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Effect of blockage on heat transfer from a cylinder to power law liquids

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Abstract

The influence of planar confining walls on the steady forced convection heat transfer from a cylinder to power-law fluids has been investigated numerically by solving the field equations using FLUENT (version 6.2). Extensive results highlighting the effects of the Reynolds number ($1 \leqslant Re \leqslant 40$), power-law index ($0.2 \leqslant n \leqslant 1.8$), Prandtl number ($1 \leqslant Pr \leqslant 100$) and the blockage ratio ($\beta = 4$ and 1.6) on the average Nusselt number have been presented. For a fixed value of the blockage ratio, the heat transfer is enhanced with the increasing degree of shear-thinning behaviour of the fluid, while an opposite trend was observed in shear-thickening fluids. Due to the modifications of the flow and temperature fields close to the cylinder, the closely placed walls (i.e., decreasing value of the blockage ratio) further enhance the rate of heat transfer as the fluid behaviour changes from Newtonian to shear-thickening fluids ($n > 1$), the opposite influence is seen with the decreasing value of the flow behaviour index (n) in shear-thinning ($n < 1$) fluids. Finally, the functional dependence of the present numerical results on the relevant dimensionless parameters has been presented in the form of closure relationships for their easy use in a new application.

Keywords: Power-law fluids; Circular cylinder; Nusselt number; Reynolds number; Prandtl number; Wall effects

1. Introduction

Owing to its fundamental and pragmatic significance, in recent years, considerable research efforts have been devoted to the study of steady cross-flow of fluids over cylinders of circular and non-circular cross-sections including square and elliptical cylinders. Extensive literature is now available on the various phenomena associated with the flow of Newtonian fluids past an infinitely long circular cylinder in an unconfined flow configuration, e.g., see Chhabra (1996, 1999, 2006), Zdravkovich (1997, 2003) and Zukauskas (1987). Hence, adequate information is now available on most aspects of the flow and heat transfer for Newtonian fluid past a cylinder, at least for an unconfined flow configuration, e.g., see Bharti et al. (2007a,b) for a short review. It is useful to add here that even for Newtonian fluids, the flow characteristics have been studied much more extensively than the corresponding heat/mass transfer problems. In contrast, much less is known about the effect of wall confinement on the momentum and heat transfer characteristics of a cylinder, even for a Newtonian fluid, e.g., see Zdravkovich (1997, 2003) and Bharti et al. (2007c). At very low Reynolds numbers, the wall effects ($\beta = H/D$, where H and D are the distance between the two parallel plane walls and the diameter of the cylinder, respectively) are known to be important (Zdravkovich, 2003) even for $\beta > 1000$ due to the slow decay of the flow (velocity) field. In spite of these features, all in all, a reasonable body of information is now available on the cross-flow of Newtonian fluids over a circular cylinder; at least as far as the macroscopic transport phenomena aspects are concerned.

On the other hand, many multi-phase and high molecular weight substances encountered in industrial practice (pulp and paper, food, polymer and process engineering applications) display shear-thinning and/or shear-thickening behaviour (Chhabra and Richardson, 1999). Owing to their high viscosity levels, such substances are generally processed in laminar flow conditions. Admittedly, many non-Newtonian fluids, notably polymeric systems display visco-elastic behaviour; the available scant literature both for the creeping flow past a single cylinder and over a periodic array of cylinders seems to

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suggest the visco-elastic effects to be minor in this flow configuration (Chhabra, 2006). Furthermore, currently available visco-elastic simulations examine the role of visco-elasticity in the absence of shear-dependent viscosity in the limit of zero Reynolds number (creeping flow) and under these conditions, the effect of elasticity is predicted to be extremely small. On the other hand, the few experimental studies available on this flow employ experimental fluids which show both shear-dependent viscosity and visco-elasticity. Therefore, not only it is unjustified to compare these experiments with numerical predictions, but it is also not obvious whether the significant differences from the Newtonian kinematics seen in the aforementioned experiments are due to the shear-dependent viscosity or due to visco-elasticity or due to a combination of both (Chhabra, 2006). Therefore, it seems justified to begin with the flow of purely viscous power-law type fluids as long as the power-law constants are evaluated in the shear rate range appropriate for the flow over a cylinder and the level of complexity can be built up gradually to accommodate the other non-Newtonian characteristics.

Evidently, the confining walls alter the detailed kinematics of the flow which directly influences the temperature field. Hence, intuitively it appears that the convective heat transfer from a cylinder to power-law fluids may improve or deteriorate depending upon the nature of the fluid and the severity of the blockage. As far as known to us, there has been no prior study on the steady forced convection heat transfer in the Poiseuille flow of power-law fluids from an isothermal circular cylinder confined in a channel. This work aims to fill this gap in the literature. At the outset, it is instructive, however, to briefly recount the available limited work on the flow and heat transfer in power-law fluids from an unconfined cylinder to facilitate the subsequent presentation of the new results for a confined cylinder.

2. Previous work

As noted earlier, while bulk of the information available on the momentum and heat transfer characteristics of a circular cylinder in Newtonian fluids has been thoroughly reviewed by Zdravkovich (1997, 2003) and the recent heat transfer literature has been reviewed by Ahmad (1996) and Bharti et al. (2007a), the corresponding limited information for power-law fluids has been summarized in recent studies (Chhabra et al., 2004; D'Alessio and Pascal, 1996; D'Alessio and Finlay, 2004; Ferreira and Chhabra, 2004; Soares et al., 2005, Bharti et al., 2006, 2007b–d, Sivakumar et al., 2006a,b, 2007;Khan et al., 2006). Suffice it to say here that reliable results on drag and heat transfer for an unconfined cylinder immersed in streaming power-law liquids encompassing the following ranges of conditions are now available: $Re \leqslant 40$; $0.2 \leqslant n \leqslant 2$; $0.7 \leqslant Pr \leqslant 1000$. In contrast, the role of blockage on the flow and heat transfer characteristics has been studied much less extensively even for Newtonian fluids, especially for finite values of the Reynolds number, as evidenced from the short literature reviews presented recently (Ben Richou et al., 2004, 2005; Bharti et al., 2007c; Chakraborty et al., 2004; Mettu et al., 2006; Khan et al., 2004).

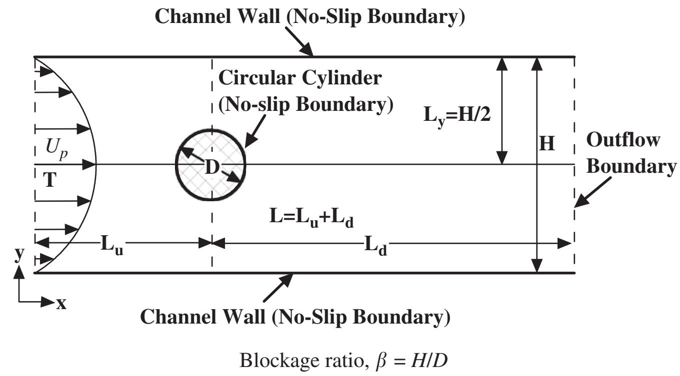

Fig. 1. Schematic representation of a confined (Poiseuille) flow over a circular cylinder.

In contrast, even less is known about the effect of wall blockage on the flow and heat transfer in power-law fluids from a cylinder. As far as known to us, there has been only one study which elucidates the effect of blockage on momentum transfer from a cylinder in power-law fluids (Bharti et al., 2007c) at finite Reynolds numbers (1–40). This study revealed significant changes in the flow field, especially in terms of the early or delayed formation of wake. Therefore, intuitively it appears that these changes in the flow field should also impinge on the prevailing temperature field which, in turn, will influence the local rate of heat transfer. However, no such study elucidating the role of confining (planar) walls on the forced convection heat transfer from a confined cylinder immersed in power-law fluids is available in the literature. This work is undertaken to seek this information. In particular, extensive numerical results on heat transfer characteristics are obtained over the following range of conditions: Reynolds number (1–40), Prandtl number (1–100), the power-law index (0.2–1.8) and for two values of the blockage ratio ($\beta = 4$ and 1.6).

3. Problem statement and mathematical formulation

The channel confined flow is approximated here by considering the two-dimensional steady, incompressible, Poiseuille flow (fully developed velocity profile) of power-law fluids across an infinitely long cylinder (of diameter D) confined symmetrically by two parallel plane solid (adiabatic) walls (blockage ratio, $\beta = H/D$) as shown schematically in Fig. 1. This geometry (Fig. 1) is identical to that studied by Bharti et al. (2007c). The oncoming power-law fluid at temperature T_∞ exchanges heat with the isothermal cylinder whose surface is maintained at a temperature $T_w(> T_\infty)$. The temperature difference between the surface of the cylinder and the streaming liquid $\Delta T\,(=T_w - T_\infty)$ is kept low (≈ 2 K) so that the variation of the physical properties, notably, density and viscosity, with temperature could be neglected. Thus, the thermo-physical properties of the streaming liquid are assumed to be independent of the temperature; furthermore, the viscous dissipation effects are also assumed to be negligible. While these two assumptions lead to the de-coupling of the momentum and the thermal energy equations, but at the same time they also restrict the ap-