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Effects on thermophysical properties of carbon based nanofluids: Experimental data, modelling using regression, ANFIS and ANN

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ABSTRACT

Viscosity, density and thermal conductivity of Diamond-COOH and MWCNT-COOH nanoparticles dispersed in water was studied without adding any surfactants or additives for a range of 20 °C < T < 50 °C and 0.0 < φ < 0.2 vol%. Accordingly, based on the experimental data, a new correlation was introduced that predicts the nanofluids' relative thermophysical properties. Besides the non-linear regression for minimum prediction error, an adaptive neuro-fuzzy inference system (ANFIS) and optimal artificial neural network (ANN) were developed. The model was fed by 120 experimental data. 70% of data points were included in the dataset training set and 30% were used as test set. The results of different theoretical models, predicted results and experimental data were compared together. The root-mean-square error (RMSE) and mean absolute percentage error (MAPE) were used to evaluate the results. The models explored the influence of material type, nanoparticle concentration and temperature on the thermophysical properties of nanofluids. As the results show the majority of theoretical models define the thermophysical properties accurately, if correct values of base fluid properties are fed to them. Yet, the current soft-computing methods show less error in comparison to the existing correlations. The ANN is recommended for future studies, as it provides the best fits to the experimental data.

1. Introduction

Three strategies can be used to make a more compact and efficient heat transfer system, including passive, active and the compound techniques. Many studies have adopted the passive technique, because it does not need an external power to function [1]. Generally, this method adds an additive to the working fluid [2,3] or uses geometrical or surface modifications to the flow channel [4,5].

Several past studies have attempted to develop new passive methods to increase the convection heat transfer coefficient or improve the effective thermal conductivity of the fluid. In one of the methods, high thermal conductive solid particles such as metal or metal oxides are added to the base liquid. To do so, suspensions of micrometer or millimeter-sized particles were used. Even though, some improvement was achieved, the thermal system showed issues, such channel abrasion and clogging as a result of the poor stability of the suspension, particularly in micro- and/or mini-channels.

Choi and Eastman [6] developed a new passive method, i.e., "nanofluids" that solved some problems of the large-particle suspensions [7]. Nanofluids comprise of nanoparticles suspensions with high thermally-conductive materials, such as metals [8], metal oxides [9] and carbon [10] into heat transfer fluids to enhance the total thermal conductivity. Usually, these nanoparticles are of order 100 nm or lower. The shape of nanoparticles can be cylindrical [11], spherical [12], or plate [13]. Compared to a low-pressure drop, the suspensions of nanoparticles may enhance the fluid's effective thermal conductivity [14]. Yet, these materials exhibit less erosion in comparison with micrometer or millimeter particles [15].

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The chemical and physical specifications of the base fluid and nanoparticles can control the thermo-physical properties of nanofluids. Thus, it is very important to use an appropriate type of nanofluids to gain a high rate of heat transfer. Viscosity and thermal conductivity have been the majority of the studies done in this area, due to influence on heat transfer enhancement [16,17] as well as the pressure drop and consequently pumping power increment factor [18,19].

Nevertheless, other researchers have studied other important parameters of nanofluids such as temperature [20], specific heat capacity [21], density [22], particle type and size [23], type of surfactant [24], weight percentage/volume fraction of dispersed nanoparticles in working fluid [25], particle shape [26] and type of base fluid [27].

There is evidence that nanofluids should be studied excessively as they are advantageous coolants [28,29]. However, there is still a gap in research on stability and preparation of carbon-based nanofluids without the use of additives or surfactants. The current research studied thermal conductivity, viscosity, and density of distilled water as base fluid as well as carboxylic multi-walled carbon nanotubes and carboxylic diamond as nanoparticles. The nanofluids with different temperatures (20 °C < T<50 °C) and various solid concentrations ($0 < \varphi < 0.2\%$) were assessed and as a result, a general, precise correlation for prediction of the nanofluids' thermophysical properties are proposed for engineering applications through the curve fitting methods, ANN and ANFIS. The findings of this study may help using the modern coolants for electronic cooling [30].

2. Nanofluids preparation and characterization

2.1. Materials

The pristine multi-walled carbon nanotubes (MWCNTs) and nano-diamond were obtained from Nanostructured & Amorphous Materials Inc. (Houston, USA). The nominal purity of the nanotubes is reported by the manufacturer as higher than 95% and nano-diamond is 97%. The specifications of the MWCNTs and properties base fluid studied are listed in Table 1.

2.2. Chemical functionalization of MWNTs and nano-diamond

In order to improve the dispersibility of MWCNTs in base liquids such as water, the pristine MWCNTs were treated with concentrated nitric and sulfuric acids. Treatment with strong acids provides not only the addition of the carbonyl groups (sbndCOOH) but also to remove impurities from the carbon nanotubes surface.

The acid functionalization of the MWCNTs was done with nitric and sulfuric acids (Synth) in proportion (1:3) respectively. The mixture of acids was added at the carbon nanotubes and stirred for 10 min. Then 100 mL of distilled water at 100 °C was slowly added to the mixture kept under magnetic stirring for about 16 h. Afterwards, the MWCNTs were separated by centrifugation of acid solution and washed with deionized water until the pH level of MWCNTs reaches a value of 7. The described method was an adaptation of Esumi, Ishigami [31] which provided the covalent attachment of sbndCOOH groups on the surface of MWCNTs.

2.3. Nanofluids preparation

Preparing a stable MWCNT based nanofluid is not a routine procedure and needs particular method. A magnetic stirrer was used to assist in the dispersion of the carbon nanotubes in water after the functionalization. Then, nanofluids sample were recirculated for 30 min in a high-pressure homogenizer, to improve the dispersion of the MWCNTs into the base fluid and to ensure the colloidal stability. This method leads to attain a stable and uniform dispersion, for breaking the agglomerations between the particles. Four volumetric concentrations were studied. Table 2 shows the masses of MWCNT and water used for manufacture of stable nanofluids.

An ultrasonicator (Hielscher Ultrasound Technology device, Model UP100H, 100 W, 30 kHz) was employed for homogenization and dispersion of the Di-COOH nanoparticles in water. The device was used at 100% amplitude and for 30-min duration, at room temperature. The masses of Di-COOH are shown in Table 3. Utilizing two-step method, it is desired to prepare nanofluids while preserving a homogeneous suspension, avoiding particles agglomeration and achieve a long-term stable fluid.

2.4. Instrumentation

The functionalized and pristine carbon nanotubes were characterized using TEM and SEM images, XRD spectra and FT-IR spectra. The X-ray diffraction was recorded with a DRX-6000 (Shimadzu), utilizing monochromatic radiation Cu-K_1 (λ = 1.54056 Å) to confirm the functionalization of carbon nanotubes. The Fourier transform infrared spectroscopy (FTIR) was carried out in functionalized and pristine nanoparticles, to distinguish the functional groups attached to the MWCNTs and diamonds surface after

Table 1
Transport properties of carbon nanotubes and water.

Parameter	Diamond	MWCNTs	Water
Purity	>95%	>95%	99%
Outside diameter (nm)	3–6	8–15	–
Inside diameter (nm)	–	3–5	–
Length (nm)	–	10–50	–
SSA (m^2/g)	–	230	–
Color	Grey	Black	Almost colorless
Odor	Odorless	Odorless	Odorless
Morphology	Spherical	Multiple wall	–
Melting point (°C)	3727	3652–3697	0.00
Boiling point (°C)	Not determined	Not determined	100
Thermal conductivity (W/m K)	1000	~1500	0.6 (20 °C)
Density (kg/m^3)	3520	~2100	998.21 (20 °C)
C_p (J/kg K)	500	710	4186 (20 °C)
Viscosity (Pa s)	–	–	0.1 Pa s (20 °C)

Table 2
MWCNT-COOH nanoparticles and water mass used for the synthesis of the stable nanofluids.

Volumetric concentration (%)	Water volume (mL) (±0.1 mL)	Nanoparticles mass (g) (±0.001 g)
φ = 0.020	1000.0	0.210042
φ = 0.080	1000.0	0.840673
φ = 0.100	1000.0	1.051051
φ = 0.200	1000.0	2.104208

Table 3
Di-COOH nanoparticles and water mass used for the synthesis of the stable nanofluids.

Volumetric concentration (%)	Water volume (mL) (±0.1 mL)	Nanoparticles mass (g) (±0.001 g)
φ = 0.020	300.0	0.14928
φ = 0.080	300.0	0.59747
φ = 0.100	300.0	0.74699
φ = 0.200	300.0	1.49547