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Research Paper

Aqueous carbon nanotube nanofluids and their thermal performance in a helical heat exchanger

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HIGHLIGHTS

- Viscosity and thermal conductivity were measured for MWCNT nanofluids.
- Pressure drop and heat transfer of nanofluids in helically coiled tubes.
- Previous correlations can reproduce the thermal behavior of MWCNT nanofluids.
- No heat transfer enhancement based on fixed flow velocity and fixed pumping power.

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ABSTRACT

This work experimentally investigated the hydraulic and thermal performance of aqueous multi-walled carbon nanotube (MWCNT) nanofluids in a double-pipe helically coiled heat exchanger. Measured viscosity and thermal conductivity values of the MWCNT nanofluids, instead of literature values or values calculated from correlations, were used for data analyses and performance evaluation of the nanofluids. A transient plane source method was adopted to measure thermal conductivity. The increase in viscosity of the nanofluids is much larger than the thermal conductivity enhancement. For example, the relative thermal conductivity is only 1.04 while the relative viscosity is 9.56 for a 1.0 wt% MWCNT/water nanofluid. Pressure drop and heat transfer characteristics were experimentally studied for aqueous MWCNT nanofluids of weight concentrations 0.02 wt%, 0.05 wt% and 0.1 wt% inside the helical heat exchanger. By using the measured nanofluid properties, the Wu et al. correlation and the Seban and McLaughlin correlation can reproduce the thermal behaviours of the tested MWCNT nanofluids for laminar flow and turbulent flow very well, respectively. Possible MWCNT effects, e.g., Brownian motion and thermophoresis, on the thermal performance in helically coiled tubes are probably unimportant. No heat transfer enhancement was found as a fixed flow velocity and a fixed pumping power were considered.

1. Introduction

Conventional heat transfer fluids (e.g., water, ethylene glycol and engine oil) have relatively low thermal conductivity values which thus limit the heat transfer rates. Due to recent progress in nanotechnology, thermal conductivity values can be enhanced by adding nanometer-sized structures (e.g., particles, fibers, tubes) in conventional fluids to form the so-called nanofluids. Thermal conductivity enhancement of nanofluids makes them potentially useful in many cooling applications.

The increase in thermal conductivity depends on nanoparticle volume concentration, morphology (e.g., primary size, shape, agglomeration in the form of clusters and aggregates), the nature of the base fluid, dispersion, colloidal stability and fluid temperature, etc [1,2]. Carbon nanotube nanofluids have received much attention over the past decade because of the high thermal conductivity of the carbon nanotube, e.g., multi-walled carbon nanotube (MWCNT) has a thermal conductivity around 3000 W/(m K). However, there exist significant inconsistencies and discrepancies in the nanofluid thermal conductivity data in literature due to the poor comparability of experimental parameters among individual studies. Difference in thermal conductivity enhancement was observed larger than an order of magnitude for nanofluids containing MWCNTs at almost the same volume concentration. For instance, Choi et al. [3] reported a nonlinear thermal conductivity increase (up to 160%) for only 1 vol.% of MWCNTs in synthetic poly (α-olefin) oil, while the thermal conductivity in Phuoc et al. [4] increases from 2.3% to 13% for 0.24

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Nomenclature

A_i	inner surface area of the inner tube (m^2)
A_o	outer surface area of the inner tube (m^2)
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
D_c	coil diameter of curvature (m)
d_a	hydraulic diameter of the annulus (m)
d_i	diameter of the inner tube (m)
d_p	average aggregate or nanocluster diameter (m)
De	Dean number, $Re_b(d_i/D_c)^{0.5}$
f_{app}	apparent friction factor
h	heat transfer coefficient (W m^{-2} K^{-1})
h_a	annulus heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
Kn	Knudsen number
L	length of the helical heat exchanger (m)
LMTD	logarithmic mean temperature difference (K)
m	mass flow rate (kg s^{-1})
n	number of turns
Nu	Nusselt number, hd_i/k
p	pitch of helical coil (m)
ΔP	pressure drop over the tube (Pa)
Pr	Prandtl number, $c_p\mu/k$
q	heat flux (W m^{-2})
Re	Reynolds number, $\rho u d_i/\mu$
T	temperature (K)
u	flow velocity (m s^{-1})
w	weight concentration

Greek symbols

Φ	volume concentration
λ	mean free path (m)
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})

Subscripts

b	bulk
bf	base fluid
c	cold side
ci	cold side inlet
co	cold side outlet
h	hot side
hi	hot side inlet
ho	hot side outlet
nf	nanofluid
p	nanoparticle

vol.% to 1.43 vol.% aqueous MWCNT nanofluids. The measured discrepancies among individual studies are possibly due to differences in thermal conductivity of MWCNTs and base fluids, and more importantly preparation methods (e.g., one-step method or two-step method, surfactants, ultrasonication time, pH value). Many experimental or analytical studies often turned to available correlations to estimate thermal conductivity and dynamic viscosity, either derived from the classical two-phase mixture theory or based on empirical models only verified by limited data sources. Generally, these property formulas were developed for suspensions containing micrometer-size particles and thus might not capture the nanofluid properties well. As illustrated by Mansour [5], such approximations can generate misleading results when assessing the nanofluid performance. Therefore, it is very important to measure thermal conductivity and viscosity values for each tested nanofluid to correctly evaluate its hydraulic-thermal performance in tubes and heat exchangers.

Heat transfer performances of nanofluids in straight tubes have been extensively studied, e.g., see Ref. [6]. Ferrouillat et al. [7] and Wu et al. [8] et al. concluded that previous single-phase correlations can accurately reproduce the thermal behaviour of nanofluids in tubes by using the measured temperature- and loading-dependent nanofluid properties in the analysis. Yang et al. [9] obtained exact solutions for fully developed laminar flow in straight tubes and concluded that: (a) the abnormal heat transfer intensification was captured, especially for titania/water nanofluids in a tube when the nanoparticle volume concentrations are larger than 2% and (b) the maximum Nusselt number is achieved at $N_{BT} \approx 0.5$, while it becomes lower than that of the pure fluid at $N_{BT} < 0.3$. The parameter N_{BT} indicates the ratio of Brownian and thermophoretic diffusivities.

Helically coiled tubes and double-pipe helical heat exchangers are widely used due to their high heat transfer coefficient and compact design [10]. Centrifugal force in the helical coils induces a secondary flow field with a couple of vortices in the tube cross section, which drives the fluid in the central part towards the outer wall and then flows back along the side walls to the inner wall, and therefore enhances the heat transfer performance. So far, there are very few investigations on performance of nanofluids in complex geometries (e.g., helical coils, enhanced tubes) and heat exchangers, especially for MWCNT nanofluids. Recently, for laminar flow Akhavan-Behabadi et al. [11] observed up to 60% enhancement in Nusselt number based on fixed Reynolds number for MWCNT/oil nanofluids inside vertical helically coiled tubes under isothermal boundary conditions.

This experimental work aims to measure the rheology behaviour and thermal conductivity of MWCNT nanofluids of different concentrations, and then to investigate hydraulic and thermal characteristics of MWCNT nanofluids in a tube-in-tube helical heat exchanger, for both laminar flow and turbulent flow.

2. Experiment

2.1. Nanofluid preparation and characterization

An aqueous multi-walled carbon nanotube suspension of 1.0 wt% concentration was purchased from Nanocyl, Belgium. According to the vendor's specification, 1.0 wt% of thin MWCNTs were dispersed in de-ionized water (97 wt%) stabilized by surfactant SDBS (2.0 wt%). The MWCNTs have an average length of 1.5 μm and an average diameter of 9.5 nm, with an average aspect ratio of 158. The surface area of the MWCNTs is 250–300 m^2/g. The carbon purity of the MWCNTs is 90%, while the remaining 10% is metal oxide. Transmission electron microscopy (TEM) characterization shown in Fig. 1 reveals that the MWCNTs are aggregated and entangled. Therefore, surfactants are needed to well disperse the nanoparticles and to reduce the aggregate size. SDBS and gum Arabic (GA) are two common surfactants. In our case, SDBS was added into the suspension to stabilize the nanofluid.

MWCNT/water nanofluids of different concentrations were obtained by diluting the provided nanofluid. The diluted mixture was mechanically stirred for 5 min followed by one-hour ultrasonic vibration. The prepared black nanofluids were stable and little nanoparticle setting was observed after one week. Five nanofluids with weight concentrations of 0.02 wt%, 0.05 wt%, 0.1 wt%, 0.5 wt% and 1.0 wt% were prepared. Volume concentration (Φ) was calculated by its weight concentration (w):