Forced convection heat transfer of polymer melt flow inside channels with contraction/expansion sections

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Abstract

Polymer melt flow inside channels with contraction/expansion sections is commonly found in numerous forming applications. Due to high polymer viscosity, this flow presents laminar behaviour, high pressure drop and relevant viscous heating effect. The analysis presented in this work comprises the numerical simulation of a set of equations (mass, linear momentum and energy conservation principles) that models this class of flow. The generalized Newtonian formulation is employed, being the apparent polymer viscosity computed as a function of temperature and shear strain rate. The governing equations are discretized using the finite difference method with central formulae (for both diffusion and convection terms). The work is focused on the assessment of the local and global Nusselt numbers based upon a parametric study of the effects of the contraction/expansion aspect ratio and entrance flow velocity. The main findings indicate that, similarly to Newtonian flows, the Nusselt number presents a good correlation with Reynolds, Prandtl and Eckert numbers.

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1. Introduction

The non-Newtonian flows are typically found in industrial applications such as petroleum and chemical processing, paper manufacture and mould forming (e.g. injection moulding and blow moulding) amongst others. In injection moulding, the polymer melt is forced under high pressure through channels into a closed mould. Due to the high temperature of the process, the non-Newtonian flow behaviour may be modelled by a constitutive relation that correlates the polymer apparent viscosity with the equivalent shear strain rate and temperature. This approach is known in the literature as Generalized Newtonian fluid model (purely viscous flows), in which the viscoelastic effects on the stress tensor are disregarded.

The literature information available on this class of flows is mainly devoted to the analysis of hydrodynamic aspects. The most recent studies attempt to understand especially the following issues: flow bifurcation phenomena [1–3], pressure drop [4,5] and unsteady flow [6,7]. Apparently, little effort has been invested on studying thermal effects (especially viscous heating) in such flows. Nonetheless, previous works on polymer melt flow in 2D plane channels and 2D / 3D sudden expansions have shown interesting features regarding viscous heating effects [8–11]. To the authors’ best knowledge, no detailed analysis based upon the non-isothermal Generalised Newtonian approach for the present geometry (comprising a plane channel with contraction/expansion sections) has been discussed in the literature. Notwithstanding, an isothermal solution for a 2D planar and axisymmetrical contraction/expansion structure using the finite element method for Oldroyd-B fluids was recently presented by Binding at. al. [12], in which only pressure drop-related issues were addressed.

In recent years, the authors have engaged in the investigation of polymer melt flow using the incompressible Generalised Newtonian approach [8–11]. Despite a good insight gained on this class of fluid flow, some interesting and relevant features still lack a deeper physical analysis. For instance, a discussion on the effects of the Reynolds and Prandtl on the local Nusselt number computed along the channel walls was presented in reference [8]; however, no effects of the Eckert number were indicated. It is known from dimensional analysis of Newtonians flows that the Eckert number is a nondimensional parameter that plays an important role when viscous heating is present. In such context, the present work aims to contribute to a better understanding of convection heat transfer in polymer melt flow. The numerical approximation was performed using central finite difference formulae to discretize both the convection and diffusion terms in a collocated mesh [13–15]. In order to control the odd-even decoupling problem, artificial viscosity terms are added externally. A brief discussion on the flow topology is included, and, more importantly, it was found that both local and global Nusselt numbers are very sensitive to the contraction/expansion aspect ratio and inlet velocities. Furthermore, the results demonstrate that average Nusselt number yields a good correlation with the Reynolds, Prandtl and Eckert numbers.