Energy Conversion and Management 105 (2015) 355–367

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Laminar convective heat transfer of hexylamine-treated MWCNTs-based turbine oil nanofluid

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ARTICLE INFO

Article history:
Received 18 February 2015
Accepted 25 July 2015

Keywords:
Carbon nanotubes
Microwave
Functionalization
Hexylamine
Heat transfer and turbine oil

ABSTRACT

Multi-walled carbon nanotubes (MWCNTs) were functionalized by hexylamine (HA) in a promising, cost-effective, rapid and microwave-assisted approach. In order to decrease defects and remove acid-treatment stage, functionalization of MWCNTs with HA was carried out in the presence of diazonium reaction. Surface functionality groups and morphology of chemically-functionalized MWCNTS were characterized by FTIR, Raman spectroscopy, thermogravimetric analysis (DTG), and transmission electron microscopy (TEM). To reach a promising dispersibility in oil media, MWCNTs were functionalized with HA. While the cylindrical structures of MWCNTs were remained reasonably intact, characterization results consistently confirmed the sidewall-functionalization of MWCNTs with HA functionalities. Then, HA-treated MWCNTs-based turbine oil nanofluids (HA-MWCNTs/TO) with different volume fractions were synthesized and employed to be investigated in terms of heat transfer potential. Convective heat transfer coefficient of HA-MWCNTs/TO as a positive parameter and pressure drop as a negative factor were investigated for various volume fractions. While results suggested a weak increase in the pressure drop by MWCNTs loading into the TO, lack of acidic agents, the performance index higher than 1 and a significant increase in the convective heat transfer open a new gateway for introducing this economical product for industrial applications in turbines and can be a capable alternative for conventional TO.

1. Introduction

Different kinds of basefluids such as oil and water have not appropriate capability to eliminate or transfer heat from industrial thermal equipment with high heat flux [1]. Thus, employing various nanoparticles, due to the high thermal conductivity of metal and carbon-based nanostructures into the basefluids, has been recently introduced as a capable technique to improve thermal performance of various heat transfer equipment [2–4]. Therefore, a novel type of fluid, so-called nanofluid has been introduced by researchers to fully realize energy optimization [5–10]. Shortly after introducing the nanofluid by Choi [11], many scientists investigated the effect of different nanostructures into various basefluids to enhance the heat transfer parameters [12]. Different nanostructures such as graphene, fullerene, carbon nanotubes (CNTs), copper oxide (CuO), and aluminum oxide (Al_2O_3) have been employed to realize above-mentioned purpose [13–18]. For example, Lee et al. [19] experimentally studied the thermal conductivity of alumina-water, alumina-ethylene glycol and CuO-ethylene glycol. They reported about 23% enhancement in the thermal conductivity of CuO-ethylene glycol. Murshed et al. [20] investigated the thermal conductivity of TiO_2-based water nanofluid. According to their reports, there is a nonlinear connection between thermal conductivity and volume concentration. While some of the metal- and/or graphene-based materials have shown higher thermal properties on a same condition, CNTs seem to be more cost-effective and comprise attractive thermal, electrical and mechanical properties [21–24]. Thus, having high thermal conductivity confirms the potential of CNTs for synthesizing superb thermally conductive nanofluids. This property makes CNTs appropriate for utilizing in thermal equipment such as thermosyphon and car radiators [25–27]. To address this issue, Choi et al. [28] demonstrated that the presence of CNTs in poly-α olefin oil enhanced the thermal conductivity of basefluid more than 160%. Also, Liu et al. [29] showed 30% enhancement in the thermal conductivity of synthetic engine oil in the presence of CNTs at a volume fraction of 0.02 using a two-step method. Even though CNTs have hopeful applications in the field of nanofluid,

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http://dx.doi.org/10.1016/j.enconman.2015.07.066
0196-8904/

Nomenclature

C_p	specific heat capacity, J/kg K
Dt	tube diameter, m
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
a	radius, nm
m^o	mass flow rate, kg/s
Nu	Nusselt number
Pr	Prandtl number
q	Heat flux, W/m^2
Q	heat transfer rate, W
Re	Reynolds number
T	temperature, °C
V	velocity, m/s
x	axial distance, m
k^c	equivalent thermal conductivity
l	length, μm
R	thermal resistance, m^2 K/W
d	diameter, nm
H	empirical factor of the CNTs aspect ratio
D	fractal index
a_a	effective radii of aggregates

Greek symbols

φ	volume fraction
ρ	density, kg/m^3
μ	fluid viscosity, Pa s
ε	performance index
Δp	pressure drop
μ_{wnf}	fluid viscosity at tube wall temperature, Pa s
H	non-straightness factor of a CNTs

Subscripts

b	bulk fluid
in	inlet
nf	nanofluid
p	particles
w	wall
11	transverse axis
33	longitudinal axis
k	Kapitza
m	maximum
a	aggregates

fundamental problems such as impurities and lack dispersivity in various solvents, due to strong intertube van der Waals interactions, have been limited applications of CNTs [21]. To improve the interactivity of CNTs, covalent and noncovalent functionalization were suggested as the general solutions elsewhere [30,31]. A variety of surfactants such as (gum arabic, sodium dodecyl sulfate, oleic acid and sodium dodecylbenzene sulfonate) has been utilized as the noncovalent groups. However, they attach on the surface of CNTs and reduce the effective area of heat transfer significantly [32–34]. Another fundamental problem of these materials is forming foam in the thermal equipment and consequently causes a disturbance in the setup performance [33]. In order to avoid mentioned hardships and to fully utilize the superior thermal performance of CNTs in nanofluids, covalent functionalization has been suggested as an effective method. For synthesizing new covalently CNTs-based nanofluids, different functional groups with hydrophilic or hydrophobic properties have been decorated on the CNTs surface [35,36]. As one of the most common covalently functional groups, carboxylic acid groups (—COOH) are utilized to enhance dispersibility of CNTs in different media. Despite the fact that carboxylic acid group has been used for bonding to other functional groups, acidic groups can provide a special condition for more corrosion in the industrial equipment. To avoid above-mentioned problems, microwave-assisted functionalization with amines using a diazonium reaction opens a simple and effective gateway for fast treatment [37]. Also, previous studies were mostly concentrated on the water-based media and lack of study on the oil media is obvious, while nanofluid applications can be more operative in equipment comprising oil-based fluid such as turbine oil [1]. Moreover, a majority of previous studies focused on the addition of surfactant and/or carboxylation for increasing CNTs stability in oil media such as turbine oils and transformer oil, which abovementioned problems will be happened.

Between various molecules, alkanes with the relatively good solubility in nonpolar solvents is, a property that is called lipophilicity, an appropriate candidate for increasing the dispersibility of CNT in oil [38–40].

In this study, in order to solve mentioned problems, multi-walled carbon nanotubes (MWCNTs) are functionalized with hexylamine (HA) in a one-pot procedure based on the microwave radiation. In order to decrease defects, our methodology does not contain acid treatment, which is common in the most of the previous studies. To verify functionalization, the treated samples were subjected to the morphological and chemical characterization. HA-treated MWCNTs were added to the turbine oil as the basefluid to enhance thermal properties. Finally, laminar convective heat transfer and pressure drop of HA-treated MWCNTs based turbine oil nanofluid (HA-MWCNTs/TO) were studied under constant heat flux.

2. Methods

2.1. Materials

The pristine MWCNTs (diameter <30 nm, length of 5–15 μm and purity >95%) were obtained from Shenzhen Nano-Tech Port Co. N,N-dimethylformamide (DMF), THF, methanol, $NaNO_2$ and H_2SO_4, all with analytical grade were purchased from Merck Inc. Also, hexylamine (HA) were prepared from Sigma–Aldrich Co. Light turbine oil (TO-32) was prepared by Behran Oil Company.

2.2. Functionalization of MWCNTs

Recently, the new mechanism for the functionalization of MWCNTs with amine groups was suggested by our groups and Ellison et al. [21,41,42]. The effect of $NaNO_2$ was suggested by Bahr et al. [43] and Price et al. [44], which involve producing a semi-stable diazonium ion and then results in a radical reaction with CNTs.

Regarding HA-treated MWCNTs, the pristine MWCNTs (200 mg) were sonicated with HA (20 ml) and $NaNO_2$ (200 mg) for 2 h at 50 °C, until a uniform suspension was provided. During sonication time, 0.5 ml of H_2SO_4 was dropped to the suspension to complete diazonium reaction. The mixture was subsequently poured into a Teflon reaction vessel (100 ml), placed into the microwave (Milestone MicroSYNTH programmable microwave system) and continuous microwave irradiation was carried out with simultaneous monitoring of power and temperature. The suspension was irradiated for 30 min at 120 °C at power of 700 W. After being cooled at room temperature, the mixture was filtrated on a PTFE