CFD Model for Critical Heat Flux during Subcooled Flow Boiling Condition

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ABSTRACT

A new CFD model for calculation of local critical heat flux (CHF) is presented. It is based on Zuber [1] and Haramura and Katto [2] correlation, which postulate hydrodynamic instability as the governing mechanism for CHF calculation. The mechanistic, averaged approach with considerable experimental background was modified so as to take into account the local flow conditions in the near wall region. In this way, the model becomes universal as it is based on local phenomena rather than on averaged values. Indeed, liquid velocity gradient obtained from wall shear stress and modified Jacob number are both introduced in the laminar sublayer region to account for convection and subcooling respectively. Besides, the introduced Prandtl number is associated to the deduced ratio of the hydraulic diameter and heated length. Finally, the interpretation of local mechanisms has been critically assessed throughout the text illustrated with general trends from other CHF correlations.

1 INTRODUCTION

Flow boiling process is associated to one of the most effective set of mechanisms that are governing the convective heat transfer. It is characterized with extremely high heat transfer coefficients during the phase change and nearly constant temperatures, which come from a significant amount of latent heat involved in the process. However, the pronounced characteristic of the boiling process is a distinct maximum in the heat flux removal capability versus the saturation temperature overheat, followed by an abrupt decrease in heat transfer coefficient. Therefore, heat flux controlled systems must normally avoid approaching this point (the critical point) as the transition is subject to an uncontrolled increase of wall temperature that may eventually lead to a system failure. In order to avoid exceeding the critical point, different prediction models have been used both to enhance the maximum thermal power of the system and to avoid the burnout-associated issues. The problem is that the correlations based on macro-hydrodynamic theory cannot be applied straightforwardly to CFD model as approaches are based on two different scales of observation. A good CFD model must be consistent for each and every cell, in particular within the boundary layer as information is passed from one cell to another. There the same averaged values may result in completely different thermal-hydraulic local conditions leading to significant variations in CHF prediction. Nevertheless, a substantial number of influential parameters make a reliable prediction of the critical heat flux even more challenging. In fact, there are several mechanisms believed responsible for effective boiling heat transfer, which is mostly controlled through the following essential parameters:
• fluid properties,
• surface treatment and superheating,
• reduced pressure,
• sub-cooling,
• forced convection,
• heated geometry, length and orientation,
• thermo physical properties and thickness of the heater.

1.1 Fluid Properties and Surface Treatment

Fluid properties can affect critical heat flux from different reasons. One is related to the difference in latent heat of vaporization among various fluids. Namely, the bigger is the latent heat of vaporization, the higher is the CHF. Indeed, smaller amount of vapour is generated at the reference heat flux, which facilitates the fresh liquid to quench the active surface. The boiling surface is thus sufficiently cooled while bubble crowding is not an issue due to the relatively smaller amount of generated vapour. Consequently, higher heat flux can normally be removed from the heated surface when higher latent heat of vaporisation is applied.

The second reason is attributed to the surface tension, which tends to increase the superheating temperature and also the bubble departure diameter. The significant increase in wall superheat particularly on smooth surfaces comes from the size of the cavities that become active nucleation sites. The smaller the cavity, the higher the temperature on the wall is required to overcome the saturation pressure within the bubble inception. Therefore, it directly affects temperature field in the boundary layer as well as bubble release frequency leading to a notable change in heat partitioning. Since superheating depends mostly on surface treatment, rather than being governed by the fluid properties only, it is also the subject to aging. Therefore, to meet a long term system requirements, surface aging and fouling has to be taken into consideration already in the early stage of the component design.

Another important transport property is the liquid viscosity. As indicated in its name it plays its important role only in convective terms. It is co-responsible for drag force and turbulence intensity and thus for velocity gradient within the laminar sub-layer.

On the other hand various fluids have different contact angles on different surfaces. It is the measure of surface wettability, which indeed may represent a significant obstacle in surface heat transfer during phase change. Moreover, elevated contact angles (liquid repellent surface) in conjunction with increased surface tension tend to keep generated vapour widespread on the boiling surface, preventing liquid from rewetting the dried slugs. Elevated void fraction near the wall eventually leads to an early CHF as heat from the surface cannot be efficiently transferred through the vapour layer.

1.2 Reduced Pressure

There are also other physical mechanisms affected by the change of liquid properties, which are either not addressed to take an essential part in phenomenon description or they are associated to a different parameter such as reduced pressure.
Figure 1: Critical heat flux (by Zuber [1], Haramura and Katto [2]) versus reduced pressure calculated for HFE7000, different geometries and flow conditions

Saturation temperature and thus the reduced pressure have crucial impact on controlling CHF. There are two most important effects that are significantly influenced by the system pressure. The first is the vapour density, which increases with pressure, meaning that the same mass of vaporized water can be compressed to a smaller volume. It directly reduces the void fraction near the wall as well as pressure losses during the vapour flow. However, excessive increase in saturation pressure has a drawback related to the decrease of latent heat of vaporization at elevated pressures. In fact, when approaching critical pressure, the vapour to liquid density difference as well as latent heat of vaporization are becoming nil, which is making the evaporation heat transfer ineffective. Thus, there is an optimum value for reduced pressure that provides conditions for maximum CHF (Figure 1). It is shown, that enhancement with proper setting of saturation pressure is achieved for all heating geometries and orientations used in the calculus.

1.3 Sub-cooling

Sub-cooling can be controlled directly by controlling the fluid temperature supplied to the boiling surface. It adds sensible heat transfer to a phase change, which enhances overall heat transfer and CHF. However, sub-cooling must, in most systems, be kept under certain limits due to thermal fatigue associated to temperature oscillations. Besides, the nature of optimized process engineering rarely allows significant sub-cooling unless required otherwise by given technology.

1.4 Forced Convection

In order to infer the significance of the local convective flow mechanisms to the increased CHF, simple flow path geometry was adopted in the study. While keeping all the parameters constant, the effect of the velocity gradient in the near wall region was studied systematically. In this respect, critical heat flux models by Haramura and Katto [2] have been plotted versus free stream velocity for two different geometries (Figure 2). One can see that critical heat flux can be notably enhanced by increasing the velocity streaming along the boiling surface. The CHF dependence vs. velocity seems to follow exponential function with exponent less than 1.
Based on simplified calculation approach of the tangential velocity in the turbulent boundary layer, the velocity gradient in the laminar sub-layer can be calculated from the free stream velocity (Eq. 1). Herein, free stream velocity refers to tangential velocity at $y^+=250$.

$$\frac{du}{dy} = \frac{1}{\nu} \left( \frac{U_\infty}{1/\kappa \cdot \ln(250) + B} \right)^2$$

(1)

By taking into consideration Figure 2 and equation 1, where the velocity gradient in the laminar sub-layer is a square function of the free stream velocity, it is soon understood that CHF enhancement by convection is the most efficient at low absolute velocities.

### 1.5 Geometry, Length and Orientation

Figure 3: Critical heat flux (by Haramura and Katto [2]) versus size of the heated surface (left) and heated length (right) for different geometries and reduced pressure 0.25
Due to different scales of observation, it is difficult, if not impossible, to deduce generalized CHF correlation, which would predict critical heat flux equally well for all test conditions. An error that depends on boundary conditions is introduced by averaging itself. Therefore, rather than looking for generalized correlation, authors have proposed different models for calculation of CHF over a limited range of test conditions. Indeed, different correlations were developed for different geometries (Figure 3) and flow conditions such as: horizontal flat plate [1], horizontal heated cylinder, vertical ribbon, small heated disc (d<Taylor wave) [2] as well as mini and micro-channels [3].

1.6 The Heater

Some models consider surface characteristics as one of the essential set of parameters for pool boiling CHF prediction (Malyshenko et al. [4], Ferjancic and Golobic [5], Dinh et al. [6]). Some other authors have made even a step further. Bicard [7] for example, developed a CHF model that assumes local wall temperature increase, during drying phase of the nucleation cycle of a single bubble, beyond the temperature at which the liquid could rewet the surface after the bubble detachment. Insufficient cooling is followed by the dry spot spreading out on the wall. In this model, not only surface characteristics are being examined but also thermo-physical properties of the wall material with effective thickness are taking crucial part in the calculus. Indeed, the wall is divided into several zones, which play their active part in bubble dynamics with corresponding heat transfer.

2 MODELING

Modelling heat transfer mechanisms during nucleate flow boiling from its incipience to the second transition region is subject to highly diverse flow patterns. Appropriate consideration of all aforementioned parameters and more are required to adequately account for individual heat transfer and fluid flow mechanism. One can hardly find any similarity between bubble dynamics during discrete bubble formation and intense evaporation where intermittent dry spots and unstable slugs of vapour take place in a rather erratic manner. However, departure from nucleate boiling (DNB) phenomenon comes with a culmination of the heat transfer coefficient followed by its rapid deterioration. Further increase in heat flux eventually leads to an abrupt drop in heat transfer coefficient that is reflected in a sudden increase in wall temperature.

An attempt has been made to provide a numerical model for calculation of the local CHF. CFD alternative approach is derived from Haramura and Katto [2] correlation (Eq. 2), which postulates Taylor and Kelvin-Helmholtz hydrodynamic instability as the governing mechanism for CHF calculation [1]. This particular expression was developed for calculation of the critical heat flux during forced convective boiling along a flat plate heated onto a certain length. It is based on a “far field” model by Zuber [1], who attributed the responsible mechanisms for DNB occurrence to the hydrodynamic instability.

\[
q_{CHF} = 0.175 \cdot G \cdot l \left( \frac{\rho_v}{\rho_L} \right)^{0.467} \cdot \left( 1 + \frac{\rho_v}{\rho_L} \right)^{1/3} \cdot \left( \frac{\sigma \cdot \rho_v}{G^2 \cdot L} \right)^{1/3}
\]  

(2)

Herein, G stands for average mass velocity, l for the specific heat of evaporation, \( \rho \) for density, \( \sigma \) for surface tension while subscripts L and V refer to liquid and vapour respectively. Because the correlation is given for the average free-stream flow properties and for rather simple geometry it gives a good perspective of the local flow conditions from the bulk flow point of view. In other words, simple flow and (heated) wall geometry conditions allow us to
assume local fluid flow conditions with a considerable confidence. As most of the heat transfer phenomena take place in the region at the near proximity to the heated wall the CFD modelling offers a good alternative for their calculation. Liquid velocity gradient obtained from the wall shear stress was thus introduced in the laminar sub-layer region to account for convection. Herein, the mass velocity was expressed in terms of velocity gradient in the laminar layer. The gradient was derived from the wall function for the viscous layer where the shear velocity was obtained from the wall shear stress along the smooth wall (Eq. 3). By replacing the averaged mass velocity with the near wall velocity gradient, though derived from well-known geometry, the correlation becomes less geometry dependent. Moreover, CHF conditions were derived from the information available on the correspondingly small scale rather than from the averaged test parameters.

\[
\frac{du}{dy} = \frac{8 \cdot v_w}{d_h} = \frac{8 \cdot G}{d_h \cdot \rho_{mean}}
\]  

(3)

Modelling approach initially proposed for pool boiling CHF is here used for forced convective phenomenon calculation at low vapour quality. Therefore, average fluid density used to calculate near wall velocity gradient from the mass velocity is considered equal to the liquid density \((\rho_{mean} \sim \rho_L)\). The characteristic length \(d_h\) of the fluid flow depicts the tube diameter for pipe flow whereas the length from the edge of the developing region and thus thickness of the hydraulic boundary layer along the wall is assumed relevant in the present study. On the other hand, the equation 2 takes into account the effect of the heated length as well. It has been shown that the critical heat flux is suppressed by the geometry size of the heater (Figure 2) due to difficulties related with heat removal capabilities from large surfaces. However, the quotient of the two lengths has been here interpreted as the ratio of the relative thicknesses of the momentum and thermal boundary layers i.e. the Prandtl number. Despite some strong assumptions considered here, there is a sound physical background why Pr could be adopted for calculation of the CHF. At small Pr, the heat diffuses very quickly as compared to the momentum, which means that the thermal boundary layer is much bigger than the velocity boundary layer. In fact, not only better heat diffusion but also bigger velocity gradients are acting on generated bubbles in the near wall region (Eq. 4).

\[
q_{CHF} = \frac{7}{80} \cdot L \cdot \left( \frac{\rho_v}{\rho_L} \right)^{0.467} \cdot \left( \rho_L + \rho_v \right)^{1/3} \cdot \left( \frac{d_h}{L} \right)^{1/3} \cdot (\rho_L \cdot \sigma)^{1/3} \cdot \left( \frac{du}{dy} \right)^{1/3}
\]  

(4)

Because the two boundary layers can develop independently, introduction of the dimensionless number “Pr” may not be the best possible interpretation for the developing flows. Besides, the Haramura and Katto’s correlation was developed for saturated flow though it neglects the effect of liquid subcooling and wall superheat. Due to the local increase of the critical heat flux as a result of the subcooled liquid presence in the near wall region, the present authors introduced new corresponding term with the adoption of the Jacob number. In addition to the latent heat of vaporisation during boiling process, it accounts for a sensible heat flux due to the local subcooling. In this respect, \(Ja^*\) stands for subcooled Jakob number (with \(\Delta T= T_s - T_f\) where \(T_s\), \(T_f\) and \(T_w\) refer to saturation, fluid and wall temperature respectively. Nevertheless, not only subcooling but also superheating is taken into account during local CFD calculation of the critical heat flux (Eq. 5).

\[
q_{CHF} = K \cdot L \cdot \left[ 1 + \left( \frac{1}{Ja^*} + \frac{(T_w - T_f)}{(T_s - T_f)} \right)^{-1} \right] \cdot \left( \frac{\rho_v}{\rho_L} \right)^{1/2} \cdot (\rho_L + \rho_v) \cdot \rho_L \cdot \sigma \cdot Pr^{1/3} \cdot \left( \frac{du}{dy} \right)^{1/3}
\]  

(5)
In contrast to the existing DNB triggering mechanisms depicted in NEPTUNE_CFD code where local criterion of void fraction above 0.82 is used, the present model follows the idea of the Taylor wavelength instability adopted from the Zuber [1] model and the macro-layer vaporisation adopted from Haramura and Katto [2] model. Finally, the present correlation resembles the properties of a “near field” as it refers to the modelling in the immediate proximity to the wall.

3 CONCLUSION

An attempt to model the critical heat flux on CFD scale has been here presented. Well established CHF correlation by Haramura and Katto [2] has been modified to take into account the local fluid properties and local flow conditions for CHF calculation. Rather than offering results based on averaged properties of the fluid flow along the heated geometry, the correlation was meant to provide local and instantaneous values of the critical heat flux. In this way the CFD model becomes universal since local flow conditions are governing the phenomena. Mechanistic, averaged approach accounts for fluid properties, reduced pressure, subcooling and superheating. However, additional work is required to set free coefficient properly, to account for thickness, material and surface treatment of the heater, gravity effects as well as heat flux enhancements brought up with nanofluids. Validation tests carried out in wide range of test conditions are required before final correlation for CFD calculation of the critical heat flux could be proposed with reasonable accuracy.

REFERENCES


