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Mixed convection of shear-thinning nanofluids past unconfined elliptical cylinders in vertical upward flow

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ABSTRACT

The numerical results on mixed convective heat transfer phenomenon between unconfined elliptical cylinders and shear-thinning nanofluids are presented herein. The cylinders are placed horizontally over which nanofluids flowing vertically upward. The governing continuity, momentum and energy equations are simultaneously solved within the limitations of Boussinesq approximation using a commercial computational fluid dynamics based solver. Further the elliptical cylinders and the computational outer domain are considered in full domain so that to effectively delineate the deviation from flow symmetry because of mixed convection. The range of Richardson number in this work is varied widely so that both the forced and natural convections via mixed convection conditions are covered. Before obtaining new results, the conventional numerical procedures of obtaining optimum domain and grid sizes along with appropriate comparisons are followed. The ranges of the pertinent parameters considered herein are as follows: volume fraction of nanoparticles, $\phi = 0.005–0.045$; Reynolds number, $Re = 1–40$; Richardson number, $Ri = 0–40$; and aspect ratio of elliptical cylinders, $e = 0.25–2.5$. Finally, the effects of these parameters on the streamlines, isotherm contours, surface pressure, surface vorticity, drag coefficients and local and average Nusselt numbers are thoroughly discussed. Briefly, the total drag coefficient (C_d) decreases with the increasing Re, decreasing Ri and decreasing e. For $\phi \leq 0.025$, C_d decreases with increasing ϕ; however, for $\phi > 0.025$ and $Re > 20$, a reverse trend is seen regardless of values of Ri and e. The average Nusselt number (Nu_{avg}) displayed mixed trends with respect to changes in Ri and e; however, it increases with increasing ϕ and Re regardless of the values of the Richardson number and the aspect ratio of elliptic cylinders.

1. Introduction

The convective heat transfer from bluff bodies has wide range of applications in many engineering processes of industrial relevance such as designing of heat exchangers, chimney stacks, cooling towers, power generators, etc. The mixed (or combined) convection is of importance when the heat transfer occur under the circumstances of comparable order of magnitudes of the buoyancy driven and external force driven velocity of fluid. The buoyancy force is in general negligible when the flow is horizontal; but in the case of vertical flow of fluids, it significantly influences the flow field and in turn the overall heat transfer. The mixed convection can be conveniently represented by the Richardson number (Ri) which represents relative strengths of the buoyancy-induced and externally-imposed flow conditions. Further, regardless the nature of the convection, the geometry of bluff body over or through which the fluid is flowing and the rheological nature of the fluid are two major factors to be considered in the convective heat transfer phenomena. In general, circular cylinders, square cylinders, elliptical cylinders, ducts and spheres are some of the common bluff body shapes one may encounter in experimental and numerical literature on the convective heat transfer phenomena. Furthermore, it has been demonstrated that the nanofluids [1] can enhance the rate of the heat transfer significantly compared to conventional heat transfer fluids such as water, oil, ethyl glycol, etc. However, the controlled preparation of nanofluids is much more demanding than other conventional colloids (such as dispersion of carbon and gold ultrafine particles in liquid media for painting and glass coating, etc.) because harsh application environment such as high shear and high temperature conditions [2]. Many nanofluids rheologically exhibit simple Newtonian behavior [3]; however, quite a few

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nanofluids also display rheologically complex non-Newtonian behavior including shear-thinning and shear-thickening characteristics [4–7]. This work is aimed to present numerical results and discussion on effects of pertinent dimensionless parameters on mixed convection phenomena of vertical upward motion of shear-thinning nanofluids past unconfined horizontal elliptical cylinders.

2. Literature review

The existing experimental and theoretical studies pertaining to nanofluids and associated heat transfer are thoroughly reviewed by Refs. [8–13]; hence only a few related studies are discussed in this section. Rashad et al. [14] investigated the steady mixed convection boundary layer flow past a horizontal circular cylinder in a stream flowing vertically upwards embedded in porous medium filled with a nanofluid. Maiga et al. [15] observed from their results obtained for the problem of the forced convection of water and glycol based Al_2O_3 nanofluids in uniformly heated tube, considerable increment in the both heat transfer and wall friction with inclusion of nanoparticles. Also they have developed a correlation for the viscosity in terms of volume fraction. Sarkar et al. [16] numerically studied the buoyancy driven mixed convection heat transfer characteristics of water-based nanofluid past a circular cylinder placed in cross flow for the Prandtl number ($Pr = 6.2$) and the range of parameters are volume fraction $0\% \leq \phi \leq 2.5\%$, Reynolds number $80 \leq Re \leq 180$, but only for two values of the Richardson number, i.e., $Ri = -1$ and $Ri = 1$ for the contribution of aiding or opposing buoyancy force to the flow respectively. They observed that increase in nano-particle loading show symmetric vortex distribution and have minimal effect of negative buoyancy. The local and average Nusselt numbers increases with increase in Re and ϕ. Sarkar et al. [17] studied the entropy generation due to laminar mixed convection of water-based nanofluid past a square cylinder in vertically upward flow. The range of parameters considered are volume fraction $0\% \leq \phi \leq 20\%$ for the Reynolds number of 100 within narrow range of the Richardson number, i.e., $-0.5 < Ri < 0.5$ and found that the total entropy generation decreases with increasing nano-particle volume fraction. Sarkar [18] simulated the buoyancy driven mixed convective flow and heat transfer phenomenon of water-based nanofluid past a square cylinder in vertically upward flow. All their simulations carried out for Reynolds number 100 for two different nanofluids with Cu and Al_2O_3 nano-particles (with the volume fraction $0\% \leq \phi \leq 20\%$.) in water as base fluid. The effect of aiding or opposing buoyancy taken in terms of Richardson number in the range of $-0.5 \leq Ri \leq 0.5$. From the simulated results they concluded that for Al_2O_3-water nanofluid at $Ri = 0.15$ completely periodic vortex shedding is found for $\phi \geq 10\%$. For Cu-water nanofluid shedding is observed for both $Ri = 0.15$ and $Ri = 0.5$ for $\phi \geq 5\%$ and $\phi \geq 10\%$ respectively. Santra et al. [5] investigated the heat transfer behavior of copper-water nanofluid as cooling medium in a two-dimensional horizontal rectangular duct with top and bottom walls acting as isothermally symmetric heat sources. Their study carried by considering the nanofluid as both Newtonian and non-Newtonian for wide range of Reynolds numbers 5 to 1500 and volume fractions between 0 and 0.05. From the obtained results they concluded that the rate of heat transfer increases with increase in flow as well as volume fraction of nano-particles. Putra et al. [19] did experiments on the heat transfer due to natural convection with nanofluid. They found that heat transfer decreases with increase in concentration of nano-particles. The viscosity of nanofluid greatly increases with adding of nano-particles as shear rate decreases. Finally the objective of this work is to numerically investigate the mixed convective momentum and heat transfer characteristics of shear-thinning nanofluids flowing

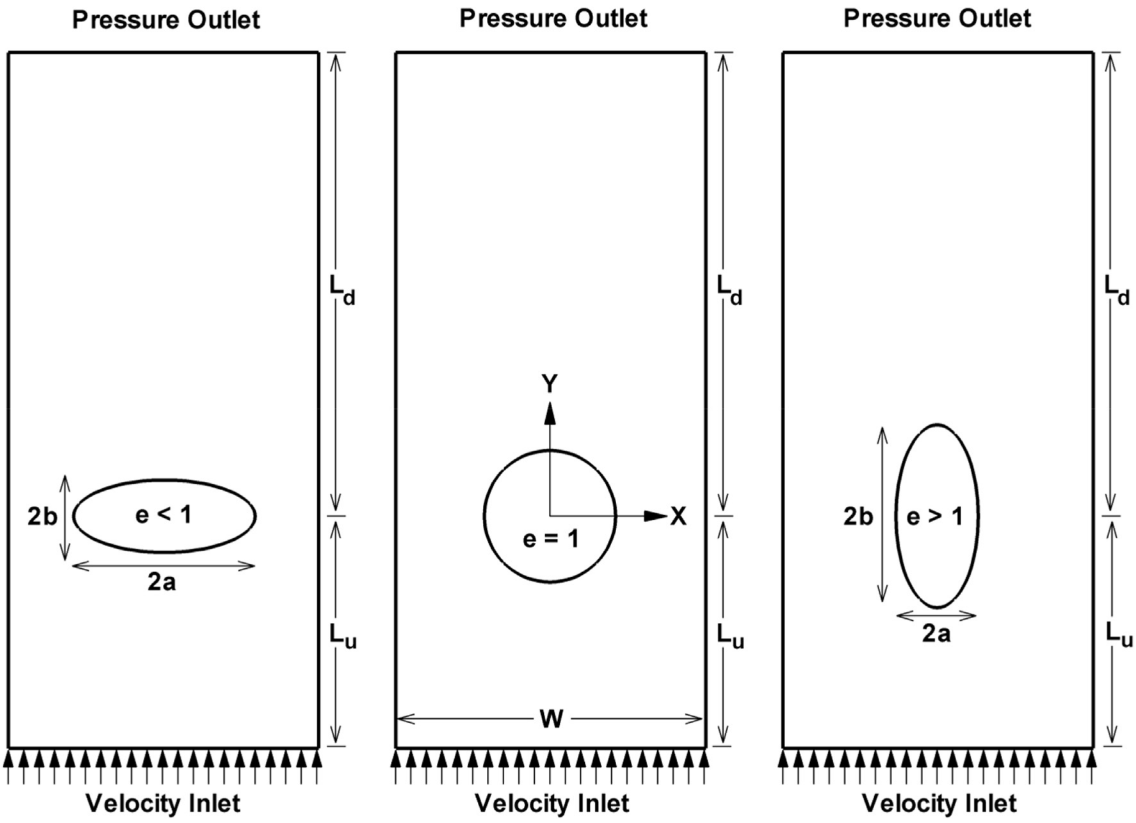

Fig. 1. Schematic diagram of flow over horizontal heated circular and elliptical cylinders placed in vertical channels.