International Communications in Heat and Mass Transfer 76 (2016) 1–5

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Remarkable enhancement of convective heat transfer with different nanoparticles in *N*-methyldiethanolamine solution in gas sweetening process☆

Mehdi Vahidi [a,b], Alimorad Rashidi [b,*], Ahmad Tavasoli [a], Sajad Kiani [b]

[a] School of Chemistry, University College of Science, University of Tehran, Tehran 11155-4563, Iran
[b] Nanotechnology Research Center, Research Institute of Petroleum Industry (R.I.P.I.), Tehran 14665-137, Iran

ARTICLE INFO

Available online 14 May 2016

Keywords:
Methyldiethanolamine
Nanofluids
Thermal conductivity
Convection heat transfer

ABSTRACT

In this work, effective thermal conductivity and convective heat transfer at different Reynolds number of nanofluid containing nanometer-size particles in *N*-methyldiethanolamine solution is measured. Thermal conductivity and stability of nanostructures in water-based nanofluid, as well as their dependence to temperature and time variation, are of a great concern. These nanofluids consists of 0.1 mass fraction of spherical silica nanoparticles (SiO_2), carbon nanofiber (CNF), UiO-66-NH_2 MOF, carbon nanotube functionalized with carboxylic acid as ligand (CNT-COOH), MgO nanoparticles, and colloidal silica. These nanofluids mixed with of *N*-methyldiethanolamine solution and thermal conductivity coefficients were measured. The appropriate result demonstrated the thermal conductivity is highly related to the optimum concentration of nanoparticle in base fluid, velocity, flow rate, and heat flux. It was found that a combination of CNF and SiO_2 nanoparticles in a 1:1 ratio with 0.1 wt.% could enhanced thermal conductivity which will induces greater enhancement by combined nanoparticle base amine fluid in heat transfer application. It has been shown increase of Reynolds number at the mass concentration 0.1 wt.% an increase in convective heat transfer coefficient of nanofluid about 13%. These results improve the thermal conductivity properties of solution in amine plants.

1. Introduction

Nanofluids are dilute liquid suspensions of nanoparticles with at least one of their principal dimensions smaller than 100 nm. Heat transfer fluids play important roles in many industrial sectors, including transportation, chemical processes, energy supply and production, and microelectronics. The thermal conductivity of heat transfer fluids is vital in the development of energy-efficient heat transfer equipments. However, conventional heat transfer fluids, such as water, oil and ethylene glycol, are inherently low efficient heat transfer fluids. There is an urgent need to develop advanced heat transfer fluids with significantly high thermal conductivities and improved heat transfer performances [1]. Maxwell was the first presenter of a theoretical basis to predict a suspension's effective conductivity about 140 years ago (1873), and his theory was applied from millimeter to micrometer sized particles suspensions but cannot be used for the prediction of thermal conductivity of nanofluids [2]. Thermal conductivities of nanoparticle–fluid mixtures have been reported by Masuda et al.[3], Artus [4], and Eastman et al. [5]. Adding a small volume fraction of metal or metal oxide powders in fluids increased the thermal conductivities of the particle–fluid mixtures over those of the base fluids. Pak and Cho [6] studied the heat transfer enhancement in a circular tube, using nanoparticle–fluid mixtures as the flowing medium. In their study, γ-Al_2O_3 and TiO_2 were dispersed in water, and the Nusselt number was found to increase with the increasing volume fraction and Reynolds number [7]. Prasher et al. [8] believe that experimental data show that nanofluids behave as Newtonian fluids; however, the viscosity of nanofluids is much higher than can be predicted by the Einstein's model, but this is likely due to aggregation of the nanoparticles. A considerable amount of experimental and theoretical work has been devoted to the thermal conductivity of nanofluids [9–14]. Up today, there are some mechanisms that investigated for transport properties of nanofluids. According to the most recent papers, for the present understanding of heat conduction in nanofluids, the enhancement of thermal conductivity of nanofluids can be related to the aggregation of nanoparticles into clusters [15]. Kim et al. is investigated of CO_2 capture in a bubble column using silica/water nanofluid [16]. They concluded that the mass transfer coefficient of CO_2 in nanofluid is 5 times higher than in the pure water alone. Effect of Al_2O_3/water nanofluid on CO_2 absorption is studied by Samadi et al. [17]. They used a wetted wall column and found that the mass transfer coefficient and the mass transfer rate increase by increasing the nanofluid concentration and liquid flowrate. Salimi et al. were

☆ Communicated by W.J. Minkowycz.
* Corresponding author.
E-mail address: rashidiam@ripi.ir (A. Rashidi).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.05.016
0735-1933/

studied the CO_2 absorption in a randomly packed column equipped with magnetic field [18]. They found that the magnetic field has the positive effect on CO_2 absorption. Other researcher studied another nanofluid for CO_2 absorption, and they figured out that addition of nanoparticles into the liquids can increase the absorption rate of CO_2 [19,20].

Todays aqueous alkanolamine solutions are widely used for the of acidic gases, such as CO_2 and H_2S from industrial, flue and natural gases. In overall, the alkanolamines present several disadvantages such as volatility, toxicity, degradation, transfer of water into the gas stream during desorption stage and high energy consumption. In recent years, use of novel technology such as nanotechnology is useful in many industries. In this work, we investigated the effect of addition of nanofluids to the *N*-methyldiethanolamin solution (as a routine alkanolamine which is used in many gas refineries) on increase of heat transfer in amine solutions in gas refinery plants.

2. Experimental

2.1. Materials

All the materials were reagent grade and used without further purification. Aqueous solution of 0.4 mass fraction *N*-methyldiethanolamine (CAS registry number 105-59-9, +99%, Sigma-Aldrich Chemical Co.) was used as a base fluid. The nanoparticles were synthesized and prepared in our groups. Spherical silica (SiO_2) nanoparticle synthesized using sol–gel method [21]. Carbon nanofiber (CNF) obtained by vertical floating catalyst method [22]. The UiO-66-NH_2 MOF have been synthesized by solvothermal method [23]. MWCNTs were synthesized during a CVD procedure over Co–Mo/MgO catalyst at 1000 °C [24] and functionalized with carboxylic acid (CNT-COOH). Colloidal nanosilica (27%) was prepared according to Sadegh hassani et al. procedure [25]. MgO nanoparticles were synthesized using chemical precipitation method [26]. Materials were balanced using analytical balance with accuracy of 0.1 mg (Mettler, model AE 200).

2.2. Preparation of nanofluids

The nanoparticles (0.1 wt.%) were slowly added in mixture of 40 wt.% MDEA aqueous solution followed by mechanical stirring for 30 min, which also described in detail at Table 1. For the purpose of nanoparticle stability, the mixture of MDEA solution and nanofluids mixed by addition of accumar-300 as surfactant under vigorous stirrer for 30 min. Please note that because of stability in water media, the colloidal nanosilica and UiO-66-NH_2 MOF does not need to accumar-300 as surfactant. The mixture of MDEA solution and various nanofluids were distributed by a high-powered ultra-sonication probe (60 kHz, 300 W) to improve the dispersion of nanoparticles in base fluid for 15 min. Sonication media would permit nanoparticles for higher stability in base fluid.

Table 1
The composition of nanofluid samples.

Nanofluid	Weight %	Composition			
		Nanoparticle (g)	accumar-300 (g)	Deionized water (g)	MDEA (g)
CNF	0.1	0.0501	0.0671	29.9102	20.0219
CNT-COOH	0.1	0.0527	0.0603	29.9958	19.9957
MgO nanoparticle	0.1	0.0499	0.0686	29.9200	20.0205
Colloidal nanosilica	0.1	0.0504		29.8470	20.3202
CNF + nanosilica	0.1	0.025 + 0.025	0.0663	29. 8341	20.1204
UiO-66-NH_2	0.1	0.0501		29.9512	20.0054
MDEA Bulk solution				30.0102	20.0114

2.3. Nanofluids analyzing apparatus

The thermal conductivity was measured by KD2 Pro thermal analyzer provided by Decagon devices, Inc., USA. According to KD2 methodology (transient hot wire), fluid samples were measured by the temperature/time response of the probe (60 mm length, 1.3 mm diameter) to an abrupt electrical pulse by a derivation of Fourier's law and temperature. Before thermal conductivity measurements, the sample was calibrated using distilled water and then, probe remained for 20 min at constant temperature. The thermal conductivities of the samples measured from the temperature range of 298, 308 and 318 K. The set up consists of a circulator and KD2 Pro device. The percentage enhancement in thermal conductivity of the samples was calculated using the relation

$$\text{Enhance}\% = \frac{K_n - K_f}{K_f} \times 100 \tag{1}$$

where K_f and K_n were base on fluid and sample thermal conductivity, respectively.

It must be considered that by experimental data measured from wall temperature, the fluids inlet temperature, heat flux, and flow rate. The local heat transfer coefficient of nanofluids can be obtained by:

$$h(x) = \frac{q^o}{T_s(x) - T_m(x)} \tag{2}$$

where $T_m(x)$ is the fluid temperature on tube, $T_s(x)$ is the tube wall temperature, $h(x)$ is the heat transfer coefficient, q^o is the amount of heat transferred (heat flux) and $\Delta T = T_s(x) - T_m(x)$ is the difference in temperature between the solid surface and surrounding fluid area. For the fully experimental tests, the system warmed up by heater and circulates by the pump for 10 min until remove bubbles. Second, the flow rate and temperature control are set until system be stable for 30 min. Finally, the average heat transfer coefficients were measured. As it shown in Fig. 1, the setup apparatus for investigation of convective heat transfer characteristics are consists of a pump (flow rate: 1.6–6 l/min), reservoir tank, test tube section (inner diameter: 11.4 mm, length: 1 m), heating and cooling devices, and a circulator bath which used in different flow regime for preserve a constant temperature. The electrically heated to tube surface section generate constant heat 800 W and were insulated by 150 mm blanket to minimize the heat loss fluids from the tube to the atmospheric condition. It can be seen that the five thermocouples (K-type) are fixed at specific places along the tube and two thermocouples (K-type) at the inlet and outlet of the test section [27].

3. Results and discussion

3.1. Thermal conductivity measurement of nanoparticle

MDEA solution (40% wt.) was used as the base fluid. According to previous articles on investigation of nanofluid enhancement in other base fluid [28], various nanoparticles were selected for preparation of nanofluid based on MDEA solution. Nanoparticles were revealed with surfactant, when dispersed in amine base fluid, and it cannot be seen the aggregating like dispersion of nanoparticles in water base fluid [29]. This property assists the stability of nanoparticles in the base fluid.

In general, compared to base fluid, the thermal conductivity of nanofluids is more sensitive to temperature [30]. The effective thermal conductivity of the nanofluids increases with an increase in the temperature [31] but the trends vary for different cases. In order to study the temperature effect of thermal conductivity of nanofluid, a thermostat bath was used. All the measurements were taken after calibrating the KD2 Pro instrument with water. Because of temperatures of absorption towers in gas refineries, the temperatures range of 298–328 K was