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Experimental and numerical investigation of nanofluids heat transfer characteristics for application in solar heat exchangers

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ABSTRACT

One of the innovative methods of improving heat transfer characteristics of heat exchangers in solar systems is applying nanofluids as the heat transfer media. In this study, laminar convective heat transfer of water-based TiO_2 nanofluid flowing through a uniformly heated tube has been investigated via experiments and numerical modeling. The thermal conductivity and dynamic viscosity of the prepared nanofluids have also been measured and modeled at different temperatures and nanoparticle concentrations. Based on the results, a maximum enhancement of 21% in average heat transfer coefficient has been obtained using TiO_2/water nanofluids. For the numerical section, the single-phase model was compared with the common two-phase numerical approaches. The numerical investigation indicated that the predicted heat transfer coefficients using single-phase and common two-phase approaches, even based on experimental thermophysical properties of nanofluids, underestimate and overestimate the experimental data, respectively. Therefore, some modifications are implemented to the common two-phase model in order to obtain more accurate predictions of the heat transfer characteristics of nanofluids. This modified model investigated the effects of particle concentration, particle diameter, and particle and basefluid material on the heat transfer rate at different Reynolds numbers. The results indicated that the convective heat transfer coefficient increases with an increase in nanoparticle concentration and flow Reynolds number, while particle size has an inverse effect. The obtained results can be very useful to the investigation of the potential application of nanofluid-based solar collectors.

1. Introduction

A solar-liquid heating collector transforms the solar energy to the internal energy of the transport medium as a kind of heat exchanger. The performance of these heat exchangers can be enhanced by improving thermophysical properties of the conventional heat transfer fluids. Recently, nanofluids have attracted great interest due to their valuable heat transfer characteristics in comparison with conventional fluids.

Several researchers [1–9] have investigated the application of these new media of heat transfer in solar collectors. Yousefi et al. [1] experimentally revealed that the Al_2O_3/water nanofluid enhances the efficiency of flat-plate collectors by 28.3%. In another study, Yousefi et al. [2] examined the effects of pH values of carbon nanotube nanofluids on the efficiency of a flat-plate solar collector. Kameya and Hanamura [3] demonstrated that the radiation absorption characteristics of base fluid were enhanced dramatically by adding Ni nanoparticles. Lenert and Wang [4] examined the capability of nanofluids as volumetric receivers in concentrated solar applications using the suspension of carbon-coated cobalt nanoparticles into Therminol VP-1 fluid. He et al. [5] experimentally expressed the suitable photo-thermal properties of Cu/H_2O nanofluids for employment in direct absorption, solar thermal energy systems.

Moreover, the recent review papers [10,11] indicated that nanofluids have great potential for applications in solar systems such as solar collectors [12], photovoltaic thermal systems [13], and thermal energy storage systems [14].

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Nomenclature

A	cross sectional area, m^2
c_p	specific heat, J/(kg K)
d_p	particle diameter, m
D_{pipe}	pipe diameter, m
h	heat transfer coefficient, $W/(m^2 K)$
k	thermal conductivity, W/(m K)
l_p	nanotube length, m
L_{pipe}	pipe length, m
Nu	Nusselt number, hD_{pipe}/k_e
p	pressure, Pa
q''	heat flux, W/m^2
R	electrical resistance, Ω
Re_e	Reynolds number, $\rho_e U_{in} D_{pipe}/\mu_e$
t	time, s
T	temperature, K
v	velocity vector, m/s
V	phase volume, m^3
V_{in}	inlet voltage to the Wheatstone bridge, V

Greek Symbols

ρ	density, kg/m^3
μ	dynamic viscosity, kg/(m s)
φ	volume concentration
κ	Boltzmann constant, 1.381×10^{-23} J/K

Subscripts

e	effective properties of nanofluid
f	base fluid
i	phase i
p	nanoparticle
w	wall

Table 1
Literature review on the experimental study of laminar convective heat transfer of nanofluids in the straight tubes.

Investigator(s)	Particle type	Particle shape	Particle concentration	Geom. L_{pipe}/D_{pipe}	Boundary condition	Enh. of h	Classical correlation ability
Li and Xuan [18]	Cu	$d_p < 100$ nm	0.3–2 vol.%	80	q'' = Const.	60%	x
Wen and Ding [19]	Al_2O_3	$d_p < 27$–56 nm	0.6–1.6 vol.%	215	q'' = Const.	30%	x
Ding et al. [20]	CNT	$d_p < 100$ nm $l_p >> 100$ nm	0.1–0.5 wt.%	215	q'' = Const.	300%	x
Heris et al. [21]	Al_2O_3 CuO	$d_p = 20$ nm $d_p = 50$–60 nm	0.2–3 vol.%	167	T_w = Const.	–	x
He et al. [22]	TiO_2	$d_p = 95$ nm	0.2–1.2 vol.%	483	q'' = Const.	26%	x
Chen et al. [23]	TNT	$d_p = 10$ nm $l_p = 100$ nm	0.5–1.5 wt.%	483	q'' = Const.	25%	–
Hwang et al. [24]	Al_2O_3	$d_p = 30$ nm	0.01–0.3 vol.%	1380	q'' = Const.	8%	x
Lai et al. [25]	Al_2O_3	$d_p = 20$ nm	0.5–1 vol.%	490	q'' = Const.	55%	x
Anoop et al. [26]	Al_2O_3	$d_p = 45$, 150 nm	1–4 wt.%	250	q'' = Const.	13%	–
Heris et al. [27]	Cu	$d_p = 25$ nm	0.2–2.5 vol.%	167	T_w = Const.	45%	x
Rea et al. [28]	Al_2O_3 ZrO_2	$d_p = 50$ nm	0.65–6 vol.% 0.32–1.32 vol.%	244	q'' = Const.	22% 3%	OK
Liao and Liu [29]	CNT	$d_p = 10$–20 nm $l_p = 1$–2 μm	0.5–2 wt.%	217	q'' = Const.	60%	x
Kim et al. [30]	Al_2O_3 C	$d_p = 20$ nm	3 vol.% 3.5 vol.%	437	q'' = Const.	20% 8%	–
Asirvatham et al. [31]	Ag	$d_p < 100$ nm	0.3–0.9 vol.%	683	T_w = Const.	150%	–
Chandrasekar and Suresh [32]	Al_2O_3	$d_p = 43$ nm	0.1–0.2 vol.%	247	q'' = Const.	60%	–
Ferrouillat et al. [33]	SiO_2	$d_p = 22$ nm	2.3–19 vol.%	50	T_w = Const.	–	OK
Kumaresan et al. [34]	CNT	$d_p < 100$ nm	0.15%–0.45 vol.%	233	–	125%	x
Rayatzadeh et al. [35]	TiO_2	–	0.1–0.025 vol.%	652	q'' = Const.	65%	–
Esmaeilzadeh et al. [36]	Al_2O_3	$d_p = 15$ nm	0.5–1 vol.%	143	q'' = Const.	19%	–
Heyhat et al. [37]	Al_2O_3	$d_p = 40$ nm	0.1–2 vol.%	400	T_w = Const.	32%	x
Wang et al. [38]	CNT	$d_p = 20$–30 nm $l_p = 5$–30 μm	0.05–0.24 vol.%	1000	q'' = Const.	190%	x

X: Classical correlations fail to predict convective heat transfer of nanofluids.
OK: Classical correlation succeed to predict convective heat transfer of nanofluids.

Most of the investigations on the application of nanofluids in solar collectors have been limited to energy and exergy analysis. There are few studies on the analysis of the hydrodynamic and convective heat transfer characteristics of nanofluids in solar systems [6].

As highlighted in several review papers [15–17], a substantial amount of experimental work has been reported on the thermal behavior of different types of nanofluids flowing through various heat exchanger geometries; among them, the circular straight tubes have received more attention in this study since they are the main component of different types of solar collectors. In this geometry, a variety of nanoparticle types and concentration levels under various thermal boundary conditions have been examined, which are listed in Table 1. This table reports the ratio of tube length to the tube diameter (L_{pipe}/D_{pipe}) and the amount of heat transfer coefficient enhancement due to the use of nanofluids. Furthermore, the ability of classical models for predicting the heat transfer coefficient of nanofluid flow through the tubes is determined.

It is evident from Table 1 that nearly all researchers have reported that the classical correlations, such as those mentioned by Shah and London [39], are incapable of predicting the superior convective heat transfer characteristics of nanofluids, which demonstrates the need for remodeling of the nanofluids heat transfer.

As for numerical modeling, numerous researchers [40,41] have adopted the single-phase approach for the simulation of