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Effects of surface functionalization on the flow boiling heat transfer characteristics of MWCNT/R141b nanorefrigerants in smooth tube

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ABSTRACT

This paper presents an experimental method to study the flow boiling heat transfer characteristics of two functionalized multi-walled carbon nanotube nanorefrigerants (MWCNT-COOH/R141b and MWCNT-OH/R141b). The experimental conditions are as follows: the nanoparticles volume fraction are individually set at 0.059%, 0.117% and 0.176%; the mass flow rate ranges from 100 to 350 $kg{\cdot}m^{-2}{\cdot}s^{-1}$; the inlet vapor quality ranges from 0.2 to 0.7. Results showed that both functionalized MWCNT/R141b nanorefrigerants can enhance the flow boiling heat transfer coefficient of a refrigerant in a tube, and the enhancement was increased with an increase in volume fraction. The heat transfer characteristics of the MWCNT-COOH/R141b nanorefrigerants were better than MWCNT-OH/R141b nanorefrigerants. At the condition of $G = 120\,kg{\cdot}m^{-2}{\cdot}s^{-1}$ and a volume fraction 0.176%, the heat transfer coefficient of the MWCNT-COOH/R141b nanorefrigerant and MWCNT-OH/R141b nanorefrigerant increased up to 23.4% and 15.18%, respectively.

1. Introduction

With the continuous improvement of science and technology, the development of heat transfer in many high-tech fields tends to focus on a small volume and high heat flux [1]. Therefore, putting forward higher requirements for strengthening heat transfer technology is an ongoing research objective. Boiling heat transfer is known for its low temperature difference and high heat flux, and in the phase change liquid, adding nanoparticles is an effective way to improve boiling heat transfer characteristics [2]. Nanorefrigerants are based on nanofluid [3] and are prepared by mixing nanoparticles with the traditional refrigerant. Domestic and foreign research on nanorefrigerants has mainly focused on the pool boiling heat transfer. A lot of pool boiling heat transfer studies [4–9] show that nanorefrigerants can improve the pool boiling heat transfer coefficient and the critical heat flux density. Furthermore, the degree of improvement is associated with the volume fraction of nanoparticles and the heat flux.

For research on flow boiling heat transfer of nanorefrigerants in the tube, Bi et al. [10,11] added TiO_2-R134a and TiO_2-R600a nanorefrigerants to the domestic refrigerator, which worked for a period of time under the same working conditions. Compared to the pure refrigerant, the nanorefrigerants of TiO_2-R134a and TiO_2-R600a, could reduce energy consumption by 7.43% and 9.5%, respectively. Henderson et al. [12] and Mahbubul et al. [13] studied flow boiling heat transfer of R134a/POE/CuO and Al_2O_3-R134a nanorefrigerants in horizontal smooth tube, respectively. Their results showed that the heat transfer coefficient of refrigerants were enhanced after adding nanoparticles and the enhancement increases with nanoparticle volume fraction increase. Akhavan-Behabadi et al. [14] did an experimental study on the characteristics of R600a/POE/CuO nanorefrigerants flow during condensation inside a horizontal smooth tube, found that nanorefrigerants can improve the heat transfer rate compared to pure refrigerant. Sun et al. [15,16] studied the four kinds of nanorefrigerant flow boiling heat transfer characteristics in the horizontal tube and micro-screwed tube. They found that nanorefrigerants can enhance the heat transfer coefficient of the base fluid, and that enhancement is thereby increased along with mass fraction, mass flow rate and vapor quality. Afranda et al. [17] studied flow boiling of nanofluids in different flow directions with experimental and simulated method, they found that the contours of vapor volume fraction in horizontal tube were completely different from the vertical tube. Abedini et al. [18] investigated behavior of low concentration nanofluids in a circular channel subjected to a constant heat flux, they found that the nanoparticle type had a small effect on this degradation, while the particle size had more effect on heat transfer coefficient variation. Abedini et al. [19] also studied the subcooled boiling of Al_2O_3-water nanofluid in both vertical concentric annulus and vertical tube, they found that Mixture model can predict axial vapor volume fraction and temperature distribution well.

With increasing the heat transfer coefficient, many researcher also

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Nomenclature

Bo	boiling number
d_{in}	inner diameter (mm)
d_{out}	outer diameter (mm)
F	two phase convective enhancement factor
F_{HT}	influence factor of nanoparticle
G	mass velocities (kg·m^{-2}·s^{-1})
h	heat transfer coefficient (W·m^{-2}·K^{-1})
H	enthalpy (kJ·kg^{-1})
h_l	single-phase forced convective heat transfer coefficient (W·m^{-2}·K^{-1})
h_{pool}	pool boiling heat transfer coefficient (W·m^{-2}·K^{-1})
h_{tp}	heat transfer coefficient in Chen model (W·m^{-2}·K^{-1})
k	thermal conductivity (W·m^{-1}·K^{-1})
L	length of experimental section (mm)
m	mass quality (g)
M	molar mass (g·mol^{-1})
n	empirical shape factor
NPT	Normal pressure and temperature

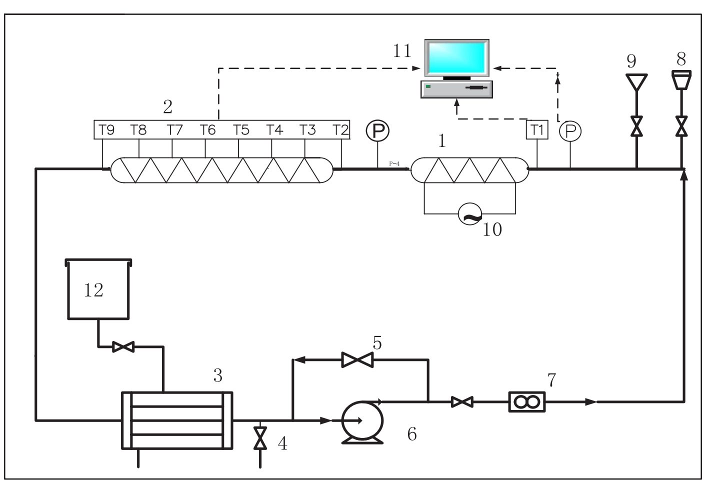
Greek symbols

ρ	density (g·cm^{-3})
Δx	the change of liquid vapor quality in experimental section
λ	thermal conductivity of copper tube (W·m^{-2}·s^{-1})
Ψ	the spherical degree of nanoparticle

Subscripts

r	refrigerant
n	nanoparticle
l	the liquid of refrigerant
v	the vapor of refrigerant
pre	preheating section
pre out	outlet of preheating section
p	pressure (kPa)
p_c	critical pressure of R141b (MPa)
p_r	relative pressure
Pr_l	Prandtl number of liquid
Pr_l	Prandtl number of liquid
Q	heating capacity (W)
q_{exp}	heat flux of experimental section (W·m^{-2})
T	temperature of nanorefrigerant (K)
t_f	average temperature of fluid in experimental section (°C)
t_{in}	inlet temperature of experimental section (°C)
t_{out}	outlet temperature of experimental section (°C)
$t_{pre,in}$	liquid temperature of inlet preheating section (°C)
t_{wi}	inner surface temperature of experimental section (°C)
t_{wo}	outer surface temperature (°C)
x	vapor quality
X_{tt}	Lockhart-Martinelli parameter
μ	dynamic viscosity (Pa·s)
φ	volume fraction
φ_{wt}	mass fraction
nr	nanorefrigerant
in	inlet of experimental section
out	outlet of experimental section
exp	experimental section
pre in	inlet of preheating section

investigated the pressure drop of nanorefrigerant. For example, Mahbubul et al. [20–22] studied the flow boiling characteristics of Al_2O_3/R134a and Al_2O_3/R141b nanorefrigerants in the horizontal smooth tube. They found that the heat transfer coefficient and pressure drop of nanorefrigerants were bigger than refrigerant in the same condition, and the increment increased with volume fractions. And exist optimum concentration of nanoparticles with refrigerants can improve the performance of a refrigeration system as to increase the energy efficiency and cooling capacity. Zhou et al. [23] comprehensive studied the flow boiling performance of Al_2O_3/R141b in micro heat exchanger. They found that the heat transfer coefficient is nonlinear with the increase of nanoparticles concentration. And considering the influence of nanoparticles concentration on heat transfer and pressure drop, they used the multi-index comprehensive evaluation method for



1-Preheating section, 2-experimental section, 3-condenser, 4-valve, 5-bypass circuit, 6-centrifugal magnetic pump, 7-turbine flowmeter, 8-exhaust unit, 9-nanorefrigerant filling device, 10-voltage regulator, 11-data acquisition system, and 12-cooling water

Fig. 1. Schematic of the experimental system. 1-Preheating section, 2-experimental section, 3-condenser, 4-valve, 5-bypass circuit, 6-centrifugal magnetic pump, 7-turbine flowmeter, 8-exhaust unit, 9-nanorefrigerant filling device, 10-voltage regulator, 11-data acquisition system, and 12-cooling water.