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A new correlation for convective heat transfer coefficient of water–alumina nanofluid in a square array subchannel under PWR condition

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HIGHLIGHTS

- Thermo-hydrodynamic properties of water–Al_2O_3 nanofluid at PWR condition is analyzed.
- Details of CFD simulation and validation procedure is outlined.
- Augmented heat transfer capacity of nanofluid is governed by larger pumping power.
- A new correlation for nanofluid *Nusselt number* in subchannel geometry is proposed.

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ABSTRACT

The computational fluid dynamic (CFD) simulation is performed to determine on the thermo- and hydrodynamic performance of the water–alumina (Al_2O_3) nanofluid in a square array subchannel featuring pitch-to-diameter ratios of 1.25 and 1.35. Two fundamental aspects of thermal hydraulics, viz. heat transfer and pressure drop, are assessed under typical pressurized water reactor (PWR) conditions at various flow rates ($3 \times 10^5 \leqslant Re \leqslant 6 \times 10^5$) using pure water and differing concentrations of water–alumina nanofluid (0.5–3.0 vol.%) as coolant. Numerical results are compared against predictions made by conventional single-phase convective heat transfer and pressure loss correlations for fully developed turbulent flow. It is observed that addition of tiny nanoparticles in PWR coolant can give rise to the convective heat transfer coefficient at the expense of larger pressure drop. Nevertheless, a modified correlation as a function of nanoparticle volume fraction is proposed to estimate nanofluid *Nusselt number* more precisely in square array subchannel.

1. Introduction

A major challenge faced by the engineers in nuclear industry is the quantification of the optimal flow of coolant and distribution of pressure drop across the reactor core since these are directly related to the power output and operating life time of reactor pressure vessel. While higher coolant flow rates leads to better heat transfer and higher Departure from Nucleate Boiling (DNB) limits, it also brings on higher pressure drop and larger dynamic loads on the core components. Thus, thermal hydraulic core analysis seeks to find proper working conditions with enhanced heat transfer and reduced pressure drop that assures both safe and economical operation of nuclear plants.

The concept of convective heat transfer enhancement by addition of micron sized particles was proposed few decades ago (Ahuja, 1975). However, the applicability of such microparticle colloids was restricted by particle settling, channel erosion, and clogging (Williams et al., 2008). Recently the idea of heat transfer enhancement through addition of tiny particles has been recommenced due to dramatic improvement in nanoparticulate colloids science. The improved heat transfer capacity of nanofluid is elucidated by several interesting phenomena such as amplified surface area of nano-sized particles, enhanced thermal conductivity of suspended particles in the fluid, aggrandized collisions and interactions between the fluid, particles and surfaces of the flow

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Nomenclature

Δp	pressure drop (Pa)	T_w	surface temperature of heater rod (K)
ρ	density (kg/m^3)	P	rod pitch (m)
v	Flow velocity (m/s)	D	rod diameter (m)
f_{iT}	turbulent friction factor (–)	Q	total heat input (W)
L	length of flow channel (m)	q''	heat flux (W/m^2)
l_e	entrance length (m)	$\dot{m}$	mass flow rate (kg/s)
EI	entrance length number (–)	φ	volume concentration of nanoparticles (%)
D_h	hydraulic diameter (m)		
μ	dynamic viscosity (N s/m^2)	*Subscripts*	
Re	Reynolds number (–)	nf	nanofluid
Nu	Nusselt number (–)	bf	basefluid
Pr	Prandtl number (–)	$s.c$	subchannel
Pe	Peclet number (–)	$c.t$	circular tube
h	convective heat transfer coefficient (W/m^2 K)	P	particle
k	thermal conductivity (W/m K)		
C_p	specific heat (J/kg K)		
T_m	bulk temperature of fluid (K)		

conduits and intensified mixing fluctuation and turbulence of the fluid (Xuan and Li, 2000).

Several experimental and numerical studies on convective heat transfer performance of different nanofluid under both laminar and turbulent flow regime exists in literature. Pak & Cho (Pak and Cho, 1998) experimentally evaluated the turbulent friction and heat transfer of dispersed fluids in a circular pipe using two different metallic oxide particles, γ-alumina (Al_2O_3) and titanium dioxide (TiO_2) with mean diameters of 13 and 27 nm, respectively. The results depicted that the *Nusselt number* for the dispersed fluids increased with increasing volume concentration as well as the *Reynolds number*. However, at constant average velocity, the convective heat transfer coefficient for the dispersed fluid was 12% less than that for pure water. This outcome was attributed to the significant increase in viscosity of nanofluid. They proposed the first empirical correlation for prediction of nanofluid *Nusselt number* under turbulent flow regime ($10^4 \leqslant Re \leqslant 10^5$).

Xuan and Li (Xuan and Li, 2003) observed the flow and convective heat transfer of the Cu–water nanofluid flowing through a straight brass tube and reported that the heat transfer coefficient of nanofluid containing 2.0 vol% Cu nanoparticles was increased by as much as 40% compared to that of water. The conventional Dittus–Boelter correlation failed to predict this augmented heat transfer data for nanofluid. They presented a new correlation for turbulent flow of nanofluid inside a tube and claimed that friction factor for nanofluid at low volume fraction did not produce extra penalty in pumping power.

Duangthongsuk and Wongwises (Duangthongsuk and Wongwises, 2010) performed experiments with TiO_2–water nanofluid under turbulent flow regime ($3000 \leqslant Re \leqslant 18{,}000$) in a horizontal tube counter flow heat exchanger. Their results revealed that albeit at lower concentration (⩽1.0 vol.%), nanofluid heat transfer coefficient was higher than the base fluid, at higher concentration (2.0 vol.%) it fell below the base fluid. This phenomenon was elucidated by the fact that as the concentration goes up, effect of viscosity increase becomes dominant over effect of thermal conductivity increase which leads to decrease in heat transfer performance of nanofluid.

Fotukian and Esfahany (Fotukian and Esfahany, 2010) investigated turbulent convective heat transfer and pressure drop of CuO–water nanofluid flowing through a tube and reported 25% increase in heat transfer coefficient with 20% penalty in pressure drop. They also noted that nanoparticle can lower the wall temperature substantially as the thermal energy transfer between the wall and nanofluid is augmented. Sharma et al. (Sharma et al., 2012) proposed a new Micro Convection Model stating that heat transfer enhancement is attributed from the combined effect of Brownian motion of the particle and the forced convection of single phase nanofluid. The Brownian motion arises mainly from the density difference between particles and fluid. Other notable works on turbulent heat transfer enhancement of nanofluid in tubular test sections are reported by (Arani and Amani, 2012; Kim et al., 2009; Sajadi and Kazemi, 2011; Sundar and Sharma, 2010).

However, an interesting experiment performed by Williams and Boungiorno (Williams et al., 2008) showed that turbulent convective heat transfer behavior of nanofluid in a tube can be predicted by traditional correlations given dimensionless parameters are based on experimentally measured temperature and loading dependent thermal conductivities and viscosities. A list of pertinent empirical correlations for nanofluid *Nusselt number* under fully developed turbulent flow is provided in Table 1.

Besides turbulent flow, a number of experiments as reported by (Asirvatham et al., 2009; Heris et al., 2006; Hwang et al., 2009; Suresh et al., 2012; Wen and Ding, 2004; Yang et al., 2005), shows that nanofluid is also capable of elevating the convective heat transfer coefficient notably under laminar flow condition. However, an experiment carried out by He et al. (He et al., 2007) with TiO_2–water nanofluid in a vertical copper tube proved that nanofluid heat transfer enhancement under laminar flow is much less than under turbulent flow.

A number of numerical studies are also reported on this interesting phenomenon. One such notable work was done by Maïga et al. (El Bécaye MaïCa et al., 2006) who numerically investigated fully-developed turbulent flow of water/Al_2O_3 nanofluid through circular tube under the constant heat flux boundary condition and proposed a new correlation. Later simulations on this issue in various flow domains such as round tubes, radiator tubes, annulus etc. were carried out by (Bianco et al., 2011; Demir et al., 2010; Izadi et al., 2009; Namburu et al., 2009; Roy et al., 2004; Yang and Lai, 2010) who also reported substantial increase in nanofluid convective heat transfer coefficient compared to base fluid.

Detailed review of the published investigations on convective heat transfer performance of different nanofluids are presented by (Daungthongsuk and Wongwises, 2007; Hussein et al., 2014; Kakac and Pramuanjaroenkij, 2009; Wang and Mujumdar, 2008; Wen et al., 2009; Wu and Zhao, 2013).

In contrary to above literatures, researches on convective heat transfer performance of nanofluid under typical PWR condition