INTERNATIONAL JOURNAL OF REFRIGERATION 36 (2013) 2017–2039

Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

Review

Review of correlations of flow boiling heat transfer coefficients for carbon dioxide

*Xiande Fang**, *Zhanru Zhou*, *Dingkun Li*

Institute of Air Conditioning and Refrigeration, Nanjing University of Aeronautics and Astronautics, 29 Yudao St., Nanjing 210016, China

ARTICLE INFO

Article history:
Received 14 February 2013
Received in revised form
23 May 2013
Accepted 25 May 2013
Available online 5 June 2013

Keywords:
Carbon dioxide
Flow boiling
Heat transfer
Coefficient
Correlation

ABSTRACT

Carbon dioxide (CO_2) has quite different flow boiling heat transfer characteristics from conventional refrigerants due to its much higher reduced pressures that make its thermodynamic and transport properties very different. There were some studies evaluating the correlations of flow boiling heat transfer coefficient for CO_2. However, either the number of correlations covered or the number of data used was limited, resulting in inconsistent conclusions. This work presents a comparative review of existing correlations for flow boiling heat transfer coefficient of CO_2. There are 34 correlations analyzed and evaluated using 2956 experimental data points of CO_2 flow boiling heat transfer from 10 independent laboratories. The Fang (2013) correlation performs best with a mean absolute deviation of 15.5%. The evaluation analysis sets a channel transition criterion for flow boiling heat transfer of CO_2. Several topics worthy of attention for future studies are identified.

Corrélations du transfert de chaleur lors de l'ébullition en écoulement pour le dioxyde de carbone : Synthèse

Mots clés : dioxyde de carbone ; ébullition en écoulement ; transfert de chaleur ; coefficient ; corrélation

1. Introduction

Due to the phaseout of conventional refrigerants that have ozone depleting effect and/or unacceptable global-warming potential, carbon dioxide (CO_2 or R744) has received renewed interest as a potential alternative refrigerant in the past 20 years (Fang et al., 2001; Yoon et al., 2004a; Thome and Ribatski, 2005; Kim et al., 2013). It has been yielding increasing marketable products such as domestic hot water heaters, heat pumps, and mobile air conditioning units. In order to design high performance evaporators for these thermal systems, it is important to

---

* *Corresponding author*. Tel./fax: +86 25 8489 6381.
E-mail address: xd_fang@yahoo.com (X. Fang).

http://dx.doi.org/10.1016/j.ijrefrig.2013.05.015

Nomenclature

Bd	Bond number, $g(\rho_l-\rho_g)D_h^2/\sigma$
Bo	boiling number, $q/(h_{lg}G)$
C	Chisholm parameter
Co	confinement number, $\sqrt{\sigma/[g(\rho_l-\rho_g)D_h^2]}$
D	inner diameter (m)
D_h	hydraulic diameter (m)
f	Moody friction factor
Fa	dimensionless number by Fang (2003), $Fa=(\rho_l-\rho_g)\sigma/G^2D_h$
Fr	Froude number
G	mass flux (kg m^{-2} s)
g	acceleration due to gravity (m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
h_{lg}	latent heat of vaporization (J kg^{-1})
L	tube length (m)
M	molecular mass (kg kmol^{-1})
Nu	Nusselt number
p	pressure (Pa)
P_R	reduced pressure, p/p_{crit}
Pr	Prandtl number
q	heat flux from tube wall to fluid (W m^{-2})
Re	Reynolds number
t	temperature (°C), time (s)
T	temperature (K)
We	Weber number
x	vapor quality
X	Lockhart–Martinelli parameter

Greek symbols

λ	thermal conductivity (W m^{-1} K^{-1})
ε	surface roughness (μm), void fraction
θ	angle (Rad), ratio of height to width of channel cross-section
Δ	increment
μ	dynamic viscosity (Pa s^{-1})
ρ	density (kg m^{-3})
τ	pair period (s)
σ	surface tension (N m^{-1})
ϕ^2	two-phase friction multiplier

Subscripts

cb	convective boiling
crit	critical point
dry	dryout
exp	experimental
film	liquid film between bubble and wall
g	saturated vapor
go	all flow taken as vapor
IA	intermittent to annular flow transition
l	saturated liquid
lam	laminar flow
lo	all flow taken as liquid
nb	nucleate boiling
pred	predicted
sat	saturated
sp	single-phase
t	turbulent
tp	two-phase
trans	laminar-turbulent transition
tt	turbulent liquid/turbulent vapor
υ	viscous
wet	wet perimeter

predict accurately the heat transfer coefficient of CO_2 flow boiling in channels.

Except when used as the low temperature refrigerant in cascade cycles, CO_2 is evaporated normally at saturation pressures around 3 MPa, several times higher than other refrigerants. The high vapor density, low surface tension and low vapor viscosity of CO_2 at evaporation make its flow boiling heat transfer characteristics quite different from those of conventional refrigerants. Hence, a number of CO_2-specific correlations of flow boiling heat transfer coefficients were proposed. On the other hand, there are a number of correlations of flow boiling heat transfer coefficients developed based on other refrigerants, and their applicability to CO_2 needs to be assessed. A few of studies evaluated the applicability to CO_2 of the correlations of flow boiling heat transfer coefficients.

Thome and Ribatski (2005) performed a comprehensive review of flow boiling heat transfer of CO_2. Based on the experimental database from several independent studies from different laboratories, they evaluated the correlations of Liu and Winterton (1991); Hwang et al. (1997); Thome and El Hajal (2004), and Yoon et al. (2004a, 2004b) with the macrochannel database and the correlations of Liu and Winterton (1991); Thome et al. (2004), and Zhang et al. (2004) with the microchannel database. For the four macrochannel correlations among which the first three are CO_2-specific, the Thome and El Hajal (2004) correlation predicted 60% of the database within ±30% error band, and the Yoon et al. (2004a, 2004b) correlation had the smallest mean absolute deviation (MAD) of 36% for vapor quality $x \le 0.9$. For the microchannel database, the Liu and Winterton (1991) correlation had the smallest MAD of 30% for vapor quality $x \le 0.9$.

Park and Hrnjak (2007) investigated experimentally flow boiling heat transfer coefficients in a 6.1 mm ID horizontal tube for CO_2, R410A, and R22 at evaporation temperatures of −15 and −30 °C, mass fluxes from 100 to 400 kg m^{-2} s^{-1}, heat fluxes from 5 to 15 kW m^{-2}, and vapor qualities from 0.1 to 0.8. They compared their measurements with the correlations of Shah (1982); Gungor and Winterton (1986); Gungor and Winterton (1987); Liu and Winterton (1991), and Wattelet et al. (1994) and found that the Gungor and Winterton (1986) correlation had the smallest MAD of 14.4%, followed by the Wattelet et al. (1994) correlation of 18.3% and the Liu and Winterton (1991) correlation of 24.3%.

Zhao and Bansal (2007) conducted the experimental study of flow boiling heat transfer of CO_2 at near −30 °C in a horizontal 4.57 mm ID stainless steel tube. With the measurements and other three independent data sources, they examined the correlations of Cooper (1984); Gungor and Winterton (1986); Jung et al. (1989); Kandlikar (1990); Liu and Winterton (1991); Kattan et al. (1998) and Yoon et al. (2004a,