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Momentum and heat transfer characteristics from heated spheroids in water based nanofluids

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ABSTRACT

In this work, the governing field equations describing the momentum and forced convection heat transfer from heated spheroids, including the limiting case of a sphere, in water based nanofluids have been solved numerically in the steady and axisymmetric flow regime over the following ranges of conditions: Reynolds number, $1 \leqslant Re \leqslant 100$; nanoparticle volume fraction, $0 \leqslant \phi \leqslant 0.06$ and aspect ratio, $0.2 \leqslant e \leqslant 5$ for two sizes (d_p), namely, 30 nm and 100 nm, of CuO and Al_2O_3 nanoparticles. Over the present range of conditions, a qualitative similar behavior is observed for both CuO and Al_2O_3 nanofluids. The detailed structure of the flow and temperature fields in the vicinity of the spheroid is analyzed in terms of streamline patterns and isotherm contours, respectively. The value of the total drag coefficient for all configurations of the spheroid is always seen to increase with the increasing value of ϕ for all values of Re, d_p and e. All else being equal, the flow detaches early from the spheroid in nanofluids comprised of 100 nm nanoparticles, whereas the flow separation delays in nanofluids containing 30 nm nanoparticles with reference to that seen in clear water. The rate of heat transfer is seen to be monotonic with ϕ for nanofluids containing 100 nm nanoparticles, whereas it is seen to be non-monotonic for nanofluids having nanoparticles of 30 nm in size. Finally, the present values of the total drag coefficient and average Nusselt number are correlated using simple analytical forms which facilitate the interpolation of the present results for the intermediate values of the governing parameters.

1. Introduction

Fluid flow through and heat transfer in a particulate system consisting of spheroidal shaped particles is frequently encountered in many industrial applications ranging from food, pharmaceutical, health and personal-care products to complex multiphase systems including fixed and fluidized bed reactors, transportation of slurries in pipeline, separation based on the gravitational settling, porous media flows in oil and refinery industries, etc. [1,2]. This stems to the importance of understanding the underlying fluid flow and heat transfer phenomena of these systems in order to design efficient and long-lasting process equipments which eventually control the quality of the final product. However, the complex fluid flow and heat transfer phenomena of these particulate systems can be well described with a good understanding of a single particle system placed under otherwise identical conditions to that of a multi-particle system. For this reason, the fluid flow and heat transfer phenomena from a single sphere situated either in a streaming fluid or falling in a stagnant fluid denotes a classical problem over the years in the domain of transport phenomena [3]. The empirical correlations deduced for the drag coefficient and Nusselt number for a sphere are regularly used as a stepping stone for the development of new correlations for other irregular shaped geometries, e.g., cube, cylinder, cone, etc., under various operating conditions, and over the years, a voluminous body of knowledge has been accrued on this topic by many researchers [4,5]. Not only for a sphere, but also for the other two classes of the spheroid, namely prolate and oblate configurations, a large body of literature is now available on the momentum and heat transfer phenomena in Newtonian as well as in non-Newtonian fluids like shear-thinning, shear-thickening, visco-plastic, visco-elastic, etc.

The early studies on flow past a solid spheroid were based on the theoretical analysis. Oberbeck [6], probably, was the first who theoretically investigated the flow past a spheroid by extending the Stokes drag law for a sphere with a shape correction factor. Theoretical analysis mainly includes the boundary layer approximations based on the scaling analysis or simplifications of the Navier–Stokes (N–S) equations by neglecting or linearizing the

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Nomenclature

a	semi-axis normal to the direction of flow, m
b	semi-axis along the direction of flow, m
$C_{p,bf}$	thermal heat capacity of base fluid, J kg^{-1} K^{-1}
$C_{p,np}$	thermal heat capacity of nanoparticle, J kg^{-1} K^{-1}
$C_{p,nf}$	thermal heat capacity of nanofluid, J kg^{-1} K^{-1}
C_p	pressure coefficient, dimensionless
C_D	total drag coefficient, $\left(=\frac{F_D}{\frac{1}{2}\rho_{bf}U_\infty^2\left[\frac{\pi}{4}(2a)^2\right]}\right)$, dimensionless
C_{DP}	pressure component of drag coefficient, $\left(=\frac{F_{DP}}{\frac{1}{2}\rho_{bf}U_\infty^2\left[\frac{\pi}{4}(2a)^2\right]}\right)$, dimensionless
C_{DF}	friction component of drag coefficient, $\left(=\frac{F_{DF}}{\frac{1}{2}\rho_{bf}U_\infty^2\left[\frac{\pi}{4}(2a)^2\right]}\right)$, dimensionless
D_∞	diameter of the outer domain, m
d_{np}	diameter of the nanoparticle, nm
e	aspect ratio, $(=\frac{b}{a})$, dimensionless
F_D	total drag force, N
F_{DP}	pressure component of drag force, N
F_{DF}	friction component of drag force, N
h	heat transfer coefficient, W m^{-2} K^{-1}
k_{bf}	thermal conductivity of base fluid, W m^{-1} K^{-1}
k_{np}	thermal conductivity of nanoparticle, W m^{-1} K^{-1}
k_{nf}	thermal conductivity of nanofluid, W m^{-1} K^{-1}
L	reattachment length from the rear of the spheroid, m
L_r	recirculation length, $(=\frac{L}{2a})$, dimensionless
n_s	unit normal vector, dimensionless
Nu_θ	local Nusselt number, dimensionless
Nu	average Nusselt number, dimensionless
N	total number of elements in the computational domain, dimensionless
N_p	total number of elements on the surface of the spheroid, dimensionless
p_s	pressure at a point on the surface of the spheroid, Pa
p_∞	reference pressure far away from the spheroid, Pa
P	pressure, dimensionless
Pr	Prandtl number, dimensionless
Re	Reynolds number, dimensionless
S	surface area of the spheroid, m^2
T	temperature, K
ΔT	temperature difference, $(=T_w - T_\infty)$, K
$\mathbf{U}$	velocity vector, dimensionless
U_∞	velocity at the inlet, m s^{-1}

List of Greek symbols

κ	Boltzmann constant, m^2 kg s^{-2} K^{-1}
ρ_{bf}	density of base fluid, kg m^{-3}
ρ_{np}	density of nanoparticle, kg m^{-3}
ρ_{nf}	density of nanofluid, kg m^{-3}
μ_{bf}	viscosity of base fluid, Pa·s
μ_{nf}	viscosity of nanofluid, Pa·s
Φ	temperature, dimensionless
ϕ	volume fraction of nanoparticle, dimensionless
θ	location on the surface of the spheroid, degree

Subscripts

w	condition at the surface of the spheroid
∞	condition corresponds to far away from the spheroid surface
bf	base fluid
np	nanoparticle
nf	nanofluid

convective terms, and then solved by various methods such as similarity solutions, series truncation methods, Fourier expansion methods [7–12] or more recently by homotopy perturbation method [13]. In addition to the fluid flow, few theoretical studies are also available on the heat transfer aspects [14]. A good review on various analytical approaches has been presented elsewhere [15]. The main drawback of most of these analytical approaches is that these methods are applicable either at low Reynolds number (below the flow separation) for fluid flow or at very low and/or high Peclet number for heat transfer. Also these approaches fail to provide the solutions for the geometries possessing geometric singularities. This eventually necessitates full-blown numerical simulations or experimental investigations. The numerical solutions are sought based on the different approaches, e.g., finite difference, finite volume, finite element or lattice boltzmann method. For instance, Masliyah and Epstein [16] numerically investigated the steady and incompressible Newtonian fluid flow past a rigid spheroid up to Reynolds number 100 by discretizing the governing equations based on the finite difference method. Zamyshlyaev and Shrager [17] carried out a similar kind of study as that of Masliyah and Epstein using the stabilization method with a finite difference variable direction scheme. Comer and Kleinstreuer [18] performed the steady state forced convection heat transfer analysis based on the Galerkin finite element method from an oblate spheroid. The corresponding unsteady state heat transfer analysis from a spheroid was performed by Juncu [19]. On the other hand, Kishore and Gu [20] investigated the momentum and heat transfer phenomena in detail from heated spheroids over wide ranges of conditions as $1 \leqslant Re \leqslant 200$, $1 \leqslant Pr \leqslant 1000$ and $0.25 \leqslant e \leqslant 2.5$. Not only for the forced convection, but also there are studies available on the other two mechanisms of heat transfer, namely, mixed [21] and free convection [22] from a spheroid in Newtonian fluids. Furthermore, the effect of wall confinement [23,24], the presence of another spheroid, i.e., spheroids in tandem arrangement [25,26], different angle of attack of the flowing fluid [27] on the fluid flow and heat transfer characteristics from a spheroid were studied in detail over wide ranges of dimensionless parameters like Reynolds number, Prandtl number, aspect ratio, etc.

On the other hand, many fluids of multiphase nature (e.g., emulsions, suspensions, foams, etc.), polymer solutions, surfactants/soaps, etc., routinely used in varieties of industries, exhibit a wide range of non-Newtonian behaviors including shear-thinning, shear-thickening, visco-elasticity, etc., under various operational and flow conditions [28]. In the literature, there are various rheological models available for characterizing these non-Newtonian behaviors, and among them the power-law and Bingham plastic fluid models are, probably, most simplest and widely used models for delineating the shear-thinning, shear-thickening, and visco-plastic behavior, respectively, of the non-Newtonian fluids. It is to be noted that for a sphere, a reasonably fair amount of knowledge is available in the domain of momentum and heat transfer phenomena for power-law fluids in the forced [29], free [30] and mixed [31] convection regime, as well as for Bingham plastic fluids in the forced [32], free [33] and mixed [34] convection regime. In addition to this, an adequate amount of literature is also now available for the oblate and prolate spheroids in non-Newtonian fluids. For instance, Tripati et al. [35,36] investigated the effect of shear-thinning as well as shear-thickening power-law fluid behavior on the flow phenomena past a spheroid. The corresponding heat transfer phenomena in