



## Study of enthalpy of evaporation, saturated vapor pressure and evaporation rate of aqueous nanofluids



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### ABSTRACT

$\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  nanoparticles were added to deionized water to study the effects of enthalpy of evaporation, saturated vapor pressure and evaporation rate. The results show that the enthalpy of evaporation decreased with an increase of nanoparticle concentration and the larger the nanoparticle size, the smaller the enthalpy of evaporation. Two experiments were built to determine the saturated vapor pressure and the evaporation rate of nanofluids. The results show that most of the nanofluids have lower saturated vapor pressure and evaporation rate than those of water, particularly with an increase of nanoparticle concentration, but a few nanofluids with lower volume concentrations show slightly larger values than those of water. Therefore, the evaporation rate of nanofluids as well as their saturated vapor pressure, can be increased or decreased, depending on their volume concentration and the type of nanofluid. Besides, a semi-analytical model for estimating the evaporation rate of water and nanofluids as a function of temperature, humidity and air velocity was developed. After comparing the modeling results with the experiment, the agreement between them is generally good. Lastly, some nanofluids were tested as an adsorbate in an adsorption cooling system, and the results show that using 0.01%  $\text{TiO}_2$  nanofluid as the adsorbate enhances the cooling performance by about 9%.

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### 1. Introduction

Nanofluids are solutions containing suspended solid nanoparticles from 10 to 100 nm in size [1–3]. They are known to exhibit different thermophysical properties from their base fluids such as thermal conductivity, viscosity, wettability and surface tension [4–6]. The thermal conductivity and viscosity of nanofluids increased with an increase in the nanoparticle concentration [7–11]. These enhanced thermophysical properties make nanofluids promising for applications in various areas of thermal management. Some review papers have summarized the state of the art use of nanofluids for thermal applications [12,13]. Nanoparticles can also increase interaction and collision among the particles and fluid [14]. Owing to these attributes, it is expected that the nanoparticle additives will affect the evaporation rate, enthalpy of evaporation, saturated vapor pressure, etc.

However, there is a lack of research about pool evaporation rate of nanofluids, and there are only a few systematic studies about pool evaporation rate of water [15,16]. Most studies have focused

on the droplet evaporation of nanofluids and/or water [1,3,17,18]. With regard to this, some relevant literature reviews about the evaporation rate of nanofluids follow: Sefiane and Bennacer [3] demonstrated that the presence of aluminum nanoparticles reduced the droplet evaporation rate compared to that of the ethanol (base fluid). Chen et al. [1] studied the effect of clay,  $\text{Fe}_2\text{O}_3$  and silver nanofluids with and without a stabilizer on the droplet evaporation rate. They found that the silver and clay nanoparticles enhanced their base fluid evaporation rate, but  $\text{Fe}_2\text{O}_3$  nanoparticles reduced the base fluid evaporation rate. The influence of  $\text{Al}_2\text{O}_3$ –water nanofluid on surface tension and phase change phenomena was experimentally investigated by Madhusoodanan et al. [17]. Their experiments showed that the addition of nanoparticles to water (droplets) increased surface tension, leading to a reduction in the evaporation rate. Moghiman and Aslani [19] in 2013 studied the evaporation rate of clay,  $\text{TiO}_2$ ,  $\text{ZrO}_2$ ,  $\text{Fe}_2\text{O}_3$  and Ni/Fe nanofluids. They investigated the influence of nanoparticle type and concentration on the efficiency of evaporation. Their results showed that  $\text{TiO}_2$ ,  $\text{ZrO}_2$ ,  $\text{Fe}_2\text{O}_3$  and Ni/Fe nanoparticles reduced their base fluid evaporation rate, but clay nanoparticles increased the evaporation rate. Recently, Gerken et al. [20] studied the droplet evaporation and surface tension of aluminum (Al)/ethanol nanofluids. The experimental results

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## Nomenclature

|                           |  |                      |   |
|---------------------------|--|----------------------|---|
| $A$                       | correlation factor of $\text{Al}_2\text{O}_3$ –water nanofluids (–)                          | $R$                  | universal gas constant, 8.314 (J/K mol)                                       |
| $B_0, B_1, B_2 \dots B_7$ | constant (–)   | $SCP$                | specific cooling power (W/kg)   |
| $C_e, C'_e$               | coefficient of evaporation (–)   | $T$                  | temperature (K)   |
| $C$                       | specific heat capacity (J/kg K)  | $T_o$                | outside atmospheric temperature (K)   |
| $COP$                     | coefficient of performance (–)   | $T_w$                | evaporating surface temperature (K)   |
| $d$                       | thickness of the boundary layer (m)  | $u$                  | average upstream velocity (m/s)   |
| $d_p$                     | diameter of $\text{Al}_2\text{O}_3$ nanoparticles (nm)                                       | $x$                  | distance from the evaporating surface (m)                                     |
| $D, D_{12}$               | diffusion coefficient of water vapor in air ( $\text{m}^2/\text{s}$ )                        |                      |   |
| $D_T$                     | thermal diffusion coefficient of water vapor in air ( $\text{m}^2/\text{s}$ )                |                      |   |
| $H$                       | relative humidity (%)  | <i>Greek symbols</i> |   |
| $h_{fg}$                  | enthalpy of evaporation (kJ/kg)  | $\alpha, \beta$      | constant (–)  |
| $J$                       | mass transfer rate of vapor per unit area per unit time ( $\text{g}/\text{cm}^2 \text{ s}$ ) | $\sigma$             | surface tension (N/m)   |
| $K$                       | thermal conductivity (W/m K)   | $\mu$                | dynamic viscosity (Pa s)  |
| $K_T$                     | thermo-diffusion ratio (–)   | $\rho$               | density ( $\text{kg}/\text{m}^3$ )  |
| $L_v$                     | enthalpy of evaporation (kJ/kg)  | $\rho_s$             | saturated vapor density at the evaporating surface ( $\text{kg}/\text{m}^3$ ) |
| $La$                      | Laplace number (–)   | $\rho_o$             | vapor density outside the boundary layer ( $\text{kg}/\text{m}^3$ )           |
| $M$                       | molar mass of water, 18.0152 (g/mol)   | $\nu$                | kinetic viscosity ( $\text{m}^2/\text{s}$ )                                   |
| $P$                       | pressure (Pa)  | $\Phi$               | nanofluid volume concentration (%)  |
| $Pr$                      | Prandtl number (–)   | $\chi$               | aspect ratio (–)  |
| $P_s$                     | saturated vapor pressure (Pa)  |                      |   |
| $P_o$                     | partial vapor pressure (Pa)  | <i>Subscripts</i>    |   |
|                           |  | $p$                  | nanoparticles   |
|                           |  | $f$                  | base fluids   |

showed that the droplet evaporation rate decreases with an increase of Al nanoparticle concentration. However, the surface tension was observed to be unaffected by Al concentration up to 3 wt.%.

The current knowledge of the evaporation of nanofluids is still in the early stage. Hence, in this study, the first objective is to study the pool evaporation rate of two different types of nanofluids. They are  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  nanofluids, while using water as the base fluid. Various mass fractions of nanoparticles and three different  $\text{Al}_2\text{O}_3$  nanoparticle sizes (13 nm, 20 nm and 80 nm) were investigated, and the implications are discussed. In addition, the enthalpy of evaporation at different temperatures and saturated vapor pressures of  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  nanofluids also lack systematic study. Thus, the second objective of this study is to extend experimental data on the enthalpy of evaporation and saturated vapor pressure of the nanofluids. Based on the saturated vapor pressure experimental results, an empirical model for estimating the saturated vapor pressure of  $\text{Al}_2\text{O}_3$  nanofluids was developed. Third, considering the importance of evaporation in various practical applications, a semi-analytical model for estimating the evaporation rate of nanofluid was developed. Comparisons between the model and experiment were made. Finally, a potential application of using nanofluids as an adsorbate in an adsorption cooling systems is discussed. The cooling performance of the adsorption cooling system, in terms of coefficient of performance (COP) and specific cooling power (SCP) are the major concern, and a comparison between using water as the adsorbate and nanofluids as the adsorbate is also made at the end of this study.

## 2. Preparation of nanofluids

The nanofluids were prepared by dispersing the various sizes of nanoparticles (13 nm, 20 nm and 80 nm  $\text{Al}_2\text{O}_3$  nanoparticles and 21 nm  $\text{TiO}_2$  nanoparticle) in the (DI water) base fluids [21,22]. Using this method to prepare the nanofluids is flexible in characterization, simple in processing and time saving in preparation. However, this method isolates the preparation of the nanofluids from the preparation of the nanoparticles. Agglomeration of the

nanoparticles should be prevented since it will affect the thermo-physical properties of the nanofluids and result in an inaccurate characterization. An ultrasonic bath was utilized to minimize the particle aggregation and improve the dispersion behavior. In addition, by controlling the pH value of the nanofluids, agglomeration of the nanoparticles in the base fluids can also be prevented. The pH determines the electrostatic charge on the particle surface. At a certain pH value, the mixture reaches an equipotential point (called the iso-electric point, IEP), at which the numbers of positive ions ( $\text{MOH}_2^+$ ) and negative ions ( $\text{MO}_-$ ) are exactly the same. In other words, if the pH value of a dispersed fluid is near the IEP, it is difficult to disperse fine particles in the base fluid. Therefore, in order to prevent particle agglomeration, the pH value has to be far from the IEP. After measuring the pH values of all the nanofluids prepared, they were far from their IEP, the IEP of all  $\text{Al}_2\text{O}_3$  nanofluids were measured between 4 and 7 (the IEP of  $\text{Al}_2\text{O}_3$  is 9.7) [23], while the IEP of all  $\text{TiO}_2$  nanofluids was measured at about 3 (the IEP of  $\text{TiO}_2$  is around 6.2) [24–26]. Lastly, during the evaporation process of the nanofluids, it should be noted that only the base fluid evaporated while the nanoparticles remained in the base fluid.

## 3. Enthalpy of evaporation

A TGA thermal analyzer (SETARM Labsys Evo) was used to measure the enthalpy of evaporation of nanofluids at different temperatures. Table 1 shows the results of enthalpy of evaporation of nanofluids. In order to minimize the experiment error, each sample was measured three times. The enthalpy of evaporation of water measured was very close to that of the theoretical value (standard value), and the standard deviation was small, proving that the measurement error of the instrument is very small. Based on the results presented in Table 1, it was found that the higher the temperature, and the higher the volume concentration of the nanofluid and the larger the nanoparticle size ( $\text{Al}_2\text{O}_3$ ), the smaller the value of enthalpy of evaporation. In detail, with a 0.01% 13 nm  $\text{Al}_2\text{O}_3$  nanofluid, the enthalpy of evaporation at the temperature from 40 °C to 100 °C is, on average, 10% higher than that of the water.

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