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Heat transfer, pressure drop and fouling studies of multi-walled carbon nanotube nano-fluids inside a plate heat exchanger

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ABSTRACT

This work presents the results of an experimental research on the heat transfer and pressure drop characteristics of multi-walled carbon nanotube (MWCNT), aqueous nano-fluids inside a plate heat exchanger (PHE), with the consideration of fouling formation of carbon nanotubes (CNTs). Influence of operating parameters such as flow rate ($700 < Re < 25{,}000$), volumetric concentration of nano-fluids (vol.% = 0.5–1.5), inlet temperature of nano-fluid (T_{in} = 50–70 °C) on the overall heat transfer coefficient and pressure drop was experimentally investigated. Results demonstrated that the heat transfer coefficient could be intensified, when flow rate and concentration of nano-particles increase. In addition, increase of temperature of inlet flow can cause a slight increase in heat transfer coefficient. In terms of pressure drop, it was seen that with increasing the flow rate and mass concentration of nano-fluids, pressure drop was intensified such that for flow rate, enhancement rate was significant, while for concentration, a small penalty was registered. Although MWCNT/water nano-fluids presented higher pressure drop and friction factor in comparison with the base fluid, they provided better overall thermal performance in comparison with the base fluid. For long-operating condition, significant fouling resistance was also measured, which was amplified by increasing the volumetric concentration of nano-fluids. A none-linear fouling behavior over the extended time was registered for nano-fluids and for the decrease of heat transfer coefficient as well.

1. Introduction

With the continuous progress of process intensification in thermal engineering systems and energy developments, demands for high efficient heat exchangers and cooling systems have been dramatically increased. Since heat exchangers have wide applications in industries, special attention has been paid for the intensification of the heat transfer in this media. For this purpose, there are passive and active techniques, which have been utilized by several researchers to obtain the better thermal performance and energy efficiency. Although there are variety types of heat exchangers with the wide applications in refrigerants, automotive, aerospace, cooling systems and micro-electronics, plate heat exchanger, PHE has been one of the major interests of researchers not only because of its anomalous heat transfer area, but also due to its lower size (compactness) in comparison with other types of heat exchangers. In fact, flat plate heat exchangers are cost-effective devices, which can exchange a large quantity of heat in a small space with extensive heat transfer area [1].

Nano-fluids are considered as not only a passive technique, but also a promising way, which open a new window to the future of advanced thermal fluid science. Nano-fluid is comprised of the solid particles with average size of less than 100 nm dispersing in a base fluid with poor thermal conductivity such as water, ethylene glycol or engine oils. Normally, these solid particles are metal oxides or carbon-based nanotubes. Carbon nanotubes, CNTs have also been regarded as wonderful materials with the special mechanical and thermo-physical properties such as anomalous thermal conductivity and heat capacity [2]. Due to the advantages of nano-fluids, many efforts have been made to investigate the potential application of nano-fluids inside the heat exchanging media. For instance, in a set of experiments conducted by Sadr et al. [3], thermal performances of nano-fluids in some industrial heat exchangers were evaluated at three mass concentrations of 2%, 4%, and 6% of SiO_2–water nano-fluids. These experiments were established to compare the overall heat transfer coefficient and pressure drop of water and nano-fluids in plate and shell-and-tube heat exchangers. Experimental results showed both augmentation and deterioration of heat transfer coefficient for nano-fluids depending on the flow rate and

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Nomenclature

A	area, m^2
C_p	heat capacity, J kg^{-1} $°C^{-1}$
D	hydraulic diameter, m
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
P	pressure, kPa
Pr	Prandtl number
Q	heat, W
Re	Reynolds number
Rf	fouling resistance, m^2 K/kW
T	temperature, °C
u	fluid velocity, m.s^{-1}
U	overall heat transfer coefficient, W/m^2. K

Subscripts–superscripts

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

Greek symbols

α	thermal diffusion, m^2 s^{-1}
ρ	density, kg m^{-3}
μ	viscosity, kg m^{-1} s^{-1}
ϕ	volume fraction or particle loading
δ	plate thickness, m
Δ	difference
η	thermal performance index
ψ	Enhancement parameter

Abbreviation

HTC	heat transfer coefficient
LMTD	log mean temperature difference
PHE	plate heat exchanger

nano-fluid concentration through the heat exchangers. They explained that the reason for the enhancement was due to the counter effect of the changes in thermo-physical properties of fluids (e.g. viscosity) together with the fouling on the contact surfaces in the heat exchangers. The measured pressure drop revealed an increase in pressure drop in comparison with the base fluid. In another study, Huang et al. [4] investigated the heat transfer and pressure drop characteristics of aqueous alumina and multi-walled carbon nanotube, (MWCNT) water-based nano-fluids in a chevron-type PHE. They found that the heat transfer can be improved by utilizing the nano-fluids, while a little heat transfer enhancement was observed based on a constant flow velocity. The heat transfer deterioration of MWCNT/water nano-fluids was more intensive than alumina/water nano-fluids due to the relatively large viscosity increase of MWCNT/water nano-fluids. In contrast to results published by Huang et al. [4], Goodarzi et al. [5] demonstrated a significant enhancement in convective heat transfer for MWCNT/water nano-fluid inside a heat exchanger. Tiwari et al. [6] put an effort to compare the heat transfer performances of various nano-fluids including CeO_2, alumina, Titana and SiO_2 in a PHE for different volumetric flow rates and concentrations. The optimum concentrations for different nano-fluids were determined, which yielded the maximum heat transfer improvement over the base fluid. They also showed that CeO_2/water nano-fluid presented the best thermal performance (maximum performance index enhancement of 16%) with comparatively lower optimum concentration (0.75 vol.%) within the studied nano-fluids. Prasad et al. [7] conducted experiments to study the turbulent forced convection heat transfer and friction of alumina–water nano-fluid flowing through a concentric tube U-bend heat exchanger. The experiments were performed in the Reynolds number ranged from 3000 to 30,000 and nano-fluid concentrations of 0.01%, 0.03%. The results indicated that an increase in Reynolds number and Prandtl number yields to an increase in the average Nusselt number, and augmentation of thermal conductivity in the nano-fluid and subsequently an enhancement in the heat transfer coefficient. The empirical correlations for the Nusselt number and friction factor were obtained as functions of the Reynolds number, Prandtl number, volume concentration and aspect ratio of inserts. Sarafraz et al. [8] investigated the thermal performance and efficiency of a heat exchanger working with biological silver/water nano-fluids. Results demonstrated that the forced convection heat transfer could be intensified in case of using nano-fluid inside the heat exchanger. Rate of intensification can be improved by increasing the mass particle loading and volumetric flow rate. Similar results for intensification of forced convection heat transfer in plate heat exchangers can be found in the literature [9–17]. In above-explained researches, most of authors have presented the positive influence of nano-fluids on the forced convective heat transfer and approved potential application of nano-fluids in heat exchangers.

For carbon nanotubes, there are few studies in the literature, which imply the outstanding thermal conductivity of this nano-fluid and their outstanding convective coefficient [18–25]. Therefore, it can be expected that by using the carbon nanotube nano-fluid as a working fluid inside a high-efficient heat exchanger such as chevron-type plate heat exchanger, considerable enhancement of heat transfer may be achieved. In this work, a set of experiments has been performed to quantify the overall heat transfer coefficient of multi-walled carbon nanotube nano-fluid and the pressure drop inside a PHE. For this purpose, experiments were conducted at different flow rates, volumetric concentrations and inlet temperatures of nano-fluids. Fouling of nano-fluid inside the heat exchanger is also measured by defining a parameter so-called fouling thermal resistance.

2. Experimental

2.1. Test rig

Fig. 1 schematically represents the test facility, which consists of three main sections: (1) Two fluid circulation units including nano-fluid loop (red: hot line) and water loop (blue: cold line). (2) Measurement instruments including the inlet and outlet RTDs, Pressure transmitters and tank thermocouples. (3) Main test sec-