Wall Effects in Convective Heat Transfer from a Sphere to Power Law Fluids in Tubes

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Introduction

The flow of power law fluids and heat transfer from a sphere immersed in power law fluids represents an idealization of various industrial processes, such as in thermal processing of foodstuffs, fixed and fluidized bed reactors, and slurry reactors. Although in most practical applications non-spherical particles and/or ensembles of particles are encountered, a thorough understanding of the hydrodynamic behavior of a spherical particle is germane to developing useful insights into the behavior of non-spherical particles and/or their clusters. Over the years, a considerable amount of literature has addressed the problem of fluid flow and heat transfer past a sphere in an unconfined region, especially in Newtonian fluids and to a limited extent in power-law fluids [1-7]. However, the flow over a sphere in a confined region is encountered in various applications such as falling ball viscometry, hydrodynamic chromatography, membrane transport, and hydraulic transport of coarse solids in pipes. Furthermore, numerous fluids of industrial importance display shear-thinning characteristics which are conveniently approximated by the simple power law model, with many of these fluids (polymer melts, polymer solutions, food emulsions, suspensions, and biological fluids) exhibiting the value of power law index, n, typically in the range of ~0.2 and ~0.8. This work thus examines the interplay between the degree of confinement and the power-law index on the drag and heat transfer from a sphere over wide ranges of the pertinent kinematic and physical parameters. In particular, the role of sphere Reynolds number, Re varying from 5 to 100, the sphere-to-tube diameter ratio, λ from 0 to 0.5 and the power law index, n from 0.2 to 1 and Prandtl number from 1 to 100 is elucidated on the drag coefficient and Nusselt number.

A sphere falling in a stagnant power-law fluid in a tube is tantamount to both the fluid and the tube wall moving around the stationary sphere at the same velocity, as shown schematically in Figure 1.

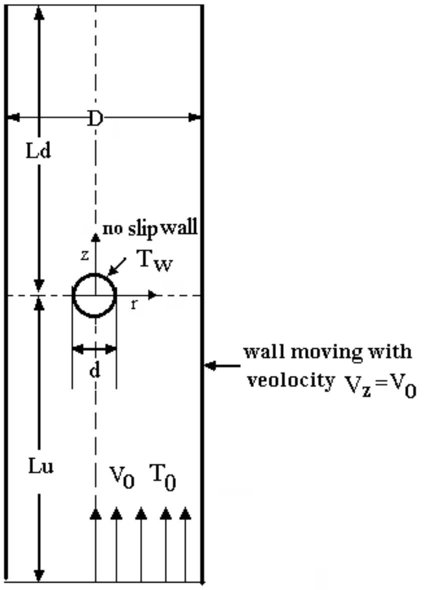

Figure 1: Schematic of flow around a sphere

Use of COMSOL Multiphysics

In this paper, the momentum equations and the energy equation together with the appropriate boundary conditions have been solved in a segregated manner using COMSOL Multiphysics (version 3.5a). Over the range of the Reynolds number considered herein, the flow is expected to be steady and axisymmetric. The flow geometry was drawn by means of the built-in CAD tools, and the flow domain was meshed using "quadrilateral" elements. The scheme of Lagrange-P_2P_1 was selected to handle the velocity-pressure coupling. Once the flow domain was mapped in terms of the velocities, temperature and pressure, global characteristic quantities such as the drag coefficient and Nusselt number were calculated through the postprocessing.

Selected results

Typical results elucidating the effect of diameter ratio and the Reynolds number on the surface averaged Nusselt number are shown in Figures 2 & 3, respectively for Newtonian and highly shear-thinning fluids at Pr=1. For a Newtonian fluid, enhancement in heat transfer with increasing degree of confinement is attributed to the sharpening of the temperature gradient in the vicinity of the sphere (Figure 2). The enhancement is further augmented in the case of shear-thinning fluid due to the enhanced levels of shearing close to the sphere surface thereby lowering the effective viscosity in this region (Figure 3).

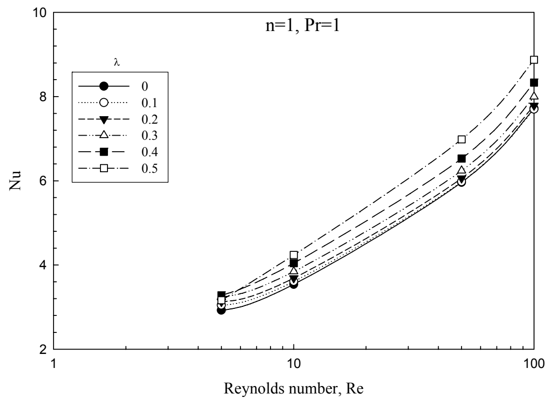

Figure 2. Influence of Reynolds number and diameter ratio on average Nusselt number in a Newtonian fluid (n=1).

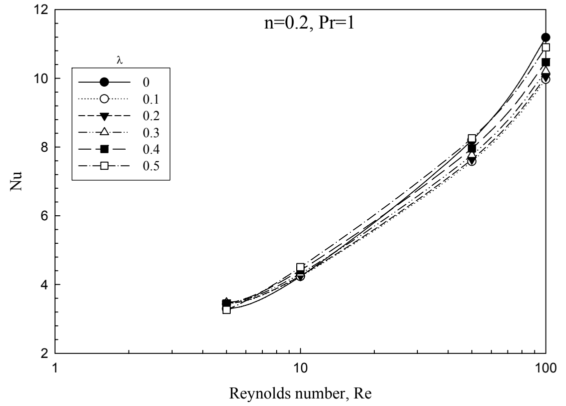

Figure 3. Influence of Reynolds number and diameter ratio on average Nusselt number in a power-law fluid (n=0.2).

Conclusion

Extensive numerical results are reported herein which delineate the effects of Reynolds number Re, power law index n, tube-to-sphere diameter ratio λ, and Prandtl number Pr on the Nusselt number around a sphere in power law fluids. The governing equations have been solved numerically using COMSOL Multiphysics over the following ranges of conditions: $5 \leq Re \leq 100$, $0.2 \leq n \leq 1$, $0 \leq \lambda \leq 0.5$, and $1 \leq Pr \leq 100$. The wall effects on the drag and mean Nusselt number in power law fluids are seen to be less severe than those in Newtonian fluids under otherwise identical conditions.

References

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