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Subatmospheric pressure boiling on a single nucleation site in narrow vertical spaces

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ABSTRACT

Compact evaporators like plate heat exchangers can play a significant role in reducing the investment cost of low cooling power sorption systems. If water is used as refrigerant, their design remains mainly empirical. The objective of this paper is thus to investigate the specific characteristics of water pool boiling in narrow channel at subatmospheric pressure in order to acquire the fundamental knowledge needed to improve the design of compact evaporators in these sorption systems. An experimental test setup was thus designed and built to study water pool boiling in narrow channel at subatmospheric pressure (from 5 to 1.2 kPa) on a vertical heated copper disk. The influence of the thickness of the narrow channel and of the pressure on the heat transfer is discussed. As the pressure and the channel thickness decrease the occurrence of a specific subatmospheric pool boiling regime is observed, degrading heat transfer coefficient. Nevertheless, the general trends of evolution are in agreement with those generally observed in the literature: heat transfer is enhanced as the thickness of the narrow channel decreases but, depending on the pressure, decreasing too much the channel thickness could lead to a deterioration of the heat transfer coefficient. A particle image velocity (PIV) device was implemented to the experimental setup in order to highlight the effect of the wake-induced flow on the heat transfer.

1. Introduction

Compactness and cost are known to be the two main limitations for the development of efficient small cooling sorption systems. As the evaporator is one of the components which need to be improved, the implementation of compact heat exchanger is a key factor to allow the development of such systems. But, working with water as refrigerant at such low pressure range (around 1 kPa for sorption systems used for air-conditioning applications such as LiBr/H_2O absorption or, silicagel/H_2O, zeolite/H_2O adsorption systems) requires a good understanding of the phenomena occurring inside the evaporator. This knowledge is all the more required as most of these phenomena limit the performance of the heat exchanger (presence of bubbles of several centimeters drying out the heat exchange area, low density of the vapour phase conducting to high velocities, onset of failure due to the influence of the hydrostatic pressure on the saturation temperature, etc.). Clausse et al. (2011) studied experimentally the feasibility to use plate heat exchangers in adsorption systems. They noticed that a too high secondary fluid temperature results in performance degradation. They explained that this might be due to a too high wall superheat resulting in a partial dry-out of the wall. Furthermore, they noticed the existence of an optimal evaporator filling for the achievable cooling power. Toublanc et al. (2014) visualized boiling regimes occurring in the channel of a single plate evaporator of dimension similar to the plate heat exchanger used by Clausse et al. (2011). They observed the occurrence of different boiling and evaporation flow regimes. Like Chang et al. (2012), they noticed that the evaporation flow regime is due to the consequence of the periodical growth of the bubbles: when the bubble deformed by the channel thickness surges out of the liquid, the liquid film that encapsulates the bubble is spread onto the evaporator wall above the liquid level. The splashed liquid droplets evolve into a liquid film above the newly formed liquid level. The evaporation process then immediately takes place. The presence of this first bubble thus seems to be necessary to initiate the heat transfer process and to avoid failure. However, although boiling under various conditions has been studied intensively in the last 3 decades, knowledge about water behavior in such conditions is scarce. This holds especially true when regarding boiling in narrow channels since, to the authors' knowledge, no previous fundamental study was carried out both in narrow space and at subatmospheric pressure despite the fact that heat transfer mechanisms are different in confined space with respect to heat transfer mechanisms in free boiling. The few results obtained

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Nomenclature

C_p	specific heat capacity (J.kg^{-1}.K^{-1})
e	channel thickness (mm)
g	gravity acceleration (m.s^{-2})
h	height (m)
heat transfer coefficient	(W.m^{-2}.K^{-1})
L_c	Capillary length (m)
L_m	length (m)
P	pressure (kPa)
q	heat flux (W.cm^{-2})
R_c	radius of the cavity (m)
r	radius of a spherical bubble (m)
t	time (s)
T	temperature (K)
U	velocity (m.s^{-1})
z	depth (m)

Subscripts and superscripts

adim	dimensionless
inst	instantaneous
l	liquid
sat	saturation
v	vapor
w	wall
$*$	local

Greek letters

α	thermal diffusivity (m^2.s^{-1})
μ	dynamic viscosity (kg.m^{-1}.s^{-1})
ϕ	diameter (m)
ρ	density (kg.m^{-3})
σ	surface tension (N.m^{-1})

Dimensionless numbers

Bo	$\frac{e}{\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}}$
Ca	$\frac{\mu U}{\sigma}$
Eo	$\frac{\rho_l g r^2}{\sigma}$
I_R	$(\frac{4}{27})(\frac{\sigma}{\rho_l \alpha^2})(\frac{R_c}{Ja^2})$
Ja	$\frac{\rho_l C p_l (T_w - T_{sat})}{\rho_v \Delta h_{lv}}$
We	$\frac{\rho_l r U^2}{\sigma}$

at subatmospheric pressure (near 2 kPa) were mostly obtained experimentally and in a free boiling environment. These experiments highlighted a huge difference between boiling phenomena as it is currently known and understood and boiling phenomena observed at such low pressure. Indeed, most of current theories available on bubble growth are based on the assumptions that the bubbles have almost a spherical shape and that the growth is relatively slow in order to consider that at each moment of the growth equilibrium between all forces that govern the bubble growth is reached. However, at subatmospheric pressure, bubbles of centimeter sizes and with a mushroom shape in horizontal orientation or flattened hemispherical shape in vertical orientation were observed (Van Stralen et al., 1975; Giraud et al., 2013). It was also shown that the bubble growth is mostly inertial (thus that the growth is rapid compared to the usual growth controlled by diffusion). None of the theories currently available on the bubble growth and bubble departure diameter can thus be applied at low pressure. Experiments also highlighted behavior which should be regarded as specific to the water boiling at subatmospheric pressure like a waiting time between two succeeding bubbles which can reach several hundreds of seconds (Raben et al., 1965; Van Stralen et al., 1975; McGillis et al., 1991; Yagov et al., 2001) and the presence of an unstable boiling regime marked by an irregular unsteady character (Wu et al., 1982; Labuntsov et al., 1978; Yagov et al., 2001; Giraud et al., 2015). These differences in boiling phenomena result in the deterioration of the boiling performance (Schnabel et al., 2008; McGillis et al., 1991; Chan et al., 2010).

As the aim of the present work is to acquire fundamental knowledge on behavior of water pool boiling in narrow channel at subatmospheric pressure, an experimental test bench was built to study the heat transfer of the water in a narrow channel formed by a heated copper vertical plane surface and an adiabatic parallel PVC plate. This aim leads to the need to discuss as a background on the meaning of the Bond number for characterizing boiling heat transfer at subatmospheric pressure, since bubbles have centimeter size and the force balance is different than at atmospheric pressure. Then, boiling curves for different channel thicknesses and pressure ranging from 5 to 1.2 kPa will be plotted and analyzed. Experiments with high velocity PIV will also help highlight the influence of the wake-induced flow for very narrow channels.

2. Bond number limitation for the characterization of subatmospheric boiling phenomena in narrow channel

The Bond number derivates from the Eötvös number (Eo) or gravity-based Bond number (Bo_g) (also named sometimes in the literature only “Bond number”) defined as $Eo = Bo_g = \frac{\rho g r^2}{\sigma} = Bo^2$. The Eötvös number gives the proportionality between buoyancy forces and surface tension forces. It was used by Bretherton in 1961 as he studied the free rise of a bubble in a vertical tube in a theoretical point of view. His study was motivated by the fact that many experimental results revealed the existence of two regions with different behavior of the boiling phenomena in narrow channels. The author noted that if the gravity-based Bond number is inferior to 0.842, then the bubble should not rise. A limit value of 2 could be also found in the literature for defining the same boundary between these two regions of different behavior (Moriyama and Inoue, 1996). Nevertheless, although the limit value of this dimensionless number may vary from one source to one another, this number was generally chosen to define criteria for the transition between a behavior governed by capillary effects and a behavior governed by viscous boundary layer phenomenon. As an image, this transition is given for a tube diameter of the same size as the bubble diameter.

Based on the Eötvös number, the Bond number known nowadays is defined as $Bo = \frac{e}{L_C}$. This Bond number is often defined as a scaling for the ratio between the thickness of the narrow channel and the departure diameter of a bubble. Indeed, the bubble detachment diameter is commonly determined by equating the resultants of the buoyancy and surface tension forces (Buyevich and Webbon, 1996). This means that at the detachment of the bubble, the ratio of the Eötvös number (which gives the proportionality between buoyancy forces and surface tension forces) is equal to unity. Thus, based on this number, the bubble departure diameter should be close to $\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$, which is also known as the capillary length (L_c).

According to famous correlations (Cole and Rohsenow, 1968; Jensen and Memmel, 1986) or to experiments (Van Stralen, 1975; Rullière et al., 2012), bubbles departure diameters have centimeter size at subatmospheric pressure while the capillary length is of a few millimeters (e.g. 2.7 mm at 2 kPa). There is thus a factor 100 between the capillary length and the bubbles departure diameter observed by Van Stralen (1975). This is due to the fact that the bubble detachment at subatmospheric pressure is no more mostly governed by the balance between buoyancy forces and the capillary forces, but rather mainly by the buoyancy forces and the inertial forces. In order to illustrate this change in governing factors, the three dimensionless numbers $We = \frac{\rho_l r u^2}{\sigma}$, $Ca = \frac{\mu_l u}{\sigma}$, $Bo_g = \frac{\rho_l g r^2}{\sigma}$ used respectively to give roughly the magnitude of inertial, viscous and gravitational forces