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Effect of heating surface morphology on the size of bubbles during the subcooled flow boiling of water at low pressure

C. Paz *, M. Conde, J. Porteiro, M. Concheiro

School of Industrial Engineering – University of Vigo, Lagoas-Marcosende, 36310-E, Spain

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ABSTRACT

An experimental investigation on the forced convective subcooled flow boiling of water was carried out using image processing. Three copper test parts of different roughness were tested at different operational conditions established through a design of experiments, covering bulk velocities from 0.1 m/s to 0.9 m/s, bulk temperature from 76.5 °C to 93.5 °C, and operating pressures from 110 kPa to 190 kPa. The boiling process has been maintained on the nucleate regimen varying heat flux from 0.1 MW/m^2 to 1 MW/m^2, though image processing was only feasible below 0.65 MW/m^2. The result of the experimental work is a database of the size distribution of the bubbles at each experimental point and presented as an electronic annex. The results confirmed that bubbles are generally smaller at higher pressure, higher velocities and higher levels of subcooling. The effect of surface morphology proved to be a very strong factor that is normally ignored by correlations and experimental works. Finally, an analysis of the possibility of the interaction of surface morphology with bubble size is presented.

1. Introduction

Due to its unquestionable industrial interest, the study of subcooled nucleate flow boiling has received considerable attention over recent decades. Despite the enormous effort made to gain insight into the processes involved, there are still many uncertainties and much contradictory experimental evidence, which make boiling an unresolved issue [1]. Hundreds of studies have tackled the process of boiling at its different scales, employing different fluids, operating conditions, absence of gravity, etc. and with very different methodologies [2–5]. Most of the works devoted to nucleate boiling have served to develop a quite large menu of correlations covering an enormous range of fluids, operational conditions and features of the heating element, so that boiling is manageable at the industrial scale today. Due to their limited range of validation, those correlations need to be carefully selected to produce solid results and can rarely be applied to new situations, geometries, materials, etc. Hence, the study of boiling has never lost interest as new challenges appear every time a new development is made.

To increase the range of applicability, which is the main drawback of the pure empirical correlations, some of the correlations are formulated with a mechanistic basis [6]. Over the years, several aspects and operational conditions of the boiling phenomenon have been noted to be essential, and therefore, some correlations are based on the individual characterisation of those key subprocesses and dependences [4] [7–9]. In the case of subcooled nucleate flow boiling, it has been noted that the whole process can be considered to be the conjunction of liquid fluid forced convection, transient conduction under and around the emerging bubbles, and microlayer evaporation at the interface of the bubble and the heating surface. Consequently, most of the processes are linked to the nucleation, growth, and departure of the bubbles, and therefore, the precise determination of their density, frequency, and size are the core of most mechanistic-based correlations used currently.

Bubble behaviour in subcooled flow boiling has been investigated by several researchers, starting in 1951 with the work by Gunther [10], who was the first to employ high-speed photography to quantify the size, lifetime, and growth of bubbles under different operational conditions. Tolubinsky and Kostanchuk [11] studied the flow boiling of water on a horizontal stainless steel plate and found a strong dependence between bubble size and pressure, especially at pressures close to atmospheric. Abdelmeseih [12] used high-speed photography to study the effect of flow velocity on bubble dynamics at artificial nucleation sites. They found that the increase in liquid velocity resulted in a decrease in bubble size, which was contradictory to the conclusions of Gunther. Bibeau and Salcudean [13] reported discrepancies between the experimental results and the theoretical prediction of bubbles sizes at low

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* Corresponding author.
E-mail address: cpaz@uvigo.es (C. Paz).

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Nomenclature

D_b	bubble diameter [m]
k	thermal conductivity [W m^{-1} K^{-1}]
M_{r1}	peak material component
M_{r2}	valley material component
p	pressure [Pa]
q''	heat flux [W m^{-2}]
R_a	arithmetic mean roughness height [μm]
R_{pk}	reduced peak height [μm]
R_q	root-mean-square roughness [μm]
R_t	maximum peak-to-valley height [μm]
R_{vk}	reduced valley depth [μm]
R_z	ten-point height [μm]
S_a	arithmetic mean surface height [μm]
S_q	root-mean-square surface height [μm]
S_z	maximum surface height [μm]
T_{12}	thermocouple 12 temperature [K]
T_{22}	thermocouple 22 temperature [K]
T_b	bulk temperature [K]
T_{sat}	saturation temperature [K]
T_{wall}	wall temperature [K]
ΔT	$=T_{12} - T_{22}$
ΔT_{sub}	subcooling [K]
v	velocity
Δx_{12}	distance between thermocouples [m]
Δx_w	distance from thermocouple 11 to the wall [m]

Abbreviations:

FDB	fully developed boiling
HTC	heat transfer coefficient
NVG	net vapour generation
ROI	region of interest

Greek:

ε	error

pressure. They found that bubbles reach a higher size during their growth and that their departure started with a smaller diameter, which implied that condensation had started before departure. This fact was later reported by Zeitoun and Shoukri [14].

If we extend the discussion to the whole range of boiling, from the very beginning, the condition and morphology of the heating element was recognized to be a factor of boiling heat transfer. In 1936, Jakob [15] reported that the morphology, corrosion, and oxidation of the heating element produced a drift in the boiling curve towards higher wall temperatures. In fact, the earliest correlation for pool boiling, proposed by Rohsenow [16] employed a proportionality constant that was dependent on the heater-fluid material combination. At that moment, no explicit influence of roughness was noted, but posterior works observed such influence [17,18].

Decades after Jakob's work, several studies revealed that bubbles were generally emanated from cavities and other singularities, and theories were formulated to establish the conditions that make a cavity a valid candidate for the nucleation of a new bubble. Corty and Foust [17] were probably the first to study the effect of surface roughness by employing different levels of polishing of copper and nickel surfaces. Bankoff [19] showed that only unwetted cavities can develop a bubble and that the shape of the cavity was critical in the trapping of vapour. He formulated a geometric criterion that established that the angle of the cavity had to be small enough in comparison with the liquid-surface contact angle to avoid the re-flooding of the cavity. Griffith and Wallis [20] found a relationship between the size of the cavity and the superheating required for nucleation. Berenson [21] studied the effect of surface roughness on the boiling curve and concluded that surface roughness should be included as an important parameter but that R.M.S. roughness is not suitable for that purpose. On the other hand, Bergles and Rohsenow [22] initially stated that commercial surfaces have such a vast variety of cavities that boiling should be surface condition independent, though this was later discussed by Mikic and Rohsenow [23].

In 1962, Hsu developed a criterion to link bubble nucleation and cavity size [24]. According to Hsu, the requisite for the nucleation site to become active is for the surrounding temperature of the bubble, placed as a half sphere on the edge of the cavity mouth, to be equal to or exceed the saturation temperature that corresponds to the pressure inside the bubble, which is estimated by balancing pressure and surface tension forces. This criterion, extensively applied and revised during the last 50 years, establishes the range of cavity sizes that may become active. Hence, bubble nucleation is directly related to surface morphology; however, if cavities are not conical, Hsu's criterion is difficult to apply. It has been reported that grooves, which are commonly the type of roughness observed in industrial applications, are ineffective vapour traps unless they are very steep or the surface is poorly wetted by the fluid, and therefore conduct to a misleading relationship between roughness and boiling enhancement. On the other hand, a 'rough' surface in terms of boiling for a regular fluid can be 'smooth' for a fluid with a high wettability [25]. It has also been reported that the presence of cavities on the surface is not required for heterogeneous nucleation [1]. Hence, the relationship between active cavities and the surface micro-structure is one of the key unsolved issues in the prediction of nucleate boiling heat transfer [26].

Additionally, single vertical parameters employed to quantify roughness, such as R_a, R_p or R_q, cannot characterize the shape and size of cavities, hence their impact on boiling. This has led to the development of other 2D or 3D parameters based on the cone angle or cavity mouth size [6], [27]. Recently, due to the clear influence of the bubble scales on the interaction of surface morphology and boiling, fractal analysis has been used with some promising results [28].

It has been noted that re-flooding of the cavities is a key in their reactivation, which is influenced by the wetting contact angle (WCA). It is generally observed that contact angle decreases with roughness [6] and changes with the nature of the coating [29] and that the contact angle made by the liquid–vapour interface at the base of the bubble with the wall varies during bubble growth and departure. Additionally, physical changes in the micro-structure of the heating surface due to erosion, chemical reaction, the filling of the pores and cavities with impurities, corrosion, oxidation, etc. have been reported to occur during boiling and produce a general decrease in HTC [1], [30,31]. These processes, generally lumped together as 'aging', tend to improve the wettability of the surface, leading to an unsuccessful trapping of vapour in the cavities and hence to a reduction in the number of active sites based on the Bankoff criteria. In fact, Wang and Dhir [32] found that the number density of active sites for a given cavity diameter decreased by a factor of 25 when the contact angle was reduced from 90° to 18° by controlling the degree of oxidation of their copper surfaces in water. In addition, the contact angle is affected by the drag forced exerted by the flow, hence, a precise measurement