Transactions of the Korean Nuclear Society Autumn Meeting
Goyang, Korea, October 24-25, 2019

Assessment of SPACE by reflood experiments with the consideration of hysteresis during boiling heat transfer

Woonho Jeong [a], Yong Hoon Jeong [a*]
[a]*Department of Nuclear & Quantum Engineering, Korea Advanced Institute of Science and Technology*
291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
[*]*Corresponding author: jeongyh@kaist.ac.kr*

1. Introduction

Predicting the heat removal rate within particular thermal hydraulic system has been one of the biggest issues on nuclear power plant safety analysis. Therefore, various thermal-hydraulic safety analysis codes focused on predicting heat flux as accurate as possible. Current thermal-hydraulic safety analysis codes estimate the heat flux based on the instantaneous local conditions hypothesis [1]. In other words, heat flux is determined by local information at any given instant. However, the boiling heat transfer is under the influence of hysteresis effect. Various research has confirmed that the boiling heat transfer rate during the wall-cooling and wall-heating is different [2]. This paper attempt to figure out the effect of boiling curve hysteresis to the estimation of cladding temperature during reflooding phase using thermal-hydraulic system code SPACE.

2. Boiling curve hysteresis and SPACE

2.1 Critical heat flux (CHF)

Current CHF correlations are based on CHF experiment conducted while heating the surface. However, it is known that CHF during surface heating is bigger than CHF during surface cooling [3]. Rajab and Winterton claimed that the CHF during surface cooling is around 55% of the CHF during surface heating [4].

2.2 Transition boiling heat transfer

Sakurai and Shiotsu observed the hysteresis of transition boiling regime by temperature-controlled steady-state pool boiling experiment under the atmospheric pressure [5]. Bui and Dhir also confirmed that the transition boiling regime is under the effect of hysteresis by the temperature-controlled boiling experiment on a vertical surface [2].

SPACE is using Bjornard and Griffith (1977) model as a default transition boiling heat transfer model [6]. The model calculates the heat flux within transition boiling regime by the interpolation of heat flux at CHF and heat flux at minimum film boiling point (eq 1, 2).

$$q''_{TB} = \xi \cdot q''_{CHF} + (1-\xi) \cdot q''_{FB} \quad (1)$$

$$\xi = \max(0.2, 1-\alpha) \cdot \left[\frac{\mathrm{T_w} - \mathrm{T_{MFB}}}{\mathrm{T_{CHF}} - \mathrm{T_{MFB}}}\right]^2 \quad (2)$$

The model is validated by experiments with surface heating so there need to a distinct correlation for the cases with surface cooling [1]. Therefore, two different transition boiling heat transfer correlations (eq 3, 4) were tested to apply the hysteresis effect.

$$\xi = \max(0.2, 1-\alpha) \cdot \left[\frac{\mathrm{T_w} - \mathrm{T_{MFB}}}{\mathrm{T_{CHF}} - \mathrm{T_{MFB}}}\right]^4 \quad (3)$$

$$\xi = \max(0.2, 1-\alpha) \cdot \left[\frac{\mathrm{T_w} - \mathrm{T_{MFB}}}{\mathrm{T_{CHF}} - \mathrm{T_{MFB}}}\right]^8 \quad (4)$$

2.3 Minimum film boiling point (MFBP)

MFBP is also under the effect of hysteresis. The research of Bui and Dhir, and Rajab and Winterton clearly shows that the MFBP differs by the direction of surface temperature change.

SPACE is using Carbajo (1985) model as a default minimum film boiling temperature model. Carbajo's correlation is [7],

$$\Delta T_{MFB} = \Delta T_{MFB,iso} \cdot (1+\beta\gamma) \cdot (1+0.1G^{0.4}) + a\Delta T_{sub} \quad (5)$$

To consider the hysteresis effect on minimum film boiling temperature, Groeneveld and Snoek's (1986) approach was applied. Groeveveld and Snoek claimed that the minimum film boiling temperature is affected by the preceding heat transfer regime [8]. 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.

$$\Delta T_{MFB} = \Delta T_{MFB,iso} \cdot (1+\beta\gamma) \cdot (1+0.1G^{0.4}) + a\Delta T_{sub} - \Delta \mathrm{T_{vapor}}\beta \quad (6)$$

The equation (6) was derived with Groeneveld and Snoek's approach and tested to apply the effect of hysteresis on MFBP.

3. Results and discussion

FLECHT-SEASET (Full-length emergency core heat transfer – Separate effects and system effects test) reflood test 31302, 31504, 31701 were selected to check the hysteresis effect on boiling heat transfer. They have identical conditions except flow velocity (7.65, 2,40, 15.50 cm/sec).

3.1 Critical heat flux (CHF)

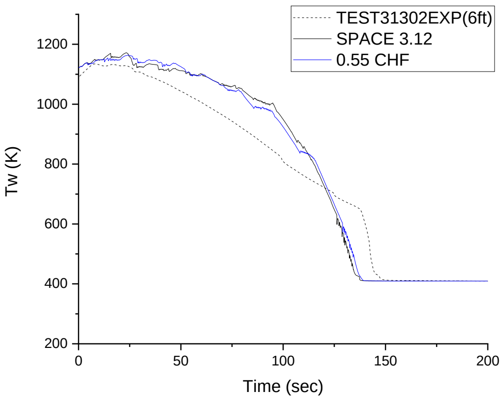

Fig. 1. FLECHT-SEASET Test 31302 results with the cooling CHF

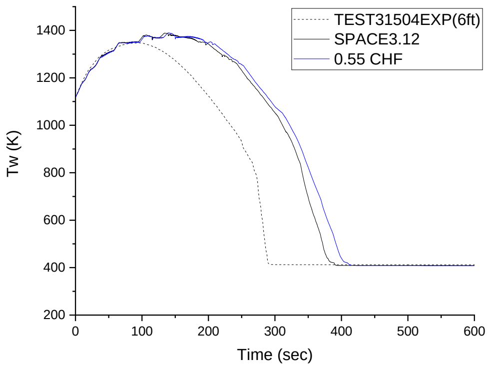

Fig. 2. FLECHT-SEASET Test 31504 results with the cooling CHF

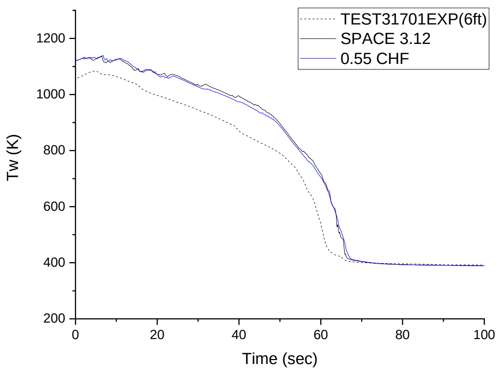

Fig. 3. FLECHT-SEASET Test 31701 results with the cooling CHF

Applied cooling CHF does not affect noticeably on the wall temperature. With the low flow rate (Test 31504), it is clear that wall temperature decreases slowly but this does not fit to the high flow cases.

3.2 Transition boiling heat transfer

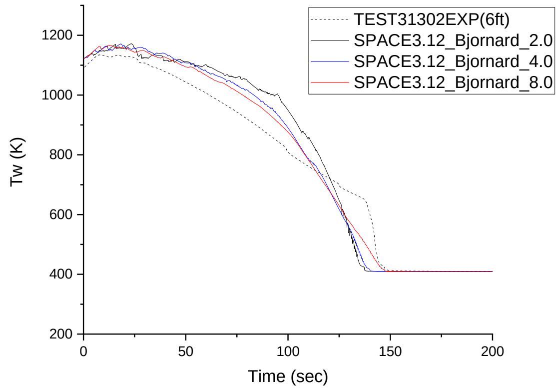

Fig. 4. FLECHT-SEASET Test 31302 results with the various transition boiling heat transfer correlation

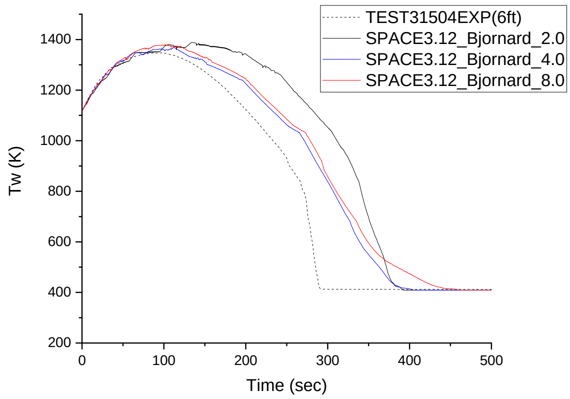

Fig. 5. FLECHT-SEASET Test 31504 results with the various transition boiling heat transfer correlation

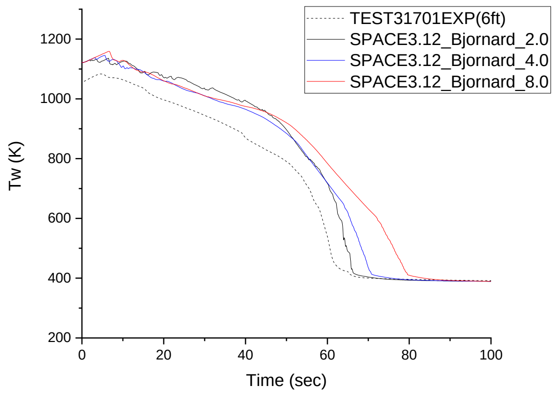

Fig. 6. FLECHT-SEASET Test 31701 results with the various transition boiling heat transfer correlation

With the application of transition boiling heat transfer hysteresis, the transition boiling heat transfer is suppressed. As expected, when transition boiling heat transfer is suppressed, wall temperature decreases slowly and quenching time is delayed. However, with the low flow rate (Test 31504), it does not show the clear interrelation between transition boiling heat transfer and wall temperature.

3.3 Minimum film boiling point (MFBP)

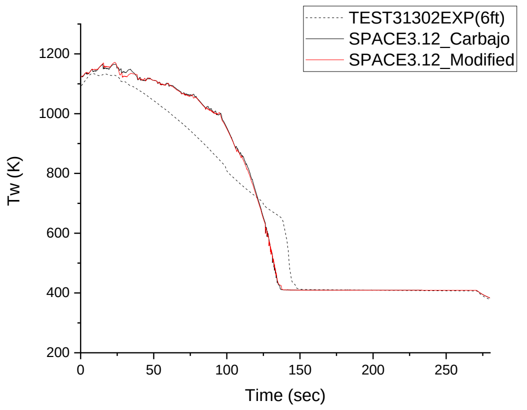

Fig. 7. FLECHT-SEASET Test 31302 results with the modified Carbajo model

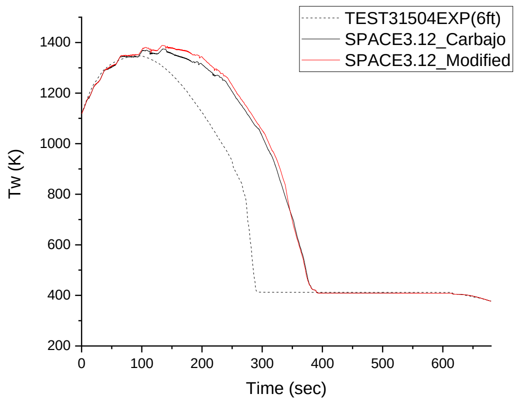

Fig. 8. FLECHT-SEASET Test 31504 results with the modified Carbajo model

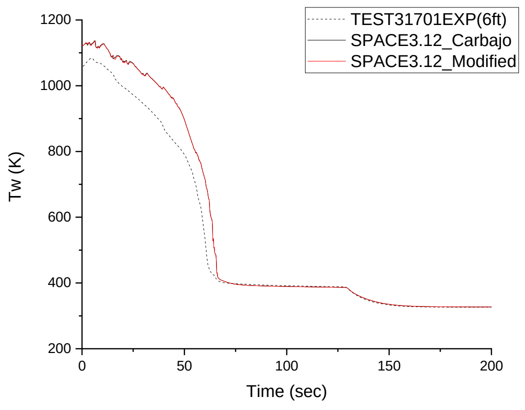

Fig. 7. FLECHT-SEASET Test 31701 results with the modified Carbajo model

MFBP hysteresis does not seem to affect the wall temperature tendency of reflood experiments.

4. Conclusion

Hysteresis occurs on critical heat flux, transition boiling heat transfer rate, minimum film boiling point. The effect of boiling curve hysteresis were estimated with reflood experiments. Minimum film boiling point was the least effective and transition boiling heat transfer rate was the most effective to both quenching time and cladding temperature. For the best estimation of reflood phenomena, hysteresis of boiling heat transfer should be considered.

REFERENCES

[1] Bjonard, T. A. and Griffith, P., PWR blowdown heat transfer, Thermal and hydraulic aspects of nuclear reactor safety, Vol.1, 1977

[2] Groeneveld, D. C.. Post-dryout Heat Transfer: Physical Mechanisms and a Survey of Prediction Methods, Nuclear Engineering and Design, Vol.32, p. 283, 1975.

[3] Bui, T. D. and Dhir, V. K., Transition Boiling Heat Transfer on a Vertical Surface, Journal of Heat Transfer, Vol.107, p.756, 1985.

[4] Rajab, I., and Winterton, R. H. S., The two transition boiling curves and solid-liquid contact on a horizontal surface," Int. J. Heat and Fluid Flow, Vol.11(2), p.149, 1990

[5] Sakurai, A. and Shiotsu, M., Temperature-Controlled Pool-Boiling Heat Transfer, Proceedings of the 5th International Heat Transfer Conference, September. 3-7, 1974.

[6] Choi, K. Y. et al., Development of wall-to-fluid heat transfer package for the SPACE code, Nuclear Engineering and Technology, Vol.41, p. 1143, 2009.

[7] Carbajo, J. J., A study on the rewetting temperature, Nuclear Engineering and Design, Vol.84(1), p. 21, 1985.

[8] Groeneveld, D. C., and Snoek, C. W., A comprehensive examination of heat transfer correlations suitable for reactor safety analysis, Multiphase Science and Technology, Vol.2, p. 181, 1986.