

TOWARDS UNDERSTANDING OF GEOMETRICAL STRUCTURE IN MICROSTRUCTURED OPTICAL FIBRES

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Summary Microstructured optical fibres can be designed for a wide range of applications. Extrusion of a preform and drawing to form a fibre is a promising fabrication process for mass production. The effects of flow during fabrication on fibre structure needs to be understood. We propose a modelling methodology suitable for complex structure and focus on flow in the cross section during preform extrusion. Excellent qualitative agreement of model results and experiment is shown and areas for model improvement are identified.

INTRODUCTION

Microstructured optical fibres (MOFs) have revolutionised optical fibre technology, promising a virtually limitless range of fibre designs for a wide range of applications [6, 8]. Complex air-glass structures in the cross section, such as seen in Figure 1(a), provide the necessary change in the refractive index to guide light along the core of the fibre. A manufacturing process that can be automated for mass production and give a high degree of precision is required. Extrusion of a preform (1–3 cm diameter $\times$ 20–30 cm long) through a die having the required structure at macroscopic size, followed by drawing (pulling) of the preform to form a fibre some kilometres in length, with the air-glass structure at microscopic size, is such a process [3]. However, the final fibre geometry is not an exact scaled copy of the extrusion die geometry due to viscous flow during both preform extrusion and fibre drawing. For example, it was intended that all air channels in the preform of Figure 1(a) have circular cross section, as did the blocked regions in the die responsible for the holes in the preform. Mathematical modelling is required to understand the geometrical adjustment that occurs during fabrication so that MOFs can realise their full potential. Ultimately an inverse model is needed to determine the required setup for a desired fibre structure.

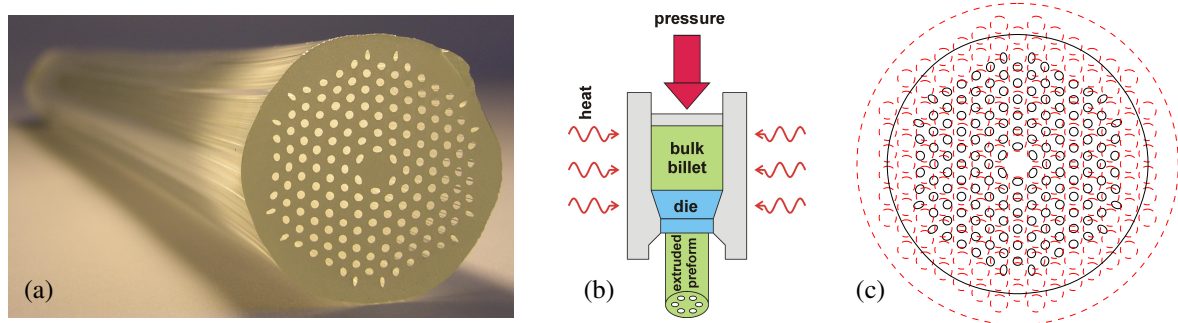


Figure 1. (a) Preform for a glass microstructured optical fibre with seven ‘rings’ of air channels, some of which do not have the desired circular cross section [3, 8]. (b) Preform extrusion [3]. (c) Output from the elliptic pore model (black) and initial geometry (red).

Numerical simulation of fibre drawing has been done [10, 11] for quite simple geometrical structure, but this is not a suitable method for handling the complex structures typically seen in MOFs. Here we propose a different methodology for efficient handling of non-axisymmetric domains of high connectivity as seen in MOFs. Specifically we exploit the slenderness of preforms and fibres to divide the flow into axial and cross-section components to be determined using two coupled models. This is an approach used for drawing of tubes [4, 5] but, unlike that work, we cannot develop a model for the cross-section flow based on a thin-walled tube. Rather, we adapt work on viscous sintering using complex variable mathematics [1, 2] for efficient solution of flow in the cross section. In this paper we consider this portion of the work.

FLOW IN THE CROSS SECTION

Consider flow in a cross section of a glass preform from the time it exits the die until it has cooled sufficiently to become solid. If we neglect gravity and assume the vertical flow component to be constant in a cross section of the preform, i.e. plug flow, then, in a Lagrangian frame of reference moving with a cross section, two-dimensional surface tension driven flow in the cross section is responsible for modification of the geometry. At extrusion temperatures molten glass has viscosity $\mu \sim 10^7$ Pa s so that the flow velocity ($\mathbf{u}$) and pressure (p) are described by the continuity and Stokes equations

$$\nabla \cdot \mathbf{u} = 0, \quad -\nabla p + \mu \nabla^2 \mathbf{u} = \mathbf{0}$$

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or, alternatively, the biharmonic equation $\nabla^4 \psi = 0$, where ψ is the streamfunction defined by $\mathbf{u} = (\partial\psi/\partial y, -\partial\psi/\partial x)$. On each boundary we have zero tangential stress, while the normal stress is balanced by surface tension:

$$-pn_i + \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) n_j = (\gamma\kappa - p_a)n_i.$$

Here γ is the coefficient of surface tension, κ is the curvature of and p_a is the ambient pressure exterior to the boundary, while n_i is the i th component of the unit normal vector to the boundary. Heat conduction in the cross section is fast (Péclet number $\sim 10^{-5}$) so that temperature is assumed to vary only with axial position, which is equivalent to time, and our cross-section flow model is isothermal at each point in time. In conjunction with the absence of time derivatives in the model, this means that changes in viscosity with time/axial position modify the time scale but not the geometrical outcome at a given dimensionless time, and heat conduction need not be coupled to the flow model [9]. Having solved for the flow, the kinematic condition $\mathbf{u} \cdot \mathbf{n} = U_n$, where U_n is the normal velocity of the boundary, is used to update boundaries. We then solve again for the flow on the modified geometry. We thus determine the time-evolution of the geometry.

The elliptic pore model (EPM) developed for late stage planar viscous sintering [2] solves this mathematical problem efficiently by assuming that each hole in the domain remains elliptical in shape and sees all other holes as point sinks with strengths given by the rate of change of area as they close under surface tension. The fluid domain is assumed to be infinite so that there is no external boundary. Figure 1(c) shows a solution yielded by the EPM for the 7-ring preform of Figure 1(a), where we have assumed $p_a = 0$ on all boundaries. An approximate external boundary has been computed by assuming points on the boundary move with the flow, i.e. surface tension on the external boundary has been neglected on the basis of a much larger curvature than for internal holes. The initial geometry is shown dashed in red and the geometry at a later time is shown superimposed on this in black.

DISCUSSION OF RESULTS & CONCLUSIONS

There is excellent qualitative agreement with the preform of Figure 1(a) in the ellipticity and orientation of the holes; in particular note those in the inner and outer rings. Nevertheless, the preform cross section contracts significantly more than seen in practice, and inclusion of surface tension on the external boundary will increase the contraction rate a little. Clearly, improvements to the model are needed. One obvious inaccuracy in the above model is the assumption of constant axial flow in the cross section. In practice, because of no-slip between fluid and surfaces of the die, the axial flow is not constant at the die exit and there is a region of transition to plug flow that we are neglecting where the well-known phenomenon of extrudate swell is seen [7]. In fact, solving our model with the initial geometry magnified by 10–20% to approximate die swell, yields a very similar hole pattern at a larger scale, with preform diameter and hole positions similar to the die, which more closely matches experiment. Assuming the transition region to be long relative to its diameter, perturbation methods are currently being used to develop an axial flow model coupled to a modified cross-section flow model (still solvable using the EPM), so as to include the transition region. Another aspect of the model needing more investigation is the assumption of the same ambient pressure p_a in interior holes and exterior to the preform as a whole.

In conclusion, we have presented a modelling strategy to enable investigation of flows occurring during fabrication of microstructured optical fibres with complex glass-air structures of high connectivity. We propose to solve separate but coupled models for the axial flow and the flow in the cross section. In this paper we have considered the flow in the cross section assuming plug flow in the axial direction and used the elliptic pore model of [2] to solve the Stokes-flow model. Excellent qualitative agreement is seen between model and experimental results but a difference in the contraction rate of the domain has yet to be properly explained. Inclusion of the transition of the axial flow from that in the die to plug flow is being explored as a key factor that may lead to better quantitative agreement between experiment and model. The remarkable qualitative agreement between model and experiment certainly encourages continuing this line of research.

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