Energy Conversion and Management 109 (2016) 10–18

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A novel approach for energy and water conservation in wet cooling towers by using MWNTs and nanoporous graphene nanofluids

S. Askari [a,b], R. Lotfi [a,c,*], A. Seifkordi [a,b], A.M. Rashidi [a], H. Koolivand [a]

[a] Nanotechnology Research Center, Research Institute of Petroleum Industry (RIPI), West Blvd. Azadi Sports Complex, P.O. Box 14665-1998, Tehran, Iran
[b] Chemical Engineering Department, Sharif University of Technology, Azadi Ave., P.O. Box 11155-9567, Tehran, Iran
[c] Mechanical Engineering Department, Penn State University, University Park, P.O. Box 16803, State College, USA

ARTICLE INFO

Article history:
Received 17 August 2015
Accepted 13 November 2015
Available online 10 December 2015

Keywords:
Cooling tower
Nanofluid
Carbon nanotubes
Porous graphene
Energy conservation
Water consumption

ABSTRACT

This study deals with an experimental investigation on the thermal performance of a mechanical wet cooling tower with counter flow arrangement by using multi-walled carbon nanotubes (MWNTs) and nanoporous graphene nanofluids. Stable nanofluids were prepared through two-step procedure by using water with properties taken from a working cooling tower in the South of Iran. Zeta potential revealed suitable stability of MWNTs and nanoporous graphene nanofluids. Thermal and rheological properties of the nanofluids were investigated. It was found that thermal conductivity increases by 20% and 16% at 45 °C for MWNTs and nanoporous graphene nanofluids, respectively. The increase in density and viscosity, particularly in low concentrations of nanoparticles, was insignificant enough for industrial applications. Moreover, it was found that by using nanofluids, efficiency, cooling range and tower characteristic (KaV/L) are enhanced in comparison to water. For instance, at inlet water temperature of 45 °C and water/air (L/G) flow ratio of 1.37, the cooling range increases by 40% and 67% for MWNTs and nanoporous graphene nanofluids (0.1 wt.%), respectively. On the other hand water consumption is reduces by 10% and 19% at inlet water temperature of 45 °C for MWNTs and nanoporous graphene nanofluids, respectively.

1. Introduction

Nowadays, urgency in energy and water conservation in industrial processes is an essential issue because of the scarcity of energy and water resources. Among different cooling processes such as evaporative cooling, vapor compression, absorption/adsorption and thermoelectric refrigeration systems, evaporative cooling by using a cooling tower is an attractive and efficient option. However still there is a large potential to improve the efficiency of cooling towers to conserve energy and decrease water consumption [1]. A cooling tower is a heat rejection device which rejects waste heat to the atmosphere through the cooling a water stream to a lower temperature level [2]. Cooling towers are widely used in thermal power plants, air conditioning systems, oil refineries, petrochemical units and other chemical plants. Based on the contact between warm water and air flow, cooling towers are categorized to dry cooling towers and wet cooling towers [3]. In dry cooling towers warm water is passed through tubes, and the air flow is passed between the tubes. As a result there is no direct contact between water and air flows and heat transfer occurs only due to the temperature difference between air and water flow. On the other hand, in wet cooling towers there is direct contact between air and water. In these cooling towers because of temperature difference between water and air flow, sensible heat transfer takes place, while latent heat transfer is induced by differences in the relative humidity of the air and saturated air at the surface of the water drops. This difference causes some water to evaporate and some moisture to enter to the thin layer of air around the drop where relative humidity is 100%. In order to increase the contact area and contact time between water and air flow in wet cooling towers, commonly, different types of packing including splash and film type are used [4]. To improve the efficiency of cooling towers, extensive research has been conducted during the last decade. For instance Gharagheizi et al. [4], investigated the performance of mechanical cooling tower with two types of film packing. In another research work, Goshayshi and Missenden [5] evaluated the effect of various arrangements of packing in atmospheric cooling towers. Hajidavalloo et al. [6] examined the thermal performance of cross flow cooling towers with splash type

* Corresponding author at: Mechanical Engineering Department, Penn State University, University Park, P.O. Box 16803, State College, USA. Tel./fax: +1 8148636274.

E-mail address: rul12@psu.edu (R. Lotfi).

http://dx.doi.org/10.1016/j.enconman.2015.11.053
0196-8904/

packing under different wet bulb temperatures. In another work Li et al. [7] studied heat and mass transport mechanism of film type cooling, which was combined with an on-site test on counter flow film type cooling tower. They developed a mathematical model on the evaporation and cooling efficiency.

Furthermore some researchers focused their study on the types of spray nozzles and examined cooling tower performance based on different types of spray nozzles [8]. In general, the research studies conducted so far for the enhancement of cooling towers' efficiency, have concentrated on the influence of parameters including working parameters such as flow rate and temperature of water, flow rate, temperature and humidity of air, packing type and characteristics and geometry of the cooling power. Some of these parameters are not controllable or cost-effective to change, while some are not applicable for working cooling towers. On the contrary, if a fluid with better thermal properties than those of water was used, it would be possible to increase the energy efficiency of working cooling towers as well as conservation in the water consumption, leading to tremendously cost reduction of the system. However to the best of our knowledge, effect of water thermal properties and application of additives for thermal enhancement of water and energy conservation in cooling towers has not been investigated yet. Introduction of solid particles in conventional heat transfer fluids has been the subject of research works for many years. Commercial fluids containing nanometer-sized solid particles are termed "nanofluids". It has been shown that nanoparticles can enhance heat transfer properties of base fluids significantly, minimizing the sedimentation and pressure drop problems which are common in micro particles and larger particles [9–14].

However one of the main challenges in application of nanofluids in the industry is the stability of nanoparticles in the base fluid. Use of surfactants can help to stabilize the nanoparticles in the base fluid. Thus finding the most suitable nanoparticle and surfactant for each system is of great importance. In recent years much attention has been given to the use of carbon nanomaterials including carbon nanotubes, graphene and carbon nanofibers as additives to improve the heat properties of fluids. These nanomaterials have lower density, lower cost and higher thermal conductivity compared to many other nanoparticles. Amiri et al. [15] investigated thermo-physical properties of graphene nanoplatelet-based nanofluids. They reported that thermal conductivity of nanofluid increases by temperature and particles concentration. Amrollahi et al. [16] investigated convection heat transfer of functionalized MWNTs in aqueous fluids in laminar and turbulent flows. The experimental results indicate that the convective heat transfer coefficient of these nanofluids increases by up to 33–40% at a concentration of 0.25 wt.% compared with that of pure water in laminar and turbulent flows, respectively. It has been shown that thermal conductivity, convective heat transfer and viscosity of nanofluids increased with an increase in the nanoparticle concentration [17,18].

Wettability and surface tension of nanofluids are two other parameters which are especially important in applications such as cooling tower. Some researchers examined the effect of nanoparticles in the wettability and surface tension of base fluid. For example, Vafaei et al. [19] demonstrated that nanoparticles have a significant effect on the wetting behavior of drops. The authors showed that the contact angle is strongly dependent on the nanoparticle concentration and nanoparticles cause considerable change in contact angle. Moreover different investigations have been performed for changing the evaporation rate and enthalpy of nanofluids [20–25]. Gerken et al. [21], examined the droplet evaporation and surface tension of nanofluids. They reported that nanoparticles cause an increase in surface tension and reduction of evaporation rate of fluids. Tso et al. [22], examined the enthalpy of evaporation, saturated vapor pressure and evaporation rate of aqueous nanofluids. They reported that most of the nanofluids have lower saturated vapor pressure and evaporation rate than water, particularly in higher nanoparticle concentrations.

The main objective of this study is to investigate the effect of nanofluids on the performance of cooling tower in terms of energy and water conservation. To achieve this goal MWNTS and nanoporous graphene water-based nanofluids were used. In the first section of the work, nanomaterial synthesis and nanofluid preparation have been explained. In order to assess the stability of nanofluids, zeta potential measurement has been used. Then thermal and rheological properties of the nanofluid, including thermal conductivity, density and viscosity have been evaluated. After that change of surface tension by adding nanoparticles, has been examined through contact angle measurement. Finally for investigating the effect of nanofluids on water and energy conservation, a cooling tower has been designed and constructed. Effect of inlet water temperature and water to air flow rate, on efficiency, cooling range and tower characteristic of cooling tower has been examined in the presence of nanofluids with a mass fraction of 0.1 wt.%.

2. Experimental section

2.1. Nanomaterial synthesis and characterization

Multi-walled carbon nanotubes (MWNTs) with purity of 95 wt.% were synthesized in RIPI using a CVD (chemical vapor deposition) method over Co–Mo/MgO catalyst [26]. The catalysts were reduced with pure hydrogen by flow rate of 200 ml min^{-1}. The temperature during the reduction steps was increased to 850 °C with a rate of 5 °C min^{-1}, and after 1 h was increased to the reaction temperature of 1000 °C. Carbon nanotubes were grown in the quartz horizontal reactor by passing a mixture of 20% methane in hydrogen with a flow of 250 ml min^{-1} over the catalyst. After carbon nanotubes growth, the methane flow was turned off and the reactor was cooled down to the room temperature in the presence of hydrogen gas.

Nanoporous graphene was prepared by CVD method in catalytic basis [27,28]. The furnace was heated up to 900–1100 °C for 30 min. The reaction was carried out using methane as the carbon source and hydrogen as the carrier gas in a ratio of 4:1. To obtain pure nanoporous graphene and remove the metal nanocatalysts, the product was stirred in 18% HCl solution for about 16 h at room temperature. Then the sample was washed several times with distilled water until the neutral product was obtained. The product was then dried at 100 °C.

Figs. 1 and 2 shows the scanning electron microscope (SEM) and the transmission electron microscope (TEM) images of MWNTs and nanoporous graphene, respectively. The tubular and filamentous morphology of nanotubes are shown clearly in these images. MWNTs have an average diameter of about 10–20 nm and an average length of 10 μm. As it can be seen from Fig. 2, the graphene structure has high porosity. The number of graphene sheets is less than 2–5.

2.2. Preparation of nanofluid and evaluation

In order to make the experiments close to the real condition, nanofluids were prepared using base water with properties taken from a working cooling tower in the South of Iran. The amount of cations and anions in the reference water was measured by using inductively coupled plasma (ICP) technique and ion chromatography, respectively. Note that stabilizing nanoparticles in this kind of water, especially in the presence of different cations and anions is very essential. In order to make stable MWNTs and nanoporous