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Nucleate pool boiling heat transfer of TiO_2–R141b nanofluids

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ABSTRACT

Nucleate pool boiling heat transfer of a refrigerant-based-nanofluid was investigated at different nanoparticle concentrations and pressures. TiO_2 nanoparticles were mixed with the refrigerant HCFC 141b at 0.01, 0.03 and 0.05 vol%. The experiment was performed using a cylindrical copper tube as a boiling surface. Pool boiling experiments of nanofluid were conducted and compared with that of the base refrigerant. The results indicate that the nucleate pool boiling heat transfer deteriorated with increasing particle concentrations, especially at high heat fluxes. At 0.05 vol%, the boiling heat transfer curves were suppressed. At high pressures of 400 and 500 kPa, the boiling heat transfer coefficient at a specific excess temperature was almost the same.

1. Introduction

In a refrigeration system, the optimum design of the evaporator depends on the correct evaluation of the nucleate boiling heat transfer of the refrigerant. In recent years, environmental concerns over the use of CFCs have led to the development of alternative fluids to replace CFC refrigerants. An innovative technique in improving heat transfer is to suspend the nanometer-size solid particles in base fluids, resulting in a substance that was called "nanofluid" by Choi [1]. Several recently published articles reported the substantial enhancement of thermal conductivity. Eastman et al. [2] also reported on the significance of thermal conductivity enhancement. They achieved up to a 60% increase in the thermal conductivity at 5 vol% of CuO nanoparticles in water. Murshed et al. [3] measured the thermal conductivity of TiO_2–water nanofluid. The thermal conductivity was enhanced by up to 33%.

Since nanofluids have a higher thermal conductivity than base fluids, the heat transfer properties of nanofluids are expected to be higher than those of the base fluids, which makes them more attractive for heat transfer applications, especially in the case of pool boiling heat transfer.

Das et al. [4,5] carried out an experiment to evaluate pool boiling heat transfer using a horizontal heater tube and nanofluids with 1%, 2% and 4% volume fractions of Al_2O_3 nanoparticles suspended in water. The results were unexpected: nanofluids were expected to enhance the heat transfer characteristics during pool boiling, however, the boiling curves of nanofluids indicated that the boiling heat transfer of the water had in fact deteriorated with the addition of nanoparticles. The resulting deterioration was dependent on the tube roughness and the increase in particle volume fraction. Furthermore, the deterioration of heat transfer performance was stronger with a smoother surface.

The deterioration in nucleate boiling heat transfer of Al_2O_3–water nanofluid was also observed in the work of Bang and Chang [6]. In this study, a very smooth horizontal flat surface was used as the boiling surface, and critical heat flux enhancement was observed.

Controversial results were reported by Wen and Ding [7], who used some surfactants and electrostatic stabilization methods. The nucleate pool boiling heat transfer of Al_2O_3–water nanofluid on a horizontal flat surface was enhanced by up to 40% at a particle concentration of 1.25% by weight.

You et al. [8] conducted an experimental study to determine the boiling curve and critical heat flux in pool boiling from a flat square polished copper heater immersed in Al_2O_3–water nanofluid. Various nanoparticles with volume fractions of Al_2O_3 that ranged from 0.001 g/l to 0.05 g/l were tested and compared with pure water. In the nucleate boiling regime of the boiling curves of the nanofluids, heat transfer enhancement and degradation were not observed. However, the critical heat fluxes of the nanofluids were significantly increased to about 200% higher than pure water when the particle volume fractions were 0.005 g/l.

Zhou [9] conducted an experiment to study the effect of acoustical parameters, nanofluid concentration and fluid subcooling on boiling heat transfer characteristics of copper-acetone nanofluid. He found that without an acoustic field, the boiling heat transfer of nanofluid was reduced. With an acoustic field, on the other hand, heat transfer enhancement was observed and the boiling hysteresis disappeared. However, the heat transfer enhancement

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Nomenclature

C_p	specific heat (kJ/kg K)
C_{sf}	empirical constant used in Eq. (4) (dimensionless)
D	tube diameter (m)
g	gravitational acceleration (m/s^2)
h_b	boiling heat transfer coefficient (W/m^2 K)
h_{fg}	heat of vaporization (kJ/kg)
I	electric current (A)
k	thermal conductivity (W/m K)
L	tube length (m)
M	molecular weight (kg/kmol)
P	pressure (kPa)
P_c	critical pressure (kPa)
p_r	reduced pressure (kPa)
Pr	Prandtl number (dimensionless)
q	heat flux (W/m^2)
T_h	average boiling surface temperature (K)
T_l	liquid temperature (K)
ΔT_e	excess temperature, defined as $\Delta T_e = T_h - T_l$ (K)
V	voltage (V)

Greek symbols

ε	surface roughness (μm)
ρ	density (kg/m^3)
σ	surface tension of liquid–vapor interface (N/m)
μ	dynamic viscosity (Pa s)

Subscripts

l	liquid phase
v	vapor phase
sat	saturation

depended on acoustic cavitations and fluid subcooling and was not affected by the addition of nanoparticles.

Previous research [8] has shown that the addition of metallic oxide nanoparticles enhances pool boiling critical heat flux. However, in the nucleate boiling regime some experiments contradicted others, in that both heat transfer degradation and enhancement were observed.

The experimental investigations described above focused on the boiling heat transfer characteristics of water-based nanofluids. There are only a few studies dealing with the heat transfer characteristics of refrigerant-based nanofluids.

Recently, Park and Jung [10,11] studied pool boiling heat transfer using a carbon nanotube suspended in halocarbon refrigerants. The experiment was carried out at only 1 vol% particle concentration and 7 °C pool temperature, and significant nucleate pool boiling heat transfer enhancement was observed.

Information on the pool boiling characteristics of refrigerant-based nanofluids is still limited. Moreover there remains room for further research especially on the point at which the presence of the nanoparticle can enhance or deteriorate heat transfer, and how nanoparticle concentration affects the nucleate boiling heat transfer at various saturation pressures.

As a consequence, the main aim of the present study was to measure the nucleate boiling heat transfer of a nanofluid suspension consisting of TiO_2 nanoparticles and a refrigerant. The effect of particle concentration at various pressures is presented for the first time. The results of this study will be useful for the utilization of new suspensions in practical heat transfer applications.

2. Preparation and characterization of nanofluids

Nanofluid is defined as a liquid in which particles of nanometer dimensions are suspended. The preparation of nanofluids is important because nanofluids have special requirements such as even suspension, stable suspension, durable suspension, low agglomeration of particles, and no chemical change in the suspension [12]. Xuan and Li [12] suggested the use of the following methods for stabilising the suspensions: (1) changing the pH value of the suspension, (2) using surface activators and/or dispersants, (3) using ultrasonic vibration. All these techniques aim to change the surface properties of suspended particles and suppress the formation of particle clusters in order to obtain stable suspensions. How these techniques are used depends upon the application.

In the present study, TiO_2 was used as a nanoparticle while R141b was used as a base fluid. The reasons for choosing TiO_2 nanoparticles are that they have excellent chemical and physical stability and are also commercially cheap. The advantages of R141b are non-toxicity, low ozone depletion potential (ODP) and low global warming potential (GWP). Refrigerant 141b is a low pressure refrigerant. Therefore it is convenient to prepare nanofluids. The properties of R141b and TiO_2 are given in Tables 1 and 2. The photograph of TiO_2 nanoparticles obtained from the transmission electron microscope (TEM) is shown in Fig. 1(a). The particle size distribution is also shown in Fig. 1(b). Nanofluids with different concentrations were prepared for the experiments. Nanoparticles of the required amount and base fluid were then mixed together. Dispersants were not used to stabilise the suspension as the addition of dispersants may have influenced the heat transfer characteristics of the nanofluid. Ultrasonic vibration was then used for 6 h in order to stabilise the dispersion of the nanoparticles. In this study, the TiO_2 nanoparticles were used at the concentration of 0.01–0.05 vol%. At these very low concentrations, the stable dispersions of nanoparticles could be kept for 3–4 weeks. This is much longer than the time required for the boiling experiment. This observation was confirmed from several tests before the boiling experiment began.

3. Experimental apparatus and procedure

This study focused on the nucleate pool boiling of refrigerants on the surface of a horizontal cylindrical heater. The schematic diagram of the boiling heat transfer apparatus is shown in Fig. 2(a). It consists of three parts: a pressure vessel, condenser and a boiling test section. The stainless steel pressure vessel is equipped with the boiling test section and condenser.

The coil condenser which the cooling water flows through hangs from the upper end of the vessel. This coil condenses the vapor produced by the heat input and the liquid formed returns to the bottom of the vessel for re-evaporation. A pressure gauge is mounted on top of the vessel to monitor the pressure throughout the experiment. A T-type thermocouple is used to measure the bulk liquid temperature during the experiment.

Table 1
Chemical formula and properties of R141b

Property	Unit	
Chemical formula	–	$C_2H_3Cl_2F$
Molecular mass	g/mol	117
Critical pressure	MPa	4.12
Critical temperature	°C	204

Table 2
Properties of TiO_2 nanoparticles

Property	Unit	
Composition	-	70% Anatase 30% Rutile
Appearance	-	White powder
Average primary particle size	nm	21
Specific surface area	m^2/g	35–65
True density	kg/m^3	4.2
Molecular mass	g/mol	79.9

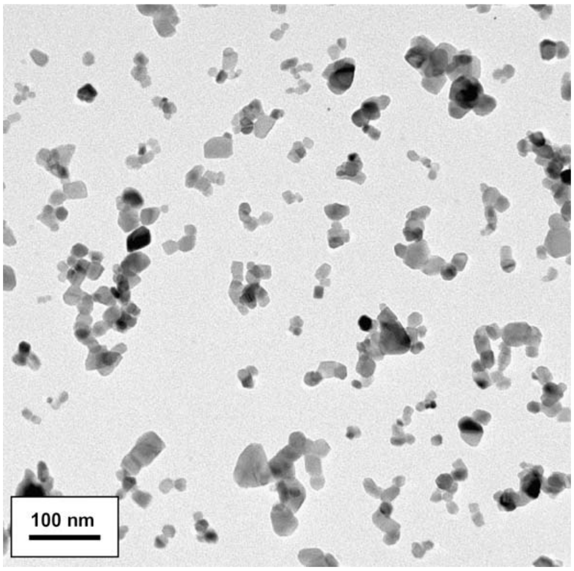

Fig. 1(a). TEM photograph of TiO_2 nanoparticles.

Fig. 2(b) shows the details of the test section. It hangs horizontally in the pressure vessel. The boiling surface is a cylindrical copper hollow sleeve (diameter $D = 28.5$ mm, length $L = 90$ mm). A resistance cartridge heater is inserted into the copper sleeve to generate heat flux from an electrical power supply. The power supply can be adjusted by an electrical transformer. Four grooves for thermocouples are machined 90° apart at the top, side and bottom of the copper sleeve. The grooves are 2 mm wide and deep, while the lengths vary. Four small holes are drilled at different radial and longitudinal locations for locating thermocouple beads. Four T-type thermocouples are inserted beneath the boiling surface via the thermocouple grooves through the small holes which are soldered with lead-tin solder. The bulges from soldering are polished off. The size of the holes is 1 mm. This size maintains the measured temperature as close as possible to the actual surface temperature. The boiling surface is sandblasted and the roughness of the boiling surface measured using a contact stylus instrument (Taylor Hobson-Form Talysurf Series 2). The average roughness of the boiling surface is 3.14 μm.

In a typical experiment, before the test begins, a vacuum pump is used to evacuate the accumulated air from the vessel. Nanofluid at a preset concentration is charged and then preheated to the saturated temperature. Measurement is first performed at the lowest power input. Data are then collected by increasing the heat flux by small increments while the saturation pressure is kept constant at the pre-selected value. Experiments were performed at four pressures of 200, 300, 400 and 500 kPa. The saturation temperature of R141b at each pressure was 53, 67, 78 and 87 °C, respectively. At each pressure, the measured boiling point of nanofluids deviated by around ±2 °C of pure refrigerant.

Each data point was taken at steady state, the condition of steady state being defined as a variation in the system saturation temperature of less than 0.1 °C.

For experiments using nanofluid, the boiling surface was cleaned by water jet to remove the sticking particles after each test. Then the surface was refinished by sandblasting. A specific size of corundum grain was used in order to ensure consistent surface roughness. In this way the boiling surface was clean and sticking particles were completely removed.

4. Data reduction

Experimental investigations were carried out to observe the boiling characteristics using a cylindrical heater. Heat fluxes, q (W/m^2), were calculated using the following equation:

$$q = \frac{IV}{\pi DL} \tag{1}$$

where I is the current (A), V is the voltage (V), D is tube diameter (m) and L is tube length (m).

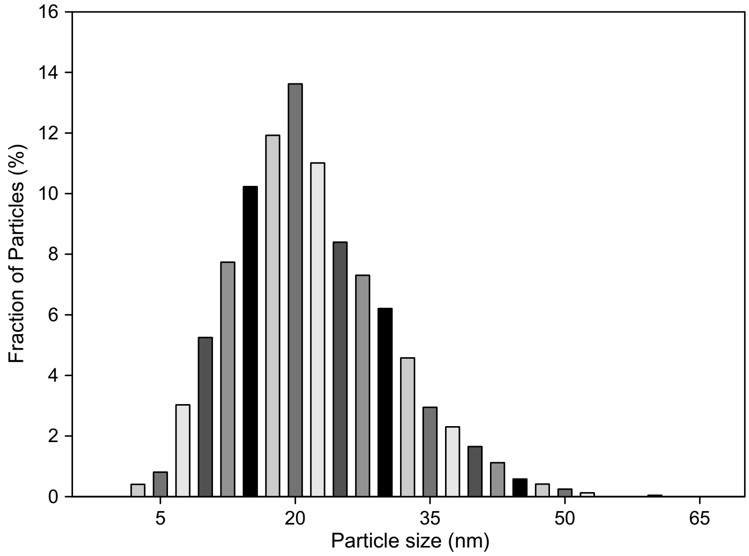

Fig. 1(b). Size distribution of nanoparticles.

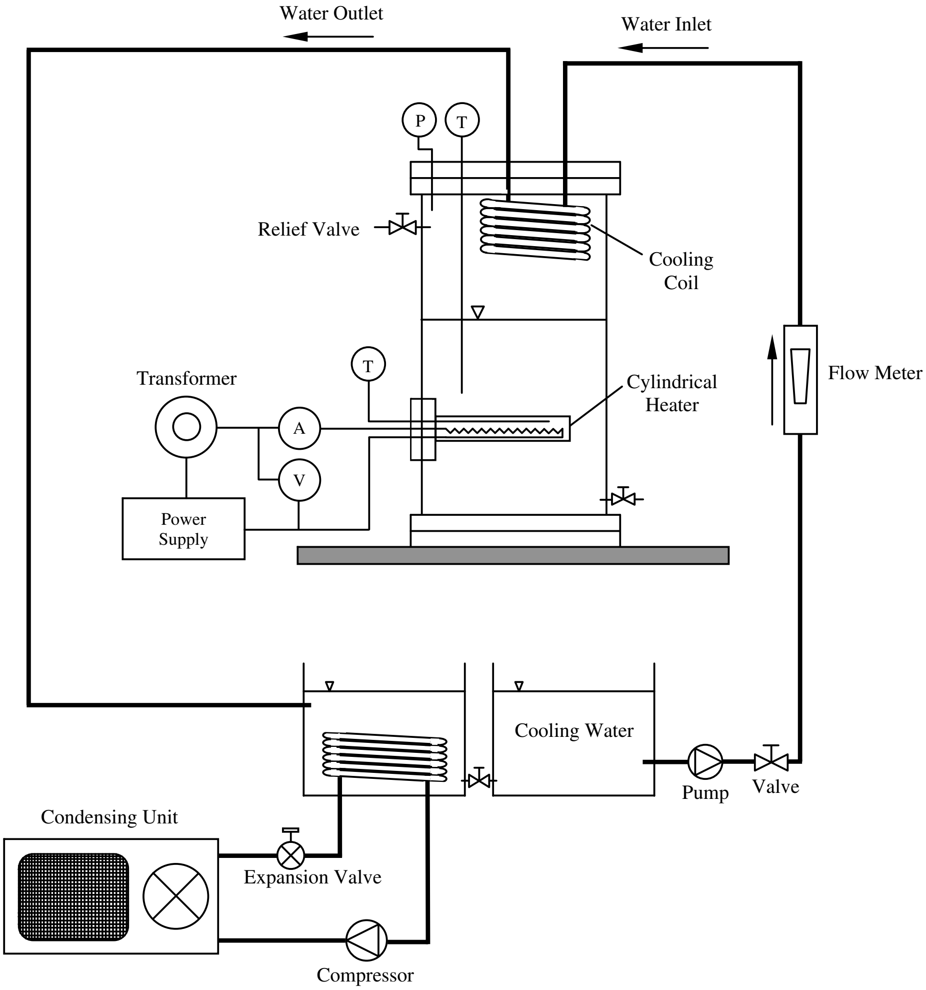

Fig. 2(a). Schematic diagram of experimental apparatus.

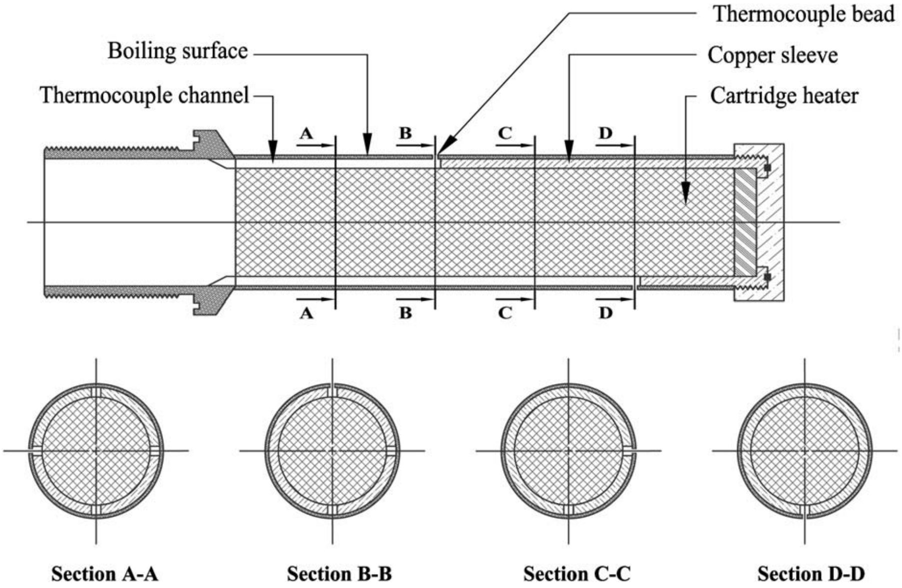

Fig. 2(b). Cross sectional view of the boiling test section.

The average boiling heat transfer coefficient, h_b is:

$$h_b = \frac{q}{T_h - T_l} \qquad (2)$$

where T_h is the average heater surface temperature (K) shown as Eq. (3), and T_l is liquid saturation temperature (K)

$$T_h = \frac{T_{h,top} + 2T_{h,side} + T_{h,bottom}}{4} \qquad (3)$$

where $T_{h,top}$, $T_{h,side}$ and $T_{h,bottom}$ are heater surface temperatures (K) measured at the top, side and bottom of the boiling surface.

A detailed uncertainty analysis performed in accordance with Kline and McClintock [13] estimated an overall uncertainty within ±5% for the average boiling heat transfer coefficient.

5. Results and discussion

Nucleate pool boiling heat transfer on the outside of the horizontal tube submerged in TiO_2–R141b nanofluid was investigated. The measurements were performed within the range of 200–500 kPa of saturation pressure and 0.01–0.05% of nanoparticle volume concentration.

5.1. Comparison of present data with existing correlations

In order to check the reliability of the apparatus, the present experimental results for the nucleate pool boiling heat transfer of refrigerant R141b were compared to the data predicted by well-known correlations.

Rohsenow [14] proposed the following correlation for predicting the nucleate pool boiling heat transfer:

$$\frac{C_{p,l}\Delta T_e}{h_{fg}Pr_l^m} = C_{sf}\left[\frac{q}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}\right]^{0.33} \qquad (4)$$

In this calculation, m is taken as 1.7 and C_{sf} as 0.0043, which is the empirical constant of copper and the R141b surface–fluid combination.

Cooper [15] derived the following predicted correlation, which includes the property of surface roughness:

$$h_b = A(p_r)^{(0.12-0.2\log_{10}\varepsilon)}(-\log_{10}(p_r))^{-0.55}M^{-0.5}q^{0.67} \qquad (5)$$

where ε is surface roughness, M is molecular weight and p_r is reduced pressure defined as P/P_c. For Cooper's correlation, the value of A is taken as 60 in the calculation. A comparison between the present experimental data and data predicted using Rohsenow's [14] and Cooper's [15] correlation is shown in Fig. 3.

As can be seen, the present results agree very closely with the prediction of Rohsenow [14] and Cooper [15]. At a saturation pressure of 500 kPa, a slight over prediction was found using Rohsenow's correlation. However, the trends confirm the validity of the present results.

5.2. Effect of nanofluid concentration

The experiments were carried out to elucidate the pool boiling of TiO_2–R141b nanofluid. TiO_2 nanoparticles were dispersed in R141b at 0.01%, 0.03% and 0.05% concentrations. The nucleate pool boiling heat transfer of pure R141b and nanofluid at different concentrations were compared and are shown in Fig. 4.

As shown in Fig. 4(a), different concentrations of TiO_2–R141b nanofluid display different degrees of deterioration in boiling heat transfer. At 0.01 vol% concentration, boiling heat transfer appears to be the same as with pure R141b. This indicates that adding an extremely small amount of nanoparticles did not affect the boiling heat transfer.

The addition of TiO_2 nanoparticles at 0.03 and 0.05 vol% concentration decreases the pool nucleate boiling heat transfer, shifting the boiling curve to the right. Since the range of the excess temperature in the natural convection regime of nanofluid is wider than that of pure refrigerant, the onset of nucleate boiling is delayed

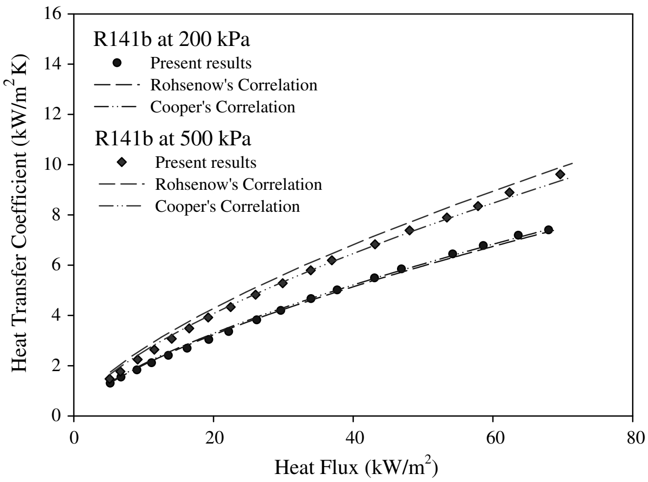

Fig. 3. Comparison of present data with Rohsenow's and Cooper's correlation.

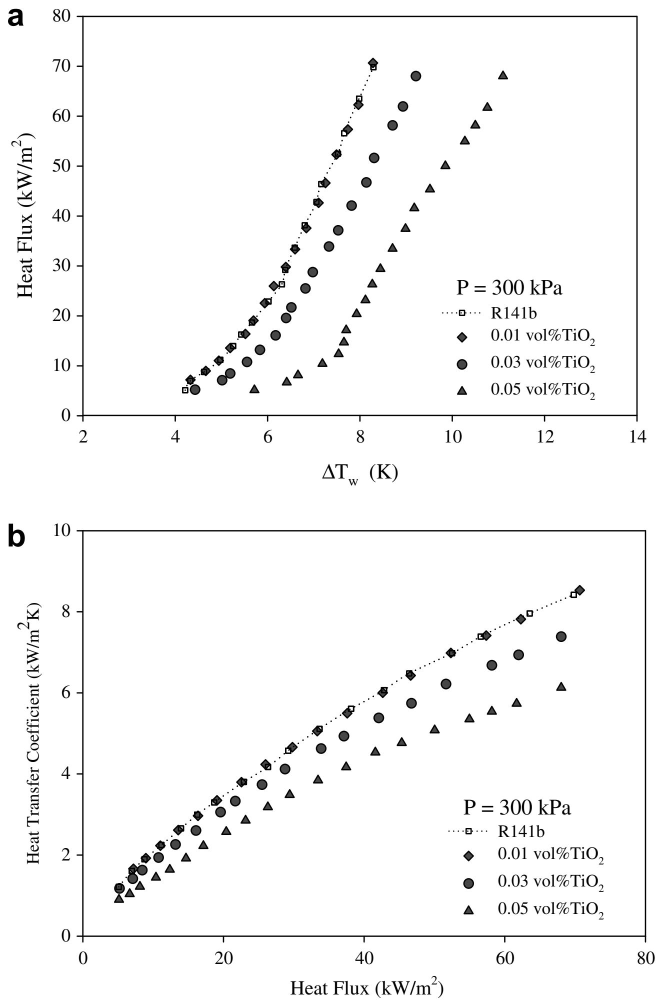

Fig. 4. Nucleate pool boiling heat transfer of TiO_2–R141b nanofluid at 300 kPa.

and the surface temperature is higher.

As shown in Fig. 4(b), at the same heat flux, the heat transfer coefficient at higher particle concentrations is lower than that at lower concentrations across the range of heat flux. At higher heat flux, the effect of concentration is prominent.

5.3. Effect of pressure

The experimental results of heat transfer measurements for pure R141b and nanofluid at various concentrations and various pressures are shown in Figs. 5 and 6.

Fig. 5(a) shows the relation between heat flux and the excess temperature for pure R141b and 0.01 vol% TiO_2–R141b nanofluid, at 200, 300, 400 and 500 kPa. As described before, the boiling heat transfer is not affected by adding an extremely small amount of particles (0.01 vol% concentration). The boiling curve of both working fluids at each pressure appears the same. As the pressure is decreased, it is clear that the curve shifts to a higher value of excess temperature.

Fig. 5(b) shows the variation of the heat transfer coefficient with heat flux. It can be seen that the heat transfer coefficient increases with increasing heat flux for both pure refrigerant and nanofluid.

The effect of pressure on the heat transfer coefficient can be clearly seen at higher heat flux, i.e., the heat transfer coefficient is much higher for a higher heat flux than for a lower heat flux.

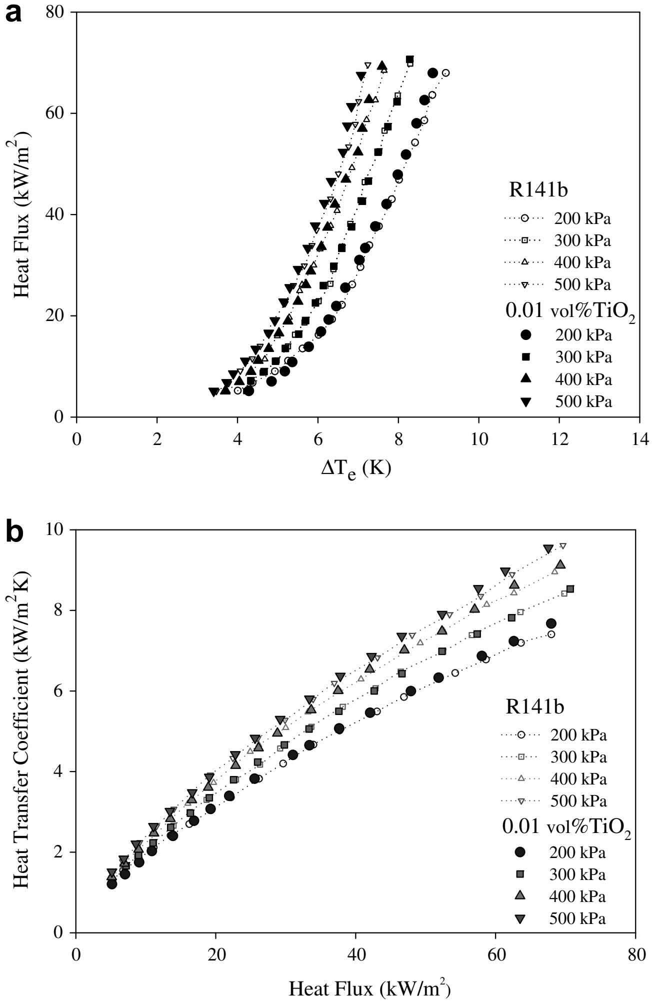

Fig. 5. Variation of heat transfer coefficient with pressure for the boiling of 0.01 vol% particle concentration.

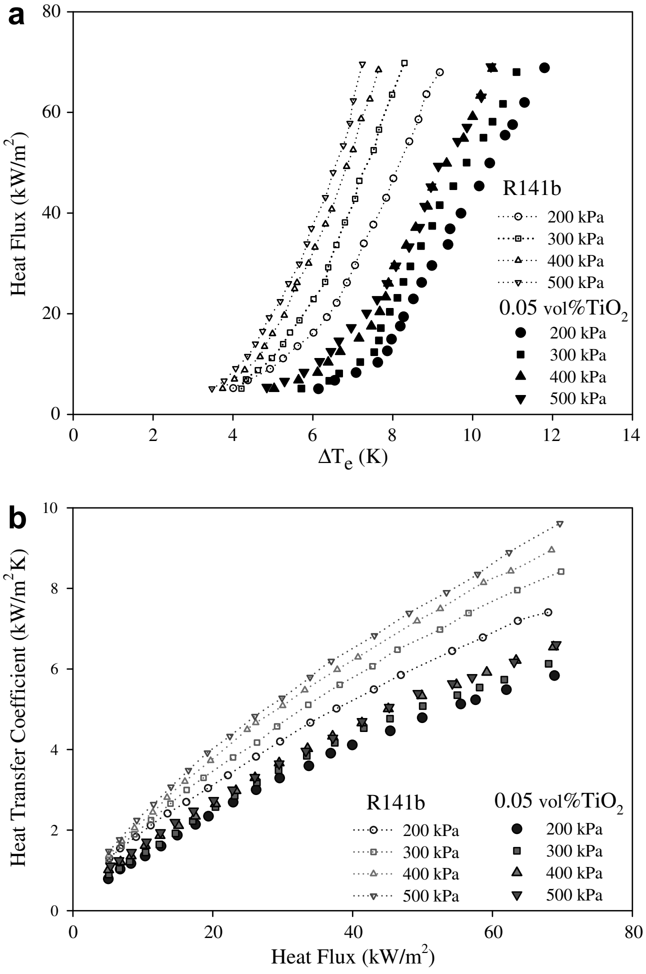

Fig. 6. Variation of boiling heat transfer with pressure for the boiling of 0.05 vol% particle concentration.

However, at very low heat flux, there is almost no effect of pressure on the heat transfer coefficient. At a given pressure, the variation may be described by the relationship, $h\alpha q^{0.7}$.

As shown in Fig. 6(a), for 0.05 vol% particle concentration, at a given heat flux, the excess temperatures of TiO_2–R141b nanofluid are higher than that of pure R141b for the entire range of measured data. This means that at the same heat flux, nanofluid boiled at a higher surface temperature compared with pure refrigerant.

The heat transfer coefficient of 0.05 vol% TiO_2–R141b nanofluid was compared with that of pure refrigerant and a clear deterioration was observed. At all pressures, the heat transfer coefficients of 0.05 vol% TiO_2–R141b nanofluid were lower than those of pure refrigerant.

As mentioned above, for pure refrigerant, the heat transfer coefficient increases with increasing heat flux and pressure. However, for 0.05 vol% TiO_2–R141b nanofluid, the increase in the heat transfer coefficient is significantly less. This can be seen in Fig. 6(b), in which, for a given heat flux, the heat transfer coefficients at various pressures are closer together than those of the pure refrigerant.

The presence of 0.05 vol% TiO_2 nanoparticles decreases the influence of pressure on the nucleate pool boiling heat transfer, especially at high pressure. As can be seen, the heat transfer coefficients at a specific excess temperature are almost the same at 400 and 500 kPa.

6. Conclusion

The results of this study indicate that the boiling characteristics of a nanofluid are different from its base fluid, not only in terms of the degradation of the nucleate boiling heat transfer, but also in that the addition of TiO_2 nanoparticles changes the effect of the pressure on the pool boiling heat transfer coefficient.

The following conclusions can be drawn from this experiment:

1. The suspended TiO_2 nanoparticles deteriorate the nucleate boiling heat transfer of refrigerant R141b. However, almost no effect results from adding extremely small amounts of nanoparticles.
2. The boiling heat transfer coefficient decreases with increasing particle volume concentrations, especially at high heat flux.
3. At higher particle concentrations, the effect of pressure on boiling heat transfer coefficients is less than that at lower concentrations. At a given heat flux, smaller differences in heat transfer coefficients are found among the various pressures.

Since nanotechnology is able to produce many types of nanometer size particles, nanofluids have become innovative types of heat transfer fluids. However, many questions remain unanswered and there is a need for further research in order to fully understand the heat transfer characteristics.

Acknowledgements

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References

[1] U.S. Choi, Enhancing thermal conductivity of fluids with nanoparticles, ASME FED 231 (1995) 99–103.
[2] J.A. Eastman, S.U.S. Choi, S. Li, W. Yu, L.J. Thomson, Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles, Appl. Phys. Lett. 78 (2001) 718–720.
[3] S.M.S. Murshed, K.C. Leong, C. Yang, Enhanced thermal conductivity of TiO_2–water based nanofluids, Int. J. Therm. Sci. 44 (2005) 367–373.
[4] S.K. Das, N. Putra, W. Roetzel, Pool boiling characteristics of nano-fluids, Int. J. Heat Mass Transfer 46 (2003) 851–862.
[5] S.K. Das, N. Putra, W. Roetzel, Pool boiling of nano-fluids on horizontal narrow tubes, Int. J. Multiphase Flow 29 (2003) 1237–1247.
[6] I.C. Bang, S.H. Chang, Boiling heat transfer performance and phenomena of Al_2O_3–water nano-fluids from a plain surface in a pool, Int. J. Heat Mass Transfer 48 (2005) 2407–2419.
[7] D. Wen, Y. Ding, Experimental investigation into the pool boiling heat transfer of aqueous based γ-alumina nanofluids, J. Nanoparticle Res. 7 (2005) 265–274.
[8] S.M. You, J.H. Kim, K.H. Kim, Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer, Appl. Phys. Lett. 83 (2003) 3374–3376.
[9] D.W. Zhou, Heat transfer enhancement of copper nanofluid with acoustic cavitation, Int. J. Heat Mass Transfer 47 (2004) 3109–3117.
[10] K.J. Park, D. Jung, Boiling heat transfer enhancement with carbon nanotubes for refrigerants used in building air-conditioning, Energy Buildings 39 (2007) 1061–1064.
[11] K.J. Park, D. Jung, Enhancement of nucleate boiling heat transfer using carbon nanotubes, Int. J. Heat Mass Transfer 50 (2007) 4499–4502.
[12] Y. Xuan, Q. Li, Heat transfer enhancement of nanofluids, Int. J. Heat Fluid Flow 21 (2000) 58–64.
[13] S.J. Kline, F.A. McClintock, Describing uncertainties in single-sample experiments, Mech. Eng. 75 (1953) 3–9.
[14] W.M. Rohsenow, A method of correlating heat transfer data for surface boiling of liquids, Trans. ASME 74 (1952) 969.
[15] M.G. Cooper, Saturation nucleate pool boiling – a simple correlation, 1st UK Natl. Heat Transfer Conf. (I. Chem. E. Symp. series No. 86) 2 (1984) 785–793.