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Quantitative prediction of critical heat flux initiation in pool and flow boiling

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ABSTRACT

Boiling is a very efficient heat transfer mechanism with a large heat transfer coefficient and it is widely found in industrial systems. However, boiling heat transfer is limited by the critical heat flux (CHF), also termed as boiling crisis. It leads to a rapid decrease of the heat transfer coefficient in temperature controlled heat transfer or to a significant jump in heater surface temperature in power controlled heat transfer cases. While the earlier effect clearly lowers efficiency the latter may even jeopardize safety. A clear understanding of the basic mechanisms leading to CHF is still lacking. In this paper a new model of priori critical heat flux (CHF-) is derived from the bubble dynamics of nucleate boiling. It holds for pool boiling and forced convective boiling and incorporates a mutual effect model and a shear stress model. The comparison between predicted and experimental results under different thermal hydraulic conditions shows a good agreement. The model is capable to explain the initiating mechanism of the boiling crisis and impacts from different variables. It can be also implemented as a sub-model in CFD codes.

1. Introduction

Depending on the wetted surface fraction, boiling can occur in three modes: (partial and fully developed) nucleation boiling, transition boiling and film boiling [1]. Nucleation boiling is most efficient and associated with a very large heat transfer coefficient due to two effects: frequent wetting and de-wetting of the wall by liquid and convective transfer of steam into the bulk fluid by departing bubbles. Transition boiling occurs from the critical heat flux point (CHF) where part of the surface starts to be irreversibly covered by vapor. From then on, the heat transfer coefficient begins to decrease for temperature controlled heat transfer under unstable conditions until all the heated wall is fully covered by vapor. This is then referred to as film boiling. For power controlled heating, a sudden drop of the heat transfer coefficient leads to a rapid increase of wall temperature, which potentially leads to heater meltdown. Understanding and predicting the complex phenomena involved in CHF is necessary for the efficient and safe operation of industrial heat transfer systems, like boilers, nuclear reactors, or electronics/microchips cooling systems. In the last decades, the mechanism for the transition from nucleation boiling to CHF and further to film boiling has been widely investigated. Different system variables affecting the CHF were already identified and analyzed: pressure [2–5], local liquid subcooling [2,6–8], mass load (in subcooled flow boiling) [9–12], heated wall length, hydraulic diameter (in subcooled flow boiling) [13,14], wettability, roughness and porosity [15–17]. Further different theoretical models to describe the CHF, such as the Hydrodynamic Instability Model [18–22], the Near-Wall Bubble Crowding Model [23,24], the Liquid Sublayer Dryout Model [25–28], Bubble interaction theory [29] and others [34] were also developed and compared with experiments. The most widely accepted CHF model are two hydrodynamics instability model at present: the hydrodynamics instability model proposed by Zuber [21] and Liquid Sublayer Dryout model proposed by Haramura and Katto [26]. The hypothesis of the Zuber's model is that the down flow of fresh liquid to the heat surface is prevented by the upward flow of vapor due to the Helmholtz instability. According to Haramura and Katto's model, the CHF is also a result of the Helmholtz instability, the columnar structure of vapor stems collapses with a vapor film blanketing a thin liquid film on the heater surface. These models are widely recognized and validated with experimental results. However if CHF is only due to hydrodynamics, it is difficult to explain the influence of the heating wall conditions (roughness, wettability, thickness, material and so on) on CHF. The other problem of the present CHF models is that the occurrence of the burnout is always treated as independent of the nucleate boiling process. Sadasivan et al. [30] concluded that due to CHF occurs as the upper limit of the nucleate boiling region, it is reasonable to expect that

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the different physical phenomena involved in the nucleate boiling region should interact such that CHF value. A realistic CHF model would be one that is a natural outcome of the description of the high heat flux nucleate boiling region. In 2009, Kolev [29] tried to build a theory to connect the nucleation boiling and CHF. He includes the effect of the shear force generated by mutual interaction of growing and departing bubbles. This shear stress shortens the bubble life cycle, reducing the bubble departure diameter which reduces the latent heat removal per bubble cycle. When this effect becomes dominant, the CHF is approached. However, the influence of the heating surface is still missing in this model except contact angle (wettability).

Today, the assessment of system designs with respect to promotion or prevention of CHF is still based on expensive experiments. Many correlations developed from such experiments have been applied in some specific 1D codes for engineering design. However, these correlations are only valid in a limited scope of applications. Computational fluid dynamics (CFD) is an attractive way to support engineering design by 3D flow simulation in the future. It would be beneficial, if occurrence of CHF could be simulated with CFD codes. However this requires a CHF model which can clearly explain the CHF initiation mechanism from nucleation boiling. Consequently, a successful CHF model should at least:

a) be able to consider both pool boiling and flow boiling;
b) be time and position dependent to explain the local wall temperature fluctuation;
c) be able to consider the effects of wall superheat and the CHF initiation mechanism;
d) cover the effects of the surface parameters;
e) be suitable to be implemented in a CFD code.

These criteria were also partly mentioned in Zhao's work [32]. In this study we analyzed the complex mechanisms of cavity activation and heat transfer in the nucleate boiling process. From this analysis, a model of priori critical heat flux (CHF-) is inferred. Further this model is developed into formulae for pool and forced convective boiling. The calculation results are compared with experimental results from different experiments for validation.

This work applies part of idea from bubble interaction theory. Instead of pure mutual effect of bubbles, we pay attention on the thermal effect during nucleation boiling on/in the wall. We also considered the mushroom structure of bubbles appear near the CHF which is well observed by experiments but with columnar of isolated bubble between the mushroom shaped bubble instead of the stem introduced by Liquid Sublayer Dryout model. Different to total sublayer dryout mechanism, we consider the columnar of bubbles dominate the CHF. This work doesn't contrary to the previous founding such as the irreversible dry spot in experiments [31,37], because we pay attention on the priori critical heat flux where the system still have stable bubble generation when the wall temperature starts to climb. When the temperature continues climbing up to certain level like introduced ~134 °C in the experiment from Kim [31] (water horizontal pool boiling at 1 atm), the irreversible dry spot will be formed. In the other word, lower than this temperature, the wall surface still has chance to be rewetted. In this work, we try to explain why even the rewetting does not stop the temperature climbing until irreversible dry out is formed and CHF is approached.

2. Results and discussion

2.1. Concept

In this paper we fundamentally consider the bubble growth process in nucleation boiling as a stable and repeating process, which consists of cavity activation, bubble growth, bubble departure and associated surface rewetting. This concept is widely accepted and has been described in many other papers [24,36,48]. In the following we will derive our CHF- model by considering in detail characteristic durations, heat fluxes, and temperatures of wall, steam and bulk liquid for the different phases in nucleate boiling. While our analysis incorporates some models developed by other researchers, the key novelty of our approach is that CHF is considered as being initialized from nucleation on/in the wall and dealing with the recovery of cavity activation and thermal layer.

A commonly accepted prerequisite of nucleate boiling is the existence of nucleation sites, which are assumed to be small micrometer size cavities in the wall. It is further assumed that in the period of rewetting after a bubble departure there is always a tiny amount of vapor remaining captured in the cavities. We need to note here, that this is a model only, but one which is strongly supported by observations [33–35]. The model assumptions for activation of a bubble are as follows.

The gas pocket in a cavity is considered as the seed for the subsequent bubble growth. It is at pressure

$$p = p_0 + p_S = p_0 + \frac{2\sigma}{r_c}. \tag{1}$$

with p_0 being the pressure in the bulk liquid, p_S the Laplace pressure of the gas-liquid interface and r_c is the critical nucleus radius for bubble grows. The heater wall is superheated at temperature $T_{wall} = T_y(0) = T_{sat}(p_0) + \Delta T_{sup}$ and has an exponential temperature profile into the bulk liquid. In the second stage, called bubble growth, the overheated gas pocket in the cavity is further fed by evaporating liquid from the superheated liquid in the thermal boundary layer. When the bubble is still small, its growth in diameter is quite fast and determined by the inertia of the liquid being displaced. Hence this period is referred to as inertia-controlled growth. As near-wall shear stress hinders displacement of liquid in the very vicinity of the wall, a small micrometer size layer of liquid remains at the wall underneath the bubble. It is referred to as micro-layer. As superheat is highest in this layer, it subsequently contributes a lot to evaporation and disappears with time. After a while the growth of bubble diameter becomes slower and it is no longer limited by liquid displacement but by evaporative heat flux and hence heat flux through the gas-liquid interface. This period is referred to as thermal diffusion controlled growth. The third stage of the bubble cycle is bubble departure from the wall, which may be preceded a sliding motion along the wall. Immediately after bubble departure liquid from the near wall region replaces the disappearing gas volume. This is the fourth phase, or quenching phase. As the replenishing liquid is on average cooler than the unaffected liquid portions near the wall it needs to be reheated such that the thermal boundary layer over the wall is restored. All the stages have certain durations. Most important is the total growth period t_g and the waiting time t_w between bubble departure and new activation.

The above description of the bubble cycle is state of the art. In the following we will further develop this concept by bringing effects in the wall around the cavity into play. In the following we will qualitatively describe our concept and in the next sections derive equations to quantitate the effects.

Firstly we define the relevant heat fluxes. The total transferred heat Q_b during bubble growth consists of three parts: heat flowing from the wall into the bubble via evaporation $Q_{b,w}$, heat flowing from the superheated liquid near the wall into the bubble $Q_{b,s}$ and condensation heat loss at the upper part of the bubble $Q_{b,c}$, that is, heat flowing out of the bubble into the bulk liquid. The importance of this concept lies in the fact that the bubble growth is fed with heat from two sources, the wall and the thermal boundary layer, though we cannot say for the moment, how the share is quantitatively. After bubble departure, a waiting time is required to reform the nucleus in the cavity and to recover the thermal layer, that is, to recover the consumed heat in the bulk. During this period of quenching, the heat Q_q will be delivered from wall to the liquid. As during bubble growth the liquid in the