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Influence of nanoparticles on reducing and enhancing evaporation mass transfer and its efficiency

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ABSTRACT

Considering the importance of evaporation in various practical applications, an experimental investigation on reducing and enhancing evaporation ability of different nanoparticles was performed. A deliberately designed experimental device was used to measure the evaporation rate of nanofluids at different air velocities. Aqueous nanofluids with clay, TiO_2, ZrO_2, Fe_2O_3 and Ni/Fe nanoparticles at the various concentrations were studied. The experimental results showed that depending on the type of nanoparticle, nanofluid evaporation can be decreased or increased. The results revealed that TiO_2, ZrO_2, Fe_2O_3 and Ni/Fe nanoparticles are able to reduce their base fluid evaporation rate, but clay nanoparticle increases its base fluid evaporation. The results also, showed that the nanofluid evaporation reduction or enhancement efficiency is affected by both nanoparticle concentration and air velocity. From the results it was also concluded that the evaporation efficiency curves of those nanoparticles that slow down their base fluid evaporation, were bowed inward and the efficiency curve of clay nanoparticle was bowed outward.

1. Introduction

Various techniques have been proposed and investigated for changing evaporation rate from free water surface [1–3]. The suggested techniques for altering evaporation rate up to now include: covering the free water surface, increasing surface area by spraying water droplets, aeration, waterfalls, wave action and using additives to water such as mineral salts. Due to the increasing development of nanotechnology, there is now capability to change the evaporation rate of water as base fluid by the addition of nanoparticles [4,5]. The existence of nanoparticles in the base fluid exhibits different thermophysical properties like viscosity, surface tension and thermal conductivity from their base fluids [6–8]. Nanoparticles also increase interaction and collision among the particles and fluid [9]. Owing to these attributes, it is expected that the nanoparticle additives affect the evaporating rate. Having investigated the evaporation rate of nanofluids, it is important to note that the evaporation efficiency (η) needs to be considered in the analysis which is defined as follow [10]:

$$\eta = \frac{|E_{DW} - E_{NF}|}{E_{DW}} \quad (1)$$

where E_{DW} is evaporation from Deionized Water (DW) and E_{NF} is evaporation from NanoFluids (NF) at the same air velocity. Depending on whether the existence of nanoparticle reduces or enhances evaporation rate, the efficiency is shown by η_{ERE} or η_{EEE}.

Sefiane and Bennacer [11] demonstrated that the presence of aluminum nanoparticles leads to a reduction of the droplet evaporation rate when comparing with its base fluid, ethanol. Chen et al. [4] studied the influence of the clay, Fe_2O_3 and silver nanofluids with and without stabilizer on the water droplet evaporation rate. They found that the silver and clay nanoparticles enhance their base fluid evaporation rate, but Fe_2O_3 slows down the evaporation rate over that of its base fluid. The effect of aluminum oxide nanoparticles (in pure water as a base fluid) on surface tension and phase change phenomena was experimentally investigated by Madhusoodanan et al. [5]. Their experiments showed that the addition of nanoparticles to pure water increases its surface tension which leads to lower evaporation. Chen et al. [4,12] also, studied the effect of different nanoparticles on DW surface tension (Table 1) and evaporation.

As can be seen, the current understanding of the evaporating process in nanofluids is only in the beginning stage; therefore, the first objective of this study is to extend experimental data on the evaporating behavior of five types of nanofluids. The second objective is to perform a comparison of evaporation between nanofluids and their base fluids to elucidate nanoparticle's ability whether to reduce or enhance its nanofluid evaporation rate over that of the base fluid. Also, in an effort to find the nanofluid evaporation reduction/enhancement efficiency, comparisons between nanofluid evaporation with that of deionized water at various nanoparticle concentrations and air velocities are made.

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Table 1
Surface tension of DW and nanofluids (percentage in weight) [12].

Fluid	Surface tension, σ (mN/m)
DW	73.60
DW + 1%PVP	70.04
DW + 0.1% clay	72.84
DW + 1% clay	52.31
DW + 2% clay	40.97
DW + 1%PVP + 0.1% Fe_2O_3	≈71.20

2. Experimental measurements

2.1. Nanofluids preparation

In the present investigation, two-step method for preparing nanofluids is used [13]. In this method nanoparticles are produced as dry powders. Then, nano-sized powders disperse into the base fluid in the second processing step, through sonication in an ultrasonic processor [14–16]. Before starting the nanoparticles dispersion into the base fluid, nanoparticles should be weighed. The mass fraction of each nanoparticle (the mass of nanoparticle per nanoparticle mass and base fluid mass) can be defined as follow [16]:

$$\text{wt.} = \frac{m_{\text{NP}}}{m_{\text{NP}} + m_{\text{BF}}} \quad (2)$$

where m_{NP} is nanoparticle mass and m_{BF} is base fluid mass. As quantities of nanoparticle mass fraction are very low, they are expressed as percent values.

Experimental measurements are performed for the ZrO_2, Fe_2O_3, Ni/Fe, TiO_2 and clay nanoparticles. The size and concentration of these nanoparticles are tabulated in Table 2. (All percentage by weight).

As it is important to reduce agglomerations and properly disperse nanoparticles in fluid, surfactant and sonication are used as means to decrease particle agglomeration and to increase stability of the suspension [4,6]. The ZrO_2, Fe_2O_3 and Ni/Fe nanofluids are stabilized by sonication and PVP, but for TiO_2 and clay nanofluids only sonication process is used to help stabilize.

2.2. Experimental apparatus and procedure

Fig. 1 shows the experimental system to measure the evaporation rate of nanofluids. The circular low speed wind tunnel of the system has an inner diameter of 0.5 m and a length of 3 m. An axial fan produces and regulates various air velocities inside the wind tunnel.

The system includes a nanofluid rectangular holding pan that is 0.3 × 0.15 × 0.1 m in length, width and depth, respectively. The pan is insulated by polystyrene panels of 2 cm in thickness around the sides and the bottom to reduce heat loss, so that heat exchange occurs mainly through the free nanofluid surface. The evaporation pan and digital scale are seated in the wind tunnel. The nanofluid mass loss in the evaporation pan is determined by the digital scale with an accuracy of ±0.1 gr. The temperature of the working nanofluid in the evaporation pan is controlled at a constant temperature of 15 °C by using an electrical heater associated with a thermocouple (with ±1 °C accuracy). An anemometer with an accuracy of 0.1 m/s is also used to measure the air velocities at 1 cm from water surface in ten different horizontal positions. The inlet air temperature is measured by a thermocouple with an accuracy of ±1 °C. The laboratory has a controlled air conditioning system to maintain the temperature at 20 °C and 50% relative humidity.

Table 2
Properties of prepared nanofluids.

Nanoparticle	Particle (% wt.)	Size (nm)	PVP (% wt.)
ZrO_2	0.02	20	1
Fe_2O_3 (sphere)	0.02	20–30	1
Ni/Fe	0.005, 0.01 and 0.02	30	1
TiO_2	0.02, 0.05 and 0.1	15–20	0
Clay (disk)	0.1, 0.5, 1 and 2	25–30	0

2.3. Uncertainty analysis

Measuring instruments have been calibrated before performing the experiments and tests are repeated for three times. The uncertainty analyses are performed using the method proposed by Coleman and Steele [17]. Neglecting data acquisition, data reduction (round off and truncation) and personal operation, the uncertainty in working nanofluid temperature data, which is mainly associated with response time of the thermocouples (0.1 s), is estimated to be 2%. Also the uncertainty in the average air velocity is about 3% and in the air temperature is estimated to be less than 2%; whereas, in worst case, the uncertainty in the evaporation mass transfer values, which is essentially related with the area of the evaporation surface and the resolution of the digital scale over a data collection period, is estimated to be 4.3%. The confidence levels for the uncertainties of the evaporation mass transfer measurements are 95%.

3. Experimental results and discussion

3.1. Comparison of evaporation rates of two base fluids

Fig. 2 compares the evaporation rates for two types of base fluids: (1) DW and (2) DW + 1%PVP for various air velocities. The comparison between evaporation rates of these base fluids indicates that DW + 1%PVP contributes to faster evaporation by a factor of approximately 1.12. This occurs because the addition of PVP to DW decreases its surface tension (Table 1) and enthalpy of vaporization [18] which lead to higher evaporation. These results are consistent with the observations of droplet evaporation rate of Chen et al. [4]. The figure also shows that as expected, an increase in air velocity increases the evaporation rate for DW and DW + 1%PVP. Here, for transient flow ($2320 < Re_D < 10000$), where air velocity is lower than 0.3 m/s, the slopes of these curves, are steeper than those of higher air velocities. The definition of Reynolds number, $Re_D = VD/\nu$, is based on the wind tunnel average air velocity (V ranged up to 1.8 m/s), wind tunnel diameter (D = 0.5 m) and air kinematic viscosity at 20 °C ($\nu = 15.11 \times 10^{-6}$ m^2/s).

3.2. Nanoparticles that slow down their base fluid evaporation rate

The evaporation rate values versus air velocity for Fe_2O_3, ZrO_2 and Ni/Fe nanofluids are plotted together with that of their base fluid DW + 1%PVP in Fig. 3. It is noticed that these nanofluids provide lower evaporation rates compared to that of their base fluid. These can be due to the viscosity and surface tension enhancement of nanofluids. The measurements of thermophysical properties of Fe_2O_3 nanofluid performed by Chen et al. [12] and Colla et al. [19] revealed that Fe_2O_3 nanoparticles exhibit a surface tension and viscosity enhancement of its base fluid. As evaporation mainly takes place near the free surface and leads to an internal fluid motion to compensate the mass loss at the free surface; a higher viscosity for the nanofluid can lead to a slower internal fluid motion and consequently could be a limiting factor for the evaporation at the free surface [11].