Analysis of the Mechanistic Critical Heat Flux Models for Downward Facing Boiling Heat Transfer

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1. Introduction

An upper limit of nucleate boiling heat transfer is determined by the critical heat flux (CHF), which is a key parameter in evaluating cooling capability of two-phase thermal-hydraulic system. Thus accurate prediction of the CHF has been one of the most important research subjects in heat transfer engineering. To explain the CHF phenomena, numerous empirical correlations and mechanistic CHF models were developed based on theoretical basis. However, it should be noted that accuracy of the empirical model cannot be assured for extrapolative purposes. In addition, when empirical correlations are used to determine the safety margin, highly conservative conditions should be adopted.

In consideration of weakness of empirical correlation, the mechanistic modeling of the critical heat flux with high accuracy is of importance in minimizing unnecessary conservatism and corresponding cost required.

Thus the objective of this study is to identify certain strengths and weaknesses of existing mechanistic models of the CHF, and to find an appropriate model applicable for the ex-vessel core catcher cooling system proposed by Song et al. [1]. Subsequently, CHF values predicted from the examined models were compared and evaluated based on experimental CHF data obtained from this study.

2. Literature review on the CHF models

In this paper, two basic concepts of the CHF triggering mechanism applicable for downward facing flat heater surface are described as follows:

- Near-wall bubble crowding model
- Liquid sublayer dryout model

The mechanistic CHF model should be capable of accommodating the observed bubble behavior of the heat transfer system, where vapor is attached to the surface by buoyancy force and accordingly obstructs the replenishment of liquid.

Among known mechanisms, liquid sublayer dryout model has been a base model during the development of the mechanistic CHF model physically applicable for downward facing flat and large heater surface, where heat is removed by boiling process under relatively low flow velocity condition, i.e. thermal-hydraulic conditions in the ex-vessel core catcher system. The existing CHF models based on the aforementioned models under such conditions are described as follows.

With physically similar concept to that in the near wall bubble crowding model proposed by Weisman and Pei [2], Brusstar and Merte developed a CHF model for pool boiling covering downward facing heater surface condition using a small copper plate [3]. The equation of the CHF model can be expressed as follows:

$$q_{CHF} = \left(\frac{\pi}{24}\right)\rho_v h_{fg}\left[\sigma g\frac{(\rho_l-\rho_v)}{\rho_v^2}\right]^{1/4} \times\left[1+0.102\left(\frac{\rho_l}{\rho_v}\right)^{0.75}\frac{c_{pl}\Delta T_{sub}}{h_{fg}}\right]\left|\sin\theta\right|^{1/2} \quad (1)$$

The effect of orientation was incorporated in the model by balancing buoyancy and drag forces. Also subcooling effect on the CHF was incorporated by adding sensible energy, which is necessary to heat up the liquid from the subcooled to saturated state. But it should be noted that this model doesn't consider effect of the subcooling on the rate of vapor condensation into the bulk liquid, and correspondingly on the buoyancy force determined by length of bubble. Thus, this CHF model is anticipated to bear less accuracy for large dimension of heater surface, where bubble terminal velocity is highly dependent of the subcooling because size of vapor sliding along the heating surface heavily relies on the subcooling of bulk liquid.

Recently, on the basis of the bubble crowding model, a downward facing CHF model for subcooled flow boiling was presented to apply for curved channel under low mass velocity and pressure conditions for IVR-ERVC situation [4]. To extend Weisman and Pei's model from vertical to inclined flow, wall heat flux partitioning model was included using Bowring's pumping factor, which is suitable for low pressure condition for accurate calculation of flow quality in bubbly layer. In addition, bubble rise velocity was calculated considering the dependence of orientation angle on bubble rise velocity in the layer. The CHF trend predicted by this model along with the orientation agrees well with the results from Theofanous and Syri (1995) and Haddad et al. (1995). However, at around the orientation angle of 10 degrees and under low subcooling conditions, two-phase flow pattern was observed as slug flow, where significantly large vapor blankets slide along the heater surface periodically. Due to the discrepancy of the flow pattern between the model and physical observations, it is regarded that this model still has some room for improvement.

On the basis of the liquid sublayer dryout model, Cheung and Haddad developed a hydrodynamic CHF model for saturated pool boiling on a downward facing curved heating surface [5]. The special variation of the CHF along the vessel can be predicted through the model, which seems to be physically appropriate.

He et al. developed an analytic model of pool boiling CHF based on the same approach as Cheung and Haddad (1997) with modification of an expression for the local critical heat flux [6]. The CHF expression includes local bubble velocity in the two-phase boundary layer while Cheung and Haddad model contains local liquid velocity in the layer instead of the bubble velocity. Also, He et al. divide the CHF in two contributions. One is heat flux needed to evaporate the thin liquid film and the other is for the depletion of liquid replenishment. With this modification, the subcooling effect on the CHF can be applied to the model by modeling the subcooled liquid in liquid replenishment term.

For the purpose of application to CANDU calandria tube surface, Behdadi et al. recently developed a CHF model based on Cheung and Haddad model [7]. In their model, a model for wall heat flux partitioning was adopted to consider subcooling effect on the CHF. The wall heat flux consists of heat flux by single phase convective heat transport, evaporative heat flux, and quenching heat flux. The heat transfer coefficient for quenching was determined based on Podowski et al.'s study (1997). Notable modification is the modeling of relative motion between liquid and vapor phase based on two different approaches, e.g. Separated Flow Model and Drift Flux Model. In the modeling of the relative motion using Drift Flux Model, a specific flow pattern in the two phase boundary of interest can be selected among bubbly flow and slug flow. Additional notable modification is non-constant void fraction distribution along the heated surface by adding a liquid mass balance equation. The assumption of constant local void fraction adopted in the Cheung and Haddad model was abandoned. Their results presented that the spatial variation of CHF is sensitive to the abovementioned modifications, e.g. the modeling of the relative motion between vapor and liquid and the assumption of void fraction distribution in the two phase boundary layer.

Through the comprehensive analysis on the CHF models, we could confirm that most of models related to downward facing CHF were developed with the aim of application to the immerged downward facing curved surface, i.e. IVR-ERVC strategy. Lack of the CHF model applicable to the ex-vessel core catcher cooling channel motivates us to develop the mechanistic CHF model in which inclined downward facing flat and large heater surface is considered at low pressure and mass velocity.

Notable modeling of the CHF was made by Sulatskii et al. [8]. They performed CHF experiments under conditions of boiling on an inclined extended (1 to 2m) surface facing downward and immersed in a large pool of water. They show that the modeling of the subcooling effect on the CHF can be improved by considering effect of the subcooling on vapor mass flow rate along the surface by adding a term representing single phase heat transfer to the subcooled liquid in calculation of the vapor mass flow rate. Subsequently, the modified Froude number can be calculated based on the vapor mass flow rate, and directly used in the equation calculating the CHF value. This CHF model could successfully predict the anomalous dependence of subcooling degree on the CHF observed in their experiments. The explicit equation for the CHF can be expressed as follows:

$$q_{CHF}(\theta) = \sqrt{\sin\theta}\left(0.16 h_{fg}\sqrt{\rho_v}\sqrt[4]{\sigma g(\rho_l - \rho_v)}\right) \times \sqrt{0.50 + 0.0047\sqrt{\frac{\rho_l}{\rho_v}} + \left(0.07\frac{c_{pl}(T_{sat}-T_l)}{h_{fg}} - 0.0057\right)\frac{\rho_l}{\rho_v}\frac{c_{pl}(T_{sat}-T_l)}{h_{fg}}} \quad (2)$$

3. Experiment

For the development of the critical heat flux model applicable to the ex-vessel core catcher cooling channel, water boiling loop was constructed and flow boiling experiments has been carried out. In the design of the test section as shown in Fig. 1, following features were considered for the appropriate simulation of the specific CHF mechanism implemented in real application. Figure 2 presents the arrangement of the studs in case of square as well as detailed view of the test section which is inclined by 10 deg from horizontal plane with up flow.

- Downward facing boiling heat transfer
- Sufficient heating surface area
- Heating method: indirect heating
- High thermal inertia of the heater
- Aligned obstacles in the cooling channel

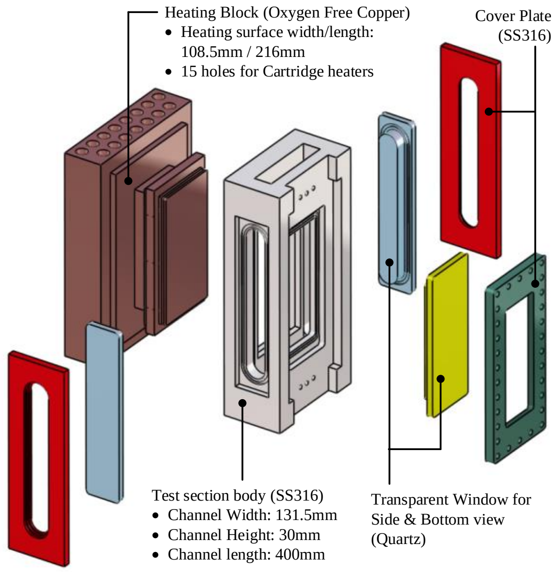

Fig. 1. Illustration of the test section assembly

4. Results and discussion

Local heat flux calculated from the set of aligned thermocouples was used to measure the CHF value, at which a sudden and continuous rise in the surface temperature beyond 170°C was observed simultaneously with abrupt decrease in the local heat flux following an incremental increase in the heater power. Due to fairly frequent appearance of reversible dry patches near the CHF, however, it is hard to measure definitive CHF value because local heat flux instantaneously drops with the transitory appearance of local dry patch. Thus in this study, the CHF was defined as an average of local heat fluxes, at which low peak (drop) of the surface temperature is observed during 1 minute before the CHF occurs.

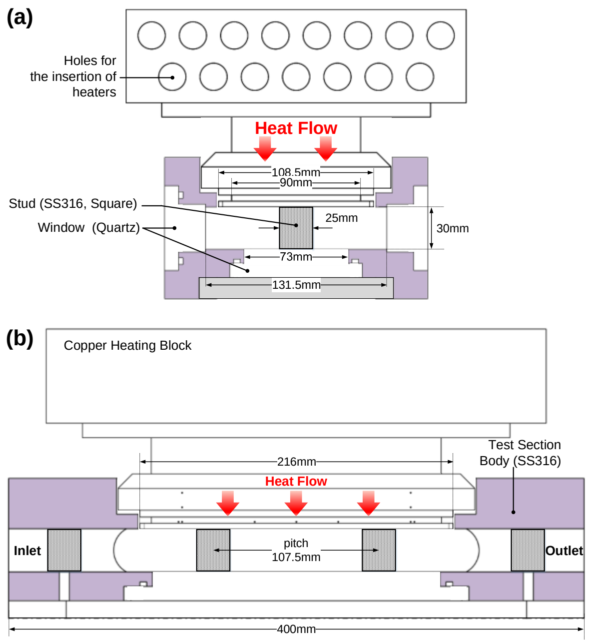

Fig. 2. Sectional views of test section with the aligned obstacles (stud); (a) transversal, (b) Longitudinal

Under low pressure (~108 kPa), mass fluxes of 210 and 40 kg/m^2-s were chosen to simulate forced convective and pool boiling conditions. Note that in the pool boiling condition buoyancy force is dominant compared with flow inertia force. The measured CHF data were compared with the examined models as following.

4.1. Flow boiling under near saturated condition

The CHF data have been obtained from the boiling loop at atmospheric pressure and low mass flux of 210 kg/m^2-s. Throughout the experiments, inlet subcooling was fixed at 5 K. The obtained data were compared with calculation results from the mechanistic CHF model developed by Park (2014) as shown in Fig. 3 [9]. Figure 3 shows that there is a significant difference in CHF values between the measured in this study and the predicted by Park et al.'s model. The discrepancy can be primarily explained by considering inadequacy of the empirical constants included in the model. The inadequacy is based on the fact that the empirical constants were determined based on the CHF data measured at above angle of 50 degrees and thus the CHF value predicted from the model may not be inaccurate under downward facing boiling condition.

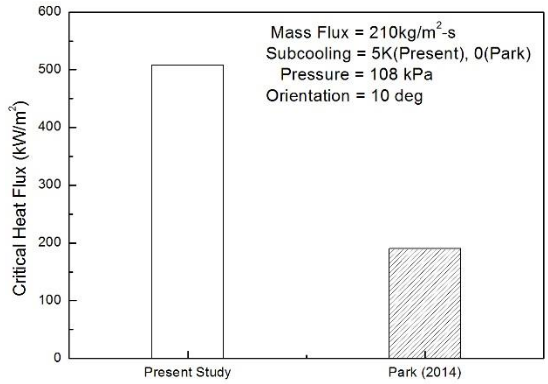

Fig. 3. Comparison of measured CHF with the model developed by Park (2014) under flow boiling

4.2. Pool boiling under near saturated condition

In experiments, inlet fluid velocity was maintained as 0.04 m/s and corresponding mass flux is 40 kg/m^2-s, which is close to pool boiling condition. As shown in Fig. 4, CHF values predicted from the existing models are all higher than the measured CHF value. This difference between the current experimental data and the CHF models can be explained by examining the base CHF data, with which the CHF models were developed. Brusstar et al. obtained their CHF data from the small-sized heater (19.1 × 38.1 mm^2) facilitating bubble escapes from heater surface to surrounding bulk liquid region and thus significantly higher CHF value could be obtained. Cheung and Haddad and He et al. used the SBLB CHF data obtained for downward facing on the exterior surface of a heated hemispherical vessel. In the curved channel, buoyancy force induced by vapor layer become stronger as the surface orientation angle increases from 0° (downward) to 90 ° (vertical). This implies that the vapor near the heating surface has higher velocity than the case of constant orientation angle of 10 degrees, e.g. present study and Sulatskii et al.

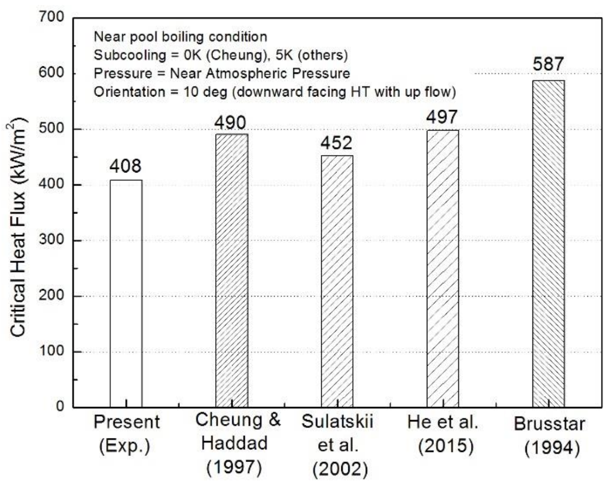

Fig. 4. Comparison of measured CHF with the models under pool boiling condition

4.3. Subcooling effect on the pool boiling CHF

The subcooling of 5, 10, 15 K were taken into account to investigate the effect of subcooling on the CHF. As seen in Fig. 5, there are two kinds of trend showing the subcooling effect. One is the linear relationship between the subcooling degree and the CHF as seen in studies of Brusstar (1994) and He et al. (2015). Another is the weak dependence of subcooling on the CHF. The CHF model of Sulatskii et al. predicts slight decrease in CHF with subcooling degree.

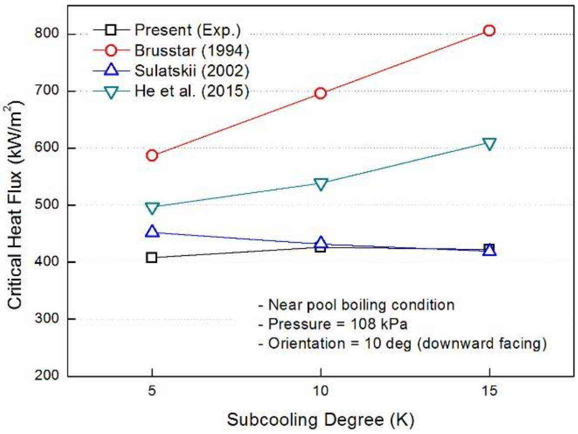

Fig. 5 The CHF variation with subcooling degree

As mentioned in Section 2, this difference in the trend can be explained by considering adverse effect of the subcooling on vapor mass flow rate along the downward facing surface of large area and constant orientation angle. In downward facing pool boiling condition, both the subcooling and boiling induced flow motion are interrelated with each other strongly because bubble size and its life time determine buoyancy force and they are highly dependent of the rate of vapor condensation into the bulk liquid. Considering clear proportionality between flow velocity and the CHF, results showing the latter trend can be explained with physical mechanism.

5. Conclusion

Present study has been carried out to find an appropriate model applicable for the ex-vessel core catcher cooling system, at which heat is removed by boiling process induced by natural circulation through downward facing flow channel. Major results from this study can be summarized as follows:

(1) Downward facing CHF models have been developed on the basic concepts of near wall bubble crowding and liquid sublayer dryout model
(2) Most of downward facing CHF models were developed for downward facing boiling on the exterior surface of a heated hemispherical vessel. It is confirmed that these models overestimate the CHF at orientation angle of 10^o when compared to CHF values under flat heater surface condition (e.g. the model of Sulatskii et al.) and CHF data obtained from this study.
(3) It is judged that there is no appropriate mechanistic subcooled flow boiling CHF model directly applicable for downward facing boiling under low flow velocity and low pressure conditions.
(4) The subcooling effect on the flow motion and associated CHF variation should be investigated thoroughly under flat heater surface of large scale and downward facing pool boiling conditions. Subsequently, modeling of the subcooling effect on the CHF should be improved considering interrelationship between subcooling degree and buoyancy induced flow motion.

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