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International Journal of Heat and Mass Transfer 51 (2008) 896–909

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Convective boiling of pure and mixed refrigerants: An experimental study of the major parameters affecting heat transfer

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Received 25 March 2007

Abstract

An experimental study is carried out to investigate the characteristics of the evaporation heat transfer for different fluids. Namely, pure refrigerants fluids (R22 and R134a), azeotropic and quasi-azeotropic mixtures (R404A, R410A, R507) and zeotropic mixtures (R407C and R417A).

The test section is a smooth, horizontal, stainless steel tube (6 mm ID, 6 m length) uniformly heated by the Joule effect. The flow boiling characteristics of the refrigerant fluids are evaluated in 250 different operating conditions. Thus, a data-base of more than 2000 data points is produced.

The experimental tests are carried out varying: (i) the refrigerant mass fluxes within the range 200–1100 kg/m^2 s; (ii) the heat fluxes within the range 3.50–47.0 kW/m^2; (iii) the evaporating pressures within the range 3.00–12.0 bar.

In this study, the effect on measured heat transfer coefficient of vapour quality, mass flux, saturation temperature, imposed heat flux, thermo-physical properties are examined in detail.

Keywords: Flow boiling; R22; R407C; R410A; R404A; R507; R417A; R134a; Smooth tube

1. Introduction

In the present study, the evaporating heat transfer characteristics of the refrigerant fluid alternative to R22 are analyzed. R22 is a HCFC, widely used in refrigerant and air conditioning plants because of its excellent thermal properties. It is well known that in a short period of time, the partially halogenated HCFCs will be phase out, since the chlorine they contain can combine with ozone in stratosphere, thus depleting the ozone layer. Therefore, the research for a replacement of R22 has been intensified in recent years.

HFCs are a new family of substances which might substitute HCFCs. Indeed, they are harmless towards the ozone layer, because they do not contain chlorine.

In order to use these new refrigerants properly, their thermodynamic, thermo-physical, transport and heat transfer properties must be known. Specifically, the detailed heat transfer characteristics in condensation and boiling, together with the associated frictional pressure drops, are very important in order to avoid both under- and over-design of evaporators, boilers and other two-phase process equipment. The accurate prediction of heat transfer characteristics in condensers and evaporators is therefore a prerequisite to increase the cycle performance through the correct sizing of each plant component.

The importance of correctly predicting saturated flow boiling heat transfer coefficients has been recognized, as seen from a large number of analytical and experimental investigations conducted in the past years [1]. There are a large number of correlations available in literature to predict heat transfer in flow boiling [2–5]. These correlations can be classified in two categories. In the first category,

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doi:10.1016/j.ijheatmasstransfer.2007.11.002

Nomenclature

A	heat transfer area (m^2)
Bo	$\frac{q}{G\Delta h_{ev}}$ Boiling number
C_p	specific heat (kJ/kg K)
D	tube diameter (m)
d_b	bubble diameter (m)
g	gravitational acceleration (m/s^2)
G	mass flux (kg/s m^2)
h	heat transfer coefficient (W/m^2 K)
p	pressure (bar)
p_r	reduced pressure
k	thermal conductivity (W/m K)
n	power exponent
nq	power exponent
q	heat flux (W/m^2)
Q	heat transfer rate (W)
T	temperature (°C, K)
u	velocity (m/s)
x	vapour quality

Greek symbols

β	liquid contact angle
δ	thickness of annular liquid film (m)
Δh_{ev}	latent heat (J/kg)
ΔT	temperature glide (°C, K)
ε	void fraction
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	time characteristics (s)

Subscripts

b	bubble
cb	convective boiling
ev	evaporative
i	inner
l	liquid phase
nb	nucleate boiling
sat	saturation
v	vapour phase
w	inner wall

the correlations are developed by experimental investigators to represent their own data with a limited data base of operating conditions. These correlations can be used only in the same range of operating conditions and with the same boiling fluids.

In the second category, the correlations are developed on the basis of large data sets from different sources with a wide range of operating conditions and with different fluids. These correlations show a wide range of applicability [6].

Even in the presence of a large body of experimental data, there are still some remarkable insufficiencies. First, few correlations are developed with new refrigerant fluids, especially for R410A, R404A, R407C and R417A. Second, different functional forms have been adopted to account for the dependence of heat transfer coefficients on the relevant operating parameters. In many cases, the correlations are not able to predict correctly the dependence of the heat transfer from such crucial parameters as evaporating pressure and fluid properties. In particular, in flow boiling, simple correlation functions cannot fully replicate the complex relationship among the variables affecting the contribution of nucleate boiling and/or convective boiling to the heat transfer coefficient.

In literature, many studies deal with convective boiling of pure and mixed HFC fluids. Heat transfer coefficients of R134a have been widely investigated with different kinds of tube surfaces: smooth, micro fin, with perforated strip-type inserts [7–14]. The refrigerant mixture R410A has been investigated during convective boiling in internally grooved horizontal tubes [15], in smooth/micro-fin tubes [16], in horizontal annular finned ducts [17]. The zeotropic mixture R407C has been tested in horizontal smooth tubes [18,19], in horizontal small tubes [20], in enhanced surface tubing [21], and in micro-fin and smooth tubes [22,23]. Different pure and mixed refrigerant fluids have been tested in convective boiling in horizontal smooth tubes [24,25].

An experimental plant was set up at the University of Naples for evaluating the heat transfer characteristics of new refrigerant fluids in convective boiling. In the present paper, the local heat transfer coefficients are evaluated for pure refrigerant fluids R22 and R134a, for azeotropic and quasi-azeotropic mixtures R507, R404A and R410A, for zeotropic mixtures R407C and R417A.

R507, R404A and R410A are azeotropic and near azeotropic mixtures of R125/R143a (50/50% by weight), R125/R143a/R134a (44/52/4% by weight), R32/R125 (50/50% by weight). R407C and R417A are zeotropic mixture of R32/R125/R134a (23/25/52% by weight) and of R125/R134a/R600 (46.6/50/3.40% by weight). R407C has a temperature glide of about 6 °C, whereas R417A has a temperature glide of about 4 °C. The flow boiling characteristics of the above-mentioned refrigerant fluids are evaluated in 250 different operating conditions with a data-base of more than 2000 data points.

The experimental tests are carried out by varying refrigerant mass fluxes within the range from 200 to 1100 kg/m^2 s; heat fluxes within the range from 3.50 to 47.0 kW/m^2; evaporating pressures within the range from 3.00 to 12.0 bar.