

## Sensitivity Analysis of MARS-KS against the ATLAS Natural Circulation Test (NC-03R)

Minki Cho <sup>a\*</sup>, Geon-woo Kim<sup>a</sup>, Changyeon Yoo <sup>a</sup>, Jegon Kim <sup>a</sup>, Joonsoo Park <sup>a</sup>

<sup>a</sup> Korea Institute of Nuclear Safety, Daejeon, Republic of Korea

\*Corresponding author: mkcho@kins.re.kr

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### 1. Introduction

Natural circulation is a key cooling mechanism for decay heat removal over a wide range of accident scenarios, including loss of offsite power, reactor coolant pump trip, and the late phase of small-break loss-of-coolant accidents (LOCAs). Its importance is even more pronounced in small modular reactors (SMRs), where the safety functions of passive safety systems play an increasingly central role.

The capability of one-dimensional system analysis codes based on the two-fluid, six-equation formulation, such as RELAP5, MARS-KS, and TRACE, to predict natural circulation has been evaluated through numerous separate-effects tests (SETs) and integral-effects tests (IETs) [1–6]. Natural circulation studies can be broadly classified into five categories: (i) single-phase natural circulation, (ii) two-phase natural circulation, (iii) reflux condensation, (iv) low-pressure/flashing natural circulation and flow instability, and (v) multidimensional and stratification effects.

Recent studies on natural circulation using MARS-KS, based on various experimental data including the GE experiments and PASCAL, have emphasized the importance of accurate pressure-drop modeling under both single-phase and two-phase flow conditions, and corresponding modeling considerations have been recommended [7]. In these studies, underprediction of two-phase pressure drop by MARS-KS was reported, and it was shown that the prediction of natural circulation flow rate for certain experiments could be improved by applying a wall-friction correction factor.

The present study was conducted to investigate the effects of the interfacial friction coefficient model and heat-loss modeling on natural circulation prediction performance. As part of the OECD-ATLAS international collaborative research project, calculations were performed for the ATLAS natural circulation test, NC-03R, with the following objectives: (1) to investigate the effect of the heat-loss model, and (2) to evaluate the effect of the default MARS-KS interfacial friction coefficient model and the rod-bundle friction model.

### 2. OECD/ATLAS NC-03R test

A variety of integral-effect tests have been conducted for large light-water reactors, and scaling analyses have been performed for the corresponding test facilities [1]. These studies investigated the variation in flow rate associated with a reduction in reactor coolant inventory and the predictive capability of system analysis codes. In this type of natural circulation experiment, phenomena such as single-phase natural circulation, two-phase natural circulation, and reflux condensation are observed.

For the ATLAS test facility, experiments on primary-side natural circulation flow under decreasing coolant inventory conditions have also been conducted. In the present study, calculations were performed for Natural Circulation Test Run 3 (NC-03R [8]), conducted as part of the OECD/NEA-ATLAS2 international collaborative research project.

The NC-03R test investigated coolant inventory depletion under a reactor power level of approximately 5%. As observed in similar inventory depletion experiments, a characteristic trend of increasing flow rate followed by decreasing flow rate with decreasing coolant inventory was observed.

### 3. NC-03R MARS-KS input modelling and base calculation result

The MARS-KS input model was developed based on the design information of the ATLAS test facility, with modifications to an input model previously developed and utilized for the evaluation of various experiments, including B3.1 and B3.2. An overview of the input modeling is presented in Figure 1.

The drained mass was simulated using a time-dependent junction component. The drain flow rate was modeled based on the time at which the measured mass reached a stabilized condition. The simulated drained mass as a function of time is shown in Figure 2.

A baseline calculation was performed using the default heat-loss model and default interfacial friction model. The baseline results revealed several limitations: (i) overprediction of the single-phase natural circulation flow rate, (ii) premature onset of two-phase natural circulation, (iii) overprediction of the two-phase natural circulation flow rate, and (iv) overprediction of flow oscillation amplitude in the two-phase flow instability region.

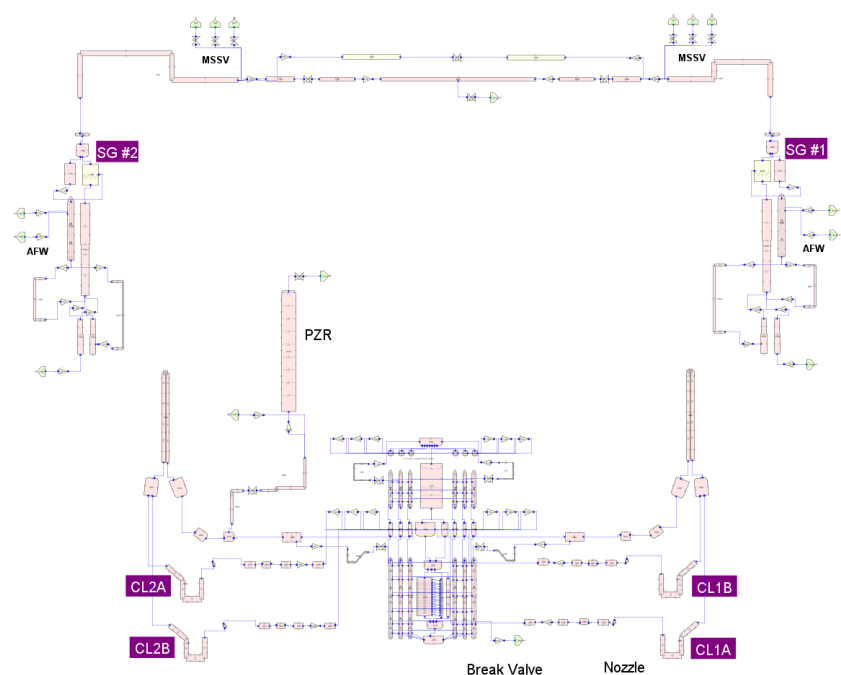


Fig. 1. MARS-KS ATLAS input model

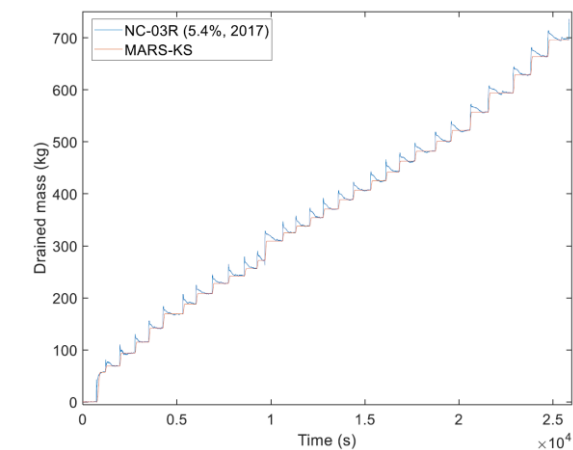


Fig. 2. Drained mass modeling result

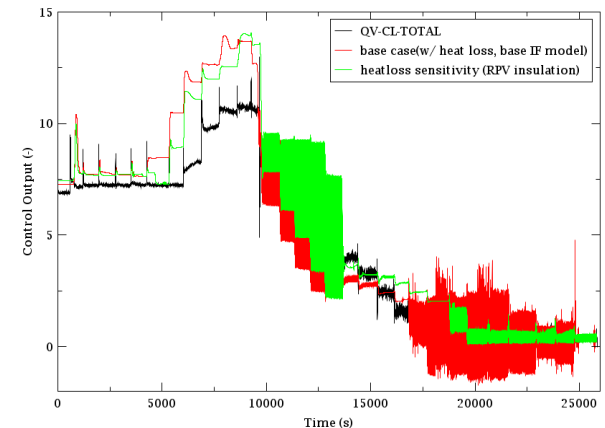


Fig. 4. heat loss sensitivity calculation result

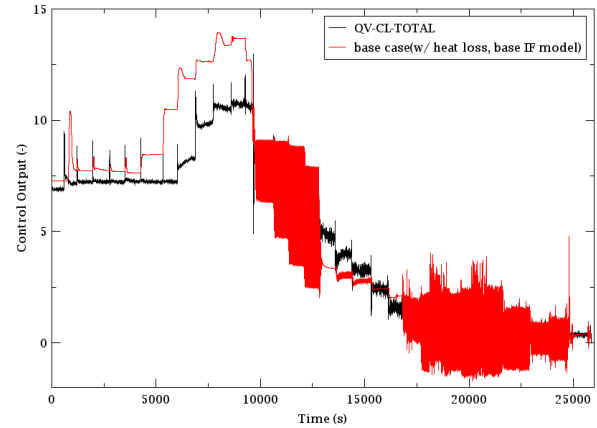


Fig. 3. base calculation result (core inlet mass flow rate, kg/s)

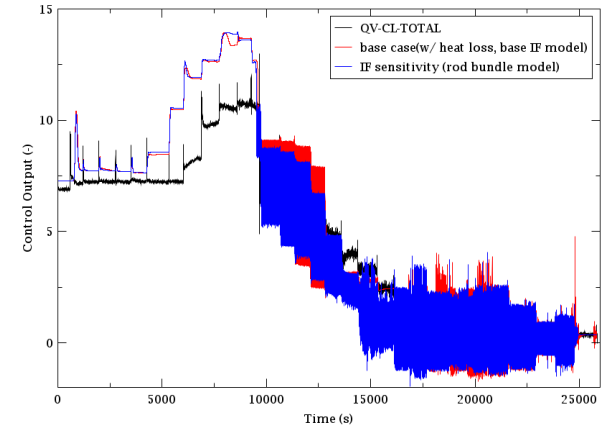


Fig. 5. Interfacial friction model sensitivity calculation result

#### 4. Sensitivity Analysis of the RPV Heat-Loss Model

A sensitivity analysis was performed for the primary-side RPV heat-loss model. Two conditions were considered: (a) the wall-temperature-dependent heat-transfer coefficient model (base case), and (b) an adiabatic RPV condition. The wall-temperature-dependent heat-transfer coefficient model was developed based on heat-loss experiments conducted for the ATLAS facility. The comparison of the calculation results is shown in Figure 4.

The results showed that, compared with the baseline heat-loss model, the adiabatic RPV condition resulted in an decrease in the single-phase natural circulation flow rate, a delay in the onset of two-phase natural circulation, a decrease in the two-phase natural circulation flow rate, an increase in the average flow rate in the instability region, and a reduction in the flow oscillation amplitude in the instability region. These results are attributed to the differences in coolant density and collapsed water level resulting from the heat loss models.

#### 5. Sensitivity Analysis of the Interfacial Friction Coefficient Model

MARS-KS currently includes three friction coefficient models: the default friction coefficient model, the rod-bundle friction coefficient model, and the ORNL friction coefficient model. The default model follows general flow regimes for pipe flow, such as bubbly, slug, and annular-mist flow, and applies correlations developed under the assumption of large Taylor bubbles confined by the pipe wall in the slug flow regime, including the Ishii and Vince-Lahey correlations. When applied to rod bundles, such as reactor cores and steam generator tube bundles, the model is known to tend to overpredict interphase friction compared with experimental observations. The rod-bundle model is based on the EPRI/Chexal-Lellouche drift-flux correlation and directly calculates the relative velocity between the gas and liquid phases, from which the interfacial friction coefficient is derived. The ORNL model is specialized for plate-type heat transfer geometries [9].

In the present study, calculations using the default friction coefficient model and the rod-bundle model were performed to investigate the effect of the interfacial friction model applied to the steam generator tubes. The comparison of the calculation results is shown in Figure 5.

The results showed that the interfacial friction coefficient model had little effect on the single-phase natural circulation region or the general two-phase natural circulation region. However, a noticeable influence on the reduction in the average flow rate was observed in the instability region. In addition, an increase in flow instability was observed even in the

relatively stable flow region following the instability region.

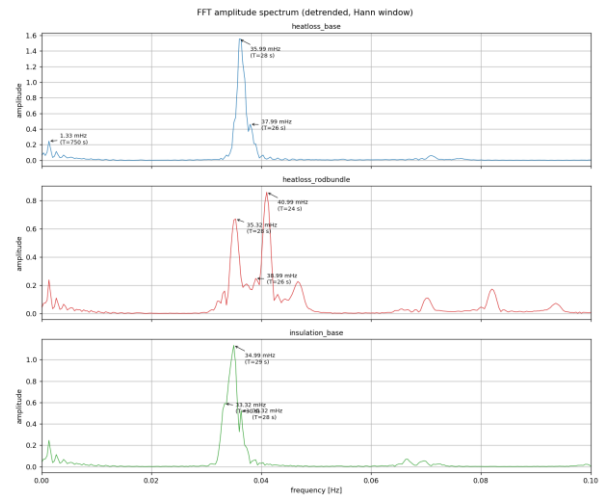


Fig. 6. FFT analysis for mass flow oscillation from instability region

In particular, analysis of the instability region between 10,000 and 13,000 s showed that, as illustrated in Figure 6, the interfacial friction model affected not only the amplitude of the flow oscillations but also the dominant frequency.

#### 6. Conclusion

The present study investigated the effects of the RPV heat-loss model and interfacial friction coefficient model on the prediction of two-phase natural circulation using MARS-KS. The RPV heat-loss model was found to affect natural circulation behavior throughout various flow regimes, whereas the interfacial friction coefficient model had its most notable impact in the flow instability region.

These results indicate that thermal-hydraulic code predictions can be highly sensitive to the choice of specific constitutive and physical models under SMR conditions. Consequently, a careful evaluation and uncertainty quantification of these physical models are warranted when applying system codes to SMR safety analysis.

From a regulatory perspective, such model-dependent sensitivities suggest that SMR licensing reviews could benefit from a technology-inclusive framework. In this context, regulatory acceptability can be effectively evaluated based on the characterization of safety-significant phenomena, rigorous treatment of model uncertainties, and the demonstration of adequate safety margins, rather than relying on pre-established analytical baselines.

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