Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Critical Heat Flux and Post-CHF Heat Transfer in Fast-Transient Flow Boiling

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1. Introduction

A reactivity initiated accident (RIA) involves a sharp increase in fission rate and reactor power. During the RIA, the nuclear fuel rod failures can occur as a result of degraded clad-to-coolant heat transfer and a prolonged period of time with an overheated cladding. RIA benchmark result performed by OECD/NEA showed that computer codes have significant uncertainties in the clad-to-coolant heat transfer modeling [1]. This is mainly attributed to the lack of sufficient experimental data and the limited knowledge on the fast-transient boiling phenomena.

Recently, Choi et al. [2, 3] performed experimental and theoretical studies on the fast-transient boiling heat transfer simulating RIA condition using THERA test facility. In the present study, critical heat flux (CHF) and post-CHF heat transfer data obtained in the THERA experiment were compared with the SPACE code and conventional correlations.

2. Experiments and Results

2.1 Experiment and Analysis Methods

Fig. 1 shows the schematics of the THERA test facility whose operating ranges are as follows:

- system pressure: 0.5 ~ 16 MPa
- test section flow rate: 0 ~ 0.3 kg/s
- rectified DC pulse power: 0 ~ 450 kW
- rectified DC pulse width: 20 ms ~ 1.25 s

The vertical test section includes a round tube made of Inconel-600 with the heated length of 500 mm. Inner diameter and wall thickness of the test section tube are 8 mm and 1 mm, respectively. De-ionized water flows upward inside of the test section tube.

High-speed infrared pyrometers with minimum response time of 0.5 ms were used to measure outer wall temperatures of the test section tube. In order to estimate wall temperature and boiling heat flux on the convective heat transfer surface inside of the test section tube, Choi et al. [2] developed a noise robust inverse heat conduction calculation method for the fast-transient flow boiling phenomena. The calculation method predicted well the inside wall temperature and convective boiling heat flux on the inner surface of the tube, even for a noisy inner wall temperature.

Experiments of the fast transient flow boiling were performed as follows. First, the test facility was kept at steady-state conditions where the mass flow rate, system pressure and inlet subcooling at the test section were maintained at predefined values. After reaching sufficient time of the steady-state condition, a stepwise power pulse with predefined maximum voltage and pulse width was applied into the test section tube. By using the inverse heat conduction calculation method, the wall temperature and the boiling heat flux at the convection boundary were obtained after the completion of the experiment.

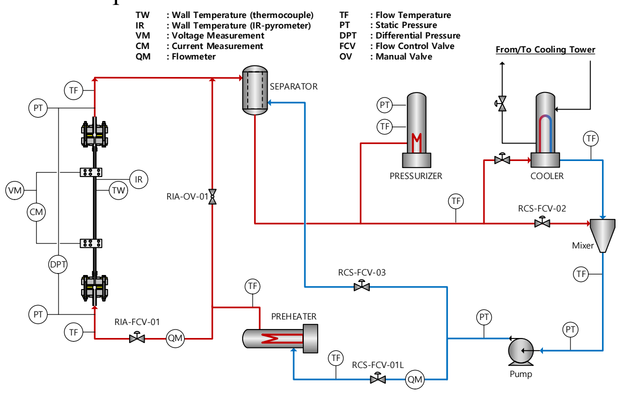

Fig. 1. Schematic of the THERA test facility

2.2 SPACE Code Predictions

The THERA experiments were simulated with the SPACE code which is based on a multi-dimensional, two-fluid, three-field model for a licensing application of pressurized water reactors [4]. The SPACE code solves a set of nine equations of mass, energy and momentum conservations for continuous liquid, vapor and dispersed liquid (droplet) fields.

Fig. 2 shows SPACE code model for the THERA experiment that consists of 9 vertical cells and 8 faces. Default models of closure equations in the SPACE code were used in the present study. Thus, the critical heat flux (CHF) and heat transfer coefficient at post-CHF region were predicted by using 2004 CHF look-up table [5] and 2006 full developed film boiling look-up table [6], respectively.

Figs. 3 to 5 compares a typical experimental result with the SPACE code predictions whose experiment was performed at a pressure of 15 MPa, mass flux of 2,100 kg/m^{2}s, inlet subcooling of 300 kJ/kg, pulse width of 402 ms, and pulse power of 83 kW.

As shown in Fig. 3, the wall superheat increase with time from the initially subcooled state up to the maximum peak while the pulse power injected into the test section, i.e., heating period. After the pulse power stops, the wall superheat decreases; test section thereby experiences a cooling period. Slope changes and abrupt change of the wall superheat represent the changes of boiling regimes. The SPACE code predicts lower wall superheat peak rather than the measured one; thereby early quenching of the test section. The prediction error in the wall superheat are significant during the cooling period than the heating period.

Figs. 4 and 5 show the wall heat flux with time and wall superheat calculated with the inverse heat conduction method. As shown in Fig. 5, the CHFs are determined from the boiling curve representing wall heat flux against wall superheat. Two peaks in the wall heat flux represents the CHFs at heating and cooling phases. Due to a hysteresis effect in the post-CHF heat transfer, the CHF depends on the heating modes. It is usually known that the CHF at cooling period is lower than the one at the heating period. The SPACE code predicts higher CHFs than the measured ones, thus lower wall superheat as shown in Fig. 3. In addition, the SPACE code predicts higher post-CHF heat transfer between the two CHF peaks than the measured ones.

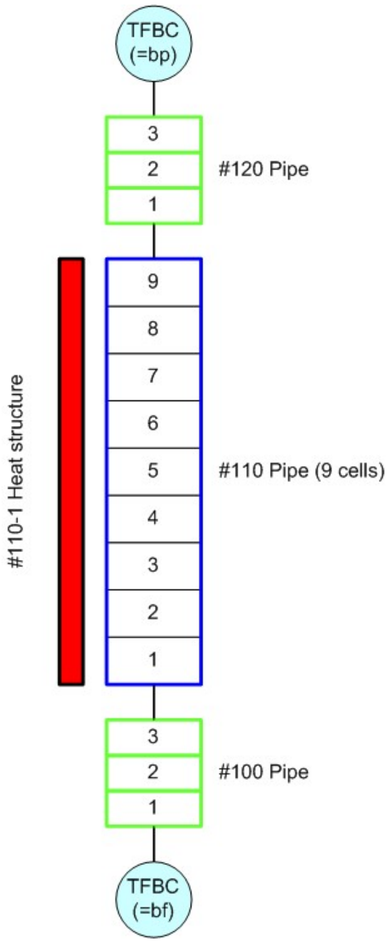

Fig. 2 SPACE code model

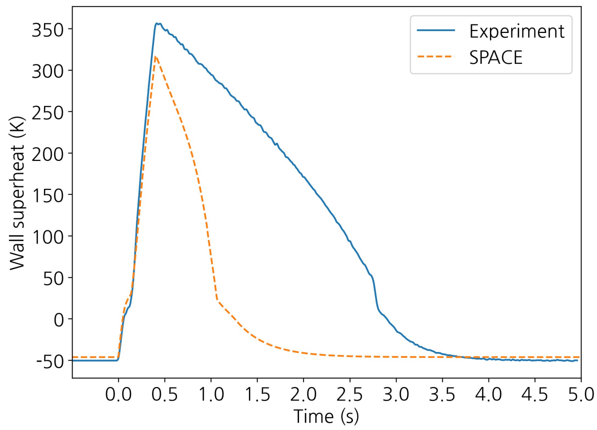

Fig. 3 Wall superheat with time

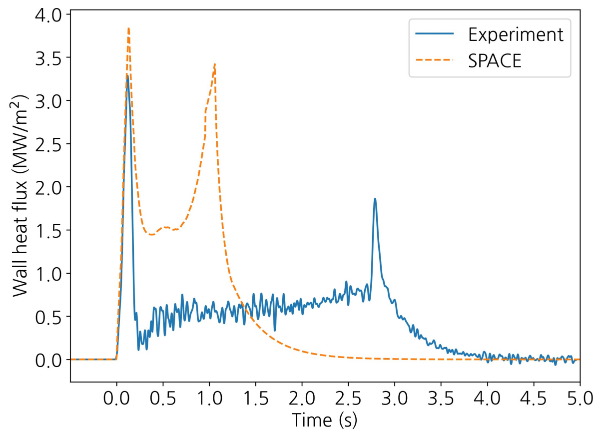

Fig. 4 Wall heat flux with time

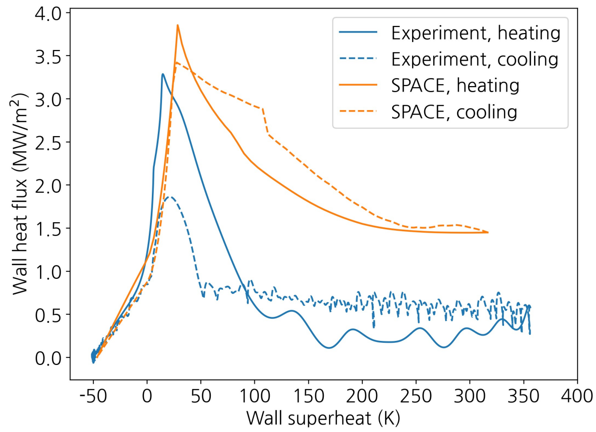

Fig. 5 Boiling curve

Fig. 6 shows CHF predictions of the SPACE code for the whole 45 test conditions performed in the THERA experiment. Mean and standard deviation of the prediction error (represented as mean and std in the figure) are shown in the Figure. In general, the SPACE code over-estimates the CHF and its prediction at cooling phase is worse than the heating phase.

For the present experiments, subcooled boiling is the prevailing heat transfer mode with very low void fractions and qualities. The flow regimes are mostly assumed to be bubbly flows. Due to low void fractions and subcooled liquid core, the vapor bubbles are predominantly attached to the wall. At the post-CHF boiling regime, the wall is covered by a thin vapor film while most of the liquid core remains at subcooled condition.

On the other hand, the SPACE code assumes one-dimensional behavior and uses volume-averaged quantities such as void fraction and vapor quality to predict heat transfer phenomena. Thus, the SPACE code does not seem to well predict the near-wall phenomena in the fast-transient subcooled boiling.

The prediction discrepancies in the CHF and post-CHF heat transfer are also mainly attributed by the significant differences in the physical mechanisms between steady-state and fast-transient heat transfer. Since the SPACE code was in general developed by using steady-state models and correlations, some corrections may be necessary for a proper prediction on the fast-transient heat transfer phenomena.

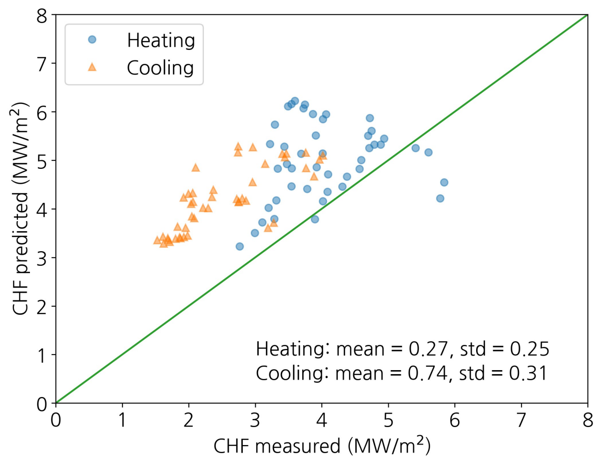

Fig. 6 CHF prediction of the SPACE code

2.3 Comparison with Conventional Correlations

Figs. 7 to 9 show CHF prediction results by a few conventional CHF correlations where the heat balance method was used. The Bobcock-Wilcox CHF correlation is highly empirical but used in the SCANAIR code developed for the RIA predictions [1]. The Bobcock-Wilcox CHF correlation shows a good predictions for both heating and cooling phases while showing systematic deviations from the experiment at high CHF values. The CHF look-up table [5] and EPRI correlation [7] show similar CHF predictions but without any systematic deviations.

In general, the CHF prediction of the conventional correlation becomes worse at cooling periods. This is mainly attributed by the hysteresis phenomena in the post-CHF heat transfer, especially in the transition boiling regime.

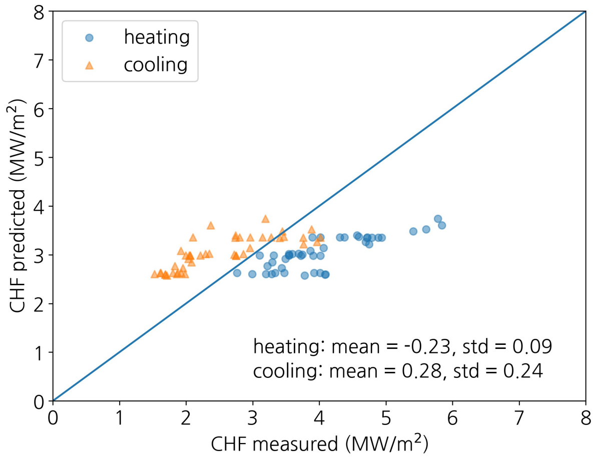

Fig. 7 CHF prediction of Bobcock-Wilcox correlation

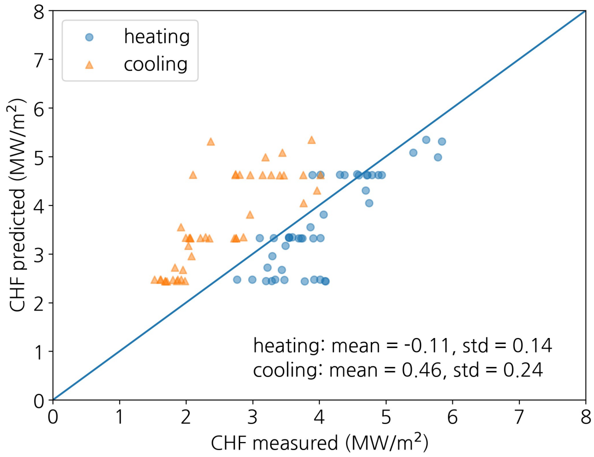

Fig. 8 CHF prediction of CHF look-up table

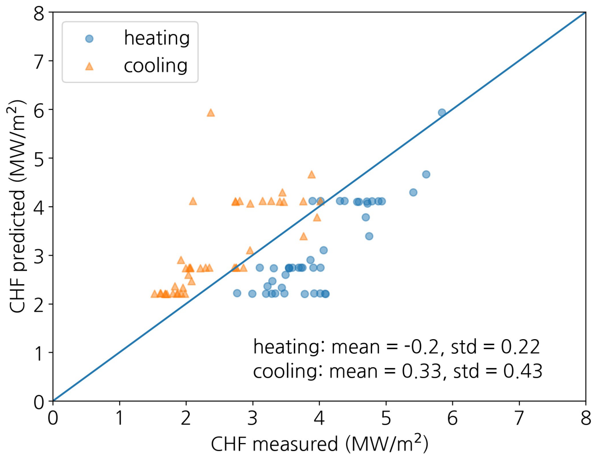

Fig. 9 CHF prediction of EPRI correlation

3. Conclusions

Experimental and theoretical studies had been performed for the fast-transient boiling heat transfer phenomena aiming at the reactivity initiated accident. The THERA experiments were compared with the SPACE code and conventional correlations. The SPACE code predicted higher critical heat fluxes, thus lower wall superheat than the experiment. In addition, the SPACE code predicted higher post-CHF heat transfer than the measured ones. The prediction discrepancies in the CHF and post-CHF heat transfer are mainly attributed to the significant differences in the physical mechanisms between steady-state and fast-transient heat transfer. Since the SPACE code was in general developed by using steady-state models and correlations, some corrections may be necessary for a proper prediction on the fast-transient heat transfer phenomena. In addition, the SPACE code does not seem to well predict the near-wall phenomena in the fast-transient subcooled boiling. The conventional CHF correlations by using heat balance method showed a reasonable CHF predictions for the present experiment.

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