International Journal of Heat and Mass Transfer 56 (2013) 107–118

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Flow boiling of R410A and CO_2 from low to medium reduced pressures in macro channels: Experiments and assessment of prediction methods

S. Grauso [a,*], R. Mastrullo [b], A.W. Mauro [b,*], G.P. Vanoli [a]

[a] Engineering Department, Sannio University, Corso Garibaldi 107, Palazzo dell'Aquila Bosco Lucarelli, 82100 Benevento, Italy
[b] Department of Energetics, Applied Thermofluidynamics and Air Conditioning Systems, FEDERICO II University, P.le Tecchio 80, 80125 Napoli, Italy

ARTICLE INFO

Article history:
Received 8 November 2011
Received in revised form 12 July 2012
Available online 27 October 2012

Keywords:
CO_2
R410A
Flow boiling
Reduced pressure
Prediction method
Assessment

ABSTRACT

CO_2 has gained renewed interest as refrigerant among natural fluids thanks to its low environmental impact and its good thermodynamic and transport properties. CO_2 provides very high heat transfer coefficients during flow boiling at medium reduced pressures. In addition, trends with vapor quality are remarkably different from conventional refrigerants working at the same saturation temperature. In this paper, the effect of the reduced pressure and its combined effect to other operating parameters (mass flux and heat flux) on flow boiling are experimentally investigated in a circular, horizontal, smooth tube of 6.00 mm inner diameter over a wide range of variation (from 0.19 to 0.64) combining experiments for R410A at low/medium reduced pressure to those at medium reduced pressure for CO_2. The analysis of flow regimes and local peripheral heat transfer coefficients allowed to define some generalized trends, independent on the fluid, finding their relationship with the reduced pressure and other operating parameters. In such a way the local heat transfer coefficient trends are motivated by the different weights of the peripheral heat transfer coefficients around the tube.

The whole database of 927 data points was used to perform a statistical analysis to assess the best prediction method for flow boiling at each reduced pressure.

1. Introduction

Natural refrigerants and halogenated refrigerant mixtures are the most used fluids alternatives to chlorinate refrigerants, whose use was banned for environmental issues such as the ozone depletion and the global warming. The benefits and the fields of application of these fluids are described in several works present in literature see for example [1–3]. Also flow boiling characteristics, required for the proper sizing of evaporators, were widely studied (view for example the reviews by Thome [4] and Thome et al. [5]).

Among natural fluids, carbon dioxide has gained renewed interest by the scientific community and industries, in particular for air-conditioning and heat pump applications. This fluid has thermodynamic properties more favorable than conventional refrigerants at the same saturation temperatures, as: higher vapor density, latent heat and liquid thermal conductivity; lower surface tension, liquid-to-vapor density ratio and liquid viscosity. However, CO_2 works at much higher saturation pressures than conventional refrigerants at the same saturation temperatures, for which correspond high reduced pressures due to its low critical temperature. This leads to lower differences between vapor and liquid thermodynamic properties, affecting both, in turn, flow boiling characteristics (see Table 1 which shows the comparison between the thermodynamic and the transport properties of the two fluids at different values of the reduced pressure).

As reported in the review by Thome and Ribatski [6], many works found that the heat transfer coefficients of CO_2 are much higher than those of other conventional refrigerants. It is supposed to be due to a high nucleate boiling contribution since the experiments show a direct and strong dependence of the heat transfer from the heat flux at different operating conditions. Conversely, a slightly dependence on the mass flux was usually found with remarkably different trends of local HTCs with vapor quality. In particular, at medium-high reduced pressures the main difference is the decreasing trend of the local heat transfer coefficients with vapor quality in the annular flow region. In order to show the effect of the reduced pressure on flow boiling of refrigerants a brief literature survey focusing the attention on experimental works with remarkable reduced pressure variations is presented.

Yun et al. [7] investigated the local heat transfer coefficients at the saturation temperatures of 5 °C and 10 °C (corresponding respectively to reduced pressures of 0.47 and 0.62) in a horizontal smooth tube of 6.00 mm I.D. Basing on the experimental evidences, they supposed the dominance of nucleate boiling contribution especially at low vapor qualities, while they explained the decreasing trends of the local heat transfer coefficients at low-medium

* Corresponding authors.
E-mail addresses: segrauso@unisannio.it (S. Grauso), wmauro@unina.it (A.W. Mauro).

0017-9310/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.09.015

Nomenclature

D	diameter (m)
G	refrigerant mass flux (kg m^{-2} s^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
HTC	heat transfer coefficient
i	specific enthalpy (J kg^{-1})
I	internal
L	length of the tube
p	pressure (bar)
q	heat flux (W m^{-2})
R	electrical resistance (Ω)
Q	thermal power (W)
sd	standard deviation (%)
t	temperature (°C)
T	temperature (K)
x	vapor quality

Greek symbols

ε_n	error (%)
$\bar{\varepsilon}$	mean error (%)
$\lvert\bar{\varepsilon}\rvert$	mean absolute error (%)
$\lambda_{30\%}$	percentage of experimental points predicted within ±30%

Subscripts

bott	related to the bottom position
cross, avg	cross sectional area averaged value
DTS	referred to diabatic test section
exp	experimental
i	inner
left	related to the left position
local	local value
o	outer
quality, avg	vapor quality averaged value
r	reduced
right	related to the right position
sat	saturation
top	related to the top position
w	wall

vapor qualities by the occurrence of partial dry-out of liquid film at the top of the tube.

According to these suppositions, Cheng et al. [8] developed a diabatic flow pattern map using six independent databases, covering a range of reduced pressure between 0.21 and 0.87. Also a flow pattern based heat transfer coefficient model was specifically proposed for CO_2, starting from the Wojtan et al. [9] flow pattern map (developed from R22 and R410A experimental data). The Cheng et al. [8] flow pattern map provides transition curves from intermittent to annular flow and from annular flow to dry-out flow at much lower vapor qualities than the Wojtan et al. [9] flow pattern map, due to the observation of the fall-down of HTCs in the annular region and the sharp drop in the dry-out region. About the HTC prediction method, they modified the coefficients and exponents of the Cooper correlation to improve the prediction of the nucleate boiling contribution as a function of the reduced pressure.

Subsequently, Cheng et al. [10] improved the transition curves of the previous flow pattern map by using new database that covered a wider range of operating conditions. In particular, the intermittent-to-annular flow transition is predicted at slightly higher vapor qualities, while the annular to dry-out transition curve is no longer predicted at low vapor qualities as the previous flow pattern map, resulting in a better fitting with the wider dry-out experimental database. Regarding the influence of the reduced pressure on local heat transfer coefficients during flow boiling for refrigerants different than CO_2, many works investigated on a saturation temperature range from −20 °C to +5 °C that for most halogenated refrigerants correspond to reduced pressures ranging between 0.10 and 0.26 [11–14].

The recent work by Del Col [15] compared heat transfer coefficients of R22, R134a, R125 and R410A in 8.00 mm horizontal smooth tube ranging the saturation temperature between 25 °C and 45 °C, with a variation of the reduced pressure between 0.19 and 0.53 for all the experimental data. In particular, for R410A experiments were carried out at reduced pressures between 0.49 and 0.53. Moreover, experiments were compared with some correlations and a modification of the Gungor and Winterton [16] correlation was proposed, which showed a good agreement with the whole database. The accuracy of the new correlation is rather different for each fluid and not always capture the experimental trends with vapor quality.

Mastrullo et al. [17] investigated the local heat transfer coefficients of carbon dioxide ranging the saturation temperature from −7.8 °C to 5.8 °C, that correspond to reduced pressures ranging from 0.38 to 0.55. They found trends of the local HTCs similar to those by Yun et al. [7].

In a further work Mastrullo et al. [18] compared the cross sectional averaged, the peripheral local heat transfer coefficients and flow pattern maps of two fluid, CO_2 and R410A, at reduced pressure equal to 0.50, in order to show the effect of the reduced pressure independently on the fluid. Although the authors found similar trends of the cross sectional averaged local heat transfer coefficient vs. vapor quality for the two fluids, significant differences were noted by analyzing their absolute values (higher for CO_2) and their dependence on the mass flux and the heat flux. They highlighted the importance of the flow pattern transitions especially on the trends of the heat transfer coefficient at the top of the horizontal tube.

Subsequently Mastrullo et al. [19] deepen the effect of the reduced pressure on flow patterns through experimental visualizations varying the reduced pressure from 0.19 to 0.64. They developed new correlations for flow pattern transitions proving that they are strictly related to reduced pressure and including all the thermodynamic properties variations in the reduce pressure variation.

The present work is a step further than that presented in [19] and its main objective is to investigate flow boiling in a macro-channel over a wide range of reduced pressure proposing a combined analysis of flow pattern transitions (obtained in [19]) and local peripheral heat transfer coefficients.

For this reason, the experiments were taken for carbon dioxide at typical air-conditioning operating conditions (saturation temperatures of 7.0 °C and 12.0 °C, reduced pressure equal to 0.57 and 0.64) with mass fluxes ranging from 150 kg m^{-2} s^{-1} to 500 kg m^{-2} s^{-1} and heat fluxes of 5.0 kW m^{-2} and 20.0 kW m^{-2} in a horizontal smooth tube of 6.00 mm I.D.

To extend the variation of the reduced pressure also the refrigerant R410A was tested by varying its saturation temperature from