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The Modified Minimum Film Boiling Correlation to Best-estimate the Cladding Temperature during Reflood Phase

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1. Introduction

The amount of heat transfer between heated wall and contacting fluid decreases significantly when the heated surface losses contact with the liquid. The heated surface temperature when it completely losses it's contact with the liquid is called minimum film boiling temperature. The prediction of the minimum film boiling point has been studied extensively because the minimum film boiling temperature is criteria of dividing efficient and inefficient heat transfer regime. Although various minimum film boiling temperature prediction methods were suggested under the circumstance, the effect of hysteresis on the minimum film boiling temperature was not considered. Various papers noted that the minimum film boiling temperature is not only determined by the local condition, but also affected by the pathway which the heated surface undergone. The modified minimum film boiling correlation which is based on the Cabajo's minimum film boiling temperature correlation (1985) was suggested to reflect the hysteresis on the boiling curve. The approach of Groeneveld and Snoek (1986), which stated that the surface vapor temperature during the transient cooling process is higher than the surface vapor temperature of the transient heating process, was applied to modify the Carbajo's minimum film boiling temperature correlation. The modified correlation was applied to the thermal-hydraulic safety analysis code SPACE and validated with the FLECHT-SEASET reflood tests. The consideration of the vapor temperature difference around the heated surface lead to the better prediction for most of the cases.

2. Modified minimum film boiling correlation

Various research was conducted to expect the minimum film boiling temperature. Among those, Carbajo's rewetting temperature correlation is based on the extensive literature survey of existing experiments and analysis about the minimum film boiling temperature. Carbajo's correlation takes into account the pressure, mass flow rate, liquid subcooling and surface condition which are known as the highly affecting factor for the minimum film boiling temperature.

However, Carbajo's correlation did not consider the effect of the hysteresis of boiling curve. Therefore, Groeneveld and Snoek's approach (1986) was applied to modify the correlation. Groeveveld and Snoek claimed that the minimum film boiling temperature is affected by the preceding heat transfer regime. If the minimum film boiling point is achieved after the nucleate boiling and transition boiling, then the vapor-water mixing is enhanced and thus, near-wall vapor temperature is almost identical to the saturation temperature. However, if the minimum film boiling point is followed after the film boiling regime, vapor temperature is much higher than the saturation temperature due to the high surface temperature.

The vapor temperature difference noted by Groeneveld and Snoek was not reflected to the process of deriving Carbajo's correlation. Therefore, new minimum film boiling temperature correlation, which takes account the vapor temperature near the heater surface, was suggested.

Current Carbajo's correlation is,

$$\Delta T_{MFB}=\Delta T_{MFB,iso}\cdot(1+\beta\gamma)\cdot\left(1+0.1G^{0.4}\right)+a\Delta T_{sub} \quad (1)$$

$$\Delta T_{MFB,iso}=\frac{1.372\times10^{6}}{T_{cr}^{2.3}}\left(\frac{T_{cr}-T_{sat}}{\sqrt{\mu_l}}\right)^{0.5} \quad (2)$$

$$\beta=\sqrt{\frac{(k\rho c_p)_l}{(k\rho c_p)_w}} \quad (3)$$

$$a=\frac{4180}{c_{p,l}}\left(\frac{i_{fg}}{i_l}\right)\left[\sqrt{\frac{(k\rho c_p)_l}{(k\rho c_p)_w}}\left(\frac{i_{fg}}{c_{p,w}\Delta T_{MFB,iso}}\right)\right]^{0.1} \quad (4)$$

Derivation of the correlation starts with the two semi-infinite slabs with constant thermal properties and different temperatures as described in Fig. 1.

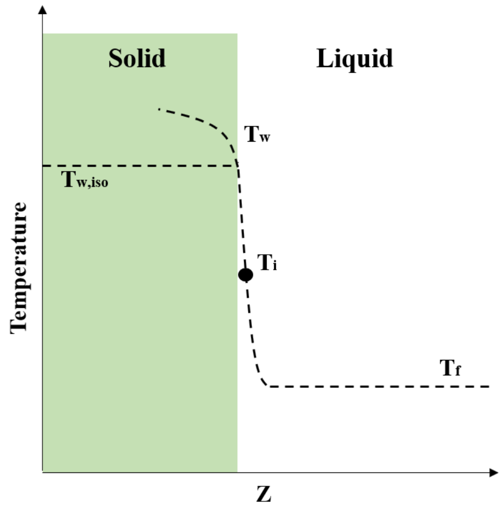

Fig. 1. Temperature of two semi-infinite slabs

The interface temperature between two semi-infinite slabs with constant temperature is,

$$T_I=\frac{T_w+T_f\sqrt{(k\rho c_p)_f/(k\rho c_p)_w}}{1+\sqrt{(k\rho c_p)_f/(k\rho c_p)_w}} \qquad (5)$$

By substituting $\beta=\sqrt{\frac{(k\rho c_p)_l}{(k\rho c_p)_w}}$, following equation is established.

$$T_w=T_I+(T_I-T_f)\beta \qquad (6)$$

Substituting minimum film boiling isothermal temperature $T_{MFB,ISO}=T_I$, $T_w=T_{MFB}$ result in the equation below.

$$T_{MFB}-T_{sat}=T_{MFB,ISO}-T_{sat}+(T_{MFB,ISO}-T_{sat})\beta \qquad (7)$$

$$\Delta T_{MFB}=\Delta T_{MFB,ISO}(1+\beta) \qquad (8)$$

With Groeneveld and Snoek's approach, the minimum film boiling temperature correlation during the transient cooling process derived as follows. The equation (9) is valid for the transient cooling process.

$$T_w = T_I + (T_I - T_{vapor})\beta \qquad (9)$$

$$T_{MFB} = T_{MFB,ISO} + (T_{MFB,ISO} - T_{vapor})\beta \qquad (10)$$

$$T_{MFB} - T_{sat} = T_{MFB,ISO} - T_{sat} + (T_{MFB,ISO} - T_{vapor})\beta \qquad (11)$$

$$\Delta T_{MFB} = \Delta T_{MFB,ISO}(1+\beta) - \Delta T_{vapor}\beta \qquad (12)$$

$$\Delta T_{MFB} = \Delta T_{MFB,iso}\cdot(1+\beta\gamma)\cdot(1+0.1G^{0.4}) + a\Delta T_{sub} - \Delta T_{vapor}\beta \qquad (13)$$

The equation (13) derived from the equation (9) and this stands for the transient cooling process. The effect of the hysteresis is reflected to the minimum film boiling temperature correlation by above modification.

3. Validation

The modified correlation was applied to the thermal-hydraulic safety analysis code SPACE and validated with the FLECHT-SEASET (Full-length emergency core heat transfer – Separate effects and system effects test) reflood tests. Peak cladding temperature and quenching time was compared to validate the correlation.

3.1 Peak cladding temperature

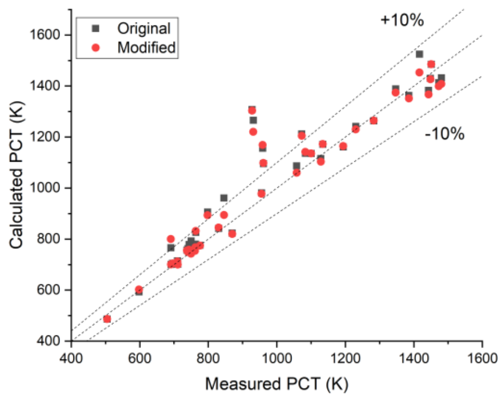

Fig. 1. PCT comparison of the FLECHT-SEASET Test

3.2 Quenching time

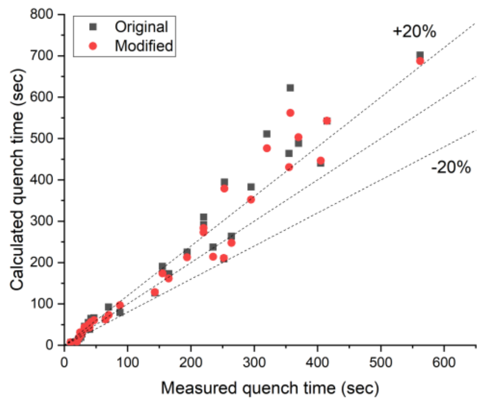

Fig. 2. Quenching time comparison of the FLECHT-SEASET Test

4. Conclusion

Based on the Carbajo's minimum film boiling temperature correlation, modified correlation is suggested to estimate the minimum film boiling temperature with consideration of the boiling curve hysteresis.

The modified correlation was applied to the thermal-hydraulic safety analysis code SPACE and validated with the FLECHT-SEASET reflood tests. Modified correlation provided the better prediction of peak cladding temperature and quenching time for most of the cases. However, the amount of prediction performance improvement was not significant. Additional research, which exclude the effect of the heat transfer correlations of other heated regions, is required to completely verify the new correlation.

5. Acknowledgments

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