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Flow boiling heat transfer and pressure drop of R-134a in a mini tube: an experimental investigation

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ABSTRACT

This paper presents the results of an experimental study carried out with R-134a during flow boiling in a horizontal tube of 2.6 mm ID. The experimental tests included (i) heat fluxes in the range from 10 to 100 kW/m^2, (ii) the refrigerant mass velocities set to the discrete values in the range of 240–930 $kg/(m^2 s)$ and (iii) saturation temperature of 12 and 22 °C. The study analyzed the heat transfer, through the local heat transfer coefficient along of flow, and pressure drop, under the variation of these different parameters. It was possible to observe the significant influence of heat flux in the heat transfer coefficient and mass velocity in the pressure drop, besides the effects of saturation temperature. In the low quality region, it was possible to observe a significant influence of heat flux on the heat transfer coefficient. In the high vapor quality region, for high mass velocities, this influence tended to vanish, and the coefficient decreased. The influence of mass velocity in the heat transfer coefficient was detected in most tests for a threshold value of vapor quality, which was higher as the heat flux increased. For higher heat flux the heat transfer coefficient was nearly independent of mass velocity. The frictional pressure drop increased with the increase in vapor quality and mass velocity. Predictive models for heat transfer coefficient in mini channels were evaluated and the calculated coefficient agreed well with measured data within a range 35% for saturation temperature of 22 °C. These results extend the ranges of heat fluxes and mass velocities beyond values available in literature, and add a substantial contribution to the comprehension of boiling heat transfer phenomena inside mini channels.

1. Introduction

Flow boiling studies in mini and micro channels have been published, mainly in the last two decades, motivated by the current trend to develop innovative compact systems in applications such as refrigeration systems, high heat flux cooling and cooling of electronic devices.

Most researchers from the available literature, point out a great increment in heat transfer achieved by small diameter channels when comparing to usual ones. Meanwhile, most of the published results present discrepancies concerning the effect of heat flux, mass velocity and saturation temperature on the value of the heat transfer coefficient.

The characteristics and mechanisms of flow boiling in mini and micro channels are not completely understood yet, and are a controversial point in the literature. According to published results, boiling heat transfer could be controlled by nucleate boiling, due to nearly exclusively dependency on heat flux [1,2], or by convective boiling, with the dependence of mass flux and vapor quality [3] or by both, depending on vapor quality range [4,5]. Moreover, some authors [6,7] claim that nucleate boiling is not the dominant heat transfer mechanism, but the transient evaporation of a thin liquid film around elongated bubbles.

The definition of such dependence and, consequently, the capability of heat transfer prediction under any of these conditions through the correlations is limited, but it has been the main goal of several researchers in this area [7–12].

Some observations from different experiments are summarized in the next paragraphs.

Tran et al. [1] studied R-12 in a 2.46 mm circular tube and observed the heat transfer dependence on heat flux, but the effects of mass velocity and vapor quality were negligible. The same tendency was reported by Lazarek and Black [2] and Wambsganss et al. [13] with R-113 boiling in a 3.1 mm and 2.92 mm tubes, respectively. However, the results shown by Yan and Lin [4], Lin et al. [5] and Choi et al. [14] demonstrated that the effects of mass velocity and vapor quality also are important.

The heat transfer coefficients obtained from experiments carried out by Lin, et al. [5] with R-141b in 1.3–3.69 mm channels showed that heat flux is important only in the low quality region ($X < 0.4$) and the heat transfer coefficient increases with the

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Nomenclature

$dh_{\max}$	heat transfer coefficient maximum uncertainty (–)
dp/dz	local pressure drop (kPa/m)
$(dp/dz)_f$	frictional pressure drop (kPa/m)
G	mass velocity (kg/(m^2 s))
h	heat transfer coefficient (W/(m^2 K))
h_{exp}	experimental heat transfer coefficient (W/(m^2 K))
h_{pred}	predicted heat transfer coefficient (W/(m^2 K))
i_f	liquid enthalpy (kJ/kg)
i_{fg}	latent heat of vaporization (kJ/kg)
$i_{i\text{-}TS}$	test section inlet enthalpy (kJ/kg)
$i_{i\text{-}PH}$	pre-heater inlet enthalpy (kJ/kg)
k	thermal conductivity (W/(m K))
$\dot{m}$	mass flow rate (kg/s)
$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}\frac{h_{pred_i}-h_{exp_i}}{h_{exp_i}}\times 100$	mean bias error (%)
P	electrical power input (W)
q''	heat flux (kW/m^2)
$\dot{q}$	volumetric heat generated (W/m^3)
q_{PH}	pre-heater heat rate (W)
r_i	internal radius (m)
r_o	external radius (m)
$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{h_{pred_i}-h_{exp_i}}{h_{exp_i}}\right)^2}\times 100$	root mean square error (%)
T_{sat}	saturation temperature (°C)
$T_{w,i}$	internal wall temperature (°C)
$T_{w,o}$	external wall temperature (°C)
$T_{w,botton}$	external wall bottom temperature (°C)
$T_{w,side\_inner}$	external wall inside temperature (°C)
$T_{w,side\_outer}$	external wall outside temperature (°C)
$T_{w,top}$	external wall top temperature (°C)
X	vapor quality (–)
$X_{i\text{-}TS}$	vapor quality in the entrance of test section (–)
η	heat transfer efficiency (–)
η_{PH}	pre-heater heat exchange efficiency (–)
η_{TS}	test section heat exchange efficiency (–)

increase in vapor quality until a point when the coefficient decreases gradually, but the inflection point in the vapor quality range is also heat flux dependent.

Saitoh et al. [15] analyzed the effect of tube diameter on boiling heat transfer of R-134a with heat fluxes in the range of 5–39 kW/m^2 and mass velocities between 150 and 450 kg/(m^2 s). For a 3.1 mm diameter tube they found a clear dependency of the heat transfer coefficient on both heat and mass flux, unlike for the 0.51 mm tube, where they observed the effect of heat flux only. These authors suggested that the contribution of forced convection to the boiling heat transfer decreases with decreasing tube diameter. Moreover, these authors observed that the pressure drop for small diameter tubes was better predicted by the homogeneous model than by the Lockhart–Martinelli correlation [16], suggesting that, as the tube diameter decreases, the flow in the liquid phase approaches laminar flow and the effect of forced convective boiling is suppressed.

In the same way, Shiferaw et al. [9] studied the refrigerant R-134a and channel diameters from 2.01 mm to 4.26 mm and found similar results. In the experiments with the 4.26 mm tube, the heat transfer coefficient increased with heat flux and saturation temperature, but it remained constant in the vapor quality range from 0.4 to 0.5 in low heat fluxes. For the 2.01 mm tube, this range moved down to 0.2–0.3 of vapor quality.

Choi et al. [14] investigated flow boiling of R-22, R-134a and CO_2 in tubes of 1.5 and 3.0 mm, employing heat fluxes from 10 to 40 kW/m^2 and mass velocities from 200 to 600 kg/(m^2 s). They observed an increase in the heat transfer coefficient with the increase in vapor quality, and also a heat flux dependence. This increase is followed by a decrease which occurs at lower qualities for higher mass velocities. In the high quality region, the heat transfer coefficient was predominantly dependent on mass velocity.

In the paper by Choi et al. [14], as in many others, the dependence of heat transfer coefficient on heat flux is interpreted as evidence that nucleate boiling is the dominant heat transfer mechanism at low quality region. Also, in the high vapor quality range, when the heat transfer coefficient becomes independent of heat flux and decreases with quality, it is claimed to indicate predominance of the convective mechanism. Most authors also verify the minor influence of mass velocity on the heat transfer coefficient with the reduction of channel diameter, associating this behavior to the decreasing of convective contribution, which is characteristic of macro channels. Moreover, some effects, like the dryout, could happen in lower vapor qualities in micro channels, as a result of confinement and the increasing relevance of surface tension, thus justifying the increase of the nucleate boiling contribution.

Jacobi and Thome [6] and Thome et al. [7], demonstrated through the two and three-zone flow boiling heat transfer models, that the dependence of the heat transfer coefficient on the heat flux is not necessarily associated with nucleate boiling, but to the evaporation of a thin liquid film around the bubbles which causes the coefficient increases as heat flux increases.

More recently, Tibiriçá and Ribatski [17] and Ong and Thome [18], presented a comprehensive study of the flow boiling in small tubes for different refrigerants, including the R-134a. The first work examined the influence of mass velocity from 100 to 700 kg/(m^2 s) and heat flux from 5 to 35 kW/m^2 and the authors found that the heat transfer coefficient increased with the mass velocity and vapor quality except for mass velocities below a threshold of 200 kg/(m^2 s), which experimented a premature and smooth decrease with increasing vapor quality. Also, the heat transfer coefficient increased with heat flux independently of the fluid or mass velocity range. In the second work [18], the heat transfer coefficient behavior for different refrigerants was associated to flow regime transition for different vapor qualities. They concluded that convective boiling seems to dominate at higher vapor qualities in the annular flow, and in the bubbly regime, at low vapor qualities, the heat transfer coefficient depends on heat flux. However, it is difficult to separate the patterns. As the mass velocity increases the transition to annular flow occurs at lower qualities.

Associated with lack of the phenomenon understanding to explain the observed trends and consequently the importance of nucleate and convective boiling contributions, is the difficulty to carry out two-phase flow experiments in small sizes tubes. According to Consolini [8], the experiments are very sensitive to instabilities that are possibly responsible for variations in the results of different studies.

The present paper aims to provide experimental results in a broader operational range and add a contribution to the comprehension of boiling heat transfer phenomena inside mini channels. The experimental results of R-134a flow boiling through a stainless