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Power-law fluids flow and heat transfer over two tandem square cylinders: effects of Reynolds number and power-law index

Abstract The low-Reynolds numbers free-stream flow of power-law fluids and forced convection heat transfer around a square cylinder and two square cylinders in a tandem arrangement are numerically investigated. In the single cylinder case, the power-law index and Reynolds numbers range from $n = 0.7 - 1.4$ and $Re = 60 - 160$ at $Pr = 0.7$. In the tandem case, the spacing between the cylinders is four widths of each cylinder side and the power-law index ranges from 0.7 to 1.6 at $Re = 40, 100, 160$ and $Pr = 0.7$. All simulations are performed with a finite volume code based on the SIMPLEC algorithm and a non-staggered grid. The effect of spatial resolution on the results is also studied for a single cylinder and tandem cylinders. The mean and instantaneous streamlines, vorticity and temperature contours, the global quantities such as pressure and friction coefficients, the rms lift and drag coefficients, Strouhal and Nusselt numbers are determined and discussed for various power-law indexes at different Reynolds numbers. A comparison between the results of the single cylinder case and the two cylinders in tandem arrangement shows that there are relatively similar results for the single cylinder and the upstream cylinder of the tandem case.

1 Introduction

The majority of the works reported in the literature deals with the flow of Newtonian fluids past a single cylinder or groups of cylinders. These bodies can be arranged in tandem, one behind another one, in an in-line arrangement, side by side, or in a staggered arrangement relative to the free stream flow. There are lots of practical flows in industrial applications and environmental situations which can be modeled as a flow over cylinders such as flows over tubular and pin-type heat exchangers, buildings, cooling of electronic components, etc.

In contrast, little information is available on the flow of power-law-type non-Newtonian fluids over a single cylinder, even in the laminar regime. In general, many materials of industrial significance exhibit non-Newtonian flow behavior, for example, most multiphase mixtures (foams, suspensions, emulsions) and high molecular-weight polymeric systems (solutions, melts and blends) exhibit a range of rheological complexities. It should be noted that most such fluids exhibit shear-thinning and/or shear-thickening viscosity behavior under appropriate flow conditions (e.g., see [1,2]). The simple power-law model is able to describe satisfactorily both the shear-thinning ($n < 1$) and shear-thickening ($n > 1$) behaviors over moderate ranges of shear rates in external flows. Therefore, the non-Newtonian fluid flow, for example, the power-law type, past cylinders, has attracted a great deal of attention these years.
Although extensive investigations have been performed for Newtonian fluid flows around square tandem cylinders, see for example [3–10], to the best of our knowledge, there is no study in the literature for non-Newtonian and particularly power-law fluid flow around tandem square cylinders. There are a few researches for power-law fluids around a single square cylinder [11–20]. Paliwal et al. [11] investigated the momentum and forced convection heat transfer characteristics for an incompressible and steady free stream flow of power-law liquids past a square cylinder numerically. The shear-thinning behavior not only reduces the size of the wake region, but it also delays the wake formation and the opposite effect is reported for the shear-thickening behavior. For a fixed value of $Re$, the flow is seen to be faster close to the cylinder in shear-thinning fluids than that in a Newtonian medium and it is reported to be impeded in shear-thickening fluids. This is a direct consequence of the dependence of the fluid viscosity on the shear rate [11].

The two-dimensional flow of power-law fluids over an isolated unconfined square cylinder was studied numerically in the range of conditions $1 \leq Re \leq 45$ and $0.5 \leq n \leq 2.0$ by Dhiman et al. [12]. The shear-thinning fluid behavior increases the drag above its Newtonian value, whereas the opposite effect occurs for shear-thickening behavior and reduces the drag below its Newtonian value. Similarly, the wake size is shorter in shear-thinning fluids than that in Newtonian fluids under otherwise identical conditions. Dhiman et al. [13] numerically investigated forced convection heat transfer to power-law fluids from a heated square cylinder for the range of conditions $1 \leq Re \leq 45$, $0.5 \leq n \leq 2.0$ and $1 \leq Pr \leq 100$.

Dhiman [14] studied heat transfer to power-law dilatant fluids from a long square cylinder (heated) confined in a channel in the steady flow regime and the effects of Reynolds number, Prandtl number and flow behavior index on the heat transfer characteristics of a cylinder is examined for the range of conditions $1 \leq Re \leq 45$, $1 \leq n \leq 2.0$ and $1 \leq Pr \leq 100$ for a fixed blockage ratio, $\beta = \frac{1}{4}$. Irrespective of the value of the flow behavior index, the value of the local Nusselt number at each corner of the square cylinder increases with an increase in the Reynolds and/or Prandtl number. The average Nusselt number increases monotonically with an increase in the Reynolds and/or the Prandtl number. Dhiman [12–14] presented more accurate results than those of Paliwal et al. [11]. They found that the average Nusselt number increases with an increase in the Reynolds and/or Prandtl number regardless of the value of the power-law index.

Sahu et al. [15] numerically studied the two-dimensional and unsteady free stream flow of power-law fluids past a long square cylinder in the range of conditions $60 \leq Re \leq 160$ and $0.5 \leq n \leq 2.0$. Over this range of Reynolds numbers, the flow is periodic in time. The leading edge separation in the shear-thinning fluids produces an increase in drag values with the increase in the Reynolds number, while the shear-thickening fluid behavior delays this separation and shows the lowering of the drag coefficient with the Reynolds number. Also, the preliminary results suggest that the transition from the steady to unsteady flow conditions occurs at lower Reynolds numbers in shear-thinning fluids than inNewtonian fluids.

Forced convection heat transfer to incompressible power-law-type non-Newtonian fluids from a heated square cylinder in the unsteady cross-flow regime has been studied numerically by Sahu et al. [16] for the range of conditions $0.7 \leq Pr \leq 50$, $60 \leq Re \leq 160$ and $0.5 \leq n \leq 1.8$. Over this range of Reynolds numbers, the flow is truly periodic for Newtonian and shear-thickening fluids, while in the case of the shear-thinning fluids, it becomes pseudo-periodic at high values of $Re \geq 140$ and low values of $n \leq 0.6$. Broadly, shear-thinning fluid behavior promotes heat transfer, whereas shear-thickening impedes it.

Numerical solutions are sought, using FLUENT, to the mass, momentum and thermal energy equations for the 2-D flow of power-law fluids over a cylinder of square cross-section by Rao et al. [17]. Extensive results are reported on streamline and vorticity contours over wide ranges of power-law index (0.2–1.4) corroborating the occurrence of onset of flow separation and the limits of the steady flow regime. The Nusselt number shows positive dependence on both the Reynolds and Prandtl numbers. Also, shear-thinning characteristics can augment the rate of heat transfer by up to 100% under appropriate conditions.

The governing equations describing the momentum and heat transfer phenomena of power-law non-Newtonian fluids over a heated square cylinder at $45^\circ$ of incidence in the two-dimensional (2-D) steady flow regime are solved numerically by Rao et al. [18]. Extensive results on the detailed structure of the flow and temperature fields as well as on the gross engineering parameters are presented over the following ranges of $0.2 \leq n \leq 1.0$, $0.1 \leq Re \leq 40$ and $0.7 \leq Pr \leq 100$. At low Reynolds numbers, the flow remains attached to the surface of the cylinder. This seems to occur for all values of power-law index, at least up to about $Re = 1$. On the other hand, twin standing vortices were seen to form at $Re = 10$ for all values of power-law index considered.

As was mentioned previously, despite non-Newtonian fluids are major components of polymer, food and other process industries, very little information is available for such fluids over bluff bodies. In addition, no prior investigation is reported in the literature for tandem square cylinders in power-law fluids. Furthermore,