International Communications in Heat and Mass Transfer 68 (2015) 267–275

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Experimental and numerical investigation of thermophysical properties, heat transfer and pressure drop of covalent and noncovalent functionalized graphene nanoplatelet-based water nanofluids in an annular heat exchanger☆

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ARTICLE INFO

Available online 2 October 2015

Keywords:
Heat transfer
Nanofluid
Turbulent flow
Forced convection flow
Graphene nanoplatelet

ABSTRACT

The new design of heat exchangers utilizing an annular distributor opens a new gateway for realizing higher energy optimization. To realize this goal, graphene nanoplatelet-based water nanofluids with promising thermophysical properties were synthesized in the presence of covalent and noncovalent functionalization. Thermal conductivity, density, viscosity and specific heat capacity were investigated and employed as a raw data for ANSYS-Fluent to be used in two-phase approach. After validation of obtained results by analytical equations, two special parameters of convective heat transfer coefficient and pressure drop were investigated. The study followed by studying other heat transfer parameters of annular pass in the presence of graphene nanopleteles-based water nanofluids at different weight concentrations, input powers and temperatures. As a result, Nusselt number profiles and friction factor are measured for both synthesized nanofluids.

1. Introduction

Nanofluid is defined as a new kind of fluid comprises different nanoparticles, which suspended in liquid molecules. Heat transfer of nanofluid can be functions of dimension, properties, volume concentration of nanoparticles etc. According to the experimental investigations, nanofluids have shown a significant potential for augmentation of energy transfer and also higher thermal conductivities in comparison to the base fluids. Owing to the nanofluid characteristics, many kinds of industries including automotive radiator systems, computer processing cooling equipment, home heating and cooling appliances, and power plant cooling systems can employ the suggested technique.

Recently a majority of developments in industrial technology are focused on the energy optimization as well as the reduction of system processing time. Consequently in the field of heat transfer, the request to increase in cooling capacities has been vital for these compact thermal systems. The conventional methods for example use of extension surfaces like fins or utilization of microchannels with high heat transfer surface are to obtain the desired high cooling efficiency. On the other hand, the cooling fluid characteristics have been taken under consideration.

The single-phase or two-phase approaches could be applied in simulating convective heat transfer by nanofluid. The single-phase method assumes that nanoparticles and base fluid move with the same velocity and they are in thermal equilibrium, so this method is easier and needs less computational time. But it is important and notable to find applicable equations which compute properties of single-phase nanofluids. However, the single-phase method has been employed in a number of numerical researches of convective heat transfer by nanofluids [1–8]. In general, the single-phase approach and experimental results have not good agreement, due to lack of appropriate equations for predicting both nanoparticles and basefluid, implying the low extent of validation in results and lack of realizing nanofluids properties. Also, some nanofluid parameters such as dispersibility, sedimentation, Brownian motion of nanoparticles in basefluids, Brownian forces, volume or weight concentration of solid particles in basefluids may influence nanofluid flow regime and heat transfer rate. Therefore, the slip velocity between nanoparticles and basefluid must be considered for simulating nanofluid flows and/or heat transfer [9]. Due to Brownian movement of particles in basefluids, two-phase approach opens a new gateway for introducing the main characteristics of nanofluids, indicating a good agreement with theoretical and experimental results [10,11]. Various multiphase approaches have been presented to predict and describe behaviour of complex flows. Numerous multiphase flow studies used the theory of interacting continua or the "Mixture Theory" [12–15]. This method works based on the underlying theory that each phase can be mathematically defined as a continuum.

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.09.007
0735-1933/

Lotfi and his colleagues [16] employed single-phase, two-phase Eulerian and two-phase mixture approaches to simulate flow behaviour in the presence of nanofluids through a straight pipe. They concluded that two phase mixture method has more accurate results than the other two approaches. Some investigators have used this approach to simulate the behaviour of nanofluids [4,5,17–19]. Mirmasoumi and Behzadmehr [18] Akbarinia and Laur [5] considered the influence of nanoparticle size on nanofluid flow in a horizontal pipe.

Also, the annular tube and/or heat exchanger are a common and unique geometry in industrial applications and specially heat transfer equipment. They attracted a large number of scientists and have been employed in different equipment such as electronic devices, air condition and ventilation systems, turbo machinery, nuclear reactors, gas turbines, and double pipe heat exchanger. So, the investigation of heat transfer in annular heat exchangers and introducing novel method for improving their performance play a vital role in energy-saving [20–22].

Abu-Nada et al. [22] investigated heat transfer rate of annular heat exchanger in the presence of Al_2O_3-based water nanofluid with single phase method. They considered different thermal conductivity and viscosity models to evaluate heat transfer improvement in the annular heat exchanger. Izadi et al. [21] have also simulated laminar forced convection of Al_2O_3-based water nanofluid in a two dimensional annular heat exchanger with the single-phase method.

The objective of the present study is abstracted in the synthesizing new kind of fluid, graphene nanopleteles-based water nanofluids at different weight concentrations, the experimental investigation of thermophysical properties of covalent and non-covalent nanofluids (GNP-SDBS- and GNP-COOH-based water nanofluids) and numerical simulation of annular heat exchanger in the presence of prepared nanofluids. To realize this goal appropriately, two-phase is employed. The comparison of analytical and proposed result by simulation in two-phase method confirmed the validity of work. Then, the nanofluids flow in a two dimensional annular pipe investigated in different weight concentrations and ratio of heat flux. As a result, Nusselt number profiles and friction factor are measured for both synthesized nanofluids.

2. Methodology

2.1. Covalent functionalization of GNP

To provide non-covalent nanofluids (GNP-SDBS-based water nanofluid) with known weight concentrations, the given amount of pristine GNP was first weighted, followed by pouring a weight ratio SDBS/pristine GNP of 0.5:1 into a vessel filled with the given distillated water.

Regarding covalent nanofluid (GNP-SDBS-based water nanofluid), based on the technique explained by Wang et al. [33] with slight modification, carboxylation of GNP was performed. In order to generate carboxylated GNP, the GNP (1 g) with a mixture of HNO_3 and H_2SO_4 (1:3 volume ratio) was first sonicated for 0.5 h at room temperature in a closed vessel. The GNP suspension was then poured into a Teflon reaction vessel and placed in an industrial microwave (Milestone MicroSYNTH programmable microwave system) with output power of 700 W and heated up to 90 °C for 15 min. The resulting suspension was cooled at room temperature and then diluted with 200 mL deionized water to reduce the power of acids for filtration. The GNP suspension was filtered through 45 μm polytetrafluoroethylene (PTFE) membrane, and the filtrate was continually washed with the deionized water to remove any unreacted acids. The functionalized sample was dried overnight at 40 °C in a vacuum. Then, the GNP-COOH produced after microwave phase was dispersed in the deionized water at room temperature. Dispersed concentration of 0.1 wt.% was easily obtained in water in the presence of COOH groups on the surface of GNPs.

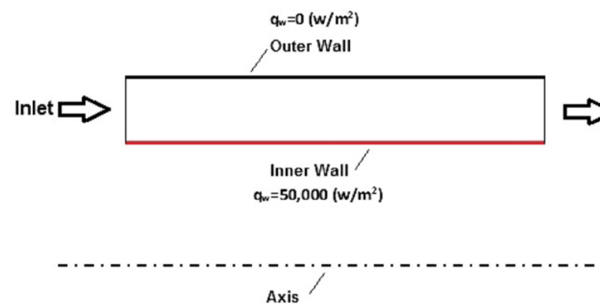

Fig. 1. 2D geometrical configuration of annular channel.

2.2. Geometry and mesh structure

This study is focused on a horizontal annulus formed between an inner heat generating solid circular cylinder and an outer isothermal cylindrical boundary undergoing turbulent convection nanofluid flow. An annular tube in the horizontal position with diameter of d and lengths of L is simulated in the present study. A two-dimensional (2D) geometry has been selected for being investigated. Fig. 1 shows the geometrical configuration taken under study.

The inlet and outlet positions of the tube, profiles of uniform axial velocity (V_0), constant temperature ($T_0 = 35$ °C) and different Reynolds numbers, are illustrated in Fig. 2.

The meshing tool available in ANSYS was used to construct the computational mesh. A structured mesh based on a rectangular grid was used throughout the domain. Several grid distributions had been tested and the results were compared to ensure that the calculated results were grid independent. Fig. 3 draws the comparison of Nusselt numbers versus the Reynolds numbers for water as a working fluid at three different grid distributions. It has shown that obtained results are independent of the number of grid points.

To reduce computational time and effort, the total grid points and the elements have employed in the whole tube are 16,441 and 16,000, respectively. A non-uniform grid was used in the meshing step, close to the wall grids as smaller to get better results. (Fig. 4).

2.3. Simulation cases and boundary conditions

A constant heat flux of 50,000 (W/m^2) is applied at the tube wall. The influence of weight fraction of nanoparticles in the range of 0 to 0.1% and the Reynolds number (Re) on the convective heat transfer is investigated. The pressure outlet boundary condition is considered.

2.4. Numerical methods

The numerical method available in the commercial CFD package of ANSYS-Fluent, V15 has been used here. Fluent uses a finite volume approach to convert the governing partial differential equations into a

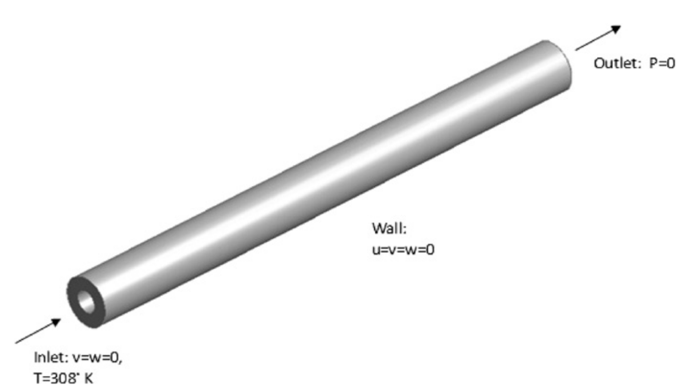

Fig. 2. Boundary conditions for the tube.