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Experimental study of boiling heat transfer in smooth/micro-fin tubes of four refrigerants

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ABSTRACT

An experimental investigation of boiling characteristics in a horizontal smooth and micro-fin tube with 9.52 mm outside diameter and 1 m length was conducted. The refrigerants tested were R22, R134a, R407C and R410A while vapour quality ranges from 0.1 to 0.9, mass flux 50, 250, 450 kg m^{-2} s^{-1} and heat flux of 5, 12.5, 20 kW m^{-2}. The saturation temperature is 5 °C. For the smooth tube, the average heat transfer coefficients of R134a, R407C and R410A are 110.9%, 78.0% and 125.2% of those of R22 in test conditions respectively. For the micro-fin tube, the average heat transfer coefficients of R22, R134a, R407C and R410A are 1.86, 1.80, 1.69 and 1.78 times higher than those of the smooth tube. The pressure drop of R22, R407C and R410A for the smooth tube is similar to each other while the pressure drop of R134a is 1.7 times higher. The average pressure drop of R22, R134a, R407C and R410A for the micro-fin tube is 1.42, 1.30, 1.45 and 1.40 times higher when compared with that for the smooth one. Considering the effect of heat transfer enhancement and pressure drop augment, the efficiency index η_1 which values the thermo-hydraulic performance at identical flow rate of R22, R134a, R407C and R410A in the micro-fin tube used is 1.31, 1.38, 1.17 and 1.27 respectively compared with the smooth tube.

1. Introduction

Micro-fin tubes are characterized by high heat transfer coefficients, low pressure drop penalty, less material consumption in manufacturing and reduction of refrigerant charge. Due to these excellent advantages, micro-fin tubes are widely used in residential air-conditioners and automobile cooling systems. Since the development of micro-fin tubes for improving the heat transfer coefficient in evaporators and condensers in refrigeration applications started by Hitachi, Ltd in 1977 [1], a number of researches have been conducted to improve the performance of micro-fin tubes by changing geometric parameters like fin number, fin height, fin angle and helical angle. Some typical results are reported in [2–5].

In order to protect environment, various R22 alternatives are now used in refrigeration applications. There are many literatures on the performance of heat transfer coefficients and pressure drop in flow condensation and boiling [2–23]. Some correlations of R22 and its alternatives have been obtained in recent years [18–23].

Schlager et al. [2] studied evaporation and condensation heat transfer coefficients of R22 in three micro-fin tubes. The mass fluxes were from 150 to 500 kg m^{-2} s^{-1} while the saturation temperature was from 273 to 278 K for evaporation and from 312 to 315 K for condensation. They found that the heat transfer enhancement ratio of the micro-fin tubes was 1.5 to 2 while the increase of press drop was only 40% when compared with smooth one at the same conditions. Chamra and Webb [3] investigated condensation heat transfer of R22 in 8 micro-fin tubes. The data were taken at the condensation temperature 297 K and the mass fluxes were from 41 to 181 kg m^{-2} s^{-1}. The cross grooved tubes had higher heat transfer coefficients than the single-helix ones with a maximum increase value of 27% at the same conditions. Li et al. [4] studied the condensation heat transfer coefficients of R22 in five micro-fin tubes with different geometries. The mass fluxes ranged from 200 to 650 kg m^{-2} s^{-1} and the saturation temperature was 320 K. The micro-fin tube with 50 fins had the largest enhancement ratio among the five tubes. The above studies mainly concentrated on the performance of different enhanced structures using R22 as working fluid. In the following presentation studies on condensation and boiling for R22 and its alternatives in micro-fin tubes will be briefly reviewed separately.

Miyara and Otsubo [5] performed an experiment to study the condensation heat transfer coefficients of R410A in three

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Nomenclature

A_o	the outside surface heat transfer area of tube [m^2]
A_i	the inside surface heat transfer area of tube [m^2]
c_p	the specific heat capacity of liquid [kJ kg^{-1} K^{-1}]
d_e	the equivalent diameter of casing channel [mm]
d_h	the fin height of micro-fin tube [mm]
d_i	the inside diameter of tube [mm]
d_o	the outside diameter of tube [mm]
h_i	in-tube heat transfer coefficients of tube [W m^{-2} K^{-1}]
h_l	the saturation liquid enthalpy of refrigerant [kJ kg^{-1}]
h_o	out-tube heat transfer coefficients of tube [W m^{-2} K^{-1}]
h_s	the latent heat of vaporization [kJ kg^{-1}]
h_v	the saturation vapor enthalpy of refrigerant [kJ kg^{-1}]
k	total heat transfer coefficients [W m^{-1} K^{-1}]
l	tube length [m]
M	molecular mass
m_w	the mass flux of water [kg s^{-1}]
n	the fin number
p_c	critical pressure [MPa]
Pr	Prandtl number
p_s	the refrigerant saturation pressure of test section [kPa]
q_w	the heat flux of test section in inner surface [W m^{-2}]
Δt_m	the logarithmic mean temperature difference of test section [°C]
Q_l	latent heat transfer capacity of the refrigerant [W]
Q_p	the heat transfer rate of preheater section [W]
Q_t	the heat transfer rate of test section [W]
t_i	the inlet water temperature inlet [°C]
t_o	the outlet water temperature inlet [°C]
t_{ri}	the inlet refrigerant temperature of test section [°C]
t_{ro}	the outlet refrigerant temperature of test section [°C]
t_s	the refrigerant saturation temperature of test section [°C]
$t_{water,i}$	the inlet water temperature of test section [°C]
$t_{water,o}$	the outlet water temperature of test section [°C]
t_{wi}	the average inner wall temperature of test section [°C]
t_{wo}	the average outer wall temperature of test section [°C]
x	the vapor quality of test section
x_i	the inlet vapor quality of test section
x_o	the outlet vapor quality of test section
α	the angle of fin [degree]
β	the helical angle of micro-fin tube [degree]
λ	thermal conductivity [W m^{-1} K^{-1}]
η_l	dynamic viscosity [Pa s]
σ	surface tension [mN m^{-1}]
ρ_l	the saturation liquid density of refrigerant [kg m^{-3}]
ρ_v	the saturation vapor density of refrigerant [kg m^{-3}]

herringbone micro-fin tubes with different fin height and helix angle. The mass fluxes ranged from 100 to 400 kg m^{-2} s^{-1} and the saturation temperature was 313 K. They found that the helical micro-fin tubes had lower heat transfer coefficients and higher pressure drop than those of herringbone tubes. Kim et al. [6] studied the condensation heat transfer of R22 and R410A in flat smooth/micro-fin aluminum multi-channel tubes. They found that the heat transfer coefficients of R410A was 5–10% larger than those of R22 for the smooth tube while 10–20% lower for the micro-fin tube. Jung et al. [7] conducted an experiment on condensation of R22, R134a, R407C, and R410A in 9.52 mm horizontal micro-fin/smooth tubes. The condensation temperature was 40 °C while the mass and heat fluxes were 100, 200, 300 kg m^{-2} s^{-1} and 7.7–7.9 kW m^{-2} respectively. They found that R134a and R410A had similar heart transfer performance to R22 while the heat transfer coefficients R407C were 11–15% lower than those of R22 for smooth tubes. For the micro-fin tube, R134a had similar heart transfer performance to R22 while R22 was better than R407C and R410A in their experimental results. Sapali and Patil [8] studied the condensation heat transfer of R134a and R404A in an 8.96 mm horizontal smooth/micro-fin tube. Their experimental results indicated that the condensation heat transfer coefficients decreased as condensing temperature increased for both smooth and micro-fin tubes. The heat transfer coefficients for R404A were 20–35% lower than those of R134a in their experiment. Zhang et al. [9] developed an experiment on condensation characters in 1.088 mm and 1.289 mm mini-tubes with R22, R410A and R407C as working fluids. They found that R410A had a better performance both in heat transfer and flow resistance compared with R22. Kondou and Hrnjak [10] investigated the condensation heat transfer of R744 and R410A in a 6.1 mm horizontal smooth tube. They found that the heat transfer coefficients of R744 were 20–70% higher than those of R410A at the same experimental conditions.

Kuo and Wang [11,12] investigated evaporation in a 9.52 mm horizontal micro-fin/smooth tube with R22 and R407C. The average heat transfer coefficients of the micro-fin tube were 2.2 times higher than those of the smooth one with R22 and the heat transfer coefficients and pressure drop of R407C was 50–80%, 30–50% respectively lower than those of R22 in their micro-fin tube. Lallemand et al. [13] obtained the boiling heat transfer coefficients in 12.7 mm horizontal smooth/micro-fin tubes with R22 and R407C. The refrigerant mass fluxes and heat fluxes were varied from 100 to 300 kg m^{-2} s^{-1} and 10 to 30 kW m^{-2}, respectively. Their experimental results showed that heat fluxes strongly influenced heat transfer at a low quality while the mass fluxes did that at a high quality and the boiling heat transfer coefficients of R407C in smooth and micro-fin tubes were 15–35% lower than those of R22. Greco and Vanoli [14] studied the heat transfer coefficients and pressure drop during the evaporation of R22 and R507 in a 6 mm horizontal smooth stainless steel tube. The heat transfer coefficients and pressure drop of R507 (R125–R143a 50%/50% in weight) were 10–30%, 30–50% respectively lower than those of R22 at the same conditions in their experiments. Kim and Shin [15] developed an experiment on evaporation of R22 and R410A in 9.52 mm horizontal smooth/micro-fin tubes. The evaporation heat transfer coefficients with R22 and R410A of the micro-fin tubes were 1.86–3.27, 1.64–2.99 times respectively larger than those of the smooth tube in their experiment. They found that the evaporating heat transfer coefficients of R410A were almost 12–29% larger than those of R22 at the same test conditions. Park and Hrnjak [16] obtained CO$_2$, R22 and R410A boiling flow characters in a 6.1 mm horizontal smooth tube. The evaporation temperatures, mass fluxes and heat fluxes were 15 and 30 °C, 100–400 kg m^{-2} s^{-1}, 5–15 kW m^{-2} respectively. The heat transfer coefficients for CO$_2$ were 2 times larger than those for R410A and R22 while the pressure drop of CO$_2$ was lower than that of R410A and R22 especially at low quality. Kundu et al. [17] investigated boiling in a 9.52 mm horizontal smooth tube of R134a and R407C. Their experimental results showed that the heat transfer coefficients and pressure drop of R134a were 55–87%, 53–86%