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Critical heat flux as a mass flux dependent local or global phenomenon: Theoretical analysis and experimental confirmation

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ABSTRACT

In this article, we report on a theoretical analysis and experimental investigations on critical heat flux (CHF) in subcooled flow boiling. Commonly, CHF is considered as a local phenomenon. A validated CHF- concept recently developed in our group indicated that CHF may be initiated in two different ways, that is, locally and globally. We designed and conducted an experiment to verify this hypothesis. The experimental results agree well with the expectations from our CHF- modelling and confirm the two mechanisms. Following that, we continued to clarify the role of different parameters, such as channel orientation, channel length and hydraulic diameter. The new concept of CHF is useful to explain and predict CHF at conditions of low pressure and low fluid velocity.

1. Introduction

Subcooled flow boiling is one of the most efficient ways to transfer heat, as it combines the uptake of latent heat by bubbles, convective heat transfer via bubble motion and an effective mixing in the thermal boundary layers. However, when the heat flux reaches a critical value, the so-called Critical Heat Flux (CHF), nucleate boiling turns into film boiling. There, parts of the heater surface become irreversibly covered by a thin vapor blanket, which lowers the heat transfer drastically [1] (Fig. 1). In power-controlled systems this may jeopardizes the safety as it can potentially lead to a meltdown of the heater. Because of this, the transition from nucleate to film boiling at CHF is still a topic of intense scientific investigation. Though many experimental studies and mechanistic models do exist, a comprehensive understanding of CHF has not yet been achieved. One difficulty comes from the fact, that an optical observation of critical heat flux on metallic heater surfaces is problematic, as the heavy pre-CHF boiling makes the heat transfer fluid opaque and further harsh pressure and temperature conditions hamper the application of measurement techniques.

From many experimental studies it is known that a number of system parameters, such as channel orientation, channel length and hydraulic diameter have a different influence on the CHF under high and low mass flux in flow boiling. However, mechanistic models [2–5] do not consider such effects. In our opinion, the reason for that is that present mechanistic models do consider CHF as a local phenomenon. Our recent analyses, however, indicate that CHF may occur in two different ways, namely in a local and a global one, which should be dependent on the system's mass flux. Local occurrence is happening at low mass flux while at high mass flux CHF appears globally. In this article, we report on a theoretical and experimental study to clarify this issue. Before that, we will firstly give a brief introduction of common knowledge and recent findings in the field.

1.1. Impacts of various parameters on CHF

In 1963, Bergles [6] identified six main system parameters affecting the CHF: pressure (p), liquid subcooling (ΔT_{sub}), mass flux (G, in subcooled flow boiling), channel length (L), hydraulic diameter (D) of channel (in subcooled flow boiling) and channel orientation (ϕ). He reported that the pressure has a rather weak influence on CHF. That is, for forced convective boiling of water CHF increases around 17% when the pressure changes from 0.14 MPa to 0.6 MPa. Vandervort et al. [7] and Celata [8] claimed that the pressure has even no significant effect on CHF when it is below 2.5 MPa. Sakurai and Shiotsu [9] did experiments to investigate the impact of subcooling on CHF. They found a linear relationship between CHF and subcooling in the entire subcooling region up to saturation. They concluded that the CHF increases with an increase of subcooling in horizontal and vertical pool boiling. Gunther [10] found for flow boiling of water in a rectangular section that CHF also has a linear relationship with subcooling. Bergles found a similar effect but only at relatively high subcooling. Celata and Mariani [2] conducted experiments to study the impact of mass flux on CHF. They indicated that high mass flux could lead to higher CHF, which was widely agreed by others [11–13]. Bergles experimentally observed an

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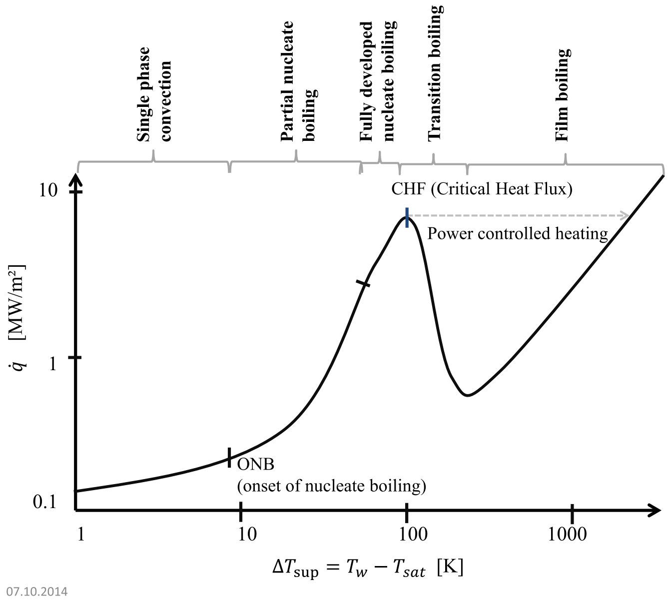

Fig. 1. Exemplary boiling curve showing the transitions from single-phase convection to film boiling.

impact of the pipe diameter (D) on CHF. He stated that CHF increases with decreasing D. However, this effect becomes less significant for hydraulic diameters above 5 mm. Nariai et al. [3], and Nariai and Inasaka [4] conducted experiments to investigate the effect of the channel length (L) and channel diameter (D) on CHF. They found that at high mass flux, CHF increases when both channel diameter and length decrease. However, at low mass flux, both effects become insignificant for sufficiently high values of L and D. They also found that CHF values are higher at high mass flux and at low mass flux with small L and D. Buoyancy and channel orientation also influence CHF. Pappell et al. [5] demonstrated in experiments with liquid nitrogen in a 12.5 mm diameter tube that buoyancy only plays a role for low mass flux. Celata and Mariani [2] found that the channel orientation plays a role only when mass flux is small. They proposed a criterion based on the comparison of the buoyancy to inertia forces basing on the modified Froude number

$$Fr = \frac{G\cos\phi}{\rho_l\left[gD\left(\frac{\rho_l-\rho_g}{\rho_l}\right)\right]^{1/2}}, \quad (1)$$

where G is the mass flux, ϕ is the orientation angle, ρ_l and ρ_g are the liquid and vapor density, g is the gravitational acceleration and D is tube diameter. They concluded that the effects due to orientation only appear when the modified Froude number is smaller than 5. While the dependency of CHF on the above parameters is well recognized, the mechanisms are still not fully included in the mechanistic models of CHF.

1.2. Mechanistic models and correlations

At present, the most popular mechanistic models of CHF can be classified into four categories [2,13]: the *hydrodynamic instability model*, the *model of critical enthalpy in the bubble layer*, the *model of vapor removal limit and near-wall bubble crowding model*, and the *liquid sublayer dryout model* (Fig. 2). Kutateladze [14] and other researchers [15,16] hypothesized that CHF of saturated horizontal pool boiling is a purely hydrodynamic phenomenon and that it is triggered by a destruction of the stability of the two-phase flow occurring close to the heated surface (Fig. 2a). In 1966, Ivey and Morris [17] further extended this model for subcooled boiling. The '*model of critical enthalpy in the bubble layer*' was proposed by Tong et al. [18]. They considered that a bubbly layer near the heater surface could trap the liquid in between. CHF is reached when this liquid layer attains a certain limiting enthalpy (Fig. 2b). The '*bubble crowding model*' was proposed by Hebel et al. [19] who considered the limit of the turbulent interchange between the bubbly layer and the bulk of the liquid and inferred that crowding of the bubbles prevents the liquid access to the heater wall (Fig. 2c). Weisman and Pei [20] further quantified this model by the assumption that CHF occurs when the volume fraction of vapor in this bubbly layer exceeds a critical volume fraction of 82%. This definition is based on their experimental observations. The '*liquid sublayer dryout model*' was proposed by Katto and Yokaya [21] and further developed by Haramura and Katto [22], Lee and Mudawar [23] and Celata et al. [24]. This model assumes that a liquid film forms near the heater wall because of a Helmholtz instability (Fig. 2d) and CHF is reached when the heater can provide the necessary latent heat to completely evaporate the liquid entering the film between the liquid sublayer and wall. All these models can to some degree achieve agreement with experimental data, but they contain quite a few empirical constants or empirical correlations [13]. As many of these model concepts and correlations are for subcooling boiling at high pressure and high velocity (HPHV) they typically produce larger disagreement at low pressure and low velocity conditions [12]. Moreover, the existing model concepts do mostly not contain the dependencies on the above-mentioned system parameters, such as channel orientations, channel length and hydraulic diameter on CHF at low and high mass flux.

2. CHF- concept and model

Recently, we developed a model of prior critical heat flux (CHF-) from the models of bubble dynamics at nucleate boiling [25]. It holds for pool boiling and forced convective boiling and incorporates a mutual effect model and a shear stress model. The model is capable to explain the initiation mechanisms of the boiling crisis and impacts of different variables. In the following section, the main idea of this CHF-concept will be briefly introduced.

The bubble growth at a small cavity in the heater wall is considered as a stable and repeatable process which consists of activation, growth, departure and reactivation with certain durations (Fig. 3). Most important periods are the total growth period t_g and the waiting time t_w between bubble departure and new activation. 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 transfer to the bulk liquid at the upper part of the bubble ($Q_{b,c}$). That is, the heat input to the bubble comes 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 regenerate the nucleus in the cavity and to recover the thermal layer. In this time, the quenching heat Q_q is delivered from the wall to the liquid. As during bubble growth the liquid in the vicinity of the bubble has gained the heat $Q_{b,c}$ and lost the heat $Q_{b,s}$, we may assume that $Q_q = Q_{b,s} - Q_{b,c}$. The heat balance can then be written as

$$Q_{b,w} + Q_q = Q_{b,w} + Q_{b,s} + Q_{b,c} = Q_b = \frac{4}{3}\pi r_d^3 \rho_g h_{fg}, \quad (2)$$

with h_{fg} being the latent heat of the fluid.

Then we define the projective area $A_b = \pi r_d^2$ of a fully developed bubble with departure radius r_d as the apparent heat transfer area for boiling heat transfer per single bubble. The heat flux in this area during bubble growth is then

$$\dot{q} = \frac{Q_{b,w} + Q_q}{\pi r_d^2 (t_g + t_c + t_w)} = \frac{Q_b}{\pi r_d^2 (t_g + t_c + t_w)} = \frac{\left(\frac{4}{3}\pi r_d^3 \rho_g h_{fg}\right)}{\pi r_d^2 (t_g + t_c + t_w)}, \quad (3)$$

where t_c is the condensation time which is only for the case where the bubble will activate, grow, shrink and collapse on the cavity in high