International Journal of Heat and Mass Transfer 64 (2013) 559–566

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental study on the heat transfer characteristics of nanorefrigerants in an internal thread copper tube

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ARTICLE INFO

Article history:
Received 19 February 2013
Received in revised form 9 April 2013
Accepted 12 April 2013
Available online 24 May 2013

Keywords:
Nanorefrigerant
Heat transfer enhancement
Internal thread copper tube
Heat transfer coefficient

ABSTRACT

The flow boiling heat transfer characteristics of four nanorefrigerants in an internal thread copper tube were experimentally studied. The nanorefrigerants were Cu-R141b, Al-R141b, Al_2O_3-R141b, and CuO-R141b. The performance of refrigerants that were added with nanoparticles at different mass fractions, quality, and mass fluxes was analyzed. The experimental parameters were as follows: nanoparticle mass fractions, 0.1 wt.%, 0.2 wt.%, and 0.3 wt.%; quality values, 0.3–0.8; and mass fluxes, 120, 210, and 330 kg m^{-2} s^{-1}. The specifications of the copper tube test section were as follows: length, 1400 mm; outside diameter, 9.52 mm; inner diameter, 8.22 mm; bottom wall thickness, 0.4 mm; tooth depth, 0.25 mm; total wall thickness, 0.65 mm; tooth apex angle, 40°; helix angle, 18°; and thread number, 60. Results showed that the maximum heat transfer coefficient of the four kinds of nanorefrigerant increased by 17–25%, the average heat transfer coefficient increased by 3–20%, and the maximum heat transfer coefficient of Cu-R141b nanorefrigerant increased by 25%.

1. Introduction

The Maxwell theory states that, adding metals, metal oxides, or other solid particles to a liquid can improve the heat transfer coefficient. However, millimeter- or micrometer-sized particles easily precipitate in a liquid, leading to pipe clogging. In 1993, Masuda et al. [1] measured the thermal conductivity of 13 nm Al_2O_3–water and 27 nm TiO_2–water. They found that when 4.3% volume fraction Al_2O_3 and TiO_2 nanoparticles were added to water, the fluid thermal conductivity increased by 32% and 11%, respectively, compared with pure water. This report is the first one on nanopowder and has thus served as a foundation for further fluid thermal conductivity studies. In 1995, Choi [2] of the U.S. Argonne National Laboratory proposed the concept of nanofluids. They prepared nanofluids by adding nanoparticles to a liquid, and found that the nanoparticles can significantly increase the thermal conductivity of the fluid. Lee et al. [3] measured the thermal conductivity of CuO–water, Cu–oil, and Al_2O_3–water with the transient hot-wire theory. They found that adding 5% volume fraction nanopowder to fluid increases, the thermal conductivity of the nanofluid by >60%. Other nanofluid researchers have pointed out that the heat transfer effect of nanofluid is better than that of pure fluid [4–9].

The concept of nanorefrigerants has been proposed based on the concept of nanofluids. Studies on nanorefrigerants [10,12–20] have shown that adding nanoparticles to refrigerants can improve the heat transfer coefficient of the base fluid. Kedzierski and Gong [12] studied the effect of CuO-R134a pool boiling heat transfer. They found that the nanoparticles increase the heat transfer by 50–275% compared with the heat transfer of pure R134a/polyolester (99.5/0.5). Peng et al. [13] studied the heat transfer characteristics of refrigerant-based nanofluid flow boiling inside a horizontal smooth tube and obtained a maximum heat transfer coefficient enhancement of 29.7%. They then proposed a heat transfer correlation, and found that the deviation between the predicted and experimental data is 20%. Kedzierski [14] studied the effect of Al_2O_3-R134a pool boiling heat transfer. They found that for 0.5% nanolubricant mass fraction, the nanoparticles increase the heat transfer by as high as 400% for the lowest heat flux compared with the heat transfer of pure R134a/polyolester (99.5/0.5). Bi et al. [15] studied the performance of a domestic refrigerator using TiO_2-R600a nanorefrigerant. They found that the performance of refrigerator with 0.5 g L^{-1} TiO_2-R600a nanorefrigerant was better than that of pure R600a system with 9.6% less energy used. Others have performed model development in this area [11,21], thereby paving the way for further studies on the thermal conductivity of nanorefrigerants and the migration characteristics of nanoparticles.

To date, the heat transfer enhancement characteristics of nanorefrigerants in an internal thread copper tube has not yet been studied. The thermal efficiency of a high-heat-exchange tube is

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.04.031

Nomenclature

Bo	bond number
d_{in}	inner diameter (mm)
d_{out}	outer diameter (mm)
F_{ht}	influencing factors of nanoparticles
Fr	Froude number,
G	mass flow rate (kg m^{-2} s^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
H	enthalpy (J)
I	current (A)
k_l	thermal conductivity of liquid (W m^{-1} °C^{-1})
L	length of test section (mm)
M	molar mass (g mol^{-1})
n_g	number of grooves
Pr L	Prandtl number of liquid
Q	heating capacity (W)
q_w	heat flux (W m^{-2})
Re	Reynolds number
Rx	geometry enhancement factor
t_f	fluid temperature (°C)
t_{in}	inlet temperature (°C)
t_{out}	outlet temperature (°C)
t_{wi}	inner surface temperature (°C)
t_{wo}	outer surface temperature (°C)
U	voltage (V)
x	quality

Greek symbols

γ	apex angle
λ	thermal conductivity of copper (W m^{-1} K^{-1})
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})

Subscripts

eq	equivalent
g	gravity
GO	gas phase with total flow rate
in	inlet of test section
L	liquid phase
m	two-phase mixture
out	outlet of test section
pre	preheating section
$pre.in$	inlet of preheating section
$pre.out$	outlet of preheating section
$test$	test section

known to be significantly higher than that of a common copper tube [22–26]. However, the effects of using nanorefrigerants in an internal thread copper tube are unknown. Thus, the heat transfer characteristics of nanorefrigerants in an internal thread copper tube were studied in this paper. Cu, Al, Al_2O_3, and CuO nanoparticles (average particle diameter = 40 nm, purity = 99%) were supplied by Xuzhou Hongwu Nano Materials Co., Ltd. The four nanoparticles were separately added to a refrigerant at 0.1 wt.%, 0.2 wt.%, and 0.3 wt.% mass fractions. R141b had an ozone depression potential of 0.089, global warming potential of 0.15, and boiling point (1 atm) of 32.05 °C. In the experiment, nanoparticles were mixed with refrigerants at normal pressure and temperature; thus, R141b was selected.

2. Experimental apparatus and process

2.1. Experimental apparatus

Fig. 1 shows the whole experimental system, including the main circuit, bypass circuit, cooling water circuits, data acquisition systems, high-speed photographic camera, and nanorefrigerant filling apparatus.

The main circuit included the preheating, test, and cooling sections. The preheating and test sections used an internal thread copper tube. The copper tube preheating section was 500 mm long. The specifications of the copper tube test section were as follows: length of test section, 1400 mm; outside diameter, 9.52 mm; inner diameter, 8.22 mm; bottom wall thickness, 0.4 mm; tooth depth, 0.25 mm; total wall thickness, 0.65 mm; tooth apex angle, 40°; helix angle, 18°; and thread number, 60. To eliminate the entrance effect, a 300 mm-long settling chamber was placed before the preheating section. The cooling section comprised a sinuous coil and a thermostatic water tank to ensure that the working fluid was restored to the initial temperature.

The nanorefrigerant filling apparatus was connected with the main circuit through the shutoff valve. The nanorefrigerant passed through the filling apparatus into the experimental system. A magnetic circulation pump was used to provide power so that the nanorefrigerant can pass through the mass flow transmitter into the preheating section. After entering the test section, the

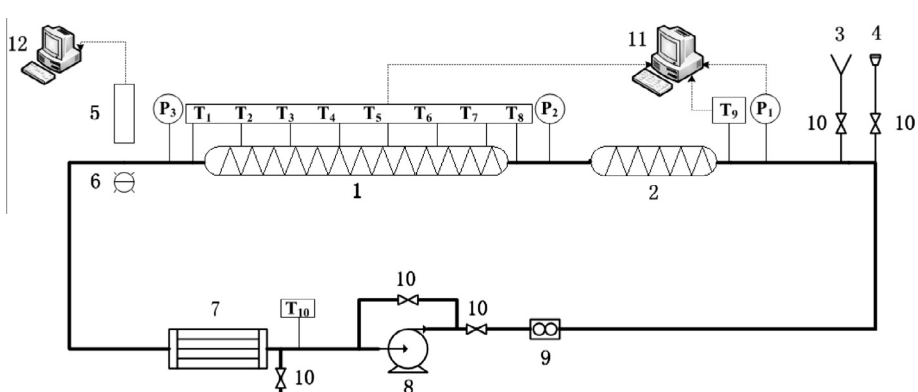

Fig. 1. Schematic of the experimental system: 1 – test section, 2 – preheating section, 3 – filling apparatus, 4 – exhaust unit, 5 – high-speed camera, 6 – light, 7 – cooler, 8 – magnetic drive pump, 9 – turbine flow transmitter, 10 – valve, 11 – data acquisition system, 12 – computer. T_1–T_{10} are temperature transmitters. P_1–P_3 are pressure transmitters.