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Conditions of liquid film dryout during saturated flow boiling in microchannels

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ABSTRACT

During saturated flow boiling in microchannels, two different trends of the dryout vapor quality (x_{do}) have been observed experimentally: $x_{do} \propto G^{-j}$ and $x_{do} \propto G^{j}$ with $j>0$. In the literature, the first trend is experimentally observed for refrigerants and CO_2 whereas the second trend is detected so far only for CO_2 at high mass velocities. In this paper, the model of Revellin and Thome [A theoretical model for the prediction of the critical heat flux in heated microchannels. International Journal of Heat and Mass Transfer 51, 1216–1225] for the saturated critical heat flux in microchannels is used to analyze and explain this change of trend. Their theoretical model predicts three different trends of dryout vapor quality. Indeed, it is shown here that when increasing the mass velocity, the liquid film at the outlet of the channel passes through two different states: laminar flow ($Re_\delta < \psi = 2300$) and transition flow ($Re_\delta = \psi$). Turbulent flow ($Re_\delta > \psi$) has been omitted in this study since no experimental data are available for this regime. Laminar film dryout yields a decrease of the dryout vapor quality with respect to G ($x_{do} \propto G^{-j}$), transition film dryout is characterized by an increase of the dryout vapor quality with G ($x_{do} \propto G^{j}$). Furthermore, a new criterion is proposed here to identify the laminar-to-transition mass velocity, one for refrigerants and another one for CO_2. The criterion gives the maximum value (upper limit) of the mass velocity for which the conventional microchannel correlations for the dryout vapor quality may be used. Notably, for a given pressure, the values of the laminar-to-transition mass velocities for refrigerants and CO_2 are approximately the same. This reinforces the idea that CO_2 is not a maverick fluid but just a normal fluid used at a higher reduced pressure in many boiling applications than conventionally used refrigerants.

1. Introduction

During saturated flow boiling, the dryout vapor quality (x_{do}) is the maximum vapor quality that can be reached before the heat transfer coefficient drops dramatically. x_{do} is related to the saturated critical heat flux (CHF) through an energy balance between the wall of the channel and the fluid. Usually, saturated CHF is the maximum heat flux that can be dissipated before dryout occurs at the outlet of the channel for a given inlet condition.

In horizontal macrochannels, due to the effect of gravity (stratification), dryout occurs first at the top side of the channel. Wojtan et al. (2005) investigated flow boiling in horizontal tubes. Annular-to-dryout and dryout-to-mist flow transition curves have been added and integrated into their new macroscale diabatic flow pattern map. These two transition curves were identified by distinct trends of the heat transfer coefficient as a function of vapor quality and by flow pattern observations to determine (and then predict) the inception and completion of dryout in horizontal tubes. The distinction of these two points is done by the shift of the position of a local dryout along the circumference of the tube: the dryout position moves from the top to the bottom around and along the tube perimeter with increasing quality and also by the irregular fluctuations of the axial dryout position due to the unstable nature of the process.

However, in small channels, we can assume a nearly uniform circumferential distribution of the liquid film, so that dryout essentially occurs simultaneously all around the perimeter. Usually, it can be observed experimentally (Wojtan et al., 2006; Jeong and Park, 2007) that when G increases, the dryout vapor quality in microchannels decreases as shown in Fig. 1. The general trend of the dryout vapor quality with mass velocity is $x_{do} \propto G^{-j}$ with j a positive number.

Wojtan et al. (2006) performed a series of tests to determine the saturated CHF in 0.509 and 0.790 mm internal diameter horizontal microchannel tubes as a function of refrigerant mass velocity, heated length, saturation temperature and inlet liquid subcooling. The channels were electrically heated by direct current. The fluids tested were two refrigerants, namely R-134a and R-245fa, and the heated length of microchannel was varied from 20 and 70 mm. The results showed a strong dependence of CHF on mass velocity, heated length

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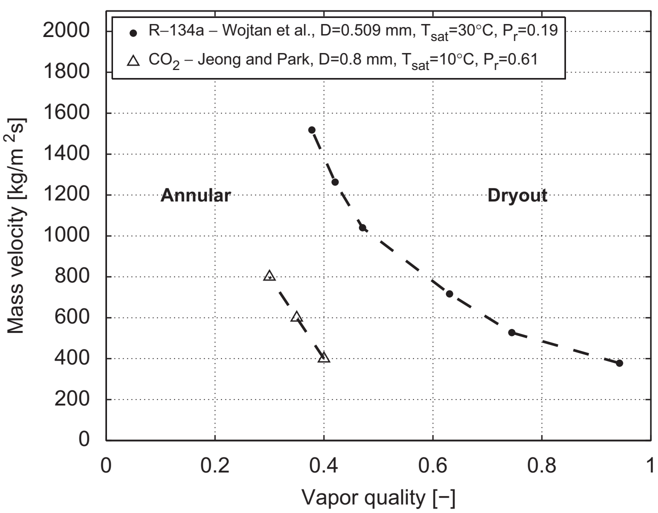

Fig. 1. Experimental mass velocity as a function of dryout vapor quality for three different fluids.

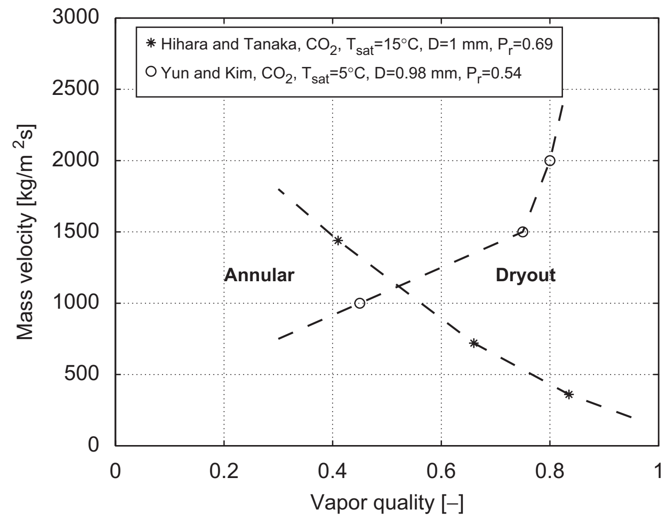

Fig. 2. Experimental mass velocity versus dryout vapor quality for CO_2 from two different studies.

and the microchannel diameter but no measurable influence of liquid subcooling (2–15 °C) was observed. They developed a correlation to predict their data. Wojtan et al. (2006) observed the occurrence of dryout in the annular flow regime at all their test conditions. This characteristic was also reported by Revellin et al. (2006). Through an energy balance based on the saturated CHF correlation, they calculated the critical vapor quality. In a mass velocity versus vapor quality diabatic flow pattern map, they reported the annular-to-dryout transition. Beyond this limit mist flow occurs. They observed that the critical vapor quality decreased when increasing the mass velocity.

Jeong and Park (2007) studied evaporative heat transfer of CO_2 in a smooth ($D = 0.8$ mm) and a grooved ($D = 0.8$ mm and eight grooves) horizontal multi-channel microtube. The channels were electrically heated by direct current. They reported nine dryout vapor quality measurements at two different saturation temperatures ($T_{sat} = 5$ and 10 °C) and for a mass velocity varying from 400 to 800 kg/m^2 s. They found an effect of the mean heat flux on the dryout vapor quality and developed a new correlation based on that of Yoon et al. (2004) for CO_2 flowing in macrochannels. They also observed a decrease of the dryout vapor quality when increasing the mass velocity.

Hihara and Tanaka (2000) performed experiments on boiling heat transfer of CO_2 in horizontal tubes ($D = 1$ mm) at an evaporating temperature of 15 °C and mass velocities varying from 360 to 1440 kg/m^2 s. The channels were electrically heated by direct current. They observed that the dryout vapor quality decreased with increasing the mass velocity.

Among the existing studies on saturated CHF and dryout in microchannels, Yun and Kim (2003) observed two different trends in the dryout vapor quality. They experimentally investigated the critical vapor quality for saturated flow boiling of CO_2 in horizontal small diameter tubes ($D = 0.98$ and 2 mm). The channels were electrically heated by direct current. They reported their results for $T_{sat} = 0$, 5 and 10 °C and for mass velocities varying from 500 to 3000 kg/m^2 s. For their 2 mm data, they discovered an increase of the dryout vapor quality with increasing mass velocity after a certain value of G called here the "transition mass velocity" ($x_{do} \propto G^{-j}$ for $G < G_{trans}$ and $x_{do} \propto G^j$ for $G > G_{trans}$ with $j > 0$). For their 0.98 mm data, they only observed the increase of the dryout vapor quality with mass velocity. They attributed the increase of the dryout vapor quality with the mass velocity to the intense deposition of liquid droplets onto the liquid film layer and dryout patch regions.

The experimental data of Yun and Kim (2003) have been plotted with those of Hihara and Tanaka (2000) for comparison in Fig. 2 where the two opposite trends are clearly distinguishable. The diameter is almost the same in both studies. Despite the opposite trends, we think that the results are compatible and we will attempt to understand the reasons and conditions of controlling dryout during flow boiling in microchannels from a phenomenological analysis based on the theoretical CHF model of Revellin and Thome (2008). Moreover, a simple criterion will be proposed for the upper valid value of G for application of two conventional CHF correlations: Wojtan et al. (2006) and Jeong and Park (2007).

2. Prediction of dryout vapor quality

2.1. Model by Revellin and Thome (2008)

Dryout vapor quality and CHF in a tube are linked by an energy balance for a channel with uniform heat flux:

$$x_{do} = \frac{4 q_{CHF} L}{G h_{lv} D} \tag{1}$$

where q_{CHF} is the saturated CHF, L is the heated length of the tube, G is the mass velocity, D is the tube diameter and h_{lv} is the latent heat of vaporization. In this relation, it is assumed that dryout occurs at the outlet of the tube first and that the fluid is saturated liquid at the inlet.

For predicting the saturated CHF, Revellin and Thome (2008) have recently proposed a theoretical model to predict the CHF under uniform or non-uniform heat fluxes in microchannels. Solving the continuity, momentum and energy equations for an annular flow without interfacial waves, the solution gives the variation in the liquid film thickness (δ) along the channel. Many observations confirm that the saturated CHF in microchannels occurs in annular flow, such has been observed in Wojtan et al. (2006) for R-134a and R-245fa and in Pettersen (2004) for CO_2 and this is what was assumed in their model. Furthermore, it is assumed that the mechanism of dryout occurs when the average liquid film is greater than 0 ($\delta > 0$) if the interfacial waves are large enough to have their trough in contact with the wall (Fig. 3). In such a situation, the vapor quality x is less than unity. Note that the entrainment and redeposition of droplets have been neglected in this model, originally developed for refrigerants,