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Effect of channel inclination on heat transfer and bubble dynamics during subcooled flow boiling

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ABSTRACT

This study explores the influence of inclination on highly subcooled flow boiling of water in a macro-channel 10 mm high, 40 mm wide and 120 mm long. Experiments have been conducted under the following conditions. Channel inclination: 0°, 30°, 45°, 60°, 90°, 120°, 150°; mass flux: 330, 630, 830 kg/m^{2}s; heat flux in the range 300–1000 kW/m^2. Temperature recordings allow analysis of channel's heat transfer performance, while high speed video recordings provide evidence of bubbles' features. A comparative thermal and optical examination is presented for the transition region (low-heat-flux), and the nucleate boiling region (high-heat-flux). In the examined range of parameters, boiling curves are influenced more by mass flux than by inclination. Overall, operation at 60° and 90° yields higher heat fluxes than at other inclinations but the effect never exceeds an increase of 10% in the heat transfer coefficient compared to the horizontal case. Experimental heat transfer coefficients are in reasonable accordance with predictions of well-known empirical correlations. The role of inclination on heat transfer is explored via the analysis of bubbles' size, area density and sliding velocity. The observed bubble dynamics are in line with the measured boiling curves and heat transfer coefficients.

1. Introduction

Flow boiling is a preferable cooling method in a plethora of applications because of the associated high heat transfer rates. In flow boiling, two complex phenomena are involved, forced convection of bulk liquid and growth/detachment of bubbles at the heated surface [1]. Understanding these phenomena is essential for increasing the efficiency and for optimizing the operation of two-phase heat exchange devices. In particular, the important role of bubbles in two-phase heat transfer mechanisms necessitates the study of bubbles behavior and their interaction in analyzing the thermal performance of heat exchangers [2].

In the absence of forced flow, pool boiling investigations have shown that changing the inclination of a heated surface from horizontal facing upwards (θ = 0°) to horizontal facing downwards (θ = 180°), leads to different boiling regimes, owing to different force balance between surface tension, buoyancy and bubble growth inertia [3]. Heat transfer coefficient, h increases when bubbles grow isolated and detach promptly from the surface and when sliding occurs (on inclined surfaces) whereas it decreases when bubbles accumulate and coalesce to form gas films covering the surface [4–6]. The presence of flow, apart from the additional forced convection term in the energy balance, imparts one more term in the bubble force balance, the hydrodynamic force, influencing boiling regimes [7]. Depending on the size of the boiling channel/tube (micro-, mini-, macro-) boiling regimes differentiate [8]. In micro-channels, due to the restricted size and vapor confinement, slug, churn and annular are the most common regimes, with no distinctive bubble dynamic behavior [9]. In mini- and macro-channels, however, dispersed bubbly flow often prevails either parallel to the heated surface after some (short or long) sliding or normal to the heated surface without sliding (lift-off) [10].

Inclination of the flow with respect to the horizontal plane (θ = 0°) can enhance boiling heat transfer rates by facilitating bubbles removal from the heated wall and liquid replenishment over the wall [7]. It has been reported that in macro- and mini-channels the effect of inclination on flow boiling is felt mostly at liquid velocities below 1 m/s [11,12], which are associated with weak inertia [13]. Investigation of channel inclination, θ, during flow boiling has attracted much attention over the past years for two reasons. One is the influence that it can have on bubbles interfacial behavior and on heat transfer performance [11], and the other is that it constitutes a fast and easy way to simulate effects encountered in experiments at modified, e.g., reduced, gravity conditions, since each θ produces different partial components of gravity normal and parallel to the heated wall [10,13]. On this common ground, several researchers conducted flow boiling experiments to examine the effect of θ on heat transfer or on bubble dynamics in tubes

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Nomenclature

A	heat exchange area, m^2
A_p	parameter defined by equation (11)
Bo	Boiling number ($q'' G^{-1} \Delta H^{-1}$)
C	parameter defined by equation (13)
C_p	specific heat, J kg^{-1} K^{-1}
D_h	hydraulic diameter, m
D_{HP}	heated equivalent diameter, m
D	bubbble diameter, m
F	darcy friction factor, -
g	gravitational constant, m s^{-2}
G	mass flux, kg m^{-2} s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
Ja	Jacob number ($\rho_l C_{pl} \Delta T_{wall} \rho_v^{-1} \Delta H^{-1}$)
k	thermal conductivity, W m^{-1} K^{-1}
L	channel length, m
l_e	entrance length, m
M	molecular weight, kg mol^{-1}
N/A	bubble density, m^{-2}
P	pressure, bar
p_r	reduced pressure, - (absolute pressure/critical pressure)
Pr	Prandl number ($C_p \mu k^{-1}$), -
Q	volumetric flow rate, m^3 s^{-1}
q*	parameter defined by equation (12)
q″	heat flux, W m^{-2}
Re	Reynolds number ($\rho u D_h \mu^{-1}$), -
S	parameter defined by equation (14)
T	temperature, °C
V_b	volume of a bubble, m^3
u	velocity, m s^{-1}
w	channel width, m
x	channel height, m

Greek symbols

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}
θ	inclination angle, °

Subscripts

aver	average
exp	experimental
f	film
FC	forced convection
in	inlet
l	liquid
mid	middle
mix	mixing cup
OBR	Onset of Bubbly Regime
ONB	Onset of Nucleate Boiling
Out	outlet
sat	saturation
sub	subcooling
v	vapor
theor	theoretical
wall	heatd wall

and channels, with only limited information provided about both effects simultaneously. First, works about refrigerants flow boiling in mini- and macro-channels/tubes are presented, being followed by water flow boiling investigations.

Flow boiling experiments with refrigerants R-134a and R407C in macro-tubes have been reported by Akhavan-Behabadi and Esmailpour [14] (D: 8.3 mm) and Kundu et al. [15] (D: 7 mm), respectively. Both studies reported the highest heat transfer coefficient, h, at 90° (vertical upward flow), and noted that θ effect is stronger at low vapor qualities (< 0.5). However, they did not investigate bubbles behavior. Zhang et al. [11,16] employed photographic evidence to identify different critical heat flux, CHF, regimes during saturated and subcooled flow boiling of FC-72 in a macro-channel (×5 mm, w2.5 mm, L101.6 mm) at different inclinations. According to their results, CHF reached a maximum value at 45°, where buoyancy helped the most to detach vapor bubbles from the heated surface, and dropped to a minimum at 225°, where vapor was mostly accumulating on the heated surface. Konishi et al. [17] and Kharangate et al. [13,18] performed flow boiling experiments in the same geometry as Zhang et al. featuring one or two opposite facing heated walls at different θ with focus on gravity effects on interfacial behavior. A peak in h was noticed at 90°, where both single-sided and double-sided heating showed better symmetry in vapor formation along the channel compared to other inclinations. Although the above works argue about effects of θ on interfacial behavior, they only report overall heat transfer results (h or CHF) and overall visual observations about the identified boiling regimes, without any information on bubble dynamics (bubble sizes and velocities).

Sugrue et al. [19] carried out flow boiling experiments with water in a rectangular mini-channel (×1.99 mm, w1.43 mm, L317.5 mm) focusing on results of departure diameters of sliding bubbles at a single value of heat flux (100 kW/m^2). They found that bubble departure diameter reached a minimum at 90°, because the tangential component of the buoyancy force is largest at that angle, but differences at various θ were very small (about 15% between 0° and 90°). There are few more studies where bubbles monitoring and bubble dynamics analysis in water flow boiling have been conducted at 90°, at various channel sizes (D_h: 3.8–19.1 mm) and different subcoolings (ΔT_{sub}: 2–75 °C) [12,20–25]. However these studies are limited to the vertical orientation and a single value of heat flux for most of the cases while they do not attempt a comparison with other inclinations or a correlation of bubbles behavior with heat transfer results.

To our knowledge this is the first study combining systematically thermal and optical results at different inclinations (θ: 0-150°) in a macro-channel (×10 mm, w40 mm, L120 mm). The current study examines the effect of θ on heat transfer characteristics (onset of nucleate boiling, onset of bubbly regime, boiling curve, heat transfer coefficient, heat transfer mechanism) and on bubble dynamics (bubble size distribution, bubble density, bubble sliding velocity) under various mass fluxes (G: 330–830 kg/m^2s) and heat fluxes (q″: 300–1000 kW/m^2). The working fluid is water, a choice chiefly motivated by the need to investigate fast cooling of hot hollow walls by internal water flow at extreme conditions (i.e. fire incidents in space vehicles) [26]. For the same reason, a high inlet subcooling (ΔT_{sub} = 70 °C) is employed as this increases CHF [13,17] by hindering dryout [18,23]. Comparison of results among different inclinations as well as with observations by other researchers offers a thorough insight of bubble's contribution to heat transfer under various gravity effective components.

2. Materials and methods

2.1. Experimental device and procedure

The experimental setup is schematically presented in Fig. 1a and consists of the test section adjusted at a flow loop. A detailed