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Thermal performance of a counter-current double pipe heat exchanger working with COOH-CNT/water nanofluids

M.M. Sarafraz *, F. Hormozi, V. Nikkhah

Faculty of Chemical, Petroleum and Gas Engineering, Semnan University, Semnan, Iran

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ABSTRACT

The main aim of this work is to investigate the heat transfer coefficient and pressure drop characteristics of carbon nanotube water-based nanofluids inside the double pipe heat exchanger. Diameters of inner and outer copper tubes (ID and OD) were 6.35 and 12.7 mm, respectively (in accordance with ANSI/ASME/API 5L). Nanofluids were prepared using two-step method at mass concentrations of 0.1–0.3% by dispersing the COOH functionalized multi-walled carbon nanotubes, (FCNTs as purchased) into the deionized water. Since this work can technically be important, thermal conductivity of nanofluids were experimentally measured using KD2 Decagon instrument at different mass concentrations and temperatures. To assess the thermal performance of nanofluids, forced convection experiments were conducted at laminar and turbulent flow regimes ($900 < Re < 10{,}500$). Influence of different operating parameters including: flow rate, mass concentration of nanofluid, inlet temperature of nanofluid on the heat transfer coefficient and pressure drop is studied. Results demonstrated that presence of carbon nanotube can enhance the thermal conductivity up to 56% at wt.% = 0.3. Likewise, CNT/water nanofluids have higher convective heat transfer coefficient in comparison with water, which is due to internal thermal conduction of CNTs. Longer stability was seen due to the COOH group attached to the CNTs. Small penalty is reported for pressure drop and friction factor as well, which is due to the presence of carbon nanotube inside the bulk of base fluid. Considering the influence of CNTs on heat transfer and pressure drop, it was found that carbon nanotube nanofluids can drastically enhance the thermal performance of heat exchanger in comparison with water up to 44% at maximum mass concentration (wt.% = 0.3).

1. Introduction

Heat exchangers play a vital, irrefutable role in many industrial processes such as: petrochemical plants, power cycles, refineries and transportations. Due to the continuous progress in thermal engineered systems, enhancement in thermal performance of such systems has always been in-demand for the industrial sectors. Thermal properties of conventional coolants such as water have been a challenge in high-heat flux applications, which limits application of these coolants in some heat transfer media [1–6]. The heart of a cooling system is its working fluid. Despite considerable efforts to improve the rate of heat transfer by different active/passive ways, there are still problems, which have remained unsolved. Extended surfaces have been the most common used but passive way for enhancing the rate of heat transfer, although space limitation is the major drawback of using this technique.

As a relatively new technique, nanofluid has been introduced by Choi [7] which is a fluid comprising the solid particles (usually a metal oxide powder or none-metallic thermal conductive powder) with mean size of 1–100 nm suspended in a base fluid (usually a traditional coolant such as: water or ethylene glycol). Nanofluid has been considered as a promising way for enhancing the heat transfer in fluids. In fact, nanofluids have higher thermal properties such as viscosity, density and thermal conductivity and implementing the nanofluids is also regarded as a passive, available and cost-effective way for industries.

Many studies have been conducted on the measurement of the evaluation of thermal performance of nanofluids in heat exchanging media [8–13]. For instance, recently, Ryzhkov et al. [14] conducted experiments on laminar convective heat transfer of water–alumina nanofluid in a circular tube with uniform heat flux using alumina/water nanofluid and showed that nanofluid can have better performance than the base fluid in the range of low pumping power and low inlet velocity. However, they did not consider the tradeoff behavior between pressure drop and heat transfer enhancement. Ho et al. [15] experimentally investigated the

* Corresponding author.
E-mail addresses: mohamadmohsensarafraz@gmail.com (M.M. Sarafraz), fhormozi@semnan.ac.ir (F. Hormozi), Vahid.nikkhah7@gmail.com (V. Nikkhah).

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Nomenclature

A	area, m^2
C_p	heat capacity, J kg^{-1} °C^{-1}
f	fanning friction factor
h	convective heat transfer coefficient, W m^{-2} °C^{-1}
k	thermal conductivity, W m^{-1} °C^{-1}
L	length, m
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
P	pressure, Pa
Q	heat, W
Re	Reynolds number
T	temperature, °C
u	fluid velocity, m s^{-1}
wt.%	weight fraction

Subscripts and superscripts

ave	average
b	bulk
bs	base fluid
hot	heating loop
nf	nanofluid
cold	cooling loop
in	inlet
out	outlet
n	number of data points
m	mean
m	mass flow, kg s^{-1}
w	wall

Greek symbols

α	thermal diffusion, m^2 s^{-1}
ρ	density, kg m^{-3}
μ	viscosity, kg m^{-1} s^{-1}
ϕ	volume fraction
Δ	difference

influence of elevated inlet fluid temperature on the turbulent forced convective heat transfer of alumina–water nanofluid in copper horizontal circular tube at a fixed heating power. Results showed that turbulent forced convection heat transfer effectiveness of the alumina–water nanofluid over that of the pure water can be further uplifted by elevating its inlet temperature entering the circular tube well above the ambient, thereby manifesting its potential as an effective warm functional coolant. Specifically, an increase in the averaged heat transfer enhancement of more than 44% arises for the nanofluid. However, they did not specify the exact influence of nanofluid on pressure drop. They only reported the results of enhancement for the heat transfer coefficient.

Somewhere else, Bahiraei et al. [16] numerically investigated the performance of the water based Mn–Zn ferrite magnetic nanofluid in a counter-flow double-pipe heat exchanger. They postulated that nanofluid flows inside the tube section as coolant, and the hot water is introduced into the shell (annulus) side. They showed that by increasing each of the parameters of concentration, particle size and magnitude of the magnetic field, higher pressure drop will be obtained followed by enhancement of heat transfer. More importantly, it was found at higher Reynolds numbers, the role of the magnetic force is diminished. In this study they ignored the role of nanoparticle on the friction factor and pressure drop and also they did not report the thermal performance of the system as function of pressure drop.

Pressure drop and convective heat transfer of water and nanofluids in a double-pipe helical heat exchanger was investigated by Wu et al. [17]. In contrast to previous studies, for both laminar and turbulent flow, no anomalous heat transfer enhancement was found. The heat transfer enhancement of the nanofluids compared to water was reported to be from 0.37% to 3.43% according to the constant flow velocity basis, while for double pipe helical heat exchanger, Reddy et al. [18] reported that heat transfer coefficient and friction factor can get enhanced by 10.73% and 8.73% for 0.02% volume concentration of TiO_2 water based nanofluids, which was controversial in comparison with that of reported by Reddy et al. [18].

For an annular heat exchanger, Sarafraz et al. [1,2] reported the reduction of heat transfer coefficient for forced convective and nucleate boiling heat transfer coefficient using CuO/water nanofluids flowing upward around the vertical cylinder with uniform heat flux. Although forced convection heat transfer was suppressed near the boiling heat transfer region, enhancement of heat transfer coefficient in convective zone was reasonable. However, they did not report the pressure drop, friction factor during the experiments.

Darzi et al. [19] performed experimental study to investigate the influence of alumina nanofluid on pressure drop and thermal performance of a double tubes heat exchanger. Results indicated that there was a merit in using the nanofluid for promoting the thermal performance of heat exchanger where there was not a severe pressure drop penalty. The findings related to the pressure drop was controversial when comparing with other studies such as [20,21] in which significant pressure drop and pumping power were reported for the nanofluid.

Arani et al. [22] conducted experiments to investigate the convection heat transfer characteristics in fully developed turbulent flow of TiO_2–water nanofluid in a horizontal double tube counter-flow heat exchanger. The results indicated higher Nusselt number for all nanofluids compared to the base fluid. It was also seen that the Nusselt number did not increase by decreasing the diameter of nanoparticles generally, thus, a new definition for thermal performance factor was proposed, which considered the pressure drop, friction factor and Nusselt number. Sahin et al. [22] investigated the steady state turbulent convective heat transfer and pressure drop characteristics of alumina–water nanofluid inside a circular tube. The effects of the volume fraction and Reynolds number were determined under constant heat flux and obtained results showed that the heat transfer increased with the increase of Reynolds number and particle volume fraction, while no significant data were reported on pressure drop and tradeoff condition between heat transfer enhancement and pressure drop.

Rooted in aforementioned literature, there are extensive literature on the study of heat transfer in nanofluids and the reported results are somehow controversial. Some researchers have reported the severe enhancement of heat transfer coefficient without any pressure drop, while there are others who argue that presence of nanoparticles can enhance the pressure drop and pumping power which induce the tradeoff condition. Therefore, a fair assessment of thermal performance of nanofluid is required considering the pressure drop and heat transfer enhancement. As a continuation of our previous study [23], in this study, an experimental investigation is conducted on heat transfer coefficient, pressure