected that PC should behaves more like a glass (and thus more like a Newtonian fluid), and it is therefore not surprising that both models have a reasonable agreement with the experimental results.

In Figure 2 the calculated results are compared with the experimental data for the PMMA capillary. It can be seen that the shear thinning effect from the Non-Newtonian fluid is more pronounced in PMMA than it is in PC. It can also be seen that the experimental results are in good agreement with the model only when shear thinning of the Non-Newtonian material is taken into account.

4. Conclusion

We have shown modified a fluid dynamics model for capillary drawing to include the shear-thinning effect of Non-Newtonian materials. The model is used to calculate the final inner and outer diameter for capillary drawing with two different materials, polycarbonate and PMMA, which shows good agreement with the experimental results. It was also demonstrated that the influence of the shear stress on the final result for the drawing differs for each polymer, as some materials are more Newtonian-like than others. Polycarbonate is more Newtonian-like than PMMA and the results for the Newtonian and Non-Newtonian model drawing differ therefore less from each other compared to the results for PMMA. For simulations with more complicated structures containing multiple holes, it should be possible to ignore the shear thinning effect for PC to simplify the simulations and use existing models for hollow fibre drawing. However, for materials where the non-Newtonian effects are more pronounced it is critical to include the shear thinning effects to accurately predict the drawing process and final results.

5. References

Argyros, A. & Pla, J., 2007. Hollow-core polymer fibres with a kagome lattice: potential for transmission in the infrared. *Optics Express,* 15(12), pp. 7713-7719.

Fitt, A. et al., 2002. The mathematical modelling of capillary drawing for holey fibre manufacture. *Journal of Engineering Mathematics,* 43(2-4), p. 201–227.

Jasion, G. et al., 2015. MicroStructure Element Method (MSEM): viscous flow model for the virtual draw of microstructured optical fibers. *Optics express,* 23(1), pp. 312-329.

Nguyen, H. & Nguyen, N., 2012. Incompressible Non-Newtonian Fluid Flows. In: *Continuum Mechanics - Progress in Fundamentals and Engineering Applications.* s.l.:Intech.

Numkam Fokoua, E. et al., 2013. Real-time prediction of structural and optical properties of hollow-core photonic bandgap fibers during fabrication. *Optics Express,* 38(9), pp. 1382-1384.

Poletti, F., Petrovich, M. & Richardson, D., 2013. Hollow-core photonic bandgap fibers: technology and applications. *Nanophotonics,* 2(5-6), pp. 315-340.

Pone, E. et al., 2006. Newtonian and Non-Newtonian Models of the Hollow All-Polymer Bragg Fiber Drawing. *Journal of Lightwave Technology,* 24(12), pp. 4991 - 4999.

Rao, M., 2007. Flow and Functional Models for Rheological Properties of Fluid Foods. In: *Rheology of Fluid and Semisolid Foods.* Boston: Springer.

Scott, G. W., Hening, B. & Wagstaff, A., 1939. The Flow of Cream through Narrow Glass Tubes. *The Journal of Physical Chemistry,* 43(7), pp. 853-864.

Xue, S. et al., 2006. Role of material properties and drawing conditions in the fabrication of microstructured optical fibers. *Journal of Lightwave Technology,* 24(2), pp. 853 - 860.

Xue, S. et al., 2005. Fabrication of microstructured optical fibers-part II: numerical modeling of steady-state draw process. *Journal of Lightwave Technology,* 23(7), pp. 2255 - 2266.

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