International Journal of Heat and Mass Transfer 127 (2018) 403–412

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Numerical study of turbulent heat transfer of nanofluids containing eco-friendly treated carbon nanotubes through a concentric annular heat exchanger

Maryam Hosseini [a,b], Ali H. Abdelrazek [a], Rad Sadri [a,*], A.R. Mallah [a], S.N. Kazi [a], B.T. Chew [a], Shaifulazuar Rozali [a], Nukman Yusoff [a]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia
[b] School of Chemical Engineering, The University of New South Wales, Sydney, NSW 2052, Australia

ARTICLE INFO

*Article history:*
Received 25 May 2018
Received in revised form 7 August 2018
Accepted 12 August 2018

*Keywords:*
Nanofluids
Multi-walled carbon nanotubes
$k$-$\omega$ model
Single phase
Heat transfer coefficient
Friction factor
Computational fluid dynamics
Heat exchanger

ABSTRACT

In this study, we conducted numerical simulations using finite volume method to examine thermal and hydrodynamic characteristics of clove-treated multi-walled carbon nanotube (C-MWCNT)/distilled water nanofluids in a concentric annular heat exchanger exposed to uniform and constant heat flux boundary conditions. We devised an environmentally friendly functionalization method to synthesize the MWCNTs where the MWCNTs were covalently treated with clove buds in one pot using free radical grafting reaction for preparation of homogeneous MWCNT nanofluid without involving existing corrosive, hazardous acid based conventional functionalization methods of carbon nanomaterials. We analysed the C-MWCNTs using Fourier transform infrared spectroscopy in order to assess the surface modification of MWCNTs. Next, we performed numerical simulations in order to predict the convective heat transfer and hydrodynamic characteristics of the nanofluids considering three concentrations of C-MWCNTs: 0.075, 0.125, and 0.175 wt.%. The effective thermo-physical properties of the nanofluids, which we obtained experimentally, were used in our three-dimensional simulations in order to solve the governing equations of fluid dynamics (continuity, momentum and energy), along with the $k$-$\omega$ turbulence model. We found that there is a good agreement between the simulation and experimental results. We also noticed that the addition of a small fraction of C-MWCNTs into distilled water significantly enhances the convective heat transfer coefficient relative to distilled water. Our results are also encouraging because we observed that the friction factor does not vary significantly for the nanofluids at their concentration range. In general, we conclude that our simulation model can be used to predict the convective heat transfer and hydrodynamic characteristics of C-MWCNT/distilled water nanofluids in a concentric annular heat exchanger with reasonable accuracy and the results show the promising capabilities of these nanofluids as coolants.



## 1. Introduction

It is essential to improve the heat transfer characteristics of thermal systems, especially heat exchangers in order to boost energy efficiency and thus, energy savings [1,2]. Most conventional heat transfer fluids such as water, ethylene glycol, and engine oils have poor thermal properties compared with most solid particles [3–6]. In recent years, much effort has been made to improve the thermo-physical properties of the heat exchanging fluids in order to enhance heat transfer in thermal processes [7–14]. In this regard, a large number of numerical and experimental studies have carried out to examine the heat transfer and hydrodynamic characteristics of thermal systems where nanofluids are used as the working fluids [14–19]. Nanofluids are basically mixtures of nanoparsticles suspended in base fluids. Nanofluids have been successfully used to enhance heat transfer of thermal systems because of their higher thermal conductivities compared with the conventional working fluids [7,8,20]. In the recent years, nanofluids are used in a wide range of applications including microchannel cooling, floor heating, and heat recovery systems [21].

In order to reduce costs associated with experimental techniques, much effort has been made to investigate the effect of nanofluids on the effective thermal parameters such as convective

* Corresponding author.
*E-mail address:* rod.sadri@gmail.com (R. Sadri).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.040
0017-9310/

heat transfer coefficient and thermal conductivity by means of numerical simulations. In this regard, both single-phase and two-phase simulation models have been developed to simulate convective heat transfer of thermal systems where nanofluids are used as the working fluids. In single-phase modeling, the nanofluids are treated as a common pure fluid in solving the conservation equations of mass, momentum, and energy. The thermal conductivities and viscosities of the nanofluids are obtained from theoretical models or empirical data. In single-phase modeling, it is also assumed that the nanoparticles are in thermal equilibrium, there are no slip velocities between the nanoparticles and fluid molecules, and the mixture of nanoparticles is homogeneous [1]. Besides, single-phase modeling is generally easier and less time-consuming compared with two-phase modeling. However, it is crucial to apply suitable equations in order to compute the properties of single-phase nanofluids [22]. In addition, in two-phase modeling, it is assumed that there are slip velocities between the nanoparticles and fluid molecules. For this reason, the nanofluids are inhomogeneous mixtures and there are variations in the nanoparticle concentration of the nanofluids.

Nevertheless, a large number of numerical studies have been carried out over the years to predict the heat transfer and hydrodynamic characteristics of nanofluids using single-phase models with an acceptable degree of accuracy [1]. Semi-analytical methods were also used to determine the heat transfer and hydrodynamic characteristics of nanofluids [1]. Researchers [23] studied the heat transfer characteristics of nanofluids in tubes using a single-phase model subject to turbulent flow conditions. They also conducted experiments as a basis for comparison and the results showed that the convective heat transfer coefficient and Nusselt number of nanofluids increase with the increase in the Reynolds number in turbulent flow conditions. They also observed that the values for convective heat transfer coefficient and Nusselt number are higher for higher volume fractions of the nanoparticles.

In a recent study, Vanaki et al. [24] found that the Nusselt number of the nanofluid containing 2.0 vol.% of copper nanoparticles increases by 39%. Sheikholeslami et al. [25] used heatline analysis for two-phase modeling of nanofluids and heat transfer. The results showed that the average Nusselt number decreases as the buoyancy ratio increases until it reaches a minimum value, and the average Nusselt number increases thereafter [2]. Namburu et al. [26] simulated turbulent flow and heat transfer enhancement of various types of nanofluids flowing through a circular pipe. The nanofluids consisted of different types of nanoparticles (CuO, $Al_2O_3$, and $SiO_2$) were dispersed into different base fluids: water and ethylene glycol. They used the $k$-$\varepsilon$ turbulent model proposed by Brian Edward et al. [27] to model the turbulent conditions. The results showed that the average Nusselt number increases when the nanoparticle concentration is increased.

Various types of heat exchangers have been used in different engineering applications. Annular tubes are commonly used in industrial thermal systems. However, annular tubes are also used in electronic devices, air conditioning and ventilation systems, turbomachinery, nuclear reactors, gas turbines, and double pipe heat exchangers. Hence, studies on heat transfer characteristics of annular tubes and the development of novel methods to enhance the heat transfer performance of annular tubes play a vital role in energy-savings [22,28,29].

Sheikholeslami et al. [30] investigated free convection heat transfer of a concentric annulus between a cold square and heated elliptic cylinders in the presence of a magnetic field. They found that the heat transfer enhancement increases with an increase in the Hartmann number; however, the heat transfer enhancement decreases with an increase in the Rayleigh number. Some researchers [31] investigated the effect of $TiO_2$/water nanofluid on the pressure drop and heat transfer of a heat exchanger. The average size of the nanoparticles was 30 nm and the nanoparticle concentrations were 0.002 and 0.02 vol.%. A horizontal double tube counter-flow heat exchanger was used for the test section and the Reynolds number was varied from 8000 to 51,000 in the experiments. The results showed that the Nusselt number increases with an increase in the Reynolds number and nanoparticle concentration. In addition, the Nusselt numbers are higher for the nanofluids compared with those for distilled water.

Nikkhah et al. [32] investigated the forced convection heat transfer of functionalized multi-walled carbon nanotube (FMWCNT)/water nanofluids in a two-dimensional microchannel. The results showed that the local Nusselt number changes in a periodic manner along the length of microchannel and the local Nusselt number increases when the Reynolds number is increased. In addition, they observed that the Nusselt number increased when the slip coefficient and weight fraction of the nanoparticles were increased. Safaei et al. [33] studied the influence of different functional covalent groups on the thermo-physical properties of carbon nanotube-based nanofluids. They also investigated turbulent forced convection heat transfer of FMWCNT/water nanofluids in a channel with a forward-facing step. They used the shear stress transport $k$-$\omega$ model to model turbulent conditions. The simulations were conducted for the following conditions: (1) Reynolds number: 10000–40000, (2) heat flux: 1000–10000 $W/m^2$, and (3) nanoparticle concentration: 0.00–0.25 vol.%. The results indicated that the Reynolds number and FMWCNT concentration have a significant effect on the heat transfer coefficient, where the local heat transfer coefficient increases with an increase of both of these parameters.

Based on the literature review, it is evident that a significant number of numerical studies have been carried out on heat transfer and hydrodynamic characteristics of nanofluids based on carbon nanomaterials. However, most of these studies involved carbon nanomaterials functionalized using corrosive and hazardous acids. To the best of our knowledge, there are no notable numerical studies regarding heat transfer and hydrodynamic characteristics of a concentric annular heat exchanger where nanofluids containing MWCNTs covalently functionalized using an eco-friendly functionalization method are chosen as the working fluids.

For this reason, we conducted a numerical study of heat transfer and hydrodynamic characteristics of a concentric annular heat exchanger where we used nanofluids containing clove-treated multi-walled carbon nanotubes (C-MWCNTs) as the working fluids. We developed a three-dimensional model of a concentric annular heat exchanger using ANSYS Fluent computational fluid dynamics (CFD) software and we performed the numerical simulations for turbulent flow conditions using the standard $k$-$\omega$ model. We considered three C-MWCNT concentrations (0.075, 0.125, and 0.175 wt.%) for the nanofluids and we chose distilled (DI) water as the base fluid. We varied the Reynolds number at 3055, 4277, 5499, 6722, and 7944. We applied a constant heat flux of 38346 $W/m^2$ at the channel walls as the boundary condition. We used the single-phase model under steady-state conditions and lastly, we validated the simulation results by comparing the data with those from experiments done by our research group.

## 2. Material and methods

In this section, we briefly describe the eco-friendly functionalization method has used for synthesizing the C-MWCNTs [20]. At first 15 g of grounded cloves was taken into a beaker containing 1000 ml of distilled (DI) water preheated at 80 °C. The mixture was then homogenized in heating mode at an agitation speed of 1200 rpm for 30 min. Next, the mixture was filtered for the clove extract solution using a 45 μm polytetrafluoroethylene (PTFE)