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A combined numerical and experimental study on the forced convection of Al_2O_3-water nanofluid in a circular tube

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ABSTRACT

This research investigates the contribution of Al_2O_3 nanoparticle suspensions on laminar forced convection heat transportation of Al_2O_3-water nanofluid flowing through a circular tube. In this regard, initially, the variation of the wall and bulk fluid temperatures and the values of local Nusselt numbers are experimentally evaluated along the tube. Next, numerically, the effect of various inlet temperatures from 25 to 50 °C on the important characteristics of the problem under study including pressure drop, Nusselt number and entropy generation are further examined through the constant property and temperature-dependent property modeling. The flow rate of the working fluid was ranged from 24 to 180 cm^3/min corresponding Re = 120–2000. The imposed heat flux was 5.51×10^2–1.23×10^4 W/m^2. It is found that the addition of nanoparticles leads to the reduction of wall temperature and the enhancement of the Nusselt number, while it also causes an increase in the pressure drop along the tube. The results further reveal that the variable-property simulation provides more accurate predictions. The predicted pressure drop is decreased, and the predicted Nusselt number is increased by considering the temperature dependency of thermophysical properties of the nanofluid.

1. Introduction

A heat exchanger has a key role in various industrial purposes such as electronics, transportation, power stations, and production processes [1]. Various methods have been used to intensify the heat transportation including applying electrical or magnetic fields, injection or suction of fluid, vibration of heated surface, and heat surface area addition (fins or ribs) [2,3]. However, the heat transfer performance is highly dependent on the specific heat and thermal conductivity of the coolant. Therefore, enhancing these characteristics of the coolants could significantly improve the heat transfer efficiency. A proper way to achieve this goal is the implementation of an appropriate type of nanofluids which can deliver super thermal performance [4,5]. In fact, Yu and Choi [6] were the first researchers who reported the beneficial influence of addition of nanoparticles into the base fluid to improve the thermal conductivity of the coolants. The literature reporting application of nanofluids for heat transfer intensification in various processes are abundant [7–10]. Modeling and identification of physical mechanisms corresponding the anomalous improvement in the effective thermal conductivity of nanofluids with low nanoparticle contents has been a concern by various researchers [11–14]. Hosseini et al. [15] proposed a dimensionless model to predict the thermal conductivity of Al_2O_3-water nanofluids. Amani et al. [16,17] investigated the thermal conductivity and viscosity of ferrite nanofluids. Alawi et al. [18] developed viscosity and thermal conductivity models of metallic oxides nanofluids including Al_2O_3, CuO, SiO_2 and ZnO nanofluids. Pryazhnikov et al. [19] conducted an experimental study to evaluate the thermal conductivity of more than 50 different nanofluids containing SiO_2, Al_2O_3, TiO_2, ZrO_2, CuO, and diamond nanoparticles dispersed in water, ethylene glycol, and engine oil as the base fluid. Another attempt is made by Dasgupta and Mondal [20] to model the thermal conductivity of various oxide-water, oxide-ethylene glycol (EG), metal-water and metal-EG systems containing ZnO, CuO, TiO_2, and Al_2O_3 nanoparticles.

Various investigations have been conducted focusing on the forced convective heat transportation of nanofluids. Minakov et al. [21] investigated the turbulent forced convection of ZrO_2 nanofluid in channels with cylindrical and spherical hollows. Mohebbi et al. [22] studied the forced convection of the CuO, Al_2O_3 and TiO_2 water based nanofluids in an extended surfaces

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Nomenclature

C_p	specific heat of water (J kg^{-1} K^{-1})
d_i	inner diameter of circular tube
d_{np}	nanoparticle diameter
d_o	outer diameter of circular tube
f	Fanning friction factor
k	thermal conductivity of the coolant (Wm^{-1} K^{-1})
k^*_{nf}	thermal conductivity ratio of nanofluid and pure water
l^+_h	length of heated section of circular tube
l^+_u	length of upstream side of the circular tube
N_s	dimensionless entropy generation rate
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
Δp	pressure drop along the channel (kPa)
r	circular tube radius
Re	Reynolds number
q''_o	heat input carried by the working fluid
Q	volumetric flow rate
T	temperature (°C)
t_w	wall thickness of circular tube
u	velocity of fluid (m s^{-1})
u^+_0	average velocity of fluid at inlet (m s^{-1})

Greek symbols

θ	dimensionless temperature
ϕ_{np}	volume fraction of nanoparticles
$\Delta\dot{s}$	total entropy generation rate
ε_{Nu}	Nusselt number effectiveness
μ	dynamic viscosity (kg m^{-1} s^{-1})
μ^*_{nf}	dynamic viscosity ratio of nanofluids and pure water
ρ	coolant density (kg m^{-3})
ω	mass fraction of nanoparticles
ψ	stream function

Subscripts

btd	bulk temperature difference
eff	effective
f	base fluid
i	inner
in	inlet
itd	inlet temperature difference
m	Al_2O_3-water nanofluid
np	nanoparticles
o	outer
out	outlet
w	wall

channel. Ambreen and Kim [23] examined the laminar forced convection of Al_2O_3 and TiO_2 nanofluids in micro and mini channels and evaluated the performance of homogeneous, discrete phase model and Eulerian-Eulerian (Mixture, Volume of Fluid, Eulerian) models. Selimefendigil and Öztop [24] studied the forced convection of pulsating nanofluid flow over a backward facing step with a corrugated bottom wall. They also proposed an efficient method for thermal predictions using combined proper orthogonal decomposition and artificial neural network. Hwang et al. [25] studied the thermal performance of a fully-developed laminar flow of Al_2O_3-water nanofluid in a tube. They showed that the thermal conductivity could be incremented up to 8% by addition of 0.3 vol% nanoparticles. Rea et al. [26] studied the viscous pressure loss and heat transportation of water-based ZrO_2 and Al_2O_3 nanofluids in a vertical tube and reported 27% and 17% improvement in the thermal performance, respectively. Ho et al. [27,28] examined the comparative performance of Al_2O_3-water nanofluids and PCM suspensions for heat transfer improvement in a tube. They revealed that the hybrid suspension outperforms the pure nanofluid, PCM suspension, or water. However, it was observed that implementation of the hybrid suspension also increases the pressure drop due to the subsequent increase in the viscosity. Therefore, both viscosity and thermal conductivity should be taken into consideration for different applications. Recently, Ho et al. [29] further explore the forced convection effectiveness of Al_2O_3-water nanofluids flowing through horizontal pipes. They concerned the effect of different nanoparticle content and various inlet temperatures. According to their results, the greater figure of merit (FOM) and average heat transfer effectiveness could be obtained for the cases with elevated inlet temperature. The benefit of applying magnetic field on the forced convection of nanofluids is also investigated by many researchers [30–32].

Numerous numerical investigations have also conducted on the forced convection effectiveness of nanofluids. Maïga et al. [33] studied the problem of laminar flow of γAl_2O_3-water and γAl_2O_3-ethylene glycol mixtures in a system of parallel, coaxial and heated disks under a uniform heat flux. They revealed that increasing the concentration of nanoparticles improves the thermal performance of nanofluids. In another study, Lotfi et al. [34] investigated the heat transportation of Al_2O_3-water nanofluids and compared the predictive ability of the single-phase model and two-phase mixture model formulations. They reported that two-phase mixture model outperforms the single-phase and two-phase Eulerian models. Later, Ho et al. [35] carried out the influence of temperature-dependent thermophysical properties of Al_2O_3-water nanofluids on the laminar forced convection effectiveness in a tube under a uniform heat flux. They found that the impacts of thermophysical properties and inlet temperature on the Nusselt number are much more profound when the temperature rise in the heated section and nanofluid concentration are increased.

This article is the second phase of our continuing attempt (see Ref. [29]) regarding further elucidate the thermal performance of the Al_2O_3-water nanofluids as a functional fluid in tubes. Accordingly, the primary objective of this work is to experimentally and numerically examine the thermal performance of this nanofluid along with the pressure drop and entropy generation in an *iso*-flux heated tube subjected to different inlet nanofluid temperatures.

2. Analysis

The numerical representation of the system subjected to analysis is presented in Fig. 1, in which thermal properties of the nanofluid flow in a circular tube of inner radius r^+_i and wall thickness t^+_w is to be estimated. A constant heat flux of q''_o is imposed to the outer surface of the tube over a finite length of l^+_h. The fully-developed velocity profile is guaranteed by providing a sufficient length of l^+_u at the upstream side of the tube. Several assumptions are considered to simplify the analysis conducted in this study, as follows:

1. The nanoparticles have the shape of a rigid spherical particle and are uniform in diameter.
2. The nanofluid has a Newtonian behavior with a homogeneous distribution of nanoparticles.