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Heat and mass transfer enhancement of the bubble absorption for a binary nanofluid

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Abstract

The main objective of this study is to enhance the heat and transfer process of absorption using the nanofluids as the working medium. Carbon nanotubes—ammonia nanofluids (the binary nanofluids) are prepared. The thermal conductivity of the binary nanofluids and the bubble absorption process enhancement are examined experimentally. The results show the thermal conductivity of the carbon nanotubes—ammonia nanofluid is higher 16% than that of NH_3/H_2O solution. And the carbon nanotubes—ammonia nanofluid has a great enhanced effect to the NH_3/H_2O absorption.

Keywords: Binary nanofluids,;Thermal conductivity; Bubble absorption; Carbon nanotubes

1. Introduction

The thermal driven absorption system has gained attention in the world as an alternative to the compression system which causes environmental problems such as global warming and ozone layer depletion. In the thermal driven absorption system, the absorber is one of the most critical components and influences the whole system performance significantly. Heat and mass transfer modes of absorption are mainly classified into two types: falling film mode and bubble mode. Kang et al. [1] studied the absorption performance of the NH_3/H_2O system for both falling film type and bubble type, and found that the size of the bubble absorber could be 47% smaller than that of falling film absorber. To obtain better absorption performance, the techniques for the enhancement of heat and mass transfer processes have been a key subject in recent years.

A nanofluid is a solid/liquid suspension in which nanoparticles are suspended evenly in liquid. Since Choi et al.[2] first defined the concept of a nano-fluid in 1995, many researchers have measured the thermal conductivities of nanofluids with diversified nanoparticles[3-5]. Nanofluids, containing only a small amount of nanoparticles, have remark-ably higher thermal conductivities than the base fluids. Especially, a nanofluid with CNTs has maximum enhancement and its thermal conductivity can increase 38% at 0.6% (V/V) CNTs[4]. Nanofluids have become one of the most attractive enhancement heat transfer media. It has been found that nanofluids also illustrate significant enhancement for the convective heat transfer[6-8] and boiling heat transfer[9, 10]. Besides enhancement for the heat transfer process, nanofluids can enhance mass diffusion performance in liquids. 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.

The benefits of nanofluids can also be used to enhance the heat and mass transfer processes of absorption. Kim et al. [12] had initially found that

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binary nanofluids have remarkable enhancement for absorption experimentally, for the NH_3/H_2O system with/without Cu and CuO particles. However, because the particles of Cu and CuO react with the ammonia in the base fluid, it is very difficult for them to stably exist in the fluids for a long period of time. The nanoparticles of Cu and CuO are not suitable for the the NH_3/H_2O absorption process.

In the present paper, CNTs with stable chemical characteristic are chosen to prepare the CNTs-Ammonia binary nanofluids. The thermal conductivity of the binary nanofluids and the bubble absorption process enhancement are examined experimentally, and the mechanism of the binary nanofluids enhancing bubble absorption is discussed accordingly.

2. Experimental apparatus and procedures

2.1 Preparation of the CNTs-Ammonia binary nanofluids

In this paper, Aligned multi-wall carbon nanotubes (A-MCNTs) are used as the nanoparticles in the binary nanofluid, since there is no chemical reaction taking place between CNTs and ammonia. In order to obtain an even dispersion solution, nitric acid is used to modify the surface of CNTs[13, 14]. One gram of CNTs is suspended in 40 ml of concentrated nitric acid (≈68%) and refluxed for an hour at 120℃. After washing with deionized water until the supernatant attains a PH around 7, the CNTs are dried at 55℃. And then the chemically treated CNTs are added directly into a base fluid. The suspension is agitated by ultrasonic applicator for two hours. A stable nanofluid is successfully produced without surfactant. Fig. 1 is the TEM micrograph of CNTs in the nanofluid.

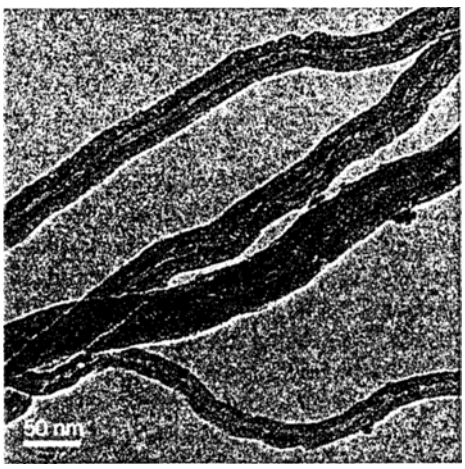

Fig. 1. TEM photo of CNTS.

2.2 Thermal conductivity measurement

The transient hot-wire method is used to measure the effective thermal conductivity of the CNTs-Ammonia binary nanofluid. For the traditional transient hot-wire method, an infinitely long fine wire is needed to serve as the heat source and thermometer, but in an actual experiment, a finite length of platinum wire is usually used, so measurement error is inevitable. In this paper, the transient double hot-wire method developed by Li et al. [15] is employed. Two fine platinum wires are embedded vertically in the fluid in this system. The two wires are at the same conditions except their lengths, so the wires have the identical end effect. The temperature difference of the two wires can be considered as a temperature increase of the finite part of an infinitely long wire. So the measurement error due to the end effect can be avoided. A detailed presentation of the transient double hot-wire method can be found in reference [15]. To determine the uncertainty for the thermal conductivity measurement, the thermal conductivity of water is measured after the installation of the experimental setup. The uncertainty of the measured thermal conductivity is estimated to be less than 3%.

In order to examine the enhanced effect of the binary nanofluids, the thermal conductivity ratio is defined as:

$$\phi = \frac{k_{eff}}{k_f} \tag{1}$$

Where φ is the thermal conductivity ratio, k_{eff} and k_f are the effective thermal conductivity of the binary nanofluid and the thermal conductivity of the base fluid, respectively.

2.3 Bubble absorption system

Fig. 2 shows the schematic diagram of bubble absorption experimental equipment. The experimental device consists of an absorber with an orifice, a buffer vessel with a pressure gauge, an ammonia vessel with a pressure reductor and a gas flowmeter. Ammonia vapor from the ammonia vessel flows into the buffer vessel after flowing through the pressure reductor. Then the ammonia vapor enters the absorber through

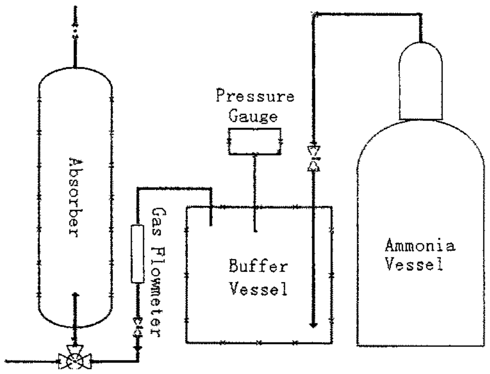

Fig. 2. A schematic diagram of the bubble absorption equipment.

Table 1. Geometrical and experimental conditions.

Parameter	Specification
Absorber	
Length	200mm
Diameter	20mm
Orifice	
Diameter	3 mm
Nanoparticles	
Type	A-MCNTs
Diameter	10~20 nm
Length	5~15 μ m
Ammonia vapor concentration	99.999%
Pressure in the buffer vessel	0.14 MPa
Ammonia volume flow rate	0.186 m^3/h

the orifice, which is located at the bottom of the absorber. A bubble is formed at the end of the orifice, and it is detached from the orifice after growing, and rises freely in the ammonia solution. The excess ammonia vapor is discharged from the top of the absorber finally. The gas flowmeter is used to measure the volume flow rate of the ammonia vapor and ensure the same volume flow rate for every experiment. The measurement error of the flowmeter is 0.005 m^3/h. The mass of the absorption is measured by a precise electronic balance with a standard deviation of 0.01 g. The pressure of buffer vessel is measured by a pressure gauge with the measurement error of 0.01 MPa. The temperature of absorption is room temperature. Because the change of room temperature is very small, the temperature of the absorber in every experiment is considered as the same temperature. The temperature of the absorber is about 14℃.

The geometric configurations of the bubble absorption experimental equipment and the experimental conditions are summarized in Table 1.

By measuring the mass of absorption and the corresponding absorption time, the absorption rate can be calculated as follows:

$$r_{ab} = \frac{m_2 - m_1}{t} \quad (2)$$

Where m_1 means the total mass of the absorber including the solution before absorption, m_2 represents the mass after absorption, t means the absorption time.

The effective absorption ratio is defined to examine the effect of the addition of CNTs on the absorption rate,

$$R_{eff} = \frac{r_{ab1}}{r_{ab2}} \quad (3)$$

Where r_{ab1} means the absorption rate of the binary nanofluid, r_{ab2} represents the absorption rate of ammonia solution.

If R_{eff} is larger than 1.0, the CNTs-Ammonia binary nanofluids can enhance the absorption performance of NH_3/H_2O. If R_{eff} is less than 1.0, the CNTs-Ammonia binary nanofluids have not enhanced the absorption performance.

3. Results and discussion

3.1 Enhancement of thermal conductivity of the binary nanofluid

Fig. 3 shows the effect of the mass fraction of CNTs on the thermal conductivity ratio of the CNTs-ammonia binary nanofluid. The base fluids used in this study as the reference liquids are deionized water, 12.5% ammonia solution and 25.0% ammonia solution. The temperature is 20℃ when the measurement is conducted. The result shows that the binary nanofluid, containing only a small amount of CNTs, has remarkably higher effective thermal conductivity than the base fluid. For the CNTs-ammonia binary nanofluid, the thermal conductivity can be enhanced by more than 16% at a mass fraction of 0.5%.

The results of the CNTs-water nanofluid are different from those for the CNTs-ammonia binary nanofluid. The thermal conductivity ratios of CNTs-ammonia binary nanofluid increase nonlinearly with mass fraction of nanoparticles. At lower mass fraction of CNTs, the thermal conductivity ratios of the binary nanofluids are almost the same as those of the water nanofluids. But with the mass fraction of CNTs increasing, the thermal conductivity ratios are gradually lower than those of water nanofluids. Ammonia is a weak electrolyte and ionizes partly in water. According to colloid stability theory, the ammonia ions in the ammonia solution facilitate the aggregation of CNTs and destroy the dispersion of CNTs in the fluid, especially at higher mass fraction of CNTs. As a result, the thermal conductivities of thebinary nanofluids at higher mass fraction of CNTs are lower than those of water nanofluids.

As shown in Fig. 3, the thermal conductivity ratios of the binary nanofluids with the ammonia concentrations of 12.5% and 25%, respectively, are

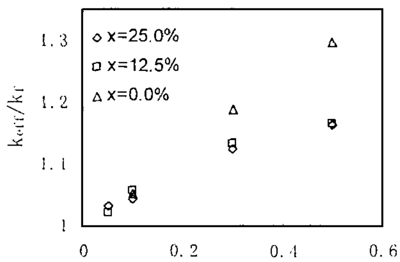

Fig. 3. Variation of the thermal conductivity ratio of the CNTs-ammonia binary nanofluids with the mass fraction of nanoparticles.

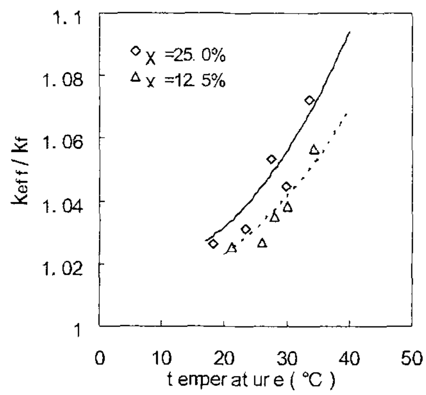

Fig. 4. Variation of the thermal conductivity ratio of the CNTs-ammonia binary nanofluids with temperature.

almost the same. Ammonia is a weak electrolyte. The concentration of ammonia ions hardly changes with the ammonia concentration in the solution. So the thermal conductivity ratios of the binary nanofluid do not change with the ammonia concentration.

Fig. 4 reveals the variation of the thermal conductivity ratio of the CNTs-ammonia binary nanofluid with temperature. The mass fraction of CNTs is 0.05%. The base fluids used are 12.5% and 25.0% ammonia solutions. The thermal conductivity ratios increase nonlinearly with temperature. According to reference[16], the temperature dependence of thermal conductivity enhancement can be shown as:

$$\frac{k_{eff}}{k_f} = 1 + A \cdot \left(\frac{1}{d_p}\right)^{0.369} \left(\frac{T^{1.2321}}{10^{\frac{2.4642B}{T-C}}}\right) \quad (4)$$

Where k_{eff} and k_f are the effective thermal conductivity of the binary nanofluid and the thermal conductivity of the base fluid, respectively; d_p denotes the diameter of nanoparticles; T is the temperature of nanofluids; A and B are constants and 1.314, 247.8 and 140, respectively.

The solid line and the dashed line in Fig. 4 are the calculated results of two kinds of binary nanofluids, respectively. It is seen that the experimental data and the calculated results have a very satisfactory agreement.

3.2 Enhancement of bubble absorption in the binary nanofluid

In this study, the effects of the mass fraction of CNTs and the initial concentration of ammonia on NH_3/H_2O absorption are studied. Fig. 5 shows the absorption rate for the binary nanofluid as a function of mass fraction of CNTs. In the figure, the percents in the legends mean the initial ammonia concentrations of the binary nanofluids. The result reveals that the absorption rates of binary nanofluids are higher than those without CNTs except those of the nanofluids with the initial ammonia concentration of 0%. And the absorption rate increases with the mass fraction of carbon CNTs.

In order to examine the effect of the CNTs-ammonia binary nanofluid on absorption performance, the effective absorption ratios are calculated. Figure 6 demonstrates the dependence of the effective absorption ratios on the mass fraction of CNTs. The effective absorption ratio increases with the mass fraction

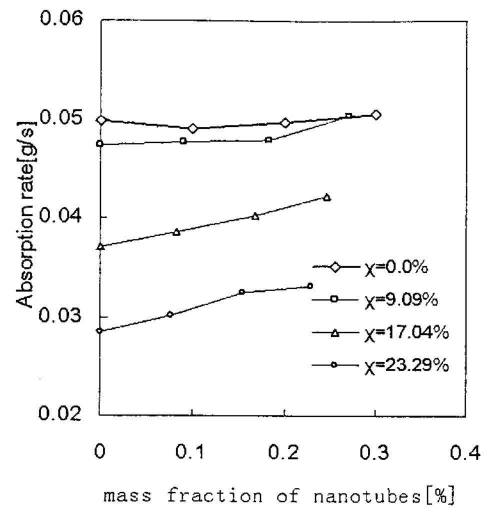

Fig. 5. Absorption rate of the binary nanofluid.

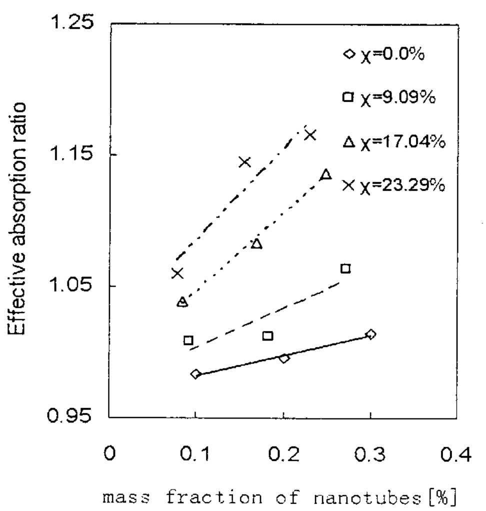

Fig. 6. Effective absorption ratio of the binary nanofluid.

of CNTs for all cases. The maximum effective absorption ratio is 1.162 for the case of 23.29% ammonia binary nanofluid with 0.23% CNTs.

When the initial concentration of ammonia is 0, the effective absorption ratio of the nanofluid equals 1 approximately. That reveals that the nanofluid can hardly enhance the bubble absorption performance. But with the initial concentration of ammonia increasing, the effective absorption ratio increases gradually. The higher the initial concentration of ammonia, the lower the absorption potential is. This means that a binary nanofluid enhances bubble absorption more significantly when the absorption potential is lower.

The significance of the addition of the CNTs can be reasonably explained by the enhancement of mass diffusion in the binary nanofluid[11] and the grazing effect[17, 18]. The addition of CNTs can form localized convection because of the Brownian motion. And the localized convection can enhance ammonia diffusion within the binary nanofluid. The grazing effect is that the nanoparticles, of which size is smaller than the thickness of concentration boundary, adsorb the ammonia vapor in the boundary layer and then desorb it into the bulk binary nanofluid. The two factors enhance the performance of NH_3/H_2O bubble absorption together.

4. Conclusions

The effective thermal conductivity and the bubble absorption performance of the CNTs-Ammonia binary nanofluids are studied experimentally. The following conclusions are drawn from the results.

The CNTs-Ammonia binary nanofluids have remarkably higher effective thermal conductivities than the base fluids. And the thermal conductivity ratio increases with the mass fraction of CNTs.

The concentration of ammonia has an insignificant influence on the effective thermal conductivity ratio of the binary nanofluid. The thermal conductivity ratios are lower than that of H_2O-nanofluids and increase nonlinearly with the temperature of binary nanofluids.

The absorption rates of the CNTs-Ammonia binary nanofluids are higher than those of ammonia solution without CNTs. The effective absorption ratio of the CNTs-Ammonia binary nanofluids increases with the initial concentration of ammonia and the mass fraction of CNTs.

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Nomenclature

d_p : Diameter of nanoparticles. m
k : Thermal conductivity, $W/m^2 {}^\circ C$
m : Mass of absorption. g

r_{ab} : Absorption rate. g/s
R_{eff} : Effective absorption ratio
T : Temperature. °C
φ : Thermal conductivity ratio
χ : Mass fraction of ammonia

Subscripts

eff : Nanofluid
f : Ammonia solution

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