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Subcooled flow boiling of R-134a in vertical channels of small diameter

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Abstract

Subcooled flow boiling heat transfer for refrigerant R-134a in vertical cylindrical tubes with 0.83, 1.22 and 1.70 mm internal diameter was experimentally investigated. The effects of the heat flux, $q'' = 1$–$26\ \text{kW/m}^2$, mass flux, $G = 300$–$700\ \text{kg/m}^2\,\text{s}$, inlet subcooling, $\Delta T_{\text{sub},i} = 5$–$15\ °\text{C}$, system pressure, $P = 7.70$–10.17 bar, and channel diameter, D, on the subcooled boiling heat transfer were explored in detail. The results are presented in the form of boiling curves and heat transfer coefficients. The boiling curves evidenced the existence of hysteresis when increasing the heat flux until the onset of nucleate boiling, ONB. The wall superheat at ONB was found to be essentially higher than that predicted with correlations for larger tubes. An increase of the mass flux leads, for early subcooled boiling, to an increase in the heat transfer coefficient. However, for fully developed subcooled boiling, increases of the mass flux only result in a slight improvement of the heat transfer. Higher inlet subcooling, higher system pressure and smaller channel diameter lead to better boiling heat transfer. Experimental heat transfer coefficients are compared to predictions from classical correlations available in the literature. None of them predicts the experimental data for all tested conditions.

Keywords: Heat transfer; R-134a; Subcooled boiling; Onset of nucleate boiling

1. Introduction

Subcooled flow boiling exists when the bulk liquid temperature remains below its saturation value but the surface is hot enough for bubbles to form. The primary formation of bubbles is known as onset of nucleate boiling, ONB. According to the classical theory (Collier and Thome, 1994; Tong and Tang, 1997) bubbles formed at the wall will condense as they move out of the developing saturation boundary layer, but the appearance of these bubbles will affect the heat transfer between the wall and the fluid. At low heat fluxes or high level of subcooling, only few nucleation sites are active and a portion of the heat is transferred by

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single-phase convection between patches of bubbles. This regime is termed partial nucleate boiling. As the heat flux is increased, more nucleation sites are activated until fully developed nucleate boiling, when the surface becomes fully active for nucleation. After that, as the bulk fluid is heated the saturation boundary layer grows and will eventually cover the entire channel, and the saturated nucleate boiling region is reached.

Recently there is a worldwide interest in compact heat exchangers of the microchannel type. Microchannel heat exchangers and evaporators present several advantages, both safety and cost wise, such as reduced size, higher efficiency and low fluid inventory. Because the governing phenomena are not yet well understood, much effort is being dedicated to the study of both single and two-phase heat transfer in mini and microchannels. As a summary, according to our previous work (Owhaib and Palm, 2004) single phase heat transfer and pressure drop can be well represented by classical correlations. On the other hand, and despite the discrepancy among different authors, it appears that boiling heat transfer and two-phase flow patterns cannot be properly predicted by the existing macroscale correlations (Owhaib et al., 2004). Nonetheless, very little work and experimental data can be found on subcooled flow boiling for tubes of these small diameters.

Shah (1977) compiled experimental data on different fluids and presented a correlation to predict heat transfer coefficients in subcooled boiling. The correlation is expressed in two equations applicable in the low and high subcooling regions, respectively. Essentially, the low subcooling region corresponds to fully developed boiling and the high subcooling region corresponds to partial or local boiling. The demarcation between the regions is dependent on the ratio $\Delta T_{sub}/\Delta T_{sat}$ and the boiling number, Bo.

Gungor and Winterton (1983) modified Chen's (1966) correlation by including the dependence on the boiling number in the enhancement factor. They also suggested Cooper's correlation for pool boiling in the evaporative term. Liu and Winterton (1991) presented a new correlation with improved accuracy, based on an explicit nucleate boiling term rather than an empirical boiling number.

A comprehensive review of subcooled boiling heat transfer correlations is presented by Kandlikar (1998). In the paper, he also reviews the different regions and locations of subcooled flow boiling, and introduces a newly defined significant void flow region, where the convective effects become important due to noteworthy void fraction. Kandlikar re-examines his correlation for saturated flow boiling and proposes methodology with correlations to predict heat transfer in each region.

More recently, Yin et al. (2000) showed that the subcooled boiling heat transfer of R-134a in a horizontal annular duct was not significantly affected by the mass flux, imposed heat flux nor saturation temperature, but and increase in the subcooling resulted in much better heat transfer. From their visualization tests, only the subcooling degree showed a large effect in the bubble size. Empirical correlations for the boiling heat transfer coefficient and bubble departure diameter were proposed.

Prodanovic et al. (2002) studied the transition from partial to fully developed boiling by experimental observations of bubble behaviour during subcooled flow boiling of water in a vertical heated annulus. They report a sharp transition due to a change in the heat transfer mechanisms. Microlayer evaporation is suggested to be the governing mechanism during partial boiling while bubble agitation and microconvection becomes the leading heat transfer mode for fully developed boiling. The information is used to develop a new model.

One of the first studies on subcooled flow boiling in microchannels was that of Peng et al. (1998). They pointed out that nucleation in small channels requires larger superheats. Bubble generation and growth was said to require a minimum amount of space, the *evaporating space*. If missing, *fictitious boiling* would be induced before nucleation starts.

Baird et al.'s (2000) subcooled experiments with water in minichannels suggested that heat transfer is enhanced above the additive sum of forced convection and nucleate boiling components. This enhancement is believed to be a result of transition form laminar to turbulent flow caused by incipient nucleation. Haynes and Fletcher (2003) on the other hand, conclude that subcooled boiling heat transfer coefficient in narrow passages can be described accurately as a simple additive combination of single-phase liquid-only convective heat transfer and nucleate boiling. The observed enhancement of the single-phase heat transfer component is attributed to dissolved gas release.

The present study reports on subcooled flow boiling heat transfer for refrigerant R-134a in vertical cylindrical tubes with 0.83, 1.22 and 1.70 mm internal diameter. The effects of the imposed wall heat flux, q'', refrigerant mass flux, G, liquid inlet subcooling, $\Delta T_{sub,i}$, system pressure, P, and internal channel diameter, D, on boiling incipience and subcooled boiling heat transfer are explored in detail.