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EXPERIMENTAL STUDY ON SUBCOOLED NUCLEATE BOILING FROM A SINGLE ARTIFICIAL CAVITY

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ABSTRACT

Bubbles condensing in subcooled water were experimentally studied in the aim of characterizing the nucleation behavior dependence on the water pool subcooled temperature. A single artificial cavity was created on a brass plate and heated by a laser beam in a water pool and high speed camera was used to capture bubble growth dynamics. Post-processing allows the measurement of important parameters such as bubble volume, rising velocity, departure diameter, detachment frequency, volume variation versus time and temperature and dry spot diameter. Three growth regimes were identified according to the bulk temperature and the heat flux supplied: an equilibrium regime, a standard nucleate boiling regime and a boiling crisis regime in which we observed the formation of a large dry spot on the solid surface. The absence of rewetting of the cavity is a key feature of this regime. The obtained results are compared with the few experimental correlations available in the literature.

INTRODUCTION

Experiments on water pool boiling under saturated and subcooled conditions have been conducted by several authors the most of which focused on critical heat flux (CHF) and related thermal aspects. More than 200 papers connected to this topic have been reviewed by Katto [1] in 1994 from both an analytical and experimental point of view in the aim to resume and compare the progresses made in CHF characterisation.

Among the great number of experiments on pool boiling, the very first moments after bubble formation from a cavity on a metal surface and the heat transfer of a collapsing bubble created under boiling conditions have been investigated by only a few authors.

The interest is more often focused on improvements in modelling CHF and transition boiling [2] or the determination of heat transfer mechanisms during bubble formation [3, 4], boiling curves or nucleation site density [5].

Even if in industrial applications condensing bubbles were generated by boiling processes in slightly subcooled liquids,

NOMENCLATURE

h	$[Wm^{-2}K^{-1}]$	Heat transfer coefficient
λ	$[Wm^{-1}K^{-1}]$	Thermal conductivity
ρ	$[kgm^{-3}]$	Density
Cp	$[Jkg^{-1}K^{-1}]$	Specific heat capacity
A	$[m^2s^{-1}]$	Thermal diffusivity
ν	$[m^2s^{-1}]$	Kinematic viscosity
q''	$[Wm^{-2}]$	Heat flux supplied
P	[W]	Laser power supplied
D	[m]	Bubble diameter
R	[m]	Bubble radius
$Rbase$	[m]	Dry spot radius
V	$[m^3]$	Bubble volume
T	[°C]	Temperature
L	$[Jkg^{-1}]$	Latent heat
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
z	[m]	Cartesian axis direction
t	[s]	Time
Dimensionless quantities		
Ja	[-]	Jakob number
Ar	[-]	Archimedes number
$\mathcal{Ma}$	[-]	Marangoni number
$\mathcal{Re}$	[-]	Reynolds number
Pr	[-]	Prandtl number
Fo	[-]	Fourier number
Pe	[-]	Peclet number
a	[-]	Energy absorption coefficient
β	[-]	Bubble radius normalized to detachment radius
τ	[-]	Normalized time
Subscripts		
d		Bubble detachment
L		Liquid
V		Vapour
max		Maximum
W		Wall
0		Initial condition for collapse
∞		Bulk liquid

nucleation and condensation problems have been generally treated separately.

Subcooled boiling occurs when the liquid near the heated surface reaches the saturation temperature while the bulk liquid is still subcooled. In this condition nucleation sites can be activated and bubbles start to grow: some of the heat flux is used to evaporate the liquid near activated sites and some to heat up the liquid. An amount of latent heat equal to the heat flux used to evaporated liquid is given back to the subcooled liquid when the bubble condenses: the net heat transfer does not change even if boiling process have begun.

Several techniques have been conceived to experimentally study the collapse of a vapor bubble into a subcooled liquid. The collapse is often induced in three main ways: by vapor injection directly in a pool of subcooled liquid [6, 7], by injection into a saturated one at subatmospheric pressure to let the condensation process start when the liquid is exposed to atmospheric pressure (flashing) [8, 9] or by heating up a solid surface to create boiling condition on it in a layer of subcooled liquid [10, 11]. Concerning this last one, different methods were considered to heat up a small surface spot, in order to create a limited number of bubbles, such as electrical heaters or cartridge heaters.

The condensation of vapour bubbles has been experimentally studied since 1959 when some results about bubbles have been published by Levenspiel [8]. In his experiences bubbles were created by flashing vapour and are observed to collapse into subcooled water. The mean size of a bubble has been proposed by Levenspiel to determine the mean heat exchange during collapse. Heat transfer coefficients of 10^4W/m^{2}K as order of magnitude have been found for bubbles departing from 1cm diameter.

The relative importance of liquid inertia and heat transfer effects on the collapse rate has been experimentally clarified for the first time in 1965 by Florschuetz and Chao [9]. The authors examined the mechanics of vapour bubble collapse under spherically symmetrical conditions. Experimental results were provided for bubbles with initial radii from 3mm to 5mm, created by flashing vapour, collapsing in water under free fall conditions. The vessel was heated up close to boiling condition at subatmospheric pressure, a bubble was injected from a nozzle and immediately after the vessel was released under free fall: when the bubble assumed a nearly spherical shape a valve on the vessel was open to expose the system to atmospheric pressure initiating the collapse of the bubble. Pressure difference ranges from 0.16MPa to 0.83MPa corresponding to a degree of subcooling varying from 5°C to 13°C. For the liquid inertia controlled collapse, the collapse rates are high and increase as the collapse proceeds, in contrast the collapse rates for heat transfer controlled collapse are relatively slow and decrease as the collapse proceeds. The importance of translational velocity when the collapse is heat transfer dominated is revealed by these results.

The collapse of a bubble with a translatory motion was evaluated from an experimental point of view in 1971 by Voloshko and Vurgaft [6]. Bubbles were created by vapour injection into subcooled water. The subcoolings considered varied from 4°C to 25°C. The authors correlated the detachment diameter directly to the degree of subcooling since no superheated layer is developed in the vicinity of the nozzle. Other experimental data about the collapse of bubbles formed by vapour injection have been provided by Kamei and Hirata [12] in 1990 and Chen and Mayinger [13] in 1992.

Both of them injected saturated vapour trough a nozzle into subcooled water. A mean heat transfer coefficient has been calculated by Kamei and Hirata [12] to be around $2x10^4$ W/m^{2}K, which is the same order of magnitude proposed by Levenspiel [8], independently from the initial diameter and subcooling. Bubble collapse has been correlated by Chen and Mayinger [13] to heat transfer using dimensionless numbers such as Ja, Re, Pr and Fo showing that Ja number indicates the relative importance of inertia and heat transfer during collapse: Ja numbers up to 80 mean that the collapse is controlled by the interface heat transfer while inertial effects become to be relevant for Ja higher than 100, which means higher subcooling degrees.

More recently Marek and Straub [14] proved that even with small temperature gradients ($1.4x10^{-4}$ K) along bubble interface a fluid motion can be observed, due to Marangoni convection, caused by a thermally induced surface tension gradient. The influence of non-condensable gases accumulation on enhancing thermocapillary convection has also been shown by the authors.

The present study aims at investigating collapse of bubbles in subcooled pool boiling for water pool temperature ranges from 92 to 99.8°C. Our experimental setup allows us to follow the whole life of a bubble created on a heated solid surface. A single artificial cavity was manufactured on the top of a thin mirror finished brass foil that was heated up by a laser beam from the bottom dry side to induce nucleation. The heating technique is similar to that used by Shoji and Takaji [15] in their experiments to characterize the behaviour of different cavity shapes in saturated pool boiling. A laser beam has been used to heat a thin plate also by Gjerkes and Golobic [16], who studied the transition from nucleate boiling to critical heat flux.

Laser beam focalization seems to be a good compromise for our purpose in terms of heating capacity, precision and shut down speed. This last is a key feature of laser beam heating systems since it would allow the elimination of the wake effect from one bubble to another by creating one single vapor bubble for each cycle. Precision of the heating spot location lets only the manufactured site to be activated.

The most of the authors [6, 9, 13, 17, 18, 19] who have focused on condensation phenomena used to create the bubble in the aim to obtain experimental data as closer as possible to theoretical hypothesis. Experiences were thus designed to obtain spherical bubble and to eliminate the effect of solid interfaces.

The present study is focused on both main aspects of subcooled pool boiling: (1) the characterisation of boiling regimes occurring at different bulk temperatures and heat fluxes on a solid surface, and (2) the analysis of vapour bubbles collapse in a subcooled liquid after their detachment from the heated surface.

In the next sections a detailed description of the experimental setup is proposed followed by a paragraph explaining the measurement techniques. Next, obtained results are presented and compared with analytical studies founded in the literature. Results are divided into two sections depending on the phase they are related to, that is boiling or condensation phase.

EXPERIMENTAL SETUP

The pool boiling facility is illustrated in Figure 1. A single artificial cavity was manufactured on the top surface of a brass plate by focusing a pulsed laser beam. The brass plate is 25mm diameter and 0.1mm thick and the cavity is 40 μm deep and approximately 0.1mm large.

The brass foil used as boiling surface is mirror finished to avoid non-controlled nucleation sites activation during boiling cycles. Expermients have shown that the only active site during the heating cycles is the artificial one.

A cylindrical glass facility filled with demineralized water is located into a thermal fluid (silicone oil) bath to maintain water at constant temperature. Around 14l of thermal bath at atmospheric pressure have been heated by an electric heater equipped with a 16l/min recirculating pump. The thermal fluid can reach a maximum temperature of 180°C and the electric heater can thermalizes up to 50l of thermal fluid with ±0.1°C of accuracy by the manufacturer facts. By varying the thermal bath temperature the water bulk temperature can be set to a certain subcooling degree or to saturation temperature. Water is degassed by repetition of multiple boiling-cooling cycles before the experiments start to minimize the presence of non-condensable gases.

Water bulk temperature is measured by a platinum resistance thermometer (Pt100 sensor) and thermal bath temperature is controlled by the internal thermometer of the heater.

Before installation in the test vessel the brass foil was washed in ultrasound bath and its active side was cleaned with ethanol to eliminate impurities.

The brass plate was fixed on the base of the cylindrical water tank and heated from the bottom by focusing a continuous laser beam on a 2mm diameter surface located exactly under the cavity.

To enhance heat absorption across the brass plate, its bottom surface was black oxidized. Supposing the fraction of energy absorbed on the heated surface to be 95% ($a = 0.95$) the heat flux supplied to the cavity can be calculated as

$$q" = \frac{4Pa}{\pi {D_L}^2} \tag{1}$$

where P is the measured power of the laser beam and D_L its diameter.

MESUREMENT SYSTEMS

A high speed camera with 5000f/s acquisition rate at maximum resolution (1280*800 pixels) was used to capture bubble dynamics with a scale factor of 0.028mm/pxl and post-processing was employed to measure several important parameters. The shadowgraph optical method was applied which consists in back lighting the test section to let the light pass through the flow field: the difference between liquid and gas refractive index maximizes the image contrast at the

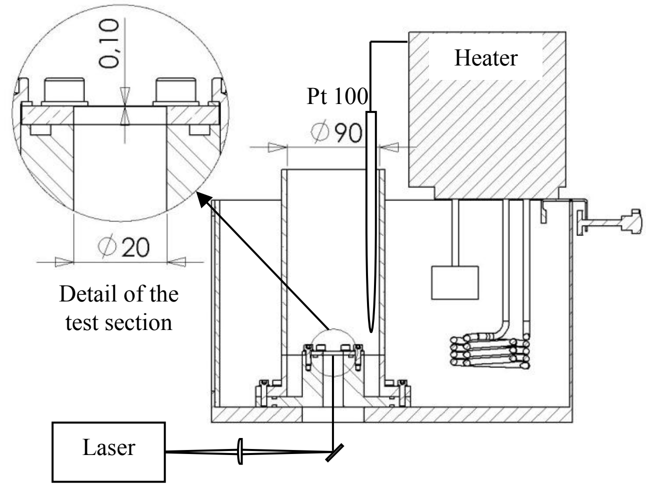

Figure 1: experimental setup

interface. Images were then processed under the hypothesis of axial symmetry for bubble volume.

First a background image is subtracted to all the images to be treated in order to fix any light intensity variation. Then a grayscale threshold is set to binarize images converting them to only black and white. The threshold value is a key choice since bubble volume is computed by counting the number of black pixel in the black and white image: figure 2 shows the volume measured for the same bubble versus different threshold values. The detachment volume varies from 10.75mm^3 to 11.65mm^3, with thresholds varying from 0.5 to 0.8. The threshold value used to process images was fixed to 0.7 since it gives the minimum error relative to the mean calculated volume.

Data show high reproducibility as confirmed in figure 3 in which bubble radius and dry spot radius evolution versus time (also called bubble base radius $Rbase$) are plotted from 3 different tests.

RESULTS AND DISCUSSION

Experiments were made for bulk temperature varying from saturation to 8°C of subcooling, the laser power ranged from 30mW to 3W corresponding to heat fluxes from 9 kW/m^2 to 900 kW/m^2.

Boling phase

Three boiling regimes have been identified as function of the bulk temperature and heat flux supplied and are illustrated in figure 4. In subcooled liquids bubbles can grow or collapse according to the heat and mass transfer across the interface. At low heat flux a steady state can be maintained when the evaporated mass flow rate at the base equals the condensing mass flow rate at the top. This regime can be reached even at small subcoolings for very low heat flux. Increasing the bulk temperature and the heat flux supplied, a standard nucleate boiling regime takes place in which bubbles grow and detach without coalescence: the collapse begins when bubbles exit the

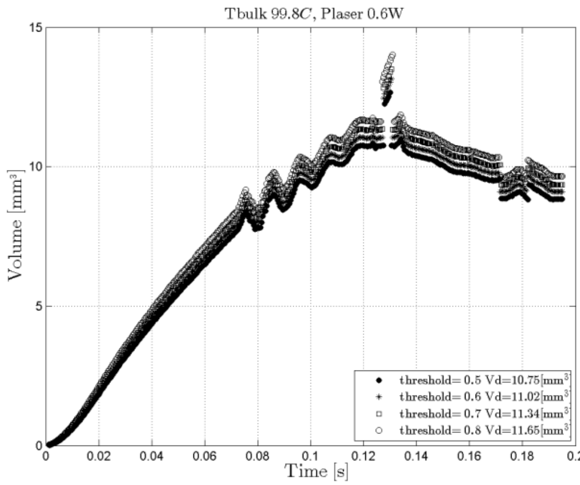

Figure 2: calculated bubble volume variation versus time for different threshold values

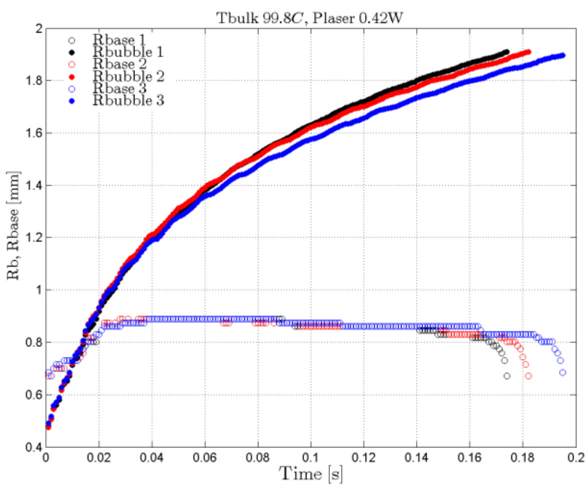

Figure 3: bubble radius and dry spot radius reproducibility

warm liquid layer above the heated surface entering the colder bulk liquid. A third regime is eventually reached for high heat fluxes in which a large dry spot is maintained above the artificial cavity avoiding cavity rewetting: bubbles grow thanks to the evaporating mass flow supplied from the dry spot and detach from this one instead of detaching from the solid surface.

Even if on a single nucleation site actual film boiling cannot be observed, since no other bubbles formed on the surface preventing coalescence into a vapour film, the single cavity configuration is essential to understand bubbling behaviours: in this case CHF is characterized by a vapour mass formation above the heated area which prevents water to rewet the solid surface.

At saturation condition, as time proceeds, the inertial, viscous, gaseous, and surface tension terms in the Rayleigh-Plesset [20] equation all rapidly decline in importance: bubbles

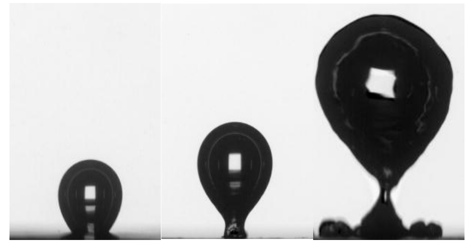

Figure 4: detachment phase for bubbles growing in subcooled water at 94°C for laser beam power respectively of 0.6W, 1.21W and 3.03W

growth is essentially thermally controlled following equation 2 proposed by Brennen [21]

$$R = \frac{1}{2C(n)} \frac{\rho_L c_{pL} \Delta T}{\rho_V L} (\alpha_L t)^{\frac{1}{2}} \qquad (2)$$

with

$$C(n) = \left(\frac{4n+1}{\pi}\right)^{\frac{1}{2}} \int_0^1 \frac{z^{3n-1} dz}{(1 - z^{4n+1})^{\frac{1}{2}}} \qquad n = \frac{1}{2}$$

where the group $\rho_L c_{pL} \Delta T / \rho_V L$ is termed the Jakob number and $\Delta T = T_W - T_\infty$, T_W being the wall temperature.

A comparison of the experimental bubble radius with the predicted radius is shown in figure 5 where the red line corresponds to equation 2. This comparison allows us to estimate the wall temperature by successive approximations. For saturated water and 0.42W heat power the estimated wall temperature is 104.5°C.

Bubble radius evolution and dry spot radius evolution at saturation conditions for laser power between 30mW and 3W are presented in figure 6. Bubble detachment radius increases as power increases to saturate around 2mm from 0.42W laser power. Bubble radius and dry spot radius curves superposed for 0.42W, 0.48W and 0.54W. The dry spot radius grows rapidly in the firsts 50ms, remains almost constant for the most of the bubble growth period and decreases rapidly during bubble neck formation until detachment.

Near saturation conditions for heat power higher than 2W the dry spot behaviour changes, its radius remaining almost constant and equal to the mean bubble radius during bubble growth as shown in figure 7. Bubble radius is not zero at t=0 since a vapour mass is always maintained in the vicinity of the nucleation site. Near the end of the growth phase bubble radius further increases because of coalescence phenomena before detachment.

The detachment volume is plotted with respect to the power supplied in figure 8 for all water temperatures investigated: the higher the power the bigger the volume is the general trend even if influence of the superheated layer thickness near the heated surface cannot be estimated. Bubbles growing in saturated (99,8°C) or very slightly subcooled (99°C and 98°C) liquid show a more linear trend of detachment volume. Bubble

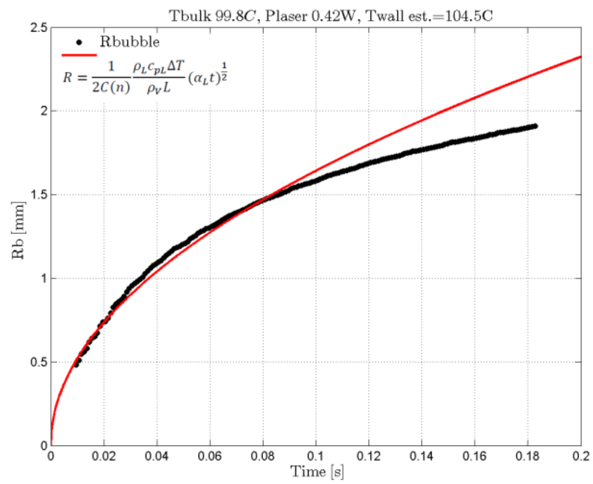

Figure 5: thermal growth into saturated water compared to thermal growth predicted by Plesset-Zwick theory

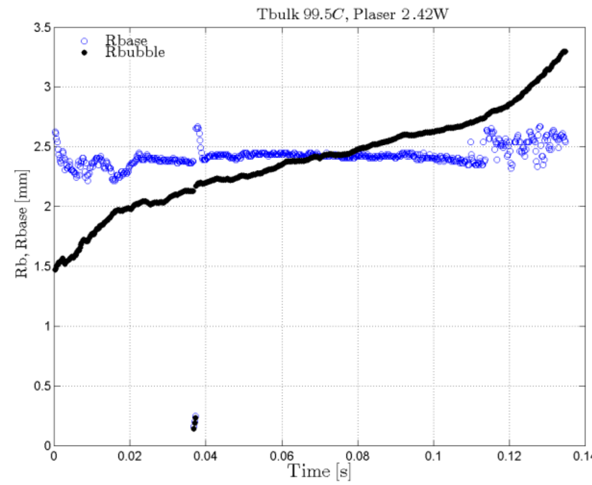

Figure 7: bubble radius evolution and related dry spot radius versus time for saturated boiling with 2.42W laser power

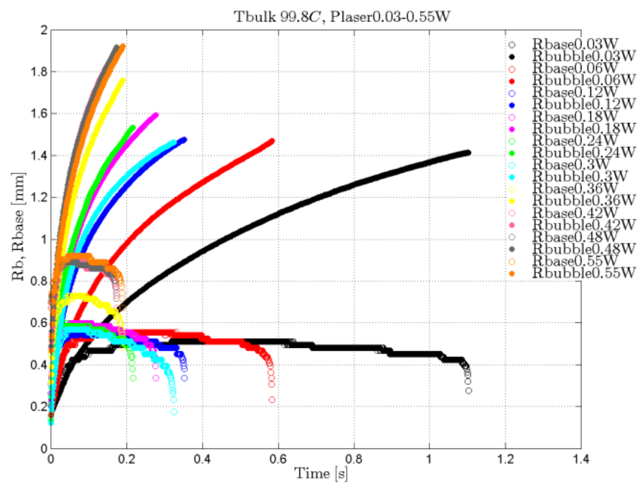

Figure 6: bubble radius evolution and related dry spot radius versus time for saturated boiling with laser power ranges from 30mW to 550mW

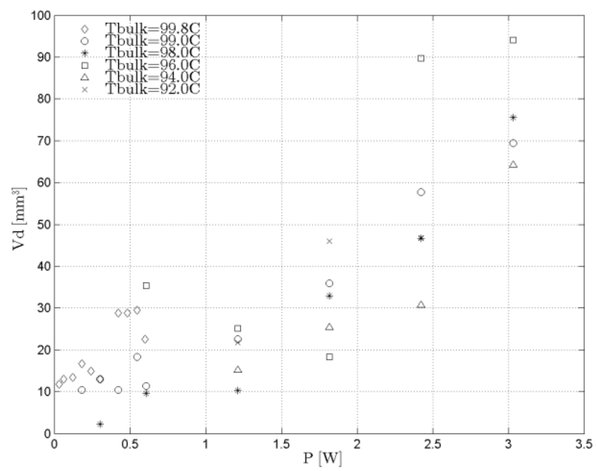

Figure 8: bubble detachment volumes versus laser beam power for saturated and subcooled boiling conditions

detachment dynamics depends on the presence of non-condensable gases, whose effect is influenced by the degree of subcooling [14].

The principal mechanism of boiling crisis in pool boiling has been identified in 1968 by Katto and Yokoya [21] as the intermittent behaviour of vapour masses and the consumption of liquid film which builds up on the heated surface. The authors found the rate of increase of vapour within a vapour mass to be almost constant through the growth period of the vapour mass, indicating that vapour is generated from the liquid film on the heated surface at a constant rate. This is confirmed by data plotted in figure 7, for experiments at high heat power, in which vapour bubble radius increases linearly with respect to time with exception of the first (until 0.02s) and last (between 1.2s and 1.4s) growth phase. A physical explanation for the CHF based on the spreading of the dry spot under a vapour bubble was proposed by Nikolayev et al. [23] for a fluid near critical point.

The spreading is initiated by the vapour recoil force coming from the uncompensated momentum of the fluid molecules being evaporated into the bubble. As this force is always directed towards the liquid side it increases the dry spot under the bubble, therefore for the case of complete wetting the CHF can be understood as an out of equilibrium drying transition from complete to partial wetting.

The theory of the spreading of the dry spot can explain the growth of the vapour mass in the vicinity of the nucleation site at high heat power.

Condensation phase

During the condensation phase we observe bubbles collapsing from their detachment volume to 25% of it, an example of which is given in figure 9. In this figure and in most of the experiments a bubble drift can be observed. The drift may be produced by a horizontal temperature gradient since the heater is placed on one side of the cylinder. Vertical and horizontal bubble translation velocity have been evaluated and compared. A one order of magnitude difference has been found which lead us to believe that bubble detachment is not influenced by this effect.

Several correlations have been proposed to predict bubble radius evolution during condensation in subcooled liquids. Florschuetz and Chao [9] proposed a model based on the continuity equation for the vapor phase, momentum equation for the bubble and temperature field equation for the liquid phase with energy conservation at the moving interface as boundary condition. To solve the liquid temperature equation, under the hypothesis of heat transfer controlled collapse, two approaches were proposed.

In the so-called plane interface approximation the effects of surface curvature and convective heat transfer are neglected so that the problem becomes that of determining the temperature field in a semi-infinite region with uniform initial temperature. The initial condition of zero radial velocity at the beginning of the collapse phase is not respected by the plane interface approximation, which gives instead an infinite velocity, because of the omission of the inertia term in the dimensionless momentum equation.

The second approach consists in using the improved approximate temperature solution of Plesset and Zwick [20] that is the solution for the heat diffusion problem across a spherical boundary with radial motion, based on a successive approximations method. The zero order solution for the temperature at the moving spherical interface is given under the assumption that appreciable variations of temperature occur only in a thin boundary layer. The inertia term being still neglected, the Plesset-Zwick approximation also results in an infinite velocity of the interface at t=0. Both solutions are thus physically inapplicable at the very beginning of the collapse: they are shown as dotted and solid blue lines in figures 10 and 11 and compared to some experimental data which are similar to those obtained by the authors.

Data presented in figure 10 refers to a bubble collapsing in water at 94°C created with a laser power of 3.5W. At the very first moments both solutions proposed by Florschuetz and Chao, represented by the solid and the dotted blue lines, miss the zero velocity condition which is confirmed by our experiments. From the middle of the collapse period the curves start to include our data between them. Others condensation models have been tested: correlations are shown in table 1 and related collapse rate are plotted in figures 10 and 11. Even if these models are more complex that the Florschuetz and Chao one [9], including bubble rising velocity, they cannot be applied to fit our results since they all are valid only for very rapid collapses.

In figure 11 experimental data for a bubble created at lower heat power (1.2W) at the same bulk temperature are well fitted

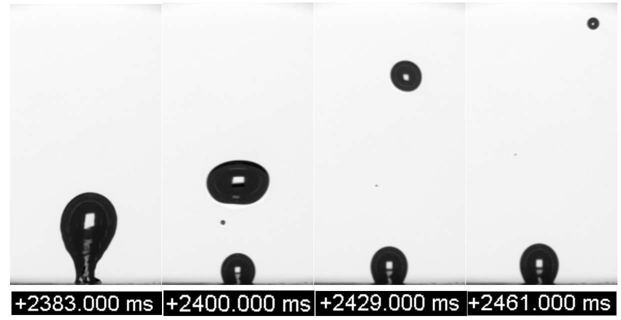

Figure 9: bubble created at 1.21W heat power condensing in water at 92°C

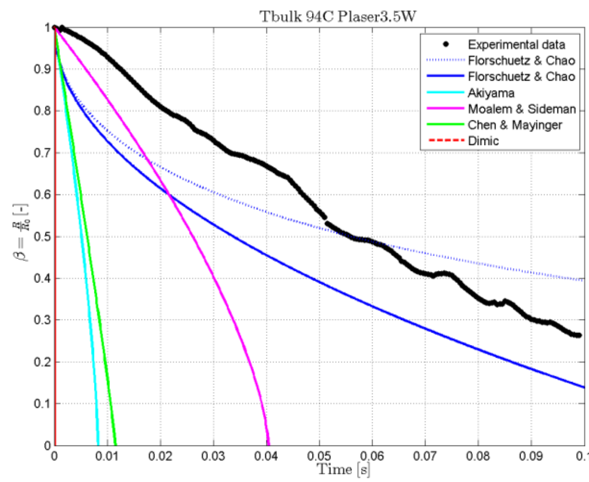

Figure 10: comparison between experimental data and collapse models for 6°C of subcooling and 3.5W heat power

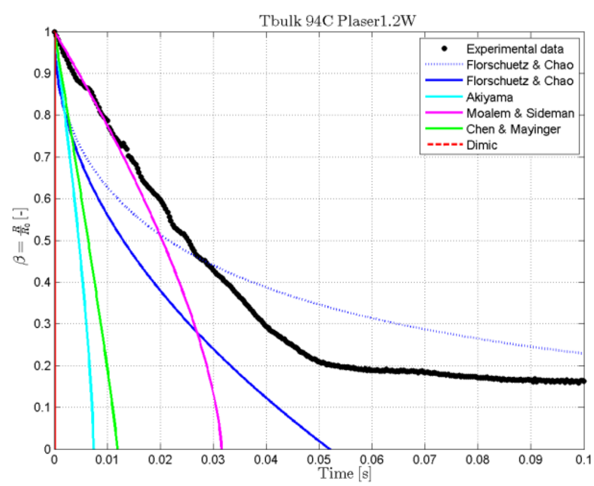

Figure 11: comparison between experimental data and collapse models for 6°C of subcooling and 1.2W heat power

Table 1: dimensionless bubble radius correlations from different condensation models

Author(s)	Correlations	Remarks
Florschuetz & Chao	$\beta = 1 - \tau^{\frac{1}{2}}$	$\tau = \frac{16}{\pi} Ja^2 Fo$
	$3\tau = \frac{2}{\beta} + \beta^2 - 3$	
Voloshko & Vurgaft	$\beta = 1 - 1.694\ 10^4 Fo$	$40 < Ja < 75$
Moalem & Sideman	$\beta = \left[1 - \frac{3}{2\sqrt{\pi}} Ja\ Pe^{\frac{1}{2}} Fo\right]^{2/3}$	$2 < R_0 < 4mm$
	$\beta = \left[1 - \frac{5}{4\sqrt{\pi}} Ja\ Pe^{\frac{1}{2}} Fo\right]^{4/5}$	$R_0 < 1mm$
Akiyama	$\beta = [1 - 2.8CPr^{-0.27} JaPe^{0.6} Fo]^{5/7}$	$C = 0.73$
Chen & Mayinger	$\beta = [1 - 0.56Re^{0.7} Pr^{0.5} JaFo]^{0.9}$	$2 < Pr < 15$ $Ja < 80$ $R_0 < 3mm$
Dimic	$\beta = \left[1 - \frac{7}{8}\left(\frac{0.694}{\pi}\right)^{\frac{1}{2}} Ar^{\frac{3}{8}} Pr^{\frac{1}{2}} JaFo\right]^{4/7}$	$Re < 4.02K_L^{0.214}$ $(Re > 2)$
	$\beta = \left[1 - \frac{7}{4}\left(\frac{2.7}{\pi}\right)^{\frac{1}{2}} K_\sigma^{\frac{1}{4}} JaFo\right]^{4/7}$	$4.02K_L^{0.214} < Re < 3.1K_L^{0.25}$
	$\beta = \left[1 - \frac{5}{2}(6\zeta\pi^2)^{-\frac{1}{4}} Ar^{\frac{1}{2}} Pr^{\frac{1}{2}} JaFo\right]^{4/5}$	$Re > 3.1K_L^{0.25}$ $(Re > 20)$ $\zeta = 2.61$

at the beginning by the Moalem and Sideman [17] correlation (the magenta line) taking into account the inertia term. The correlation predicts a too rapid collapse and fits no more our data 0.015s after the beginning of the collapse phase.

Further improvements in predicting collapse rate seem to be necessary, including inertia term to capture the beginning of the collapse phase.

CONCLUSION

An experimental study of bubbles growth and collapse in subcooled water has been done. The experimental setup was designed to follow a single bubble from its formation on a solid surface from a single artificial cavity to its collapse in the aim to include the influence of a heated wall and its thermal boundary layer on bubble growth and condensation.

Three different boiling regimes have been identified with respect to main parameters such as heat power subcooling degree. Results concerned the influence of these parameters on bubbles growth and collapse rate, detachment volume and dry spot area.

Experimental data have been compared to analytical models from the literature for both the boiling and condensation phase, showing a substantial agreement even if further improvements are needed, especially in evaluating the first phase of bubble collapse.

Future investigations will include the influence of boiling regimes on condensation rate. Further experiments will also include an estimation of heat and mass transfer during condensation aiming at evaluating the heat partitioning between sensible and latent heat during subcooled boiling.

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