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Enhancement of bubble absorption process using a CNTs-ammonia binary nanofluid☆

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ABSTRACT

The main objective of the paper is to investigate the enhancement of the heat and mass transfer characteristics for a NH_3/H_2O bubble absorption process using the CNTs-ammonia binary nanofluid as a working medium. Using the surface modification of CNTs, the CNTs-ammonia binary nanofluid is successfully prepared without the addition of any dispersants. The effects of the mass fraction of CNTs, the initial concentration of ammonia in the binary nanofluid and the flow rate of ammonia vapor on NH_3/H_2O bubble absorption are studied experimentally. The mechanism of the binary nanofluid enhancing bubble absorption is discussed accordingly. The results show that the mass fraction of CNTs has an optimum value to the effective absorption ratio of the binary nanofluid, and the effective absorption ratio increases with the initial concentration of ammonia increasing.

1. Introduction

In the thermal driven absorption system, the absorber is one of the most critical components and influences the whole system performance significantly. To obtain better performance of absorption, the techniques for the enhancement of heat and mass transfer processes have been the key subject within the recent years. A nanofluid is a suspension in which nanoparticles (d_p<100 nm) are suspended evenly in a base fluid [1]. Many researchers have measured the thermal conductivities of nanofluids with diversified nanoparticles [2–5]. Nanofluids have remarkably higher thermal conductivities than the base fluids. Especially, for the nanofluid with Carbon NanoTubes (CNTs), its thermal conductivity can be increased by 38% at 0.6% (V/V) CNTs [3]. Nanofluids have illustrated their significant enhancement for the convective heat transfer [6–9] and the critical heat flux of the boiling[10]. Besides its enhancement for heat transfer process, Krishnamurthy et al. [11] reported that the diffusion coefficient of a dye in a nanofluid containing 20 nm Al_2O_3 nanoparticles is higher about 13 times than that in water without nanoparticles.

Nanofluids can be used to enhance the heat and mass transfer processes of absorption. Because the solution of the absorption system is a binary mixture and the nanofluid is considered as a single phase fluid by the definition, the absorption medium with nanoparticles is named as the binary nanofluid [13]. Kim et al. [12,13] had firstly found that the binary nanofluids have remarkable enhancement for NH_3/H_2O absorption performance experimentally. However, because the particles of Cu and CuO in Kim's experiment react easily to the ammonia in the base fluid, they are not suitable to the NH_3/H_2O absorption process. The study about the absorption enhancement in the binary nanofluid is just beginning at present. And many problems need be solved urgently.

In the present paper, the carbon nanotubes (CNTs) with stable chemical characteristics will be employed to prepare the CNTs-ammonia binary nanofluid. The bubble absorption process enhancement will be examined experimentally, and the mechanism of the binary nanofluid enhancing bubble absorption will be discussed in detail.

2. Experimental apparatus and procedures

In this paper, aligned multi-wall carbon nanotubes (d_p = 20 nm, L = 5–10 μm) are used as the nanoparticles in the binary nanofluid. In order to obtain the even dispersion solution, nitric acid is used to modify the surface of CNTs [14,15]. Then the chemically treated CNTs can be added into the base fluid. The suspension is agitated by ultrasonic applicator for 2 h. Stable nanofluid is successfully prepared without surfactant. Fig. 1 reveals the suspensions with 0.2 wt.% pristine CNTs and treated CNTs in 15 wt.% aqueous ammonia. They were settled for three days. Almost all PCNTs deposited, leaving upper fluid transparent. In sharp contrast to PCNTs, TCNTs were well dispersed in aqueous ammonia.

Fig. 2 shows the schematic diagram of the bubble absorption equipment. The concentration of ammonia vapor is 99.999%. The diameter of the absorber is 20 mm and its length is 200 mm. The absorber is connected with a tee valve. The ammonia vapor is discharged to the water in a tank through the tee valve when its flow rate is adjusted. After the flow rate has been adjusted, the tee valve is switched and the ammonia vapor enters the absorber through the orifice(its

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Nomenclature

C_{np}	mass fraction of CNTs, %
C_A	concentration of ammonia, %
m_1	total mass of absorber before absorption, g
m_2	total mass of absorber after absorption, g
r_{ab1}	absorption rate of ammonia solution, gs^{-1}
r_{ab2}	absorption rate of binary nanofluid, gs^{-1}
R_{eff}	effective absorption ratio
t	absorption time, s
V_A	flow rate of ammonia vapor, $m^3\ s^{-1}$
Δr_{ab}	difference between r_{ab2} and r_{ab1}, gs^{-1}

Subscripts

A	ammonia
eff	nanofluid
np	CNTs

diameter is 2.7 mm) at the bottom of the absorber. The flow rate of the ammonia vapor is measured by the gas flowmeter. Its measurement deviation is 0.005 m^3/h. The pressure of buffer vessel is measured by a pressure gauge with the measurement deviation of 0.01 MPa. The temperature of absorption is room temperature about 14 °C.

The total mass of the absorber including the ammonia solution is measured by a precise electronic balance with the standard deviation of 0.0001 g. By measuring the total mass of the absorber before and after the absorption and the corresponding absorption time, the absorption rate can be calculated as Eq. (1). The maximal relative deviation of the absorption rate is 0.7%.

$$r_{ab} = \frac{m_2 - m_1}{t} \tag{1}$$

The effective absorption ratio is defined to examine the effect of the addition of CNTs on the absorption rate. It is defined as Eq. (2). According to error transfer principle, the maximal relative deviation of the effective absorption ratio is 1.4%. In order to improve the dependability of the experimental data, the experiment in the same condition is repeated for five times.

$$R_{eff} = \frac{r_{ab2}}{r_{ab1}} \tag{2}$$

3. Absorption performance in CNTs-ammonia binary nanofluids

3.1. Effect of the mass fraction of CNTs in the binary nanofluid

The flow rate of ammonia vapor in the experiment is controlled at 0.175 $m^3\ h^{-1}$. Fig. 3 shows the variation of the absorption rate for the CNTs-ammonia binary nanofluid with the mass fraction of CNTs. The absorption rate increases with the mass fraction of CNTs increasing at first, then remains reasonably constant. Fig. 4 demonstrates the variation of the effective absorption ratio on the mass fraction of CNTs. The effective absorption ratio increases with the mass fraction of CNTs increasing at first, and then decreases. Especially, this trend is more obvious for the higher concentration (>14.08%) of ammonia. Namely, the optimum mass fraction of CNTs exists for the absorption enhancement in the binary nanofluid. The trend is different from the results of Kim's experiment [12], in which the effective absorption ratio increases linearly with the mass fraction of nanoparticles increasing. The main reason is that the mass fraction of nanoparticles in their experiment is very low and only 0.1 wt.%, and the effective absorption ratio doesn't reach the maximum value yet.

The mechanisms of the nanofluid enhancing bubble absorption have four possible factors as follows.

CNTs in the binary nanofluid can cause the micro-convection in aqueous ammonia because of the Brownian motion of nanoparticles. This micro-convection can improve the mass diffusion of ammonia in the binary nanofluid. According to the Krishnamurthy's experiment [11], the enhancement of the diffusion coefficient firstly increases with the mass fraction of the nanoparticles increasing, and then decreases.

CNTs in the binary nanofluid can cause the grazing effect, which was described by Kars et al. [16] and Alper et al. [17]. The grazing effect is that the particles in the liquid adsorb gas molecules in the gas–liquid interface, then move right through the concentration boundary layer, finally pick up the adsorbate in the bulk liquid. According to Reference [16], the enhancement of the grazing effect on absorption firstly increases with increasing the mass fraction of particles, and then remains constant. The effects of the mass fraction of CNTs on the enhancement of mass diffusion and grazing effect can explain just the variational trend of the effective absorption ratio with the mass fraction of CNTs.

Fan et al. [18] found that the gas holdup in the nanofluid is higher than that of water at the same flow rate of the gas. CNTs in the binary nanofluid can cause the similar effect. The increase in the gas holdup can lead to an increase in the area of the gas–liquid interface for the same flow rate of ammonia vapor, therefore improve the absorption rate of the ammonia vapor.

CNTs in the binary nanofluid can enhance the thermal conductivity of aqueous ammonia [15] and the heat transfer in the absorption process. Absorption process is a combined heat and mass transfer process. The improvement of heat transfer can decrease the temperature at the gas–liquid interface, heighten the absorption potential of aqueous ammonia. So enhance the absorption rate of the ammonia vapor.

Because the adding of CNTs has only a slight effect on the kinetic viscosity of the aqueous ammonia at small mass fraction of CNTs [15], its variety has hardly affected the absorption process.

3.2. Effects of the initial concentration of ammonia in the binary nanofluid

The flow rate of ammonia vapor in the experiment is controlled at 0.175 $m^3\ h^{-1}$. Fig. 5 shows the variation of the effective absorption ratio with the initial concentration of ammonia. The effective absorption ratio increases with increasing the initial concentration of ammonia.

It is known that the absorption rate becomes slower with the initial concentration of ammonia increasing. The bubbles in the absorber become more and more. They intensify the disturbance of

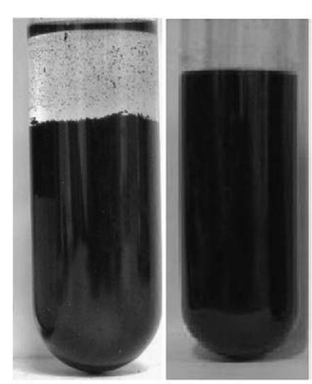

Fig. 1. Digital pictures of CNTs suspensions. (a) PCNTs (b) TCNTs.