Powder Technology 318 (2017) 441–450

Contents lists available at ScienceDirect

Powder Technology

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

Experimental investigation and modeling of thermal conductivity and viscosity for non-Newtonian hybrid nanofluid containing coated CNT/Fe_3O_4 nanoparticles

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ARTICLE INFO

Article history:
Received 7 March 2017
Received in revised form 1 May 2017
Accepted 8 June 2017
Available online 13 June 2017

Keywords:
Hybrid nanofluid
Fe_3O_4 nanoparticles
Carbon nanotubes
Thermophysical properties
Neural network

ABSTRACT

The thermal conductivity and viscosity of the water-based hybrid nanofluid containing both Fe_3O_4 magnetic nanoparticles and carbon nanotubes (CNTs) are measured at the temperatures between 25 and 55 °C, Fe_3O_4 volume concentrations between 0.1 and 0.9%, and CNT volume concentrations between 0 and 1.35%. To prevent agglomeration and sedimentation of particles, Tetramethylammonium Hydroxide (TMAH) and Gum Arabic (GA) are utilized for coating Fe_3O_4 nanoparticles and CNTs, respectively. Owing to the interaction between the molecules of these two surfactants, the magnetic nanoparticles and CNTs are connected physically. The variations of the thermal conductivity and viscosity in terms of temperature and both concentrations are evaluated and discussed. A non-Newtonian behavior is observed for this nanofluid, such that its viscosity decreases by the shear rate increment. Using the experimental data, two Artificial Neural Network (ANN) models are developed for prediction of the thermal conductivity and viscosity in terms of effective parameters. The mentioned models have a proper ability to predict these properties.

1. Introduction

Nanofluids have emerged as an interesting and novel class of nanotechnology-based heat transfer fluids and have grown significantly in the past few years. Compared to conventional fluids, the superior thermal conductivity and better convective heat transfer as well as little pressure drop have made nanofluids one of the most promising emerging technologies in heat transfer applications [1–6].

Among surveys in the field of nanofluids, some investigations have concentrated on magnetic nanofluids [7–11]. Magnetic nanofluids or ferrofluids are colloids of a non-magnetic base fluid and magnetic nanoparticles which are coated with surfactant layers such as oleic acid to make proper stability. Magnetic nanoparticles employed in magnetic nanofluids are usually synthetized in various sizes and forms from metal materials (i.e. ferromagnetic materials) such as iron, cobalt, nickel as well as their oxides such as spinel-type ferrites, magnetite (Fe_3O_4), and so forth.

The key characteristic of this kind of nanofluids (i.e. ferrofluids) is that besides enhancement of thermal properties, they have both magnetic properties like other magnetic materials and flowability similar to conventional liquids. Such unique feature makes it possible to control heat transfer and fluid flow as well as particles movement by employing magnetic fields and hence, they have a significant potential for being applied in different fields such as thermal engineering, bioengineering, electronics, and so forth [12]. Sheikholeslami [13] examined influence of Coulomb forces on thermal performance of Fe_3O_4–H_2O magnetic nanofluid inside a cavity. The final formulas were solved via Control Volume based Finite Element Method. The influences of volume fraction of Fe_3O_4, supplied voltage and Reynolds number on the hydrothermal characteristics were considered. Results indicated that existence of electric field can alter the nanofluid flow style. Moreover, Nusselt number enhanced with increment of supplied voltage. Imtiaz et al. [14] investigated the magnetohydrodynamic flow of a magnetic nanofluid by a curved stretching surface. Water was used as base fluid and Fe_3O_4 as nanoparticle. System of ordinary differential equations was obtained by appropriate transformations. It was observed that magnitude of velocity enhances for larger curvature parameter. Temperature was increasing function of radiation parameter and Biot number. Also, surface drag force and pressure had direct relationship with volume fraction.

One type of nanoparticles, which has been considerably utilized in preparing nanofluids, is CNT. CNTs are allotropes of carbon having cylindrical nanostructures. Since their discovery in 1991 [15], these nanoparticles have attracted significant attention because of their extraordinary structural, mechanical, and electrical characteristics.

In the area of heat transfer fluids, employing hybrid nanofluids is a new challenge and opportunity. Hybrid nanofluids, produced from

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http://dx.doi.org/10.1016/j.powtec.2017.06.023
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Nomenclature

A	Hessian matrix
e_{max}	maximum absolute error
g	gradient
k	thermal conductivity, W/mK
m	number of weights and biases
n	shape factor
R^2	coefficient of determination
T	temperature, K
x	vector of weights and biases

Greek symbols

α	learning rate
φ	volume concentration, %
ψ	particle sphericity

Subscripts

f	base fluid
nf	nanofluid
p	particle

mixing different kinds of nanoparticles, can be applied as promising nanofluids for heat transfer improvement. Hydrothermal characteristics in them can be different as compared to usual nanofluids and this fact needs to be explored. It can open a route to develop diverse nanofluids with many outstanding applications.

Functionalizing CNTs with magnetic nanoparticles can combine the characteristics of magnetic nanoparticles and CNTs, which can cause advanced materials with novel thermal, chemical, and physical features as well as promising applications [16–18]. Indeed, by combining CNTs and magnetic nanoparticles in a base fluid, a modern type of hybrid nanofluids can be prepared.

Very few studies have been performed on these hybrid nanofluids. Sundar et al. [19] investigated the convective heat transfer coefficient and friction factor for flow of CNT-Fe_3O_4/water hybrid nanofluid flowing through a circular tube under constant wall heat flux. The results revealed a maximum of 31.1% enhancement in Nusselt number with a penalty of 1.18-times increment of pumping power for the concentration of 0.3% in comparison with base fluid.

A mixture of carbon nanofibers and magnetic nanoparticles coated with surfactant was evaluated by Parmar et al. [20]. By hydrophobic interactions, the magnetic nanoparticles adhered to the wall of carbon nanofibers. Therefore, the ferromagnetic characteristic was added to the carbon nanofibers without disturbing the high yield of tube formation. This process caused the spatial organization of the carbon nanofibers in the direction of magnetic field.

Hong et al. [21] investigated the thermal conductivity of the hybrid nanofluid containing 0.01 wt% CNT and 0.02 wt% Fe_2O_3 in water under the various magnetic field strengths. The authors mentioned that the thermal conductivity can be improved by external magnetic fields. They claimed that the Fe_2O_3 nanoparticles form aligned chains under magnetic field and help to connect the CNTs which causes thermal conductivity enhancement.

Baby and Sundara [22] studied the thermal conductivity of Fe_3O_4/CNT hybrid nanofluid. They showed that the thermal conductivity augments in the presence of magnetic field, such that about 20% enhancement was observed for a volume fraction of 0.03%. The increase in the thermal conductivity of this nanofluid was attributed to the chain formation of magnetic nanomaterials in the base fluid in the presence of magnetic field.

A review in the relevant literature reveals that in the studies conducted about this area, hybrid ferrofluids have been considered as Newtonian nanofluids. In addition, no comprehensive and accurate model has been presented to predict the thermal conductivity and the viscosity of these ferrofluids. In the present work, the effects of temperature, concentration of TMAH coated Fe_3O_4 nanoparticles, and concentration of GA coated CNTs on the viscosity and thermal conductivity of the Fe_3O_4–CNT/water hybrid nanofluid are experimentally investigated. These ferrofluids are considered here as non-Newtonian nanofluids, such that the shear rate is taken into account as an important parameter. The interaction between the two surfactants leads to the physical attachment of magnetic nanoparticles and CNTs. Eventually, the ANN is employed to model the thermal conductivity and viscosity of the hybrid ferrofluids using the data obtained from experimental measurements. To our knowledge, this paper is the first research that develops the accurate models to predict thermophysical properties of non-Newtonian hybrid ferrofluids.

2. Experimental

2.1. Preparation of nanofluids

The hybrid nanofluid, containing Fe_3O_4 magnetic nanoparticles and multi-wall CNTs, is assessed in this contribution. For this purpose and conducting the relevant experiments, the hybrid nanofluid is prepared with different concentrations. In order to synthesis of the hybrid nanofluid, the pure ferrofluid is firstly synthetized by means of the method introduced by Berger et al. [23]. The required reagents were of analytical grade and purchased from Merck.

For preparation of the ferroeluids, 1.0 mL of stock $FeCl_2$ solution and 4.0 mL of stock $FeCl_3$ solution are firstly combined together, and then 50 mL of 0.7 M aqueous NH_3 solution is added dropwise. In this stage, Fe_3O_4 precipitate initiates to form instantaneously. After evacuating the redundant liquid, the remaining solution is centrifuged for 1 min at 1000 rpm. A dark sludge remains at the bottom of the tube in this step. Then, 8 mL of 25% TMAH solution is added and stirred till the thorough suspension of solid in the fluid occurs. Eventually, by stirring the solution for about 30 min, the excess ammonia is evacuated [23].

The CNT nanofluid is produced using the method presented by Garg et al. [24]. The CNTs with purity of about 99%, outer diameter of 10–30 nm, and length of 10 μm were purchased from Research Institute of Petroleum Industry (RIPI, Tehran, Iran). The SEM and TEM images of the CNTs are shown in Fig. 1. For preparation of the CNT nanofluid, GA fine powder is dissolved in water by a magnetic stirrer. Then, CNTs are added to the solution and the resultant suspension is ultrasonicated for 40 min using an ultrasonicator. It is noteworthy that the mass concentrations of GA and CNTs are 0.25 and 1%, respectively.

After preparing the ferrofluid and the CNT nanofluid separately, the hybrid nanofluid is produced by addition of the desired amount of the CNT nanofluid to the synthesized ferrofluid followed by sonication of the mixture for 5 min. The hybrid nanofluids are prepared according to the volume concentrations presented in Table 1. Indeed, a hybrid nanofluid has two concentrations as two different nanoparticles (i.e. Fe_3O_4 nanoparticles and CNTs) are used. According to this table, three CNT concentrations are regarded for each Fe_3O_4 concentration. The TEM image of the hybrid nanofluid is illustrated in Fig. 2. This image confirms that Fe_3O_4 nanoparticles are attached to the walls of CNTs. This non-covalent attachment is due to the interaction between the TMAH coated magnetic nanoparticles and GA on the surface of nanotubes.

The stability of nanofluids is a very important issue, and it has been investigated by various researchers [25–27]. A proper stability for nanofluids is found by three factors: low agglomeration, low sedimentation and high structural integrity. The most often used technique to assess the stability of nanofluids is the static position approach. In this technique, the samples are left standing for 30 days, and the distance