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Saturated flow boiling heat transfer and critical heat flux in small horizontal flattened tubes

Cristiano Bigonha Tibiriçá [a,*], Gherhardt Ribatski [a], John Richard Thome [b]

[a] Department of Mechanical Engineering, Escola de Engenharia de São Carlos (EESC), University of São Paulo (USP), São Carlos, Brazil
[b] Laboratory of Heat and Mass Transfer (LTCM), École Polytechnique Fédérale de Lausanne (EPFL), Station 9, Lausanne CH 1015, Switzerland

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ABSTRACT

This paper presents experimental results for flow boiling heat transfer coefficient and critical heat flux (CHF) in small flattened tubes. The tested flattened tubes have the same equivalent internal diameter of 2.2 mm, but different aspect height/width ratios (H/W) of ¼, ½, 2 and 4. The experimental data were compared against results for circular tubes using R134a and R245fa as working fluids at a nominal saturation temperature of 31 °C. For mass velocities higher than 200 kg/m^{2}s, the flattened and circular tubes presented similar heat transfer coefficients. Such a behavior is related to the fact that stratification effects are negligible under conditions of higher mass velocities. Heat transfer correlations from the literature, usually developed using only circular-channel experimental data, predicted the flattened tube results for mass velocities higher than 200 kg/m^{2}s with mean absolute error lower than 20% using the equivalent diameter to account for the geometry effect. Similarly, the critical heat flux results were found to be independent of the tube aspect ratio when the same equivalent length was kept. Equivalent length is a new parameter which takes into account the channel heat transfer area. The CHF correlations for round tubes predicted the flattened tube data relatively well when using the equivalent diameter and length. Furthermore, a new proposed CHF correlation predicted the present flattened tube data with a mean absolute error of 5%.

1. Introduction

Flow boiling in small diameter channels, also named micro-scale channels, has been considered one of the main methods to enhance heat transfer in applications requiring compactness and high heat flux removal rate [1–3]. Despite the benefits that can be achieved by using micro-scale tubes and the large number of studies performed worldwide in the recent years, the accurate predictions of the heat transfer coefficient and critical heat flux are still a tough issue. A factor that explains this scenario is the huge number of variables affecting the two-phase flow and heat transfer mechanisms: i.e. mass velocity, heat flux, saturation temperature, vapor quality, fluid type (all of them evaluated by Tibiriçá and Ribatski [1]), flow direction (vertical, horizontal), gravitational acceleration [4], vibration [5], tube diameter [6], tube length [7], tube material and surface roughness [7,8], presence of additional components in the fluid [9], nanoparticles [10], surfactants [11], and thermal–hydraulic instabilities [12,13]. Another factor that requires a careful investigation is the effect of non-circular channel geometries on the flow boiling heat transfer. The present paper investigates this effect based on experimental heat transfer results obtained for small flattened tubes, which are plain round tubes pressed flat on top and bottom and kept round at the two corners. As far as the present authors know, this is the first study concerning flow boiling heat transfer and critical heat flux for small flattened tubes.

2. Previous studies on flattened tubes

According to Wilson et al. [14] and Quiben et al. [15], heat exchangers based on flattened tubes can potentially be used in a wide range of industrial applications, such as air-conditioning, heat pump and refrigeration systems, automotive radiators, fuel cell engines, among others. Such tubes are also applicable to the cooling of secondary components within blade servers, where a flattened tube is sufficient rather than a cold plate. Compared to a circular tube, a flattened tube has a higher ratio of surface area to cross-sectional area, which may enhance the heat transfer rate and improve the heat exchanger compactness. Multi-microchannels evaporator cold plates have a high H/W ratio and are mostly rectangular in their cross-section. A flattened tube allows the observation of stratification effects by changing the tube orientation

* Corresponding author.
E-mail addresses: bigonha@sc.usp.br (C.B. Tibiriçá), ribatski@sc.usp.br (G. Ribatski), john.thome@epfl.ch (J.R. Thome).

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Nomenclature

A	internal cross-sectional area, (m^2)
A_{cir}	surface area of circular channel, (m^2)
$A_{non,cir}$	surface area of a non-circular channel, (m^2)
D	diameter, (m)
D_{eq}	equivalent diameter, $D_{eq} = \sqrt{\frac{4A}{\pi}}(m)$
D_h	hydraulic diameter, $D_h = \frac{4A}{S}(m)$
E	heat rate, (W)
G	mass velocity, (kg/m^2 s)
h	heat transfer coefficient, (W/m^2 K)
$\bar{h}$	average heat transfer coefficient, (W/m^2K)
H	height, (m)
(H/W)	height–width ratio
i	enthalpy, (J/kg)
L	heated length, (m)
L_{eq}	equivalent length, (m)
m	mass flow rate, (kg/s)
P	electrical power, (W)
p	pressure, (Pa)
q	heat flux, (W/m^2)
Re	Reynolds number, (dimensionless), $\mathrm{Re} = \frac{G \cdot D}{\mu}$
S	perimeter, (m)
t	tube wall thickness, (m)
T	temperature, (K)
W	width, (m)
x	vapor quality, (dimensionless)
z	axial position, (m)
Greek symbols	
μ	dynamic viscosity, (Pa s)
Δp	pressure drop, (kPa)
Δi_{in}	inlet subcooling enthalpy, (J/kg)
ε	mean absolute error, (%)
$\lambda_{(\pm 30\%)}$	fraction of data predicted within ε <±30%, (%)
ρ	density, (kg/m^3)
σ	surface tension, (N/m)
Subscripts	
bottom	bottom of the tube
eq	equivalent
exit	exit of the test section
exp	experimental
h	hydraulic
heated	heated length
i,orig	internal initial diameter
in	pre-heater inlet
l	liquid
lv	liquid–vapor
left	left-hand side of the tube
local	at a specific position in the tube
out	outlet
r	reduced
right	right-hand side of the tube
sat	saturation temperature
sp	single-phase
top	top of the tube
tp	two-phase
w	inner wall of the tube

(horizontal or vertical orientation of the flat face). Furthermore, corner effects in non-circular tubes may be different due to the surface tension effects on the liquid film during annular flows. Additionally, flattened tubes can greatly reduce the refrigerant charge in direct-expansion evaporators and condensers minimizing refrigerant leaks and their impacts on the environment [16].

Wilson et al. [14] evaluated the refrigerant charge, pressure drop and heat transfer during condensation of R134a and R410A in flattened tubes. They tested four different flattened tubes, all derived from a round tube of 8.91 mm internal diameter and concluded that the heat transfer coefficient and pressure drop increases with increasing height/width ratio. This result was already expected since in their experiments the tubes with higher flattening had a smaller internal cross-section area and also smaller hydraulic diameters. In fact, after flattening the original round tube with 8.91 mm internal diameter, their flattened channels had 7.79 mm, 6.37 mm, 4.40 mm, and 1.84 mm hydraulic diameters.

Nasr et al. [17] conducted flow boiling heat transfer and pressure drop measurements in flattened tubes for R134a. Their flattened tubes were obtained from an 8.7 mm round tube and presented internal heights of 6.6, 5.5, 3.8 and 2.8 mm. They concluded that as a tube is flattened, the heat transfer coefficient and pressure drop are enhanced, but again, the hydraulic diameters and internal cross-section area of the tested flattened tubes were significantly decreased due to the flattening.

Quibén et al. [15] conducted heat transfer and pressure drop flow boiling experiments in horizontal flattened tubes with equivalent diameters of 8.6, 7.17, 6.25, and 5.3 mm with R22 and R410A and aspect ratios of (H/W) = 0.1, 0.15, 0.175 and 0.28. They used the equivalent diameter to compare their results with correlations from the literature rather than the single-phase turbulent flow hydraulic diameter approach. The equivalent diameter is defined as the diameter of a circular tube whose cross-sectional area is the same as that of the non-circular channel. As mentioned by Cheng et al. [18], the equivalent diameter gives the same mass velocity as in non-circular channels and correctly reflects the mean liquid and vapor velocities, something that the hydraulic diameter in a two-phase flow does not. The heat transfer model of Wojtan et al. [19] developed for round tubes predicted Quibén et al. [15] flattened tube database with a mean absolute error of 24% when using the equivalent diameter for comparisons.

The analysis of the flow boiling literature for flattened tubes has revealed the absence of CHF experimental data and also heat transfer and pressure drop data for small tubes. Besides, most of the conclusions posted in the previous studies do not address the flattening effect on the heat transfer coefficient and pressure drop properly, since they are based on experimental data referred to hydraulic diameters instead of the equivalent diameter. Therefore, as correctly highlighted by Cheng et al. [18] and above mentioned, the conclusions are based on data obtained under different mass velocity conditions. Concerning the above discussion, the present study has the following objectives: (i) report new experimental saturated flow boiling heat transfer coefficient and critical heat flux results for different flattened tubes with an equivalent diameter of 2.2 mm, (ii) evaluate the flattening effect on the HTC and CHF by comparing results of flattened and circular tubes; (iii) verify if correlations developed for round tubes are appropriate for flattened tubes and investigate if any special procedure is needed to adjust the available correlations to flattened tubes; (iv) compare the performance of leading flow boiling and CHF correlations available in the literature when using the equivalent and hydraulic diameters to demonstrate the best approach.