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An experimental study of pool boiling and falling film vaporization on horizontal tubes in R-245fa

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ABSTRACT

This study investigates heat transfer performance on horizontal copper tubes in refrigerant R-245fa, having zero ozone-depleting potential. Pool boiling and falling film vaporization experiments were conducted at saturation temperatures of 5 °C (a typical saturation temperature of evaporators in commercial chiller units) and 20 °C, while heat fluxes varied from 4.5 to 48.5 kW/m^2. A smooth tube, a fin tube of 0.4 mm fin height, 60 FPI (Fins Per Inch), and a new boiling enhanced tube (mesh tube) were tested. Falling film vaporization heat transfer coefficient of the fin tube is greater than that in pool boiling, but the opposite results were found for the mesh tube. The mesh tube yielded up to 5 and 7 fold heat transfer enhancement in falling film vaporization and pool boiling, respectively. Under the same test conditions, R-245fa resulted in slightly higher heat transfer coefficients than R-123. New correlations of falling film vaporization on smooth tubes with and without boiling are proposed. The falling film evaporation (non-boiling) correlation predicted the data within ±16%. The falling film vaporization correlation accounting for nucleate boiling predicted heat transfer coefficients with ±20% uncertainty for data of smooth tube in the range of $Re_f = 115–372$, $Bo_F = 0.044–0.473$, $We_F = 0.000165–0.00168$ and $Pr_f = 6.26–7.15$.

1. Introduction

In order to reduce energy consumption and environmental impact, introduction of non-chlorine refrigerants and development of high efficiency devices are necessary for the refrigeration and air-conditioning industry. Currently, R-245fa (1,1,1,3,3-pentafluoropropane) is a viable alterative to R-123 as a working fluid in low-pressure water chillers because of its zero ozone-depleting potential. Nucleate boiling and falling film vaporization of refrigerants are the main heat transfer modes in flooded-type and spray-type evaporators in water chiller systems. Kedzierski [1] tested R-245fa, R-123 and a mixture of R-234fa and iso-pentane on a flatted enhanced boiling surface (Turbo-BIII-LP). He found that the R-245fa yielded a 27% higher boiling heat transfer coefficient than R-123, with heat flux varying from 8 to 100 kW/m^2. He [1] did not test R-245fa in falling film vaporization mode. Lack of evaporator design data has hindered application of R-245fa in chillers. To resolve this problem, pool boiling and falling film vaporization performance of R-245fa were tested in this study.

The boiling enhanced tubes, having numerous artificial nucleation sites, are widely used in these evaporators. Commercial structured boiler tubes are made by forming reentrant shape cavities on low-fin tubes. Pool boiling test data of commercial structured tubes with refrigerants R-11, R-12, R-123, R-134a, R-22, R-410A and R-407 were reported in [2–6]. Ribaski and Thome [6] found the level of enhancement was 2.4–5.2 fold for Gewa-B™, and 1.8–7.0 for Turbo-BII-HP™, compared with a plain tube.

Chien and Webb [7–9] designed an enhanced boiling surface by piercing pores on a thin copper sheet soldered on fin tips of a low-fin-tube. They performed systematic tests of geometric parameters in R-123, R-134a and R-22 at 26.7 °C. Chien and Huang [10] investigated a new enhanced boiling surface. The surface was made by wrapping brass mesh of 80–120 mesh per inch on 40–60 FPI tube of 0.2–0.4 mm fin height. Pool boiling performance of the new enhanced tubes was tested with refrigerant 134a at 5, 10 and 26.67 °C saturation temperatures. By forming numerous nucleation sites on the mesh and keeping the tunnels under the mesh in suction-evaporation mode, boiling heat transfer coefficient was enhanced 3–8 fold in R-134a as compared with the smooth tube.

A falling film evaporator requires much less refrigerant than a flooded evaporator for the same chiller capacity. Fujita and Tsutsui [11–13] performed R-11 falling film evaporation tests on

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Nomenclature

A_e	total surface area of evaporation (m^2)
Bo_F	modified Boiling number
C_{fm}	empirical constant in Eq. (11)
C_p	specific heat constant for a fixed pressure (kJ/kg K)
D	tube diameter (m)
G	mass velocity (kg/m^2 s)
g	acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2K)
h_{cv}	convective heat transfer coefficient (W/m^2K)
$h_{\exp}$	experimental value of heat transfer coefficient (W/m^2K)
h_{fg}	latent heat of evaporation (kJ/kg)
h_l	single phase liquid convection coefficient (W/m^2K)
h_{nb}	nucleate boiling heat transfer coefficient (W/m^2K)
h_{pred}	heat transfer coefficient predicted by the new model (W/m^2K)
Ka	Kapitza number
k	thermal conductivity (W/mK)
L_h	heated length (m)
M	molecular weight
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
P_r	reduced pressure
P_s	system pressure
Pr_f	liquid Prandtl number
q''	heat flux (W/m^2)
R_p	surface roughness (μm)
r	tube radius (m)
Re_f	film Reynolds number
S_{spr}	correction factor of nucleate boiling in falling film
T	temperature (°C)
v_g	specific volume of vapor (m^3/kg)
We_F	modified Weber number

Greek Symbol

δ	film thickness (m)
ΔT_{ws}	wall superheat (K)
α	thermal diffusivity (m^2/s)
Γ	mass flow rate per unit length (kg/s m)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m/s^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscript

cv	convective
exp	experimental
f	liquid
in	inlet
nb	nucleate boiling
pred	predicted
s	saturated
w	tube wall

a bundle of 25 mm diameter plain tubes. They observed the drip patterns and categorized them into discrete droplets, droplets, columns, disturbed columns and sheet modes. Based on a turbulent flow analysis, they proposed a correlation which predicted the heat transfer coefficients within ±20% of their R-11 data. Roques and Thome [14] conducted falling film tests on four types of tubes at three tube pitches and three nominal heat flux levels for R-134a at 5 °C. Test results of falling film vaporization have been measured for the arrays made of plain, Turbo-BII HP, Gewa-B, and High-Flux tubes. They identified several flow modes of inter-tube flow pattern but found no discernible difference in heat transfer coefficients of different flow modes in the respective zones.

Moeykens et al. [15,19] performed a series of falling film vaporization tests on a single horizontal tube as well as bundles (of horizontal tubes) in R-123, R-134a and R-22. Chang and Chiou [20] tested falling film vaporization on a three by five plain tube bundle using R-141b. They found that evaporation heat transfer can be enhanced by adding a liquid collection tray under each tube. Ribatski and Jacobi [21] provided a comprehensive review of falling film vaporization on horizontal tubes. They concluded that some basic mechanisms responsible for the heat transfer remain unclear. Occurrence of nucleate boiling and its impact is obfuscated by the effects of flow rate, fluid properties and heat fluxes. Some models focusing on the prediction of heat transfer coefficient have been proposed, but they do not include nucleate boiling, vapor-shear, and interfacial waviness effects [21]. Chien and Cheng [22] developed a superposition model for falling film vaporization of refrigerants on smooth horizontal tubes. The predictive uncertainties against data of R-22, R-123, R-134a and R-141b [11–13,15–20] on four different apparatuses were within −20∼+25%. They [22] assumed that the total heat transfer coefficient is the summation of nucleation boiling term and a convection term. The convection term was based on a correlation for falling film on vertical plates.

R-245fa has the advantage of zero ozone depletion potential and is a good alternative for R-123. However, there is little design data for refrigeration system using R-245fa. Kedzierski [1] tested R-245fa on a flatted enhanced boiling surface, but no data was provided for boiling on horizontal tube. To the authors' best knowledge, heat transfer data of falling film vaporization of R-245fa on horizontal tubes are not available in accessible open literature. In this study, pool boiling and falling film vaporization performance were tested. Tests were performed on a plain tube, a boiling enhanced tube, and a finned tube using R-245fa. A new correlation accounting for the effect of nucleate boiling was also developed based on the Chien and Cheng [22] model with the improvement on the convection term, using the non-boiling falling film evaporation test data of horizontal tube.

2. Experiment setup

2.1. Apparatus

A new test apparatus (Fig. 1) was constructed to perform both pool boiling and falling film vaporization tests. For the falling film vaporization tests, working fluid was evaporated in the test cell and then it entered the condenser section, separated from the evaporator section by a steel plate above the fluid distributor. The steel plate guides the condensate to flow from two sides and prevents the condensate from falling on the test tube directly. The liquid at the bottom of the test vessel passes through a filter and is pumped into the test cell by a gear pump, driven by a variable speed pump drive. A flow meter was connected between the pump and the test cell for flow rate measurement. Care was taken to ensure no vapor bubbles entered the pump by inspecting the sight glass of the flow meter. Liquid entered the test cell through a liquid distributor placed 9.5 mm above the test surface. Sight glasses were placed on