Assessment of MARS-KS Predictive Capability for Post-CHF Wall Heat Transfer Coefficients Using Quasi-Steady-State IAFB/ISFB Experimental Data

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1. Introduction

In the safety assessment of light water reactors (LWRs), ensuring adequate core cooling performance during a loss-of-coolant accident (LOCA) is important. During a large-break loss-of-coolant accident (LBLOCA), a rapid loss of coolant may lead to an increase in fuel cladding temperature, and the emergency core cooling system (ECCS) injects coolant into the reactor core to limit the temperature rise. During this process, the high-temperature fuel cladding is subjected to post-critical heat flux (post-CHF) heat transfer conditions. In particular, the injection of subcooled coolant may lead to the development of flow regimes such as inverted annular film boiling (IAFB) and inverted slug film boiling (ISFB). Therefore, accurate prediction of post-CHF heat transfer is important for reliable evaluation of the peak cladding temperature (PCT) and the cooling performance of the ECCS.

However, the heat transfer characteristics of individual post-CHF flow regimes are still insufficiently understood, resulting in considerable uncertainties in thermal-hydraulic code predictions. In addition, previous assessments of system thermal-hydraulic analysis codes have primarily relied on integral reflood experiments conducted under transient conditions. Since multiple thermal-hydraulic phenomena occur simultaneously during the reflood process, it is difficult to independently evaluate the predictive capability of models for specific post-CHF flow regimes using integral experiments alone.

In contrast, quasi-steady-state experiments using the Direct Hot-Patch technique can establish well-defined IAFB and ISFB flow regimes [1]. Therefore, these experimental data enable direct and quantitative evaluation of the predictive capability of post-CHF models. In the present study, the predictive capability of MARS-KS, a system thermal-hydraulic analysis code, is evaluated using publicly available quasi-steady-state IAFB/ISFB experimental data obtained through the Direct Hot-Patch technique.

2. MARS-KS Analysis Model

In this section, the MARS-KS analysis model for the assessment of post-CHF heat transfer is presented. Quasi-steady-state IAFB/ISFB experimental data obtained using the Direct Hot-Patch technique were selected as benchmark data. The test section was modeled based on the experimental geometry and measurement locations to compare the calculated post-CHF heat transfer behavior with the benchmark data.

2.1. Benchmark Data

The quasi-steady-state IAFB/ISFB experimental data obtained using the Direct Hot-Patch technique [1] were used as benchmark data to evaluate the post-CHF heat transfer model of MARS-KS. Unlike conventional transient reflood data, these experiments established IAFB and ISFB flow regimes under quasi-steady-state conditions and measured the wall heat transfer characteristics of individual post-CHF flow regimes. This approach minimizes the influence of complex thermal-hydraulic phenomena occurring during the transient reflood process, allowing the heat transfer characteristics of individual post-CHF flow regimes to be evaluated separately. Therefore, these experimental data were selected as benchmark data to independently assess the IAFB/ISFB heat transfer prediction capability of MARS-KS.

2.2. Modeling for reference model in MARS-KS

To simulate the post-CHF heat transfer behavior observed in the benchmark experiment, a MARS-KS model was developed based on the test section of benchmark experiment. The test section was modeled as a vertical round tube, consistent with the benchmark experiment. As shown in Fig. 1, the 1,550mm test section was nodalized into seven volumes: an inlet, two unheated sections, two hot-patch notches, a heated pipe, and an outlet. Since the governing equations in MARS-KS are discretized and solved on a nodal basis, the computational volumes were divided at locations where changes in the test-section wall thickness correspond to the boundaries between the heated and unheated sections.

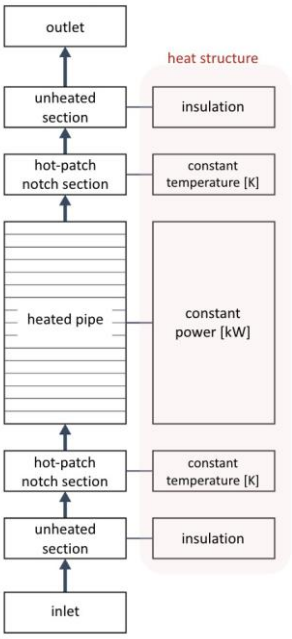

Fig 1: MARS-KS nodalization of the test section

Table 1: Geometrical information of test section [1].

parameter	value [mm]
Inner diameter of the tube	12.95
Wall thickness of the tube	3.05
Wall thickness of the notch	1.55
Heated pipe section length	1,000
Total test section length	1,550

A heat structure was connected to each volume to represent the heated wall of the test section, and the actual wall thickness of each section was incorporated into the model. The heated pipe was further divided into 16 nodes corresponding to the axial locations of the thermocouples in the experiment. To ensure consistency between the calculated and experimental data, the wall temperature and heat transfer coefficient were extracted at the nodes corresponding to the experimental measurement locations.

2.3. Analysis Conditions

MARS-KS calculations were performed based on the benchmark experimental conditions presented in Table 2. Mass fluxes of 150, 250, and 450 kg/m²·s, inlet subcooling of 12, 20, and 30 °C, and system pressures of 25, 40, and 60 psia were applied.

Table 2: Experimental conditions of the benchmark data [1].

G [kg/m²·s]	Inlet Subcooling [°C]	Pressure [psia]
150, 250, 450	12, 20, 30	25, 40, 60

The inlet coolant temperature was determined from the difference between the saturation temperature at each system pressure and the inlet subcooling specified in the reference experiment, according to the definition of subcooling. The initial fluid velocity was calculated from the mass flux given in the reference experiment. The initial wall temperature of the test section was set to 900 K, and the heating power of the pipe was adjusted to maintain the wall temperature above 600 °C to simulate the quasi-steady-state post-CHF conditions of the experiment.

In addition, the reflood mode of MARS-KS was activated to apply the inverted post-CHF flow regime models, including IAFB and ISFB, observed in the reference experiment. Since MARS-KS considers inverted flow regimes under conditions involving hot walls and activation of the reflood model, the reflood mode was applied to simulate the quasi-steady-state IAFB/ISFB experimental conditions [2].

3. Results and Discussion

3.1. Wall Heat Transfer Coefficient

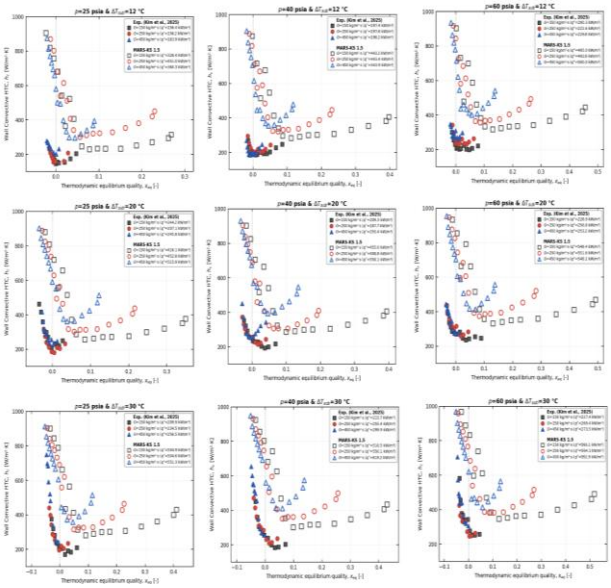

Fig 2: Comparison of wall convective HTC between the benchmark experiment and MARS-KS for different mass fluxes.

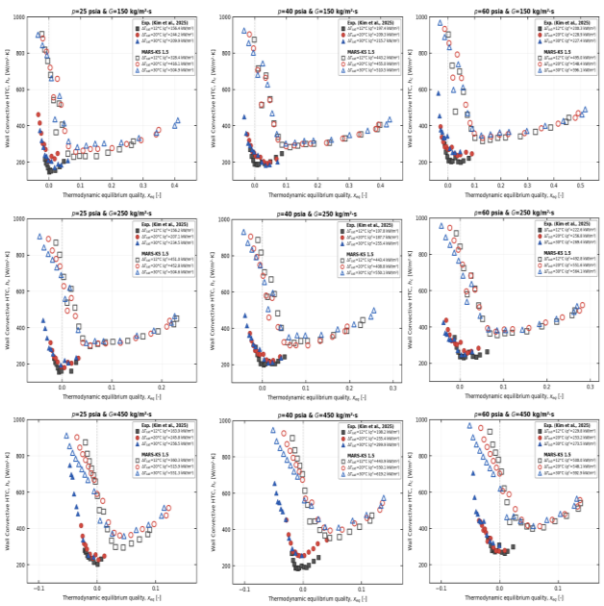

Fig 3: Comparison of wall convective HTC between the benchmark experiment and MARS-KS for different inlet subcooling conditions.

Figs. 2 and 3 compare the wall convective heat transfer coefficients (h_c) predicted by MARS-KS with the benchmark experimental data under various mass flux, pressure, and inlet subcooling conditions. MARS-KS reproduced the general trend of the h_c with increasing thermodynamic equilibrium quality (x_{eq}). In the subcooled region ($x_{eq} < 0$), the h_c decreased as x_{eq} increased. As x_{eq} approached zero, the h_c reached a minimum and then exhibited an increasing trend.

In contrast, MARS-KS generally tended to overpredict the h_c in the highly subcooled region compared with the benchmark experimental data. This discrepancy was particularly pronounced at lower x_{eq} values and decreased as x_{eq} increased.

In the x_{eq} >0 region, the MARS-KS generally reproduced the experimental trend of increasing h_c with increasing x_{eq}, although differences in the magnitude of h_c remained.

These prediction characteristics were generally observed over a wide range of mass flux, system pressure, and inlet subcooling conditions.

3.2. Flow Regime Prediction

The void fraction, flow regime, and heat transfer mode were analyzed to examine whether MARS-KS reproduced the IAFB and ISFB flow regimes observed in the Direct Hot-Patch benchmark experiments under the corresponding thermal-hydraulic conditions.

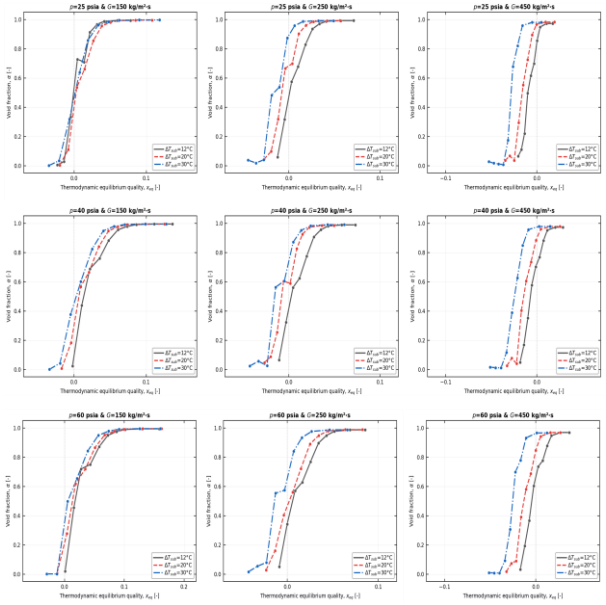

Fig 4: Void fraction as a function of x_{eq} predicted by MARS-KS

Fig. 4 shows the void fraction predicted by MARS-KS as a function of thermodynamic equilibrium quality. The predicted void fraction increased with increasing x_{eq}, with a rapid increase observed near x_{eq} =0. As x_{eq} further increased into the positive region, the void fraction gradually approached unity.

The flow regime analysis showed that slug flow was predicted in the low x_{eq} region under most conditions and transitioned to mist flow as x_{eq} and the void fraction increased. The IAFB and ISFB flow regimes observed in the benchmark experiments were not predicted by MARS-KS. In contrast, the heat transfer mode remained in film boiling throughout the analyzed region. Therefore, MARS-KS predicted the post-CHF film boiling condition at the test-section wall, while the corresponding local flow regimes differed from the IAFB/ISFB regimes observed in the benchmark experiments.

4. Conclusion

In this study, the post-CHF heat transfer prediction capability of MARS-KS was evaluated based on quasi-steady-state IAFB/ISFB experimental data obtained using the Direct Hot-Patch technique. Under various mass flux, system pressure, and inlet subcooling conditions, MARS-KS reproduced the overall variation of the wall convective heat transfer coefficient with thermodynamic equilibrium quality (x_{eq}), and generally predicted the experimental behavior in which the heat transfer coefficient decreased with increasing x_{eq} , reached a minimum, and then increased again. However,

MARS-KS showed a tendency to predict higher heat transfer coefficients than the benchmark experiment.

As a result of analyzing the flow regime and heat transfer mode of MARS-KS, the heat transfer mode remained in film boiling throughout the analyzed region, whereas the IAFB and ISFB flow regimes observed in the benchmark experiment were not reproduced. Instead, under most conditions, slug flow appeared in the low - x_{eq} region and changed to mist flow as x_{eq} and the void fraction increased.

Therefore, MARS-KS predicted the overall variation of the wall heat transfer coefficient and the film boiling condition under quasi-steady-state post-CHF conditions, but differences were observed in the magnitude of the heat transfer coefficient and the reproduction of the IAFB/ISFB flow regimes. In particular, the IAFB/ISFB flow regimes were not reproduced even while the film boiling heat transfer mode was maintained, indicating that both the heat transfer mode and the prediction of the local flow regime need to be considered when evaluating the post-CHF heat transfer prediction of MARS-KS.

ACKNOWLEDGEMENT

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REFERENCES

[1] K. M. Kim, Q. Liu, A. Burak, J. Kelly, S. Bajorek, and X. Sun, Exploring Wall Heat Transfer Characteristics in the Inverted Annular/Slug Film Boiling Regimes by Direct Hot-Patch Technique, Applied Thermal Engineering, Vol. 281, 128697, 2025.
[2] MARS Code Manual, Volume I: Code Structure, System Models, and Solution Methods
[3] MARS Code Manual, Volume III: Programmer's Manual