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Effects of hybrid nanofluid mixture in plate heat exchangers

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ABSTRACT

Heat transfer and pressure drop characteristics of a hybrid nanofluid mixture containing alumina nanoparticles and multi-walled carbon nanotubes (MWCNTs) were experimentally investigated in a chevron corrugated-plate heat exchanger. A MWCNT/water nanofluid with a volume concentration of 0.0111% and an Al_2O_3/water nanofluid with a volume concentration of 1.89% were mixed at a volume ratio of 1:2.5. A small amount of MWCNTs was added in order to increase the mixture thermal conductivity. Experiments with water used as both hot and cold fluids were carried out first to obtain a heat transfer correlation for fluids flowing in the chevron plate heat exchanger. The results of the nanofluid mixture were compared with those of the Al_2O_3/water nanofluid and water. Results show that the heat transfer coefficient of the hybrid nanofluid mixture is slightly larger than that of the Al_2O_3/water nanofluid and water, when comparison is based on the same flow velocity. The hybrid nanofluid mixture also exhibits the highest heat transfer coefficient at a given pumping power. The pressure drop of the hybrid nanofluid mixture is smaller than that of the Al_2O_3/water nanofluid and only slightly higher than that of water. Therefore, hybrid nanofluid mixtures might be promising in many heat transfer applications.

1. Introduction

Heat transfer enhancement techniques are very important in a wide range of industries. A lot of methods have been proposed in the literature such as augmentation of heat transfer area (e.g., modulated surface and fins) and vibration of the heated surface. With the development of thermal engineering and industrial intensification, more efficient yet small in size heat transfer systems are needed. The compact plate heat exchanger (PHE) is thus widely used in many applications including food processing, heating and cooling applications and chemical industry [1,2]. In PHEs, the flow inside the narrow corrugated channels may separate and reattach successively, creating strong turbulence or mixing and thus enhancing the heat transfer [3–5]. Nilpueng and Wongwises [3] investigated the heat transfer coefficient and pressure drop of water inside a plate heat exchanger with a rough surface and compared the results with those in a smooth heat exchanger. They found that the heat transfer coefficient and pressure drop both increase with increasing surface roughness. Wajs and Mikielewicz [4] experimentally studied the heat transfer performance of ethanol–water flowing in plate heat exchangers with metallic porous layer. Heat transfer augmentation was found in such a heat exchanger construction within some flow ranges.

Another approach to improve the heat transfer is using nanofluids as nanofluids might have higher thermal conductivities than the base fluid and tend to cause little pressure drop penalty. Godson et al. [6] reported a maximum heat transfer augmentation of 12.4% by using silver/water nanofluid at a volume concentration of 0.4% and $Re = 25{,}000$. Wu et al. [7] investigated the heat transfer performance of Al_2O_3/water nanofluids in a double-pipe helical heat exchanger and found that the heat transfer enhancement of nanofluids was very small at a flow velocity basis. The discussion shows that discrepancies exist among different experimental data. Thus, further investigations on convective heat transfer of nanofluids are needed.

Compared to the experimental work of nanofluids in simple flow geometries [8,9], the investigations on the heat transfer of nanofluids in complex or enhanced geometries are limited [1,10–16]. Pandey et al. [1] experimentally observed higher heat transfer coefficients of Al_2O_3/water nanofluids (2 vol.%, 3 vol.% and 4 vol.%) than water in a corrugated PHE. The heat transfer coefficient (HTC) increased with increasing Reynolds number and Peclet number. The 2 vol.% nanofluid presented the highest HTC at a giving pumping power and the HTC decreased with increasing particle volume concentrations due to the effect of the increase in viscosity outweighing the effect of the increase in thermal conductivity.

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Nomenclature

A	total heat transfer area, m^2
b_c	half of the plate depth, m
c_p	specific heat, J/(kg K)
D	hydraulic diameter, m
f	friction factor, dimensionless
HTC, h	heat transfer coefficient, $W/(m^2 K)$
L	length, m
LMTD	log mean temperature difference, K
m	mass flow rate, kg/s
N	number of channels, dimensionless
Nu	Nusselt number, hD/λ, dimensionless
P_p	pumping power, W
Pr	Prandtl number, $c_p\mu/\lambda$, dimensionless
Q	heat, W
Re	Reynolds number, $\rho uD/\mu$, dimensionless
T	temperature, K
U	overall heat transfer coefficient, $W/(m^2 K)$
u	velocity, m/s
V	volumetric flow rate, liter/s
w	plate width, m

Greek symbols

ΔP	pressure drop, Pa
δ	plate thickness, m
Φ	surface enlargement ratio, dimensionless
ϕ	volume concentration, vol.%
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3

Subscripts

ave	average
b	base fluid
c	cold
cal	calculated
e	equivalent
exp	experimental
h	hot
i	inlet
nf	nanofluid
o	outlet
p	nanoparticle
plate	plate
w	water

Pantzali et al. [10] experimentally and numerically investigated the efficacy of CuO/water nanofluids as coolants in a miniature PHE. They found that the nanofluids had a potential in designing compact and efficient heat transfer systems as less nanofluid flow rates were required at a given heat load.

Recently, hybrid nanofluid mixture has received increasing interest as it may have enhanced thermal properties and heat transfer [17–23]. Wu et al. [17] prepared hybrid nanofluid mixtures of Al_2O_3/water nanofluid and MWCNT/water nanofluid (Sample 1: MWCNT/water 0.278 vol.% 10 mL and Al_2O_3/water 1.89 vol.% 25 mL and Sample 2: MWCNT/water 0.278 vol.% 10 mL and Al_2O_3/water 5.0 vol.% 25 mL) and experimentally measured the thermal conductivity and viscosity of the nanofluid mixtures. They found that the thermal conductivity enhancement for Sample 1 was 7.2%, which was higher than the two original nanofluids. Han et al. [18] synthesized a hybrid sphere/CNT nanoparticle with CNTs attached at the surface of spherical oxide nanoparticles. It was found that the thermal conductivity enhancement was about 21% when the volume concentration of the hybrid sphere/CNT nanofluid mixture was 0.2%. The significant thermal conductivity enhancement was caused by the following reason: In the hybrid nanoparticles, CNTs attached to the alumina/iron oxide sphere, provided a rapid thermal path between CNTs. As a result, the thermal resistance between the nanoparticles and fluids was reduced and the heat could be transported quickly. Suresh et al. [19] prepared hybrid Al_2O_3–Cu/water nanofluid of 0.1% volume concentration by dispersing homogeneous Al_2O_3–Cu nanocomposite powder into certain amount of deionized water. They investigated the heat transfer performance of Al_2O_3–Cu/water hybrid nanofluid of 0.1% volume concentration and found that the Nusselt number was 13.56% higher than that of water at $Re = 1730$. Labib et al. [20] numerically investigated the convective heat transfer of combined/hybrid nanofluid mixture of Al_2O_3 nanoparticles into CNT/water nanofluid and found that the nanofluid mixture could improve the heat transfer performance significantly. They suggested that the heat transfer enhancement might be due to the shear shinning behavior of CNT nanofluids.

On the basis of the open literatures, most of the previous works related to nanofluids are focused on pure nanofluids in simple geometries. Thus the authors are motivated to investigate the heat transfer and pressure drop characteristics of a hybrid nanofluid mixture containing alumina nanoparticles and multi-walled carbon nanotubes (MWCNTs) experimentally in a chevron corrugated-plate heat exchanger. A small amount of MWCNTs was added in order to improve the mixture thermal conductivity. The results were compared with those of water and Al_2O_3/water nanofluids. Experimentally measured thermo-physical properties of Al_2O_3/water nanofluids (i.e., viscosity and thermal conductivity) were used in this work. Possible heat transfer correlations were proposed for water and nanofluids flowing in PHEs.

2. Experimental investigation

2.1. Experimental apparatus

The experimental test rig is schematically shown in Fig. 1. There are mainly two experimental loops. One is the hot fluid loop, where the hot fluid was circulated by a pump and fed into the chevron plate heat exchanger, passed through a rotameter, and returned to the reservoir, thereby forming a closed loop. The other is the cold fluid loop, where the cold water was pumped and passed a control valve and a rotameter and then entered the plate heat exchanger in counter flow, forming an open loop. The hot fluid was stored in a 5 l reservoir and was heated by a power supply, which was inserted at the bottom of the reservoir and had a maximum value of 6 kW. The cold fluid was stored in a 5 l tank. On each side, two rotameters were used to measure the mass flow rates. One is for small ranges of mass flow rates and the other is for large ranges. All rotameters were calibrated using a stopwatch-and-weighing technique for water and nanofluids (including hybrid nanofluid mixture and Al_2O_3/water nanofluid) at different temperatures. A differential pressure transducer with an accuracy of ±0.075% was used to measure the pressure drop between the inlet and outlet ports of the stream. Four calibrated T-type thermocouples with an accuracy of ±0.1 K were also installed at the inlet and outlet of the hot and cold streams to mea-