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Post-dryout heat transfer characteristics in horizontal mini-tubes and a prediction method for flow boiling of CO_2

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ABSTRACT

The post-dryout heat transfer coefficients were analyzed by differentiating them into two regions, based on their observed trends. One is a transition region. The other is a fully dryout region. The effects of test conditions for heat flux and saturation temperature on the boundaries of the two regions were also investigated, and the existing models for post-dryout heat transfer coefficients were verified for both regions. To develop a prediction method for flow boiling of CO_2, we applied the critical liquid film model, to predict the point of dryout vapor quality. The Yun et al. model and the Groeneveld model are used to estimate the heat transfer coefficients prior to and subsequent to the point of dryout vapor quality, respectively. The former shows a mean deviation of 38%, and the latter gives 36.4% for the three different data sources.

Caractéristiques de transfert de chaleur après l'assèchement dans les minitubes horizontaux et une méthode de prévision pour l'ébullition en écoulement du CO_2

Mots clés : Frigorigène ; Dioxyde de carbone ; Ébullition ; Tube horizontal ; Microcanal ; Expérimentation ; Coefficient de transfert de chaleur

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Nomenclature

g	gravitation constant ($m\,s^{-2}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$\dot{m}$	mass flux ($kg\,m^{-2}\,s^{-1}$)
p_r	reduced pressure (–)
q	heat flux ($kW\,m^{-2}$)
Re	Reynolds number (–)
T	temperature (°C)
TR	Transition region

Greek symbols

Γ	mass flow rate per unit periphery of tube ($kg\,m^{-1}\,s^{-1}$)
δ	critical liquid film thickness (m)
μ	dynamic viscosity ($N\,s\,m^{-2}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)

Subscripts

l	liquid
out	outlet
r	refrigerant
s	saturation
v	vapor
w	wall

1. Introduction

Carbon dioxide (CO_2) has been widely investigated as a working fluid of automobile air-conditioners, bending machines, water heater heat pumps, and residential air-conditioners, due to increasing environmental concerns. However, a CO_2 system shows a lower efficiency compared with Freon based conventional systems, which is mostly due to the transcritical process of CO_2 during the heat rejection process. There have been various efforts to improve the efficiency of the CO_2 system to make it equivalent to or better than the conventional systems, made. This goal can be achieved by the improvement of each of the system components, by installation of additional apparatuses, and by the variation of system configuration. Regarding heat exchangers of the system, micro- or mini-channel heat exchangers have been used. However, since the heat transfer characteristics of micro/mini-channels are different from conventional sized tubes, and CO_2 shows unique thermo-physical properties compared with Freon, achieving an understanding of the two-phase heat transfer characteristics of CO_2 in a micro/mini-channel is essential to develop a compact heat exchanger appropriate for the transcritical CO_2 system. The density ratio of ρ_l/ρ_v and the surface tension of CO_2, at standard working temperature, are much lower than those of the conventional refrigerants. Due to these properties, liquid film dryout occurs at the point of moderate vapor quality. This phenomenon relates to the increase of the liquid droplet entrainments (Yun and Kim, 2003), a direct flow transition to annular flow (Yun and Kim, 2004), and earlier transition to mist flow even at lower mass flow rates and vapor qualities (Thome and Ribatski, 2005). Since a dramatic change of heat transfer coefficients was observed prior to and subsequent to the dryout point, it is a standard practice to develop separate prediction models for them.

Several researchers have studied the boiling heat transfer characteristics of CO_2 in micro- and mini-channels for which the hydraulic diameters were approximately 1.0 mm. Pettersen (2004) investigated flow vaporization of CO_2 in a micro-channel tube. He showed that critical vapor quality decreased, and a rapid reduction of the heat transfer coefficient occurred at high mass fluxes and high saturation temperatures. He developed the model for estimating the convective boiling heat transfer coefficient of CO_2 by separating it into prior to and subsequent to dryout. Hihara and Tanaka (2002) measured boiling heat transfer coefficients and pressure drops of CO_2 in a smooth round tube with an inner diameter of 1.0 mm. Critical vapor quality was significantly affected by mass flux. Thome and Ribatski (2005) performed a comprehensive review of flow boiling heat transfer and two-phase flow of CO_2 in both a macro-channel (ID > 3 mm) and a micro-channel. They analyzed the experimental data for the heat transfer coefficients, pressure drops, flow patterns, and compared them with the existing models. According to their comparison, the models achieved poor predictive power for the micro- and mini-channels. Thome and El Hajal (2004) updated the Kattan–Thome–Favrat's flow boiling heat transfer model for CO_2, by considering the importance of nucleate boiling in the heat transfer mechanism. Their model predicted 73% of the CO_2 database, which contains 404 data points, within ±20%. However, as mentioned by Thome and Ribatski (2005), it achieved poor results for small diameter tubes with early dryout vapor. For macro-tubes, Yoon et al. (2004) investigated the boiling heat transfer characteristics of CO_2 in a horizontally positioned tube, with an inner diameter of 7.53 mm. They developed a model for the point of dryout vapor quality based on their experimental data, and suggested models for the heat transfer coefficients. Schael and Kind (2005) studied the flow patterns and heat transfer characteristics of flow boiling of CO_2 in a horizontal micro-fin tube and a smooth tube. The diameter of the test tube was 9.52 mm, and the measurement was performed under mass fluxes between 75 and 250 $kg\,m^{-2}\,s^{-1}$. The heat transfer coefficient was proportional to q^n ($0.5 < n < 0.55$). It gradually decreased with respect to vapor quality. For prediction methods for CO_2 flow boiling, Cheng et al. (2008a) modified their previous model (Cheng et al., 2006) by separating the post-dryout region into two regions. One is the dryout region. The other is the mist flow region. The dryout inception and the dryout vapor quality end point for the dryout region were calculated by using the flow pattern map for CO_2 (Cheng et al., 2008b). This was improved by considering boiling heat transfer characteristics. However, the suggested dryout vapor quality end point for the dryout region was based on limited experimental data. Its validity is open to question.

As shown in the previous studies, the rapid reduction of the heat transfer coefficient of CO_2 occurs at moderate vapor quality, for micro- and mini-channels, and the heat transfer characteristics observed prior to and subsequent to dryout vapor qualities are important for the design of the micro-channel heat exchanger. However, investigations of