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Effect of channel height and mass flux on highly subcooled horizontal flow boiling

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Experiments of highly subcooled flow boiling of water in horizontal macrochannels with orthogonal cross-section are performed. Explored parameters are channel height (3 and 10 mm) and mass flux (330–830 kg/m^2 s). The range of applied heat fluxes is 200–1000 kW/m^2. Aging of the copper boiling surface is examined during a 48 h continuous operation and is found to gradually reduce heat transfer rates compared to a polished surface. Yet, aging reaches a steady condition already at 24 h of operation with about 10% lower heat transfer rates than for the polished surface. Using the steady aged surface in the main experiments, three heat transfer regions are identified: (a) forced convection region, before the onset of boiling, depending highly on mass flux but for the most part being channel height independent, (b) nucleate boiling region depending highly on channel height but for the most part being mass flux independent, and (c) a transition region in-between depending on both mass flux and channel height. The 3 mm channel promotes initiation of boiling at lower wall superheats leading to better heat transfer efficiency compared to the 10 mm channel, except for the highest mass fluxes where their performance is comparable. The largest enhancement in heat transfer coefficient provided by the 3 mm channel compared to the 10 mm channel is ~15–20% and is found at the lowest mass flux 330 kg/m^2 s. Analysis of the present data supports the notion that heat transfer is dictated by the thickness of the thermal boundary layer and the density of active nucleation sites.

1. Introduction

Flow boiling has received considerable attention over recent decades because of the high heat fluxes achieved with relatively small increments of the boiling surface temperature and with the compact size of the equipment. Subcooled flow boiling takes advantage of absorbing substantial wall heat fluxes while at the same time the bulk liquid temperature remains below saturation [1]. Subcooling conditions lead vapor bubbles to grow and detach rapidly and then re-condense, when they move from the superheated near wall region (i.e. thermal boundary layer) to the cold bulk liquid [2]. This bubble behavior prevents film boiling and dry-out of the liquid layer, which would occur at high vapor qualities (>0.5) and would decrease heat transfer rates [3]. The advantage of avoiding a net generation of vapor, which may cause problems of pressure rise and vapor agglomeration in the recirculation of closed cooling systems [4], makes the subcooled flow boiling a very efficient and attractive heat removal process. Therefore, it is not surprising that subcooled flow boiling is commonly practiced in heat removal applications that involve large heat dissipation capabilities, such as power production, laser systems and packed electronics [5].

Subcooled boiling region, which is also known as partial boiling or boiling inception, begins with the onset of nucleate boiling (ONB), where the relevant heat transfer mechanism is dominated by two conflicting processes [2,6]:

(a) Macroconvection due to liquid motion: For a constant heat flux, q'', as mass flux, G, increases the thermal boundary layer becomes thinner (affected by fluid's velocity and properties) and ONB is shifted to higher wall superheats, ΔT_{wall}.
(b) Evaporation of the liquid microlayer close to the heated wall: For a constant mass flux, as heat flux increases thermal boundary becomes thicker and ONB is shifted to lower wall superheats. The presence of bubbles in the thermal

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Nomenclature

A	heat exchange area, m^2
A_p	parameter defined by Eq. (10)
C	parameter defined by Eq. (12)
C_p	specific heat, J kg^{-1} K^{-1}
D_h	hydraulic diameter, m
f	darcy friction factor, –
G	mass flux, kg m^{-2} s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	channel length, m
l_e	entrance length, m
M	molecular weight, kg mol^{-1}
P	pressure, bar
p_r	reduced pressure, – (absolute pressure/critical pressure)
Pr	Prandl number (C_p μ k^{-1}), –
Q	volumetric flow rate, m^3 s^{-1}
q"	heat flux, W m^{-2}
Re	Reynolds number (ρ u D_h μ^{-1}), –
S	parameter defined by Eq. (13)
T	temperature, °C
u	velocity, m s^{-1}
w	channel width, m
x	channel height, m

Greek symbols

α	channel aspect ratio (x/w)
ΔH	latent heat of vaporization, J kg^{-1}
ΔT	temperature difference, °C
Δx	distance, m
μ	dynamic viscosity, N s m^{-2}
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}
φ	contact angle, °

Subscripts

aver	average
f	film
FC	forced convection
in	inlet
mix	mixing cup
out	outlet
sat	saturation
sub	subcooling
wall	heated wall

boundary layer constitutes the two-phase thermal boundary layer and its thickness is affected also by bubble dynamics (size, velocity).

The influence of the above two mechanisms on flow boiling efficiency is significantly affected by the interplay of the various parameters involved in the process (e.g. channel geometry, surface and fluid properties, operating conditions, degree of subcooling, ΔT_{sub}). As a consequence, the wide diversity of influences of those factors practically rules out a coherent theory that could predict heat and mass transport phenomena during subcooled flow boiling [7,8].

Thus, despite the large number of studies that have experimentally examined the effect of various parameters on flow boiling, none can safely describe the influence of channel's size on heat transfer characteristics (ONB, heat transfer coefficient, h, wall superheat) during subcooled flow boiling. In microchannels (hydraulic diameter, D_h: 10–200 μm), there are works stating that decreasing the channel size increases the heat transfer coefficient [9–12], but there is also evidence for the opposite [13]. This conflict originates from the flow patterns that occur at different combinations of channel size and working conditions (mass and heat flux) affecting the heat transfer mechanism. The conditions that result in bubbles restricted by the limited size of the channel do not allow liquid replenishment to the heated wall and deteriorate heat transfer [11,13]. In minichannels (D_h: 200 μm – 3 mm), the effect is more prevalent, as literature consents that the heat transfer performance improves with the size reduction, because the smaller the size the lower wall superheat and heat flux are needed to initiate boiling. The enhancement caused by size reduction in minichannels is attributed to the larger radial gradient of the liquid axial velocity, which reinforces shear force on nucleated bubbles [14–16]. However, in both mini- and micro- channels it has been found that apart from the channel's diameter/size, the aspect ratio α (height/width), influences heat transfer performance as well, as it could modify the flow patterns because of the change in the cross-section area [17–19].

Conventional size channels (D_h > 3 mm), often referred to as macrochannels, are large enough to permit bubble nucleation, growth and detachment, unlike micro- and mini- channels, where a single bubble can plug the whole cross-sectional area [20]. In all size cases though, microscale phenomena in the thermal boundary layer define the dominant heat transfer mechanisms, i.e., competition between forced convection and nucleate boiling [21]. Experimental works in macrochannels [1,22] provide confirmation of transitions between heat transfer mechanisms, mainly based on temperature analysis of the thermal boundary layer and the heated surface. Subcooled flow boiling in macro-channels has been widely studied in the past two decades, however a comprehensive work examining and explaining the effect of channel size at different flow rates on heat transfer performance is still missing.

The present study examines the influence of the height, x, of a macrochannel having orthogonal cross-section on heat transfer characteristics (ONB, boiling curve, heat transfer coefficient) during subcooled horizontal flow boiling of water for various heat and mass fluxes. The heat transfer area explored in the current work focuses on the flow boiling incipience region, which is related to high heat transfer coefficients and relatively low wall superheats; namely the optimum conditions for highly efficient cooling devices that have not been sufficiently investigated in existing literature [3]. The examined macrochannel heights are large enough to allow bubble growth and detachment within the thermal boundary layer. Under these conditions, high heat flux values are assessed (i.e. $q'' > 700\ kW/m^2$) without the undesired dryout, which would have appeared in mini- and micro- channels at the same mass fluxes [11,23]. The employment of high subcooling conditions (ΔT_{sub} = 70 °C) contributes to the same direction of avoiding dryout [24,25] and is motivated by specific applications that require instant cooling at extreme conditions (i.e. fire incidents) where violent flow of cold liquids is used to maintain walls at low temperature [26]. In addition, it must be stressed that the heated surface itself, its structure and wettability [27] as well as alterations during the boiling process (aging of the surface) [7,13,28,29] have been seen to affect flow boiling heat transfer