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Full Length Article

Assessment of nanofluids for laminar convective heat transfer: A numerical study

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ABSTRACT

In this article, a numerical study of laminar forced convective heat transfer in a circular tube is presented, incorporating entropy generation and wall shear stress analysis. Three different nanofluids, Al_2O_3–water, ZrO_2–water and TiO_2–water, are considered under constant heat flux boundary condition using single phase approach. Performance of nanofluids is compared with the base fluid by keeping the Reynolds number, mass flow rate and discharge criteria constant for various volume fractions of nanoparticles. A non linear dependence of base fluid thermo-physical properties with temperature is considered in this study. For same Reynolds number comparison criteria, the heat transfer coefficient for nanofluids is found to be significantly higher as compared to the base fluid. However, for same mass flow rate and same discharge comparison criteria, an increment in the heat transfer coefficient is found to be insignificant. The performance factor is found to be poor for the nanofluids and also, it decreases with an increase in particle loading. However, it is nearly similar for all kinds of comparisons. The entropy generation decreases for the nanofluids under same Reynolds number comparison, but the decrement is found to be negligible for the other two comparison bases. The wall shear stress increases with an increase in particle loading for all three comparisons.

1. Introduction

Colloidal suspensions made by dispersing nanoparticles (NPs) in a base fluid with various concentrations are termed as nanofluids (NFs). The concept of NFs was first materialized by Choi [1] after performing experimental investigations on various nanoparticles in Argonne National Laboratory (ANL). NPs basically are solids, which influence base fluid thermo-physical properties such as thermal conductivity, viscosity, specific heat and density [2]. The thermal conductivity of conventional base fluids increases by adding NPs, which increases heat transfer coefficient. But at the same time, viscosity also increases, which in turn increases the pumping power. The trade-off between these two contradictory effects on thermo-physical properties is vital when considering NFs as heat transfer fluids. Studies on convective heat transfer of NFs, mostly in circular tubes, could be found from the literature [3–5]. Frequently, comparing NF performance with base fluids for laminar conditions has been reported at equal Reynolds number. Li and Xuan [6] experimentally investigated Cu/water NF in a circular tube of length 800 mm and diameter 10 mm, under same Reynolds number (Re) comparison criteria and constant heat flux boundary condition. The effects of the volume fractions (0.5–2%) and the Re (800–2100) on the heat transfer and flow characteristics were examined. They declared maximum 60% enhancement in heat transfer coefficient (HTC) for 2.0% particle volume fraction. Wen and Ding [7] performed a series of experiments to investigate the effect of Re (500–2100) and particle volume fraction (0.6 and 1.6%) on the heat transfer characteristics of the y-alumina/water NF in a circular tube of length 950 mm and diameter 4.5 mm. They reported 47% enhancement in local HTC at local distance $(x/D) = 63$, for 1.6% particle loading (volume fraction) for Re 1600. They also utilized same Re comparison criteria under constant heat flux boundary condition. Maïga et al. [8] investigated y-alumina/water and y-alumina/ethylene glycol under constant heat flux boundary condition for Re less than 1000. They reported 67% enhancement in HTC for 7.5% particle loading (volume fraction) for Re 1000. A circular tube of length 1 m and diameter 10 mm was selected for comparing the NF performance with two different base fluids at the same Re under a wide range of

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Table 1
Experimental studies for forced convective heat transfer of NFs for laminar flow conditions.

Author	Basis of comparison	Nanofluid	Particle loading	Reynolds no. (Re)	Geometry	Result
Li &Xuan [6]	Same Re	Cu/water	0.5–2 vol%	800–2100	D = 10 mm L = 800 mm	Heat transfer coefficient (HTC) increases up to max. 60% for 2.0 vol% particle loading.
Wen & Ding [7]	Same Re	γ-Alumina/water	0.6, 1 & 1.6 vol%	500–2100	D = 4.5 mm L = 950 mm	47% enhancement in local HTC at x/D = 63 for 1.6 vol% particle loading, Re = 1600
Maïga et al. [8]	Same Re	γ-Alumina/water, γ-Alumina/ Ethylene Glycol	0–10 vol%	250–1000	D = 10 mm L = 1m	63% enhancement in HTC for 7.5 vol% particle loading, Re = 1000
Zeinali Heris et al. [9]	Same Re	CuO/water, Alumina/water	0.2–3 vol%	650–2050	D = 6 mm L = 1m	HTC increases with decrease in particle size and increase in particle loading
Chen et al. [10]	Same Re	Titanate nanotube/water	0.5, 1.0 & 2.5 wt%	1100–2300	D = 3.9 mm L = 2m	Enhancements in local HTC at 0.5, 1.0 and 2.5 wt% at x/D = 50.4 are respectively 11.8%, 23.5% and 24.9%.
Anoop et al. [11]	Same Re	Alumina/water	1, 2, 4 & 6 wt%	500–2000	D = 4.75 mm L = 1.2m	For x/D = 147, for 45 nm particle (4 wt%) with Re = 1550, the enhancement in HTC was around 25% whereas for 150 nm particle it was found to be around 11%.
Suresh et al. [12]	Same Re	Alumina–Cu/water Hybrid	0.1 vol%	500–2000	D = 10 mm L = 1m	Max. enhancement of 13.56% in Nusselt number at a Reynolds number of 1730
Davarnejad et al. [13]	Same Re	Alumina/water	0.5–2.5 vol%	420–990	D = 6 mm L = 1m	HTC increases by increasing velocity and decreasing particle diameter
Haghighi et al. [14]	Same Re Same m* Same Q**	Alumina, Zirconia & Titanate/ water	9 wt%	200–2200	Microtube D = 0.30 mm L = 30 cm	30% enhancement in HTC when compared keeping the same Re, but negligible enhancement for other two comparison bases.
Haghighi et al. [15]	Same pumping power	Alumina, Zirconia & Titanate/ water	9 wt%	10–2300	D = 3.7 mm L = 1.5m	At equal Re comparison, HTC increased by 8–23%, whereas at equal pumping power, HTC decreased

m* = mass flow rate (kg^{s-1}), Q** = Discharge ($m^{-3}s^{-1}$), L, D = Length and diameter of test section.

particle volume fractions (0–10%). Zeinali Heris et al. [9] investigated laminar convective heat transfer of metal oxide NFs (CuO/water and alumina/water) under same Re comparison criteria for a wide range of particle loadings (0.2–3% by volume). They considered a circular tube of length 1 m and diameter 6 mm for their analysis. Also, they reported that the HTC of NFs increases with a decrease in particle size and increase in particle loading. Chen et al. [10] investigated local heat transfer characteristics of titanium oxide nanotube/water NF under laminar conditions (Re = 1100–2300) for three different particle loadings (0.5, 1 and 2.5% by weight). They utilized a circular tube of length 2 m and diameter 2.9 mm with constant heat flux boundary condition under the same Re comparison criteria for their analysis. Also, they reported enhancement in local HTC for NFs at 0.5, 1 and 2.5% particle loadings as 11.8%, 23.5% and 24.9% respectively. Similar studies [11–13] were reported showing enhancement in HTC of various NFs under laminar conditions keeping the same Re number comparison criteria.

However, a few studies were also reported with other bases of comparison. Owing to higher viscosity of NFs, they must be operated in higher mass/volume flow rates to have a Reynolds number equal to that of their corresponding base fluid. Comparing heat transfer coefficients of NFs and base fluids at equal mass flow rates, equal discharges, equal pumping powers and equal pressure drops could be a reasonable method. Haghighi et al. [14] investigated the heat transfer characteristics of three different NFs (alumina/water, zirconium oxide/water and titanium oxide/water) under laminar condition (Re = 200–2200) keeping the same Re, the same mass flow rate and the same discharge comparison criterion in a micro tube. They reported a maximum 30% enhancement in HTC when compared keeping the same Re but negligible enhancement for other two comparison bases. They also reported in another investigation for circular tube [15] that at an equal Re comparison HTC increased by 8–23% whereas at an equal pumping power comparison it decreased. The experimental studies for forced convective heat transfer of NFs for laminar flow conditions are summarized in Table 1.

Many numerical works investigating NFs are reported recently. In the year 2014, Togun et al. [16] simulated Cu/Water NF using single phase modeling approach to study its heat transfer characteristics over a backward-facing step. They reported increment in HTC for NFs over the base fluid keeping the same Re comparison criteria. In the same year, Goodarzi et al. [17] also investigated Cu/Water NF mixed convection in a rectangular shallow cavity using a two-phase mixture model. They reported that for a specific Grashof and Richardson number, the HTC increases with increase in particle loading. Safaei et al. [18] in the same year investigated multi walled carbon nanotube/Water NF in a forward facing contracting channel using single phase simulation technique. They also reported increment in HTC for NF over base fluid under the same Re criteria. No devoted numerical study, exploring comparison criteria other than same Re comparison, is found in literature. This gives the motivation to assess NFs for laminar convective heat transfer using non conventional comparison approaches.

In this study, Al_2O_3/water, ZrO_2/water and TiO_2/water NFs are numerically investigated for equal Re, equal mass flow rate and equal discharge comparison criteria under constant wall heat flux boundary condition. A complete assessment of NFs for laminar flow convective heat transfer is carried out which includes performance factor, entropy generation and wall shear stress calculations too. The particle loading is varied from 0.5% to 2% with an interval of 0.5% by volume. A circular tube with length of 1 m and diameter of 0.01 m with laminar flow conditions (Re = 1150–1900) under single phase modeling approach is adopted for the heat transfer analysis. Mass flow rates (0.006–.011 kg/s) and volume flow rates (0.08–.13 m^3/s) are selected such that the flow remains laminar under same mass flow and same volume flow rate comparison bases. Performance factor, entropy generation and average wall shear stress for all NFs are also investigated.

2. Mathematical modeling

The mathematical modeling of the NFs is done using single phase approach. In literature many studies are reported using single phase modeling to simulate NFs [19,20]. However, multi-phase techniques are more accurate and complex for simulating NFs than single