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Forced convective heat transfer of nanofluids around a circular bluff body with the effects of slip velocity using a multi-phase mixture model

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ABSTRACT

Forced convective heat transfer around a circular cylinder using nanofluids has been numerically analyzed employing a mixture model based Multi-Phase Modeling (MPM) approach. A hot circular cylinder with a constant wall temperature is exposed to a free stream of Al_2O_3–H_2O nanofluid at ambient temperature. The flow is steady, laminar and two dimensional in the Reynolds number range of $10 \leqslant Re \leqslant 40$. The governing equations of flow and energy transfer along with the respective boundary conditions are numerically solved using a Finite Volume Method (FVM) based on SIMPLE algorithm. The prime aim of this work is to highlight the effects of slip velocity, volume concentration and diameter of nanoparticles on heat transfer characteristics of nanofluids. Results indicate that heat transfer increases with increase in nanoparticle volume fraction. The highest mean Nusselt number is observed at $\phi = 5\%$ at any Reynolds number. It is also noted that, nanofluids with smaller nanoparticles result in higher heat transfer rates. Particular attention has been paid to the variation of heat transfer characteristics when the modeling approach is switched from Single-Phase Modeling (SPM) to mixture model based MPM. It is revealed that higher heat transfer rates are observed in MPM which considers the effects of slip velocity.

1. Introduction

Forced convective heat transfer around bluff bodies is a frequently encountered scenario in many industrial applications such as cooling of electronic components, nuclear reactors, shell type heat exchangers, pin fins and use of thin wires as probes and sensors, etc [1]. In addition to these practical applications, this scenario is also a classical problem in fluid mechanics and heat transfer. A considerable volume of information on various flow phenomena observed in this flow configuration has accumulated in literature over the years. Excellent review articles and books consolidating the current state of the art of fluid flow and heat transfer over a circular cylinder are now available in literature [2–10]. However, the heat transfer performance in engineering applications is limited by the low thermal conductivity of traditional industrial coolants such as air, water, engine oil and ethylene glycol. Nanofluids which are obtained by suspending fine nanosized particles in conventional cooling liquids are the new generation coolants with enhanced thermal conductivity and good stability. They find applications in electronic component cooling, automobiles, nuclear reactors, energy storage and solar absorbers, etc [11]. Hence, several experimental and numerical research attempts are in progress to utilize nanofluids in thermal applications to achieve enhanced heat transfer performance.

In recent years, several numerical investigations on nanofluid flow and heat transfer around bluff bodies have been reported in literature. Nanofluids due to their different effective thermophysical properties exhibit modified flow and heat transfer characteristics. Valipour and Ghadi [12] numerically analyzed the forced convective heat transfer around a solid circular cylinder using nanofluids. The effective thermal conductivity and viscosity of nanofluids were determined using Hamilton-Crosser model [13] and Brinkman model [14], respectively. Nanofluids exhibited stronger vorticity and enhanced heat transfer rates. A similar study on forced convective heat transfer past a square cylinder by Valipour et al. [15] also confirmed their observations on circular cylinder. A numerical study on forced convective nanofluid flow around a circular cylinder by Vegad et al. [16] in which the effective properties were calculated using Maxwell Garnett model [17] and Brinkman model [14] also showed synonymous results. Abu-Nada et al. [18] in their numerical study on mixed convective heat transfer around a circular cylinder showcased that the heat transfer enhancement is dependent on thermal conductivity of nanoparticles and particle volume fraction. Bing and Mohammed [19] performed a numerical study on upward laminar mixed convective flow around a circular cylinder and showed that nanofluids with smaller nanoparticles produced higher heat transfer rates.

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Nomenclature

Notations

a	acceleration [m/s^2]
c_p	specific heat capacity [J/kg K]
D	diameter of the cylinder [m]
d_f	basefluid molecular diameter [m]
d_p	diameter of the nanoparticle [m]
f_{drag}	drag function
H	enthalpy [J/kg]
k	thermal conductivity [W/m K]
Nu	Nusselt number
P	pressure [N/m^2]
T	temperature [K]
Pr	Prandtl number
Re	Reynolds number
V,v	velcoity components [m/s]

Greek symbols

μ	dynamic viscosity [kg/ms]
ν	kinematic viscosity [m^2/s]
ϕ	nanoparticle volume fraction
ρ	density [kg/m^3]

Subscripts

dr	drift velocity
f	basefluid (primary phase)
M	mean value
m	mixture
nf	nanofluid
p	nanoparticle (secondary phase)
pf	slip velocity
S	local value
s	phase

Farooji et al. [20] numerically simulated a laminar nanofluid flow around a circular cylinder and exhibited that there is an optimum particle volume fraction for a given nanoparticle diameter at which the maximum heat transfer will be observed. A numerical analysis of transient natural convective boundary layer flow past a vertical cylinder using nanofluids by Chamkha et al. [21] showcased the dependence of heat transfer enhancement on nanoparticle shape. It was noted that spherical particles are capable of producing 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. Sarkar et al. [22] made a detailed study on wake dynamics and heat transfer using nanofluids in forced and mixed convective flow past a circular cylinder at high Prandtl numbers. A stabilizing effect in flow and enhanced heat transfer were noted at higher Richardson numbers. Similar results were obtained in a numerical study of mixed convective flow around a circular cylinder using nanofluids [23]. A buoyancy driven mixed convective flow around square cylinder using nanofluids by Sarkar et al. [24] showed that heat transfer is a function of particle volume fraction. Addition of nanoparticles to the basefluid resulted in more number of low frequency higher energy modes in a mixed convection flow around a square cylinder [25]. 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 [26].

It is to be noted that all the available works on nanofluid flow around cylindrical bodies are based on a Single-Phase Modeling (SPM) approach. In SPM, it is assumed that nanofluids are homogeneous fluids with effective properties. The effective properties are calculated using theoretical models and it is considered that the nanoparticles and liquid move with the same velocity. It is also hypothesized that the particles and basefluid are in thermal equilibrium. This approach is simpler and computationally less expensive. In reality, nanofluids are heterogeneous suspensions consisting of randomly moving particles and a continuous fluid phase. Factors and mechanisms such as gravity, friction between the fluid and solid particles, thermophoresis, Brownian motion, the phenomena of Brownian diffusion, sedimentation and dispersion may exist along with the main flow of nanofluid. Also, the difference in density of nanoparticles and fluid may cause a difference of velocity between both the phases. These factors indicate that the fluid and particles will not have same velocity and there will be a velocity slip between them [27]. Hence, it is obvious that Multi-Phase Modeling (MPM) approach is more suitable for modeling flow and convective heat transfer of nanofluids. In MPM, dynamics of each phase is explicitly considered and it aids in understanding the behavior of fluid phase and solid particles in the heat transfer process [28]. There are two MPM approaches for modeling the flow of solid–liquid mixtures [29,30], namely the Lagrangian–Eulerian approach and Eulerian–Eulerian approach. Lagrangian–Eulerian approach analyses the fluid phase using the Eulerian model and the solid particles are analyzed using a Lagrangian approach. This approach is suitable only when the solid particle volume fraction is less. In nanofluids, the number of particles is extremely high due to very small size of nanoparticles. Hence, Lagrangian–Eulerian approach is not economic for solving nanofluid flow problems due to software limitations, memory, time and CPU requirements, etc. The second approach is Eulerian–Eulerian approach which considers the particle phase as continuum and is more suitable for nanofluid problems [31]. There are three different Eulerian–Eulerian models which are more popularly used for solving nanofluid problems, namely (i) VOF (Volume of Fluid), (ii) Mixture and (iii) Eulerian [28,32–51]. Out of the three Eulerian models, mixture theory which is also known as the theory of interacting continua [31,52–54] is more popular due to its simplicity in theory and implementation. The mixture model considers the mixture as a whole, instead of two separate phases and hence, it is straightforward, relatively inexpensive and considerably accurate for a wide range of multi-phase flows [52].

For the first time in literature, Behzadmehr et al. [32] employed the Eulerian-mixture model to predict the forced convective heat transfer in a circular tube using Cu–Water nanofluids. It was observed that, mixture model produced more accurate results than SPM and matched well with the experimental results. Mirmasoumi and Behzadmehr [39] utilized mixture model to numerically study the mixed convective heat transfer of nanofluids through a horizontal tube. It was observed that the thermal parameters are notably influenced by the nanoparticle distribution and higher concentration of nanoparticles was observed at the bottom and near wall region. Laminar flow of nanofluids in a curved tube was numerically studied by Akbarinia and Laur [28] using mixture model. Effects of particle diameter have been exclusively analyzed and it was concluded that increasing the particle diameter increases the axial velocity and decreases the Nusselt number. Also, an uniform distribution of nanoparticles was observed all over the tube. A mixture model based numerical study was carried out by Alinia et al. to investigate the mixed convection heat transfer inside a two sided lid driven cavity filled