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Nucleate pool boiling heat transfer of TiO_2–R141b nanofluids

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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