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Heat transfer and particle migration in nanofluid flow around a circular bluff body using a two-way coupled Eulerian-Lagrangian approach

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ABSTRACT

Nanofluids are engineered suspensions of fine nanoparticles in basefluids. Being a two-component system, different numerical approaches are available to model the thermo-fluidic behavior of nanofluids. In this study, a two-way coupled Eulerian-Lagrangian approach based Discrete Phase Modeling (DPM) has been used to numerically study the flow and heat transfer of nanofluids around a circular bluff body. A 2-D, laminar, steady and forced convective flow of Al_2O_3-H_2O nanofluid around a hot circular cylinder at a constant temperature has been considered. Governing equations of motion and energy transfer for the continuous phase (basefluid) were solved using a finite volume approach and the nanoparticles (discrete phase) were individually tracked in a Lagrangian reference frame by solving the particle force balance equation. Results are presented at $10 \leqslant Re \leqslant 40$ and particle volume fraction (ϕ) varying from 0% to 5%. Heat transfer performance of nanofluids is presented in terms of local and average Nusselt numbers. As expected, Nusselt numbers increased with increase in particle volume fraction and Reynolds number. Results indicated that the heat transfer characteristics are notably influenced by Brownian motion and thermophoresis. Effects of reflect and trap boundary conditions for the particulate phase at the cylinder wall, on heat transfer characteristics of nanofluids are also discussed. Special attention has been paid to the distribution of nanoparticles in the flow domain. It is noted that, nanoparticle distribution is non-homogeneous in the proximity of cylinder and in the recirculation region. This observation is in complete contradiction with the basic assumption of conventional Single Phase Modeling (SPM) approach. Results of DPM analysis significantly vary from that of the SPM approach. Furthermore, it is observed that nanofluids with smaller nanoparticles are capable of producing higher heat transfer rates.

1. Introduction

Flow and heat transfer around bluff bodies is a classical scenario, which is very common in several industrial applications such as electronic cooling, nuclear reactors, heat exchangers and thin wire probes and sensors [1]. Due to its industrial relevance and interesting flow behavior, this scenario is a renowned topic of research and numerous works are reported in available literature. The current state of the art of fluid flow and heat transfer over a bluff body are described in many review articles and books [2–5]. Recent advancements in technology has led to miniaturization, high power output and thus, resulting in a high heat flux density in several industrial devices. Hence, increasing the heat transfer efficiency has become the top priority in many industries. But, the performances of current heat transfer systems are limited by the low thermal conductivity of traditional industrial coolants such as air, water, engine oil and ethylene glycol. Nanofluids which are engineered suspensions of fine nanoparticles in conventional cooling liquids posses enhanced thermal conductivity and good stability. Owing to their superior thermal transport characteristics, nanofluids are promising coolants for several high heat flux applications such as electronic components, automobiles, nuclear reactors, energy storage devices and solar absorbers [6]. Thus, many researchers are involved in experimental and numerical attempts to study the thermo-fluidic behavior of nanofluids in a variety of applications.

Numerical investigation of nanofluid flow and heat transfer around bluff bodies is a trending topic in recent times. Flow and heat transfer characteristics of nanofluids are different from the basefluids due to their altered thermo-physical properties. A numerical study on forced convective heat transfer around a solid circular cylinder using nanofluids was carried out by Valipour and Ghadi [7]. Hamilton-Crosser [8] and Brinkman [9] models were used to determine the effective thermal conductivity and viscosity of nanofluids, respectively. An enhancement in heat transfer was

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Nomenclature

$\boldsymbol{V}$	velocity vector in x or y direction [m s^{-1}]
C_p	specific heat [J kg^{-1} K^{-1}]
D	diameter of the cylinder [m]
d_p	diameter of the nanoparticle [m]
F, f	force [N]
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
K_B	Boltzmann constant [J K^{-1}]
m	mass [kg]
n	normal direction to the cylinder surface [m]
np	number of particles in a cell volume
Nu	Nusselt number
p	pressure [Pa]
Re	flow Reynolds number [J/kg K]
T	temperature [K]
t	time [s]
u, v	velocity components in x and y directions [m s^{-1}]
x, y	rectangular coordinate components [m]
A	surface area [m^2]
Pr	Prandtl number

Greek symbols

δV	cell volume [m^3]
δ	distance between particles [nm]
λ	fluid mean free path [m]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ν	kinematic viscosity [m^2 s^{-1}]
ϕ	nanoparticle volume fraction
ρ	density [kg m^{-3}]

Subscripts/superscripts

∞	far stream value
B	Brownian
D	drag
f	basefluid (continuous phase)
M	mean/average value
p	nanoparticle (discrete phase)
S	local/surface value
th	thermophoretic
w	wall

observed in nanofluids when compared to the basefluids. Nanofluids exhibited stronger vorticity than the basefluids. Similar observations were reported by Valipour et al. [10] in a study of nanofluid flow around a square cylinder. Vegad et al. [11] performed a numerical study on forced convective nanofluid flow around a circular cylinder in which Maxwell Garnett [12] and Brinkman models [9] were employed to calculate the effective properties of nanofluids. Synonymous observations of increased heat transfer while using nanofluids were reported. A numerical study on mixed convective heat transfer around a circular cylinder by Abu-Nada et al. [13] showcased that the heat transfer enhancement is a function of thermal conductivity and volume fraction of nanoparticles. Bing and Mohammed [14] performed a numerical study on upward laminar mixed convective flow around a circular cylinder. It was reported that nanoparticles with smaller diameters led to higher heat transfer rates. A numerical study on laminar nanofluid flow around a circular cylinder by Farooji et al. [15] exhibited that there exists an optimum particle volume fraction that gives the maximum heat transfer for a given nanoparticle diameter. Effect of nanoparticle shape on heat transfer enhancement was showcased by a numerical analysis of transient natural convective boundary layer flow past a vertical cylinder using nanofluids by Chamkha et al. [16]. Results indicated that nanofluids with spherical nanoparticles produced higher heat transfer rates. Notable aspect of this work is that, Brownian motion and thermophoresis were considered while determining the effective thermal conductivity of nanofluids. A detailed study on wake dynamics and heat transfer of nanofluids in forced and mixed convective flow past a circular cylinder at high Prandtl numbers was carried out by Sarkar et al. [17]. Results indicated that a stabilizing effect in flow and enhanced heat transfer rates were observed at higher Richardson numbers. Similar results were obtained in a numerical study of mixed convective flow around a circular cylinder using nanofluids [18]. Mixed convective nanofluid flow around a square cylinder was numerically studied by Sarkar et al. [19] and the results indicated that, a strong relation exists between the nanoparticle volume fraction and mean Nusselt number. Addition of nanoparticles to the basefluid resulted in more number of low frequency higher energy modes in a mixed convective flow around a square cylinder [20]. During a mixed convective vertical flow and heat transfer around a square cylinder using nanofluids, addition of nanoparticles to the basefluid caused a decrease in total entropy generation [21].

It is to be noted that, all the reported works on nanofluid flow around bluff bodies are based on Single Phase Modeling (SPM) approach. SPM considers nanofluids as homogeneous liquids with effective properties calculated using theoretical correlations. It is also hypothesized that the nanoparticles and basefluid move with the same velocity and exist in thermal equilibrium. It is arbitrarily assumed that the nanoparticle distribution is homogeneous through out the flow domain. Even though this approach is simpler and computationally cheap, accuracy of the results depend greatly on the theoretical models used for prediction of effective properties of nanofluids. Also in reality, nanofluids are heterogeneous suspensions of randomly moving nanoparticles in a basefluid (continuous phase). Several factors such as gravity, friction between the fluid and solid particles, thermophoresis, Brownian motion, sedimentation and dispersion co-exist with the main flow of nanofluids. Furthermore, a difference in velocity between the discrete phase (nanoparticles) and the continuous phase (basefluid) exists due to the difference in their densities. All these phenomena indicate that, basefluid and nanoparticles will not have same velocity and there will be a velocity slip between them [22]. Thus, it is clear that, it is necessary to classify nanofluids as a two-component system which brings up different approaches of Multi Phase Modeling (MPM) to numerically model the thermo-fluidic behavior of nanofluids. Different types of MPM models used for simulating nanofluids are (i) VOF (Volume of Fluid), (ii) Mixture model, (iii) Eulerian-Eulerian and (iv) Discrete Phase Model (DPM). Among the available multiphase models, mixture model is more commonly used due to its simplicity and relatively lesser computational expenses. Mixture model has been used to numerically analyze the nanofluid flow and heat transfer in several flow scenarios like horizontal straight tubes, curved tubes, lid driven cavity, inclined enclosure, shallow cavity and circular annulus by several researchers and convincing results were obtained [23–35]. Even though mixture model has been widely used, due to its ability to capture the effects of slip velocity; accuracy of the results are still