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An experimental study of flow boiling in minichannels at high reduced pressure

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ABSTRACT

This paper presents an experimental setup and experimental data for heat transfer and pressure drops in flow boiling. Experimental study on hydrodynamics and heat transfer were performed for R113 and RC318 in two vertical channels with diameters of 1.36 and 0.95 mm and lengths of 200 and 100 mm, respectively. The inlet pressure-to-critical pressure ratio (reduced pressure) was $p_r = p/p_{cr} = 0.15–0.9$, the mass flux ranges were between 770 and 4800 kg/(m^2 s), and inlet temperature varied from 30 to 180 °C. The primary regimes of flow boiling were obtained for conditions that varied from highly subcooled flows to saturated flows and include data for dryout onset. A comparison between the experimental and calculated data for pressure drops is presented. The influence of flow conditions (i.e., mass flow rate, pressure, inlet temperature, and the channel diameter) on the heat transfer coefficient and heat flux is presented in addition to a comparison between the experimental and calculated data for flow boiling heat transfer.

1. Introduction

An important trend in the development of new technologies is miniaturisation of technical objects, an effort that requires extensive background knowledge of hydrodynamics and heat transfer in single-phase convection and flow boiling in small-diameter channels. The ability to accurately predict the pressure drops and heat transfer and the choice of minichannel geometry and working conditions are important factors for design and selection of the optimal settings of heat exchangers.

Experimental investigations conducted on fluid flow and flow boiling heat transfer in regular channels ($d > 3$ mm), showed that the heat transfer is determined by the interaction of two mechanisms: convection and boiling. Calculation of the heat transfer coefficient is performed in one of two ways. When one mechanism is dominant, the calculation is performed using the formulas for the respective components while neglecting the influence of the other mechanism. When convection and boiling are approximately the same, heat transfer is determined by addition or interpolation of these two mechanisms. The most well known methods in the literature for determining the heat transfer coefficient in forced fluid flow boiling through regular channels are Labuntsov's [1] and Chen's [2] methods. The peculiarities of heat transfer in subcooled flow boiling are described by Dedov in [3].

In minichannels ($0.2 < d \leq 3$ mm [4]), peculiarities can result from the characteristic scale of the phenomena that occur in boiling flow and the linear scale of the channel. Investigations of heat transfer in mini- and micro-channels have been conducted for a long time. Before channels with a hydraulic diameter of $\leq$3 mm were highlighted as a 'special' type in the 1950–60s, a number of studies on fluid flow and heat transfer in subcooled and saturated forced flow boiling were performed. The most well-known studies are those of Ornatskiy and Kichigin [5] and Ornatskiy and Kriticheskiye [6], which investigated boiling heat transfer of water in a tube of $d = 2$ mm, under $p = 1.0–22.5$ MPa of pressure, with a mass flow rate of $G = 5000–30{,}000$ kg/(m^2 s) and inlet subcooling from 200 to 5 °C. The results of these studies do not give reason to doubt that channels with diameters of 1–3 mm are regular channels. These experiments were conducted via traditional methods, i.e., using fixed parameters for subcooled inlet flow and changing the electrical load on the test section incrementally from regimes of single-phase convection to regimes of critical and supercritical thermal loads.

Another accepted method for heat transfer research in a channel obtains experimental data for a saturated flow in the test section input by changing the steam quality (at fixed pressure, velocity, and heat flux) using an additional upstream pre-heater.

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Nomenclature

d	diameter, m
L	channel length, m
G	mass flux, $kg/(m^2 \cdot s)$
p	pressure, Pa
V	volume flow rate, l/min
Pr	Prandtl number
T	temperature, K
M	molar mass, g/mol
Re	Reynolds number
Q_{los}	heat losses, W
q	heat flux, W/m^2
x	vapour quality
c_p	specific heat, J/(kg·K)
h_{lg}	latent heat of evaporation, J/kg

Greek symbols

α	heat transfer coefficient, $W/m^2 \cdot K$
Δp	pressure difference, Pa
ΔT_s	wall superheat, K
ρ	density, kg/m^3
σ	surface tension, N/m
μ	dynamic viscosity, $H \cdot s/m^2$
λ	thermal conductivity, W/m·K

Subscripts

calc	calculated
exp	experimental
boil	boiling
conv	convective
sub	subcooled
in	inlet
out	outlet
l	liquid
g	gas
w	wall
s	saturated
r	reduced

This method is generally accompanied by studies of the flow pattern and allows the allocation of flow regimes.

A 1982 study by Lazarek and Black [7] was one of the first to measure the heat transfer coefficient, pressure drop and critical heat flux of saturated flow boiling with R113. Lazarek and Black performed this investigation in a circular vertical tube with an inner diameter of 3.15 mm, at pressures ranging from 0.13 to 0.41 MPa, with a mass flux of $G = 125–750\ kg/(m^2s)$ and a heat flux from 14 to 380 kW/m^2. The experiments began with inlet subcooled flow conditions in a two-part vertical test section heated by direct current. The results showed that heat transfer in saturated boiling is strongly dependent on heat flux but negligible in quality, which suggested that nucleate boiling controlled the heat transfer. As a result of data compilation, an empirical formula was derived for investigation of flow conditions in which the mechanism of boiling was predominant. The heat transfer coefficient in the formula is not dependent on the steam quality of fluid flow. The experimental results are in a good agreement with other empirical and semi-empirical correlations of various authors for regular tubes.

Wambsganss et al. [8] described the results of studies on fluid flow and heat transfer for R113 in a tube with a 2.92 mm diameter using a test section heated by direct current and with subcooled inlet flow. The authors compared their results with values calculated from ten different empirical correlations, and the most precise results were calculated using the values from Lazarek and Black [7]. However, Wambsganss et al. observed a decrease in the heat transfer coefficient with increasing steam quality, probably due to partial drying out of the wall.

Kew and Cornwell [9] conducted experiments on R141b in channels with diameters of 1.39, 2.87 and 3.69 mm. According to their data, the behaviour of the critical heat flux (CHF) for diameters of 2.87 and 3.67 mm is similar to that observed in regular channels. However, a difference appears for the 1.39 mm diameter tube. When quality is high, the CHF falls sharply because the channel is blocked by steam. Furthermore, Kew and Cornwell showed that the flow patterns in minichannels (isolated bubbles, confined bubbles and an annular slug flow regime) differ from patterns in regular channels. Comparison of Kew and Cornwell's experimental data with other empirical correlations for regular channels has not yielded good results.

Interesting experimental data were obtained by Wambsganss et al. [10] in their study using a circular channel with an inner diameter of 2.46 mm and a rectangular channel with linear parameters of 4.06 × 1.7 mm. Their experiments were performed on R12 and R113 at pressures ranging from 0.5 to 0.8 MPa, with vapour quality of $x < 0.94$, mass flux of $G = 44–832\ kg/(m^2\ s)$ and heat flux from 3.6 to 129 kW/m^2. The results of this work show that when $x < 0.2$, the heat transfer coefficient does not depend on x. Tran et al. proposed their own formula in which the heat transfer coefficient depends on the boiling number, Weber number and the relationship of liquid density to vapour density. No geometrical effect was found.

Results for flow boiling heat transfer in a tube with a 1 mm inner diameter using FC-72 as the working fluid were reported by Gugliermetti et al. [11]. This study aimed to identify the best correlation or model to predict the available experimental database. A comparison of several models and correlations available in the literature for both micro- and macro-scales was performed by the authors, with a focus on current preliminary analysis of saturated boiling conditions. Experimental data were collected in the pressure range of 3–5 bar, with mass flux from 800 to 1200 kg/m^2s and thermal fluxes from 1.6 to 181 kW/m^2. The best results in this preliminary analysis of saturated boiling points were obtained for the micro-scale empirical correlations of Li and Wu [12], with >91% of data within ±30% error and a mean absolute percent error (MAPE) of 13.4%. Among the macro-scale correlations, only the Chen correlation [2] presents good results has a lower degree of agreement with the experimental data.

As mentioned previously, peculiarities exist in minichannels resulting from the characteristic scale of the phenomena that occur in boiling flow and the linear scale of the channel. Two-phase flow regimes become dominant in understanding the heat transfer mechanisms in these channels. Heat transfer calculated with the common formulas for regular channels does not agree well with experimental data for minichannels, if at all. Thus, new methods for determining heat transfer are needed.

The available databases on two-phase heat transfer and hydrodynamics in channels of small diameter have led to a large number of studies that focus on analysis of previously performed studies. In these studies, the authors carefully assessed whether the existing calculation methods correspond to the various arrays of