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The effect of the cross-sectional geometry on saturated flow boiling heat transfer in horizontal micro-scale channels

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ABSTRACT

In the present paper, convective boiling heat transfer results of R134a for circular, square and triangular tubes are presented. The evaluated channels present the same external perimeter and equivalent diameters of 1.100, 0.977 and 0.835 mm, respectively. Experiments were performed for mass velocities ranging from 200 to 800 kg/m^2 s, heat fluxes from 15 to 85 kW/m^2, saturation temperatures of 31 and 41 °C, and vapor qualities from 0.05 to 0.95. In order to perform reasonable comparisons among the test sections, the tests were run under similar mass velocities for the three geometries. The experimental data were carefully analyzed and discussed focusing on the effect of the cross-sectional geometry. It was found that for low heat fluxes, the heat transfer coefficient for the circular channel is higher. While for high heat fluxes, the heat transfer coefficient for the triangular channel is higher than for circular and square channels. Subsequently, the experimental data were compared with predictive methods from literature which are usually developed based only on data for single circular channels. Statistically, Kanizawa et al. [24] and Kim and Mudawar [34] provided reasonable predictions of the overall database. However, none of the methods captured adequately the experimental trends for the triangular channel.

1. Introduction

In the last two decades, the number of studies concerning flow boiling in micro-scale channels has increased because of the need of dissipating high amounts of heat. In the last years, several experimental studies on two-phase heat transfer coefficient and pressure drop have been performed. However, as pointed out by Sempértegui-Tapia and Ribatski [1], several aspects are still unclear since studies from independent laboratories provide quite different behaviors. Besides, according to the literature review by Tibiriçá and Ribastki [2], almost 97% of the studies on single channels were performed for circular cross sections, while 87% of the studies concerning micro-scale multi-channels were performed for rectangular cross sections and 9% for triangular cross sections. These facts indicate the need of performing careful experiments and obtaining accurate data for single-channels with non-circular geometries in order to support the development of precise predictive methods for multi-channels configurations.

In this sense, the present paper focus on the study of the effect of the channel geometry on saturated flow boiling in horizontal micro-channels. For this purpose, heat transfer experimental data were collected for circular, square and triangular single-channels. The evaluated channels present the same perimeter corresponding to equivalent diameters of 1.100, 0.977 and 0.835 mm, respectively. Experiments were performed for mass velocities ranging from 200 to 800 kg/m^2 s, heat fluxes from 0 to 85 kW/m^2, saturation temperatures of 31 and 41 °C and vapor qualities from 0.05 to 0.95. Additionally, the experimental results were compared against the most quoted predictive methods from the literature, including methods developed for conventional channels and methods specially proposed for micro-scale channels. The methods were evaluated according to the following two criteria: the mean absolute error (MAE) and the parcel of data predicted within ± 30% of error band. The results are carefully analyzed and discussed.

2. Experimental apparatus

2.1. General description

The experimental setup is comprised of refrigerant and water circuits. The water circuit is intended to condense and subcool the working fluid. The refrigerant circuit is schematically shown in Fig. 1. In the refrigerant circuit, the test fluid is driven through the circuit by a self-lubricating oil-free micropump. The liquid flow rate is set by a variable-frequency drive acting on the micropump. Downstream the

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Nomenclature

A	area, m^2
C_C	area ratio vena contracta, dimensionless
dp/dz	pressure drop gradient, kPa/m
D	diameter, m
f	friction factor, dimensionless.
G	mass velocity, kg/m^2 s
i	enthalpy, J/kg
h	heat transfer coefficient, kW/m^2-K
I	electric current, A
K	loss coefficient, dimensionless
k	momentum correction factor, dimensionless
L	length, m
$\dot{M}$	mass flow rate, kg/s
MAE	mean absolute error, %
p	pressure, kPa
P	electrical power, W
Ra	arithmetical mean roughness, µm
Re	Reynolds number, dimensionless
Rt	maximum roughness height, µm
S	perimeter, m
T	temperature, °C
v	velocity, m/s
V	voltage, V
x	vapor quality, dimensionless
z	position along the tube, m

Greek letters

α	void fraction, dimensionless
β	energy momentum coefficient, dimensionless
η	parcel of data predicted within a certain error band, %
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
ϕ	heat flux, kW/m^2
ς	aspect ratio for rectangular channels, dimensionless
σ_A	area ratio of contraction/expansion, dimensionless

Subscripts

1ϕ	single-phase
2ϕ	two-phase
Acc	accelerational
con	contraction
eff	effective
eq	equivalent
env	environment
exp	expansion
f	frictional
G	saturated gas phase
$G0$	two-phase mixture as gas
H	hydraulic
in	inlet
int	internal
I	irreversible
$loss$	loss
L	saturated liquid phase
$L0$	two-phase mixture as liquid
LG	difference between vapor and liquid properties
max	maximum
out	outlet
ph	pre-heater
$pred$	predicted
R	reversible
sat	saturation
ts	test section
w	wall

micropump, the mass flow rate is measured with a Coriolis flow meter. Upstream the pre-heater, the fluid inlet conditions are determined by a thermocouple and an absolute pressure transducer. Downstream the test section, a visualization section, a tube-in-tube heat exchanger, and a refrigerant tank are sequentially located. The heat exchanger is responsible for condensing the vapor created in the heated sections. Additional details of the experimental set up can be found in Tibiriçá and Ribatski [3] and Sempértegui-Tapia et al. [4].

2.2. Pre-heater and test section

For the experimental tests in the circular cross-sectional channel, the pre-heater and the test section are formed by a 490 mm horizontal AISI-304 stainless-steel tube, acquired from *Goofellow Cambridge Limited*, with an OD of 1.47 mm and an ID of 1.1 mm. The arithmetical mean roughness of the circular test section was measured with the optical profiling system Wiko® NT1100 equipment, and a mean average surface roughness (Ra) of 0.289 µm was found based on three measurements along the test section length. Fig. 2 shows an image of the inner surface of the test section and its roughness profile.

The pre-heater and the test section are 200 and 150 mm long, respectively. Both sections are heated by applying direct DC current to their surface. The pre-heater and the test section are thermally insulated. The power is supplied to the test sections by an independent DC power source controlled from the data acquisitions system. The pre-heater, test and visualization sections are connected through junctions made of polyvinylidene fluoride (PVDF) specially designed and machined to match up their ends and keep a smooth and continuous internal surface. Once the fluid has left the test section, its temperature is determined from a 0.25 mm thermocouple whose hot junction is flush-mounted into the pipe wall. The corresponding absolute pressure is estimated from the total pressure drop over the preheater inlet and the test section outlet given by a differential pressure transducer, Δp, and the inlet absolute pressure.

For tests with non-circular channels, a parcel of the length of the test section (190 mm) originally with circular shape was molded into square and triangular shapes. The segments of the test section with triangular and square shapes were obtained through a process of progressive conformation using a steel matrix composed of two-block with grooves designed especially for each cross section. A uniform compressive stress of approximately 10 tons was provided to the matrix to get the desired shape. The inner surface roughness of the test sections were also evaluated after the conformation process. The cross-sectional area and internal perimeter of the square and triangular channels were estimated through the image processing of the profiles shown in Fig. 4a and b, respectively, using the software MATLAB R2015a.

Table 1 shows the geometrical characteristics of the test sections evaluated in the present study. This table reveals significant differences of the arithmetic mean roughness of the test sections.

For non-circular channels, the sudden changes of shape from circular into non-circular, and vice versa, are associated to contraction and expansion of the channel cross section. Thermocouples were attached 5 mm downstream the sudden contraction and 5 mm upstream the sudden expansion (necessary distance to minimize the effects of the sudden contraction and expansion on the thermocouples measurements). The thermocouples were fixed tightly against the tube surface.