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New experimental data of CO_2 flow boiling in mini tube with micro fins of zero helix angle

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ABSTRACT

Heat transfer and pressure drop characteristics of CO_2 flow boiling in mini tube with micro fins of zero helix angle were experimentally investigated. The working conditions cover mass flux from 100 to 600 kg m^{-2} s^{-1}, heat flux from 1.67 to 8.33 kW m^{-2}, vapor quality from 0 to 0.9 and saturation temperature from 1 to 15 °C. The results show that the heat transfer coefficient increases with increasing vapor quality, but sharply decreases at vapor quality around 0.2~0.4 under most conditions, and the dryout vapor quality decreases with the increasing heat flux and saturation temperature. Pressure drop increases with increasing mass flux and heat flux, or decreasing saturation temperature, and mass flux is the major influence factors. The enhancement ratio of heat transfer coefficient is higher than that of pressure drop, which shows potentials of using such kind tubes to enhance the overall heat transfer performance. A heat transfer coefficient correlation and a pressure drop correlation for 0° helix angle micro-fin tube were developed, and they agree well with the experimental data.

De nouvelles données expérimentales d'ébullition en écoulement du CO_2 dans un mini-tube avec micro ailettes à angle d'hélice nul

Mots clés : CO_2 ; Ebullition en écoulement ; Echangeur de chaleur ; Micro-ailettes ; Chute de pression

1. Introduction

Carbon dioxide (CO_2) has been used as a refrigerant in vapor compression systems for more than 160 years (Peterson, 2005). As a natural refrigerant CO_2 possesses many advantages in thermo-physical properties among which its low ODP and GWP (ODP is 0, and GWP is 1) are the most distinguished features compared with the commonly used refrigerant HCFCs, CFCs and HFCs. In the past decade with the more and more serious issues of ozone depletion and global warming, CO_2 has become more attractive than ever before for refrigeration applications

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Nomenclature

a, b, a', b'	Length of a side, m
Bd	Bond number
Bo	Boiling number
c_p	Specific heat capacity, J kg^{-1} K^{-1}
D	Diameter, m
f	Fin height, m; frictional coefficient
G	Mass flux, kg m^{-2} s^{-1}
g	Local acceleration, m s^{-2}
h	Heat transfer coefficient, W m^{-2} K^{-1}
h_{lv}	Latent heat, J kg^{-1}
Pr	Prandtl number
p	Pressure, Pa
Q	Heating power, W
q	Heat flux, W m^{-2}
Re	Reynolds number
r	Tube diameter, m
T	Temperature, °C
X_{tt}	Martinelli number
x	Vapor quality

Greek symbol

δ	Liquid film thickness, m
ε	Vapor fraction
θ_{dry}	Dry angle
λ	Thermal conductivity, W m^{-1} K^{-1}
μ	Viscosity, Pa s
ρ	Density, kg m^{-3}
σ	Surface tension, N m^{-1}
Φ	Heat generation per unit volume, W m^{-3}

Subscript

acc	accelerating
b	boiling
crit	critical
exp	experimental
fric	frictional
i	inner
in	inlet
l	liquid
lo	liquid only
out	outlet
pre	preheater
pred	predicted
o	outer
sat	saturation
sur	surrounding
tp	two-phase
v	vapor
wet	wetted
wi	inner wall
wo	outer wall

in which exchangers with mini channels are widely used. Therefore, for designing and optimizing such heat exchanger, CO_2 flow boiling characteristics and heat transfer enhancement in mini channels should be investigated in the first place.

For enhancing flow boiling heat transfer in channels, tubes with micro fins are often used in heat exchangers. Usually the micro-fin tube has dozens of fins (usually 10–40) on the inner surface of the tube, and the fin helix forms a certain angle (usually 5°–60°) with the axial direction of the tube. The fins not only provides much more heat transfer area (up to 2 times of that in smooth tube with the same inner diameter), but also promotes the mixing of liquid and vapor, which enhances the flow boiling heat transfer. The existing researches reveal that the heat transfer coefficient in micro-fin tube can be up to 100% higher than that in smooth tube under the same conditions (Hu et al., 2011; Kim et al., 2002). On the other hand, the fins also increase the two-phase flow pressure drop. As the fin helix has an angle with the direction of the flow, form drag is also included in the flow resistance. The existing researches also reveal that the pressure drop in micro-fin tube can be 100% higher or more than that in smooth tube under the same conditions, and the pressure drop increment caused by fins is more significant with the decrease of tube diameter (Kim et al., 2002). As well known, pressure drop in evaporator has significant influence on the performance of the system, so the conventional micro-fin tubes with a certain helix angle may not be that excellent for system performance improvement under some circumstances, especially for mini channels.

Considering both heat transfer enhancement and pressure drop increment caused by fins, mini tubes with micro fins which are parallel to the axial direction of the tube (zero helix angle) may have potential in CO_2 refrigeration applications. On one hand such kind tubes provide as much heat transfer area as conventional micro-fin tubes do, and may have the similar enhancement on heat transfer as conventional micro-fin tubes do; on the other hand the fins have the same direction with the flow direction (zero helix angle), which diminishes the form drag and reduces the pressure drop.

Most of the existing investigations on flow boiling in micro-fin tubes focused on fins with a non-zero helix angle. Among these investigations, many used HCFCs or HFCs as the working fluid, e.g. Seo and Kim (2000), Kim et al. (2002), Yu et al. (2002), Ding et al. (2009) and Hu et al. (2011), and found more than two-fold increases in heat transfer coefficients. The previous researches using CO_2 as the working fluid are limited, and the tube diameters are large, e.g. Schael and Kind (2005). Regarding CO_2 flow boiling in small diameter micro-fin tubes, Dang et al. (2010) conducted an experimental investigation on CO_2 flow boiling heat transfer and pressure drop in a small diameter micro-fin tube. Then found that the heat transfer coefficients were 1.9–2.3 times the value in smooth tubes of the same diameter under the same experimental conditions. The enhancement ratio of the pressure drop was 1.5–2.1, which was smaller than that of the heat transfer coefficient. Gao et al. (2007) investigated the flow boiling heat transfer of CO_2 and CO_2–oil mixtures in smooth and micro-fin tubes. The effect of area enhancement on the heat transfer coefficient for the micro-fin tube was pronounced at a high vapor quality, high mass velocity, and low oil circulation ratio, with a maximum enhance of 1.3 for heat transfer coefficient. Jeong and Park