Journal of Molecular Liquids 223 (2016) 572–588

Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq

Nanofluid flow and heat transfer around a circular cylinder: A study on effects of uncertainties in effective properties

R. Deepak Selvakumar, S. Dhinakaran *

The Center for Fluid Dynamics, Discipline of Mechanical Engineering, Indian Institute of Technology Indore, Khandwa Road, Simrol, Indore 453 552, Madhya Pradesh, India

A R T I C L E I N F O

Article history:
Received 18 December 2015
Accepted 13 August 2016
Available online 22 August 2016

Keywords:
Nanofluids
Circular cylinder
Heat transfer
Effective properties
Uncertainties
Finite-volume method

A B S T R A C T

Nanofluids are considered to be the coolants of future; in the interest of their enhanced thermal conductivity. But, the dilemma in prediction of their effective properties is a major problem in assessing their real heat transfer potential. A numerical analysis of flow and heat transfer from a hot circular cylinder exposed to an uniform stream of nanofluid has been performed to showcase the effects of uncertainties in effective properties of nanofluids. Water based nanofluids with ultra-fine Titania (TiO_2) nanoparticles with the particle volume fraction varying from 0% to 2% have been considered. A steady, laminar, 2-D flow with forced convective heat transfer has been taken into account in the Reynolds number range of $1 \leq Re \leq 40$. Finite-volume method based on SIMPLE algorithm is used to solve the governing equations. Three cases of analysis have been carried out in which the thermal conductivity and viscosity of nanofluids are determined using two sets of theoretical models and one set of experimental thermal conductivity and viscosity data from literature, respectively. Flow and heat transfer characteristics of nanofluids are found to be dependent on particle volume fraction and Reynolds number. Enhanced drag, altered wake lengths, modified flow separation and higher heat transfer rates are seen in nanofluids. But, a comparative scrutiny of the three cases; apparently shows that the flow and heat transfer characteristics differ both quantitatively and qualitatively between each case. This work promulgates the importance of a precise effective thermal conductivity and viscosity models for nanofluids to promote the real time application of nanofluids in developing high efficiency heat transfer systems.

1. Introduction

With the advent of high power and miniature devices, efficient heat removal has become indispensable to achieve the desired performance and reliable functioning of numerous products ranging from high functionality palm tops to huge automobile engines. Thus, development of energy efficient heat transfer systems has become the top priority in many high-tech industries. Heat transfer techniques which are being used widely at present; such as increasing the surface area by fins, micro-channel cooling and dual phase cooling techniques have already reached their limits due to the poor intrinsic thermal conductivities of conventional heat transfer liquids. Due to this pressing need for new and innovative cooling liquids, the novel concept of nanofluids, i.e., cooling liquids suspended with fine nanoparticles, was developed [1]. Nanofluids, by virtue of their enhanced and adjustable thermo-physical properties, find real-time applications in several heat transfer and energy systems [2–5]. Hence, analysis of flow and heat transfer characteristics of nanofluids has become a trending topic among researchers [6–17].

Many industrial applications like power electronics cooling, heat exchangers, chimney stacks, cooling towers, power generators and nuclear reactor fuel element cooling, etc., mimic the flow around circular cylinders [18]. For instance, a setting of nuclear fuel element cooling involving flow around circular cylinders is shown in Fig. 1. Owing to the enhanced effective properties of nanofluids and numerous heat transfer applications, numerical analysis of flow and heat transfer around cylinders using nanofluids has become an active area of research. Nanofluids due to their different effective thermo-physical properties exhibit modified flow and heat transfer characteristics. Valipour and Ghadi [19] 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 [20] and Brinkman model [21], 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. [22] also confirmed their observations on circular cylinder. A numerical study on forced convective nanofluid flow around a circular cylinder by Vegad et al. [23] in which the effective properties were calculated using Maxwell-Garnett model [24] and Brinkman model [21] also showed synonymous results. Abu-Nada et al. [25] in their numerical study on mixed convective heat transfer around a circular cylinder showcased that the heat transfer enhancement is dependent on

* Corresponding author.
E-mail address: ssdhinakar@gmail.com (S. Dhinakaran).

http://dx.doi.org/10.1016/j.molliq.2016.08.047

Nomenclature

Notations	
C_D	Drag coefficient, $\frac{F_D}{0.5\rho_f U_\infty^2 2a}$
c_p	Specific heat capacity, [JKg^{-1}K^{-1}]
θ_s	Flow separation angle
p	Dimensional pressure, [Nm^{-2}]
r	Dimensional radial coordinate
R_∞	Extent of external boundary
u, v	Dimensional components of velocity, [ms^{-1}]
m, n	Number of grids in r and θ direction
Re	Reynolds number, $\frac{\rho_f U_\infty a}{\mu_f}$
Nu_s	Local Nusselt number, $-\frac{k_{eff}}{k_f}\frac{\partial\Theta}{\partial n_s}$
C_P	Pressure coefficient, $\frac{P-P_\infty}{\frac{1}{2}\rho_f U_\infty^2}$
a	Radius of the cylinder
L_r	Wake length
P	Non-dimensional pressure, $\frac{p}{\rho_f U_\infty^2}$
R	Non-dimensional radial coordinate
t	Dimensional time, [s]
U, V	Non-dimensional components of velocity
Pr	Prandtl number, $\frac{\nu_f}{\alpha_f}$
Re_{cr}	Critical Reynolds number
Nu_M	Mean Nusselt number, $\frac{1}{\pi}\int_0^\pi Nu \sin\theta\, d\theta$
Greek symbols	
ρ	Density, [kgm^{-3}]
μ	Dynamic viscosity, [kgm^{-1}s^{-1}]
ω_s	Surface vorticity
Φ	Dependent variable, (U, V, Θ)
Θ^*	Dimensional temperature, [K]
θ^*	Dimensional coordinate
α	Thermal diffusivity, [m^{2}s^{-1}]
ν	Kinematic viscosity, [m^{2}s^{-1}]
ϕ	Nanoparticle volume fraction, [in %]
τ	Non-dimensional time, $\frac{tU_\infty}{a}$
Θ	Non-dimensional temperature, $\frac{(\Theta^*-\Theta^*_\infty)}{\Theta^*_S-\Theta^*_\infty}$
θ	Non-dimensional coordinate
Subscripts	
∞	Far field value
S	Surface value
m	Mean or average value
DV	Drag due to viscous forces
f, bf	Fluid or Base fluid
p	Nanoparticle
nf, eff	Effective property of nanofluid
DP	Drag due to pressure forces

thermal conductivity of nanoparticles and particle volume fraction. Bing and Mohammed [26] 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. Farooji et al. [27] 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. [28] 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. [29] 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 [30]. A buoyancy driven mixed convective flow around square cylinder using nanofluids by Sarkar et al. [31] 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 [32]. 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 [33].

In general, there are two approaches for numerically modeling the nanofluid flow and heat transfer. The primary approach is single-phase modeling which considers nanofluids to be a homogeneous fluid with effective properties. It is also hypothesized that the particles and basefluid are in thermal equilibrium and move with same velocity. The second method for modeling nanofluids is the two-phase approach, in which the basefluid and nanoparticles are considered to be heterogeneous and the velocity slip between them is taken into account. Even though articles on two-phase modeling of nanofluids are coming up [34–49], majority of the works available in literature follow single-phase approach due to its simplicity and lesser computational expense [50–52]. Single-phase approach utilizes theoretical models to predict the effective properties of nanofluids. But, review of related literature reveals that there is an inconsistency in prediction of effective properties of nanofluids. No single model is capable of comprehensively explaining all available experimental data [53]. It is also essential to note that, almost all available works on nanofluid flow around bluff bodies follow single-phase approach, in which available formulas based on

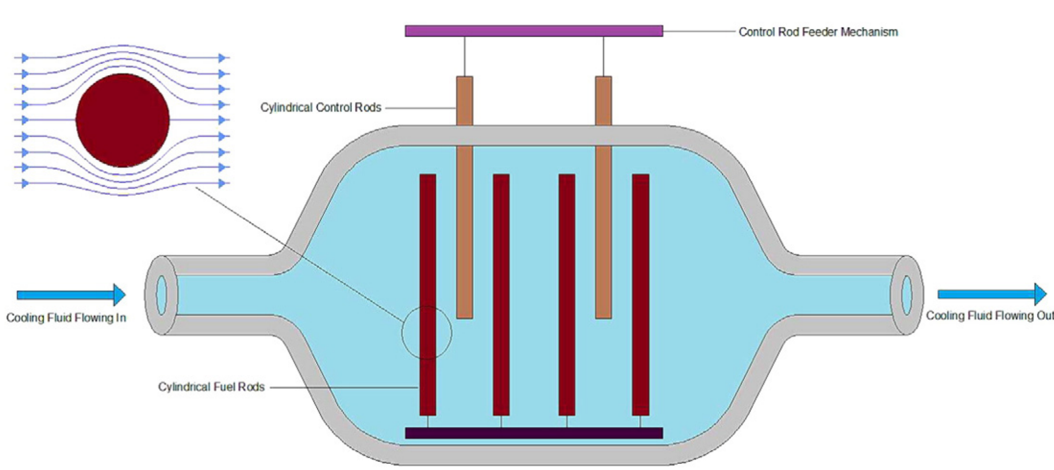

Fig. 1. A simple sketch of a nuclear reactor which involves the flow of coolant around control rods and fuel rods which imitate the scenario of flow around circular cylinders.