Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

A Preliminary CHF Model Development and Data Comparison with Vertical Heaters under Pool Boiling Conditions

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1. Introduction

Critical heat flux (CHF) is one of major indicators to guarantee the safety of systems where boiling occurs. With development of observation techniques, physical explanations have been realized based on bubble dynamics. On this basis, bubble departure diameter, nucleation site density and other bubble-related parameters should be included to explain the phenomenon. In addition, prediction of the occurrence is also important when boiling systems are designed or thermal margin should be looked through. For wide applicability, physical meaning should be integrated in the predicting techniques. Therefore, in this study, from previous observation and noticeable approaches, a new heat flux term and approach were considered for better prediction.

2. Methods and Results

Dry patch phenomena has been continuously reported, and related model approaches [1,2] have been tried as well. Basically, hot spots are formed by bubble interactions, and dry patches are formed for higher wall temperatures. From here, these are divided into two: Quenchable or unquenchable. The first condition does not lead to CHF occurrence even with residence of dry patches for certain period of time. Fluid is resupplied after the time.

2.1 Quenchable Dry Patch in the Model

When a quenchable dry patch is formed or removed, the size of it, including the bottom area, changes with time. In this study, the change is assumed to be caused by heat dissipation into a heater material, and the thickness of it has been calculated with Helmholtz instability considering relative velocity formed by boiling.

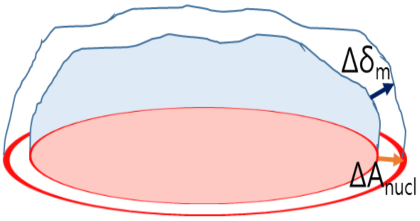

Fig. 1. Change of a quenchable dry patch with time.

$$q_{R-D}'' = \rho_g \frac{d}{dt}\left[\delta_{R-D} A_{R-D}\right] h_{fg} / A_w$$

$$\text{where } \delta_{R-D} \approx C_1 2\pi\sigma / \rho_g \left(1 + \rho_g / \rho_l\right) / v_g^{\,2}$$

$$v_g = q_{R-D}'' / \rho_g h_{fg} * \left(A_w / A_{R-D}\right)$$

$$\rightarrow q_{R-D}'' = 2\pi\sigma\left(1 + \rho_g / \rho_l\right)\left(\rho_g h_{fg} / q_{R-D}''\right)^2 h_{fg} \frac{d}{dt}\left[A_{R-D}^{\,3} / A_w^{\,3}\right]$$

$$= 2\pi\sigma\left(1 + \rho_g / \rho_l\right)\left(\rho_g h_{fg} / q_{R-D}''\right)^2 h_{fg} * 3A_{R-D}^{\,2} / A_w^{\,3} * \frac{dA_{R-D}}{dt}$$

Heat dissipation underneath a quenchable dry patch into the heater material has been calculated using accumulated amount of heat and volume averaged heat conduction equation. In here, temperature inside the patch is evenly assumed to be Leidenfrost temperature, a definition for complete dryness.

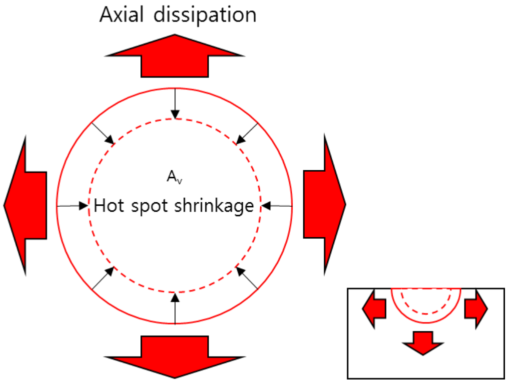

Fig. 2. Heat dissipation underneath a quenchable dry patch.

$$\frac{\rho_{solid} c_{p,solid} T_L V_{R-D}}{\Delta t} = \frac{\int_0^{R_{R-D}} k_{solid} \frac{T_L - T_w}{r} 2\pi r^2 dr}{V_{R-D}}$$

$$= \frac{\rho_{solid} c_{p,solid} T_L \left(2/3\pi R_{R\_D}^{\,3}\right)}{\Delta t} = \frac{\rho_{solid} c_{p,solid} T_L \left(2/3\pi R_{R\_D} R_{R\_D}^{\,2}\right)}{\Delta t}$$

$$= \frac{\rho_{solid} c_{p,solid} T_L \left(2/3 R_{R\_D} A_{R-D}\right)}{\Delta t} = \frac{k_{solid}\left(T_L - T_w\right)\pi R_{R\_D}^{\,2}}{}$$

$$\rightarrow \left|\frac{\Delta A_{R-D}}{\Delta t}\right| = \frac{9\left(T_L - T_w\right)}{4 T_L R_{R\_D}^{\,2}} \frac{k_{solid}}{\rho_{solid} c_{p,solid}}, \text{ where } R_{R\_D} = \sqrt{\frac{A_{R-D}}{\pi}}$$

In this study, condition for the formation of a hot spot has been based upon from the previous approaches [3,4] where surrounding number of dry-spots(bubbles) was crucial for the formation. The number of it was set to be 5 as done previously, and a criterion to trigger an unquenchable dry patch was assumed to be based on the number of surrounding hot spots in this study, and the process was similar. To account for the hot spot site density, hot spot distribution function was calculated with critical hot spot numbers to trigger an unquenchable dry patch. The critical number of hot spots was assumed to be affected by material thermal property since heat dissipation was a mechanism to dissipate the accumulated heat.

Total heat flux from a heater consist of nucleate boiling heat flux, film boiling heat flux and heat flux from quenchable dry patches. To describe the downward-facing condition, a constant was added to Rohsenow correlation [5] when boiling curve information were not provided. Berenson correlation [6] was used for film boiling heat flux term.

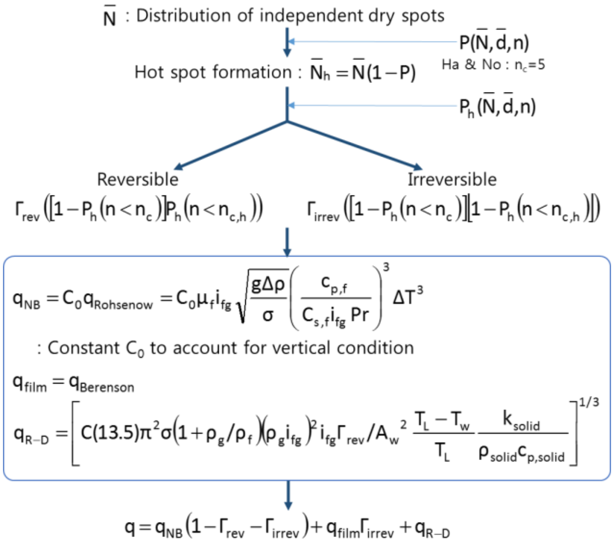

Fig. 3. Total heat flux and heat flux from quenchable dry patches considering hot spot phenomena.

2.2 Comparison with Experimental Data

Material, wettability, pressure and width effects have been considered in this study. For the heater material, copper, stainless steel (SS304) and carbon steel (SA508) have been used to fulfill the purpose. Relatively large sizes (including large-enough scale) were selected, and the orientation was vertical condition. The width effect has been addressed from SS304 and SA508 data.

For the Cu data comparison (Fig. 4), nucleate boiling heat flux data were acquired from the boiling curves provided from the previous study [3,7]. Thermal property term used in the heat flux from quenchable dry patches was based on Cu properties. Three kinds of wettability conditions were considered: 14, 38, 69°. For the bubble departure diameter and nucleation site density correlations, a correlation proposed by Phan et al. [8], where wettability effect was mainly considered, and their own correlation, respectively, were used. The critical number of hot spots, which was assumed to be a function of thermal property, was calculated based on data from different wetting conditions. For the SUS304 and SA508 data comparisons (Fig. 5-7 and Fig. 8-9, respectively), nucleate boiling heat flux terms were made from Rohsenow correlation where a constant was added to account for complex phenomena occurs on downward-facing morphology. The constant values were acquired from atmospheric pressure data. Regarding bubble departure diameter and nucleation site density correlations, the correlations made by Kocamustafaogullari and Ishii [9] were used to account for pressurized environments. The pressure conditions considered were 1, 2, 4 and 10 bar (expressed on the x-axis of the graphs). With whole data, the critical numbers of hot spots were calculated which predict the data mostly well.

The results show that the proposed model tends to predict well if the width scale is large enough. For narrow ones, because of active vapor mergence during sliding, residence times of merged vapors became shorter. It led to over-prediction at high pressure conditions since a constant used in nucleate boiling heat flux term was calculated from atmospheric data points.

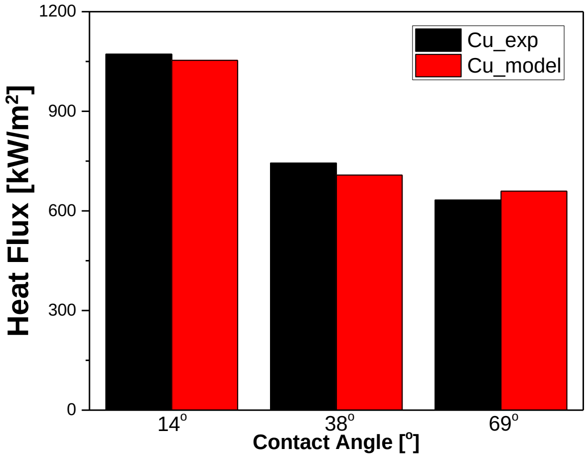

Fig. 4. Cu data comparison; 3 kinds of wetting condition (Size: 63 mm by 103 mm).

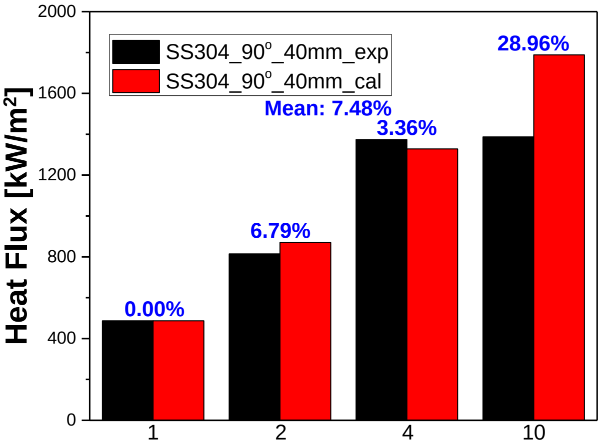

Fig. 5. SS304 data comparison; Size: 40 mm by 100 mm).

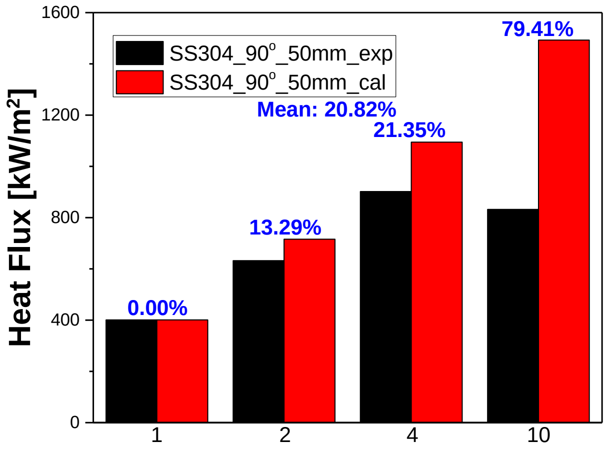

Fig. 6. SS304 data comparison; Size: 50 mm by 100 mm).

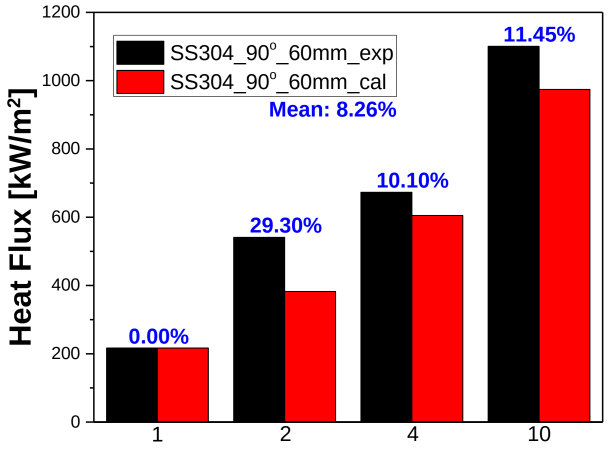

Fig. 7. SS304 data comparison; Size: 60 mm by 100 mm).

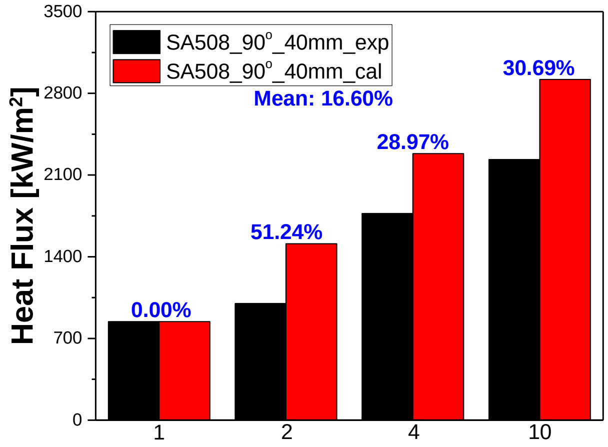

Fig. 8. SA508 data comparison; Size: 40 mm by 100 mm).

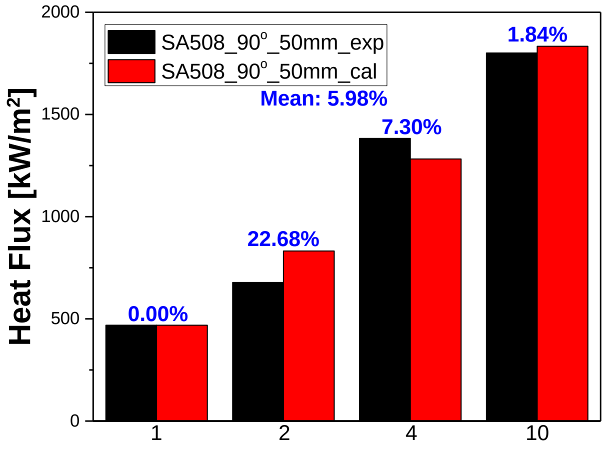

Fig. 9. SA508 data comparison; Size: 50 mm by 100 mm).

3. Conclusions

A CHF prediction model has been proposed which is mainly triggered by hot spot-induced dry patch phenomenon. The critical number of hot spots varied depending on materials caused by different thermal properties. According to the comparison trend, the predictability became improved as the width size increased. This trend was made by a constant in nucleate boiling heat flux term calculated from atmospheric data. Based on the results, the CHF prediction model developed in the study is expected to show good predictability at least for a large-scale geometries.

NOMENCLATURE

ρ_{solid} = Density of a heater material
$c_{p,solid}$ = Heat capacity of a heater material
k_{solid} = Thermal conductivity of a heater material
ρ_g = Saturated density of vapor
ρ_l = Density of liquid (=ρ_f in this study)
$\delta_{R\text{-}D}$ = Thickness of a reversible dry patch (=δ_m in this study)
v_g = Vapor growth velocity
h_{fg} = Enthalpy of evaporation
T_L = Leidenfrost temperature
$V_{R\text{-}D}$ = Hemispherical volume under a reversible dry patch
$A_{R\text{-}D}$ = Area of a reversible dry patch
A_w = Total heat transfer area
$R_{R\text{-}D}$ = Radius of a reversible dry patch
$q_{R\text{-}D}$ = Heat flux of a reversible dry patch
q_{NB} = Heat flux by nucleate boiling
q_{film} = Heat flux by film boiling
$q_{Berenson}$ = Heat flux correlation made by Berenson
σ = Surface tension
N = Active nucleation site density
N_h = Hot spot site density
n_c = Critical number of dry spots
n_h = Critical number of hot spots
Γ_{rev} = Area occupied by reversible dry patches

Γ_{irrev} = Area occupied by irreversible dry patches

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