Integral Effect Test Based Validation of the Passive Auxiliary Feedwater System (PAFS) Condensation Model in the SPACE code

Jong Hyuk Lee[1]*, Hae Min Park[1], and Sung Won Bae[1]
1 Korea Atomic Energy Research Institute, 111, Daedeok-daero 989, Yuseong-gu, Daejeon, Republic of Korea
E-mail: leejonghyuk@kaeri.re.kr

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1. Introduction

The introduction of passive safety systems has driven a significant paradigm shift in nuclear power plant design, particularly in enhancing inherent and simplified safety features. In this context, the innovative small modular reactor (i-SMR), which is currently under active development in the Korean nuclear industry, adopts passive safety systems. Thorough the systematic integration of passive safety features, the i-SMR design aims to enhance safety margins, improve accident mitigation capability, and strengthen overall plant safety performance.

In this study, the applicability of the SPACE code [1] is assessed by simulating integral effect test data for the Passive Auxiliary Feedwater System (PAFS), one of the key passive safety systems adopted in the i-SMR design. For the integral effect test, the C2.3 test [2] performed within the framework of the OECD/NEA ATLAS-3 project was employed in this study. The C2.3 test represents a steam line break (SLB) scenario in which the accident is mitigated by the PAFS operation, thereby enabling the evaluation of its performance. Therefore, the C2.3 test data are considered appropriated validation data for assessing the capability of the SPACE code to predict thermal-hydraulic behavior of the PAFS.

2. SPACE modeling

SPACE modeling has been conducted to analyze the post-test of the ATLAS C2.3 test using the SPACE code. Fig. 1 and Fig. 2 illustrate the nodalization for the RCS and the PAFS of ATLAS, respectively. Fig. 1 depicts the nodalization of the ATLAS facility including the reactor pressure vessel, the reactor core, two hot legs, four cold legs, two steam generators, and the main steam pipe break part, which is designed to simulate the double-ended guillotine breaks of an SLB accident with connecting to the outlet of the SG #1. A single train of PAFS is connected to an SG #2 of ATLAS and it consists of a steam supply line, a return-water line, and a horizontal type of heat exchanger submerged in a Passive Condensation Cooling Tank (PCCT), as shown in Fig. 2.

The target scenario of ATLAS C2.3 is a SLB with an operation of PAFS. The sequence of events is summarized in Table 1.

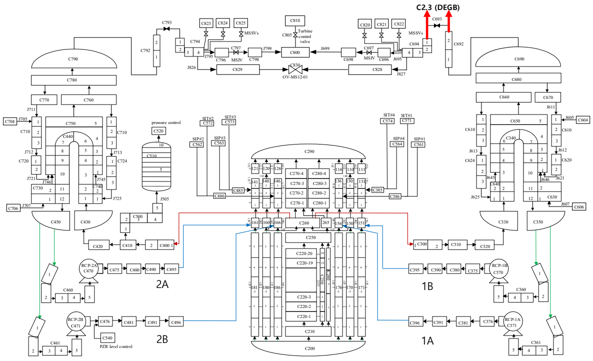


Fig. 1. SPACE nodalization diagram of the ATLAS facility

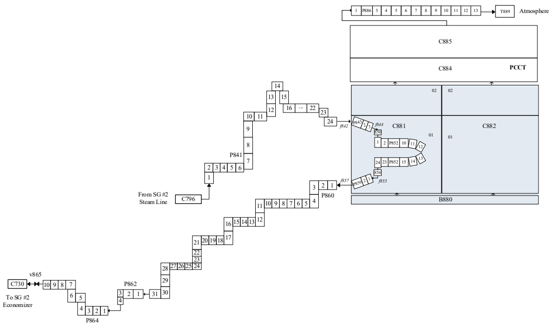


Fig. 2. SPACE nodalization diagram of the ATLAS-PAFS

Table I: Sequence of events for the ATLAS C2.3 test

Event	Remark
SLB initiated	Break valve open
Main Feedwater Isolation Valve closed	Coincidence with break
Low SG pressure (LSGP) signal actuated	Reactor trip
Main Steam Isolation valve closed	LSGP signal with a delayed time
SG#2 Main Steam Safety Valve (MSSV) firstly opened	SG#2 pressure reached to the Max. set pressure
SG#1 Dry-out	
SG#2 MSSV open/close operated	Within a Min/Max. set-value of SG#2 pressure
PAFS actuated	SG#2 level reached to the set value.
SIP injected	Prim. Pressure reached to the set value.
Test ends	

3. Validations

The steady-state conditions of the ATLAS C2.3 experiment were reproduced with satisfactory agreement relative to the measured data, thereby providing a reliable initial state for the subsequent transient analysis. Based on this steady-state calculation, a transient simulation of the steam line break (SLB) was performed. The break configuration adopted in the calculation was selected from a prior sensitivity analysis to ensure realistic discharge behavior.

Figure 3 presents the cumulative mass discharged through the break located upstream of the main steam safety valves (MSSVs) in SG#1. Immediately after the initiation of the SLB, the pressure in SG#1 rapidly decreased and reached the low steam generator pressure (LSGP) trip setpoint. This triggered a reactor trip, followed by a reduction in primary system pressure. As illustrated in Fig. 4, the primary pressure subsequently increased due to degradation of secondary-side heat removal capability. During this period, the MSSVs operated in a cyclic manner within their predefined maximum and minimum set-pressure limits. The continuous inventory depletion of SG#2 through MSSV discharge eventually reduced its level to the actuation setpoint of the PAFS. As the transient progressed, the primary pressure dropped sufficiently to initiate the safety injection pump (SIP), at which stage the experimental sequence was concluded. The activation behavior of the SIP is also reproduced appropriately in the simulation (Fig. 5).

A previous study [3] improved the PAFS condensation heat transfer model implemented in the SPACE code to enhance the prediction of condensation behavior in the PAFS heat exchanger. Fig. 6 compare the simulation results obtained with and without the application of the improved PAFS condensation model. When the condensation model was not applied, significant oscillations in the return-line flow rate were observed not only during the early phase of the accident but also throughout the transient period. In contrast, when the PAFS condensation model was incorporated, initial flow oscillations were still present however, the flow rate gradually stabilized and showed good agreement with the test data. These results indicate that the application of the PAFS condensation model is necessary for accurately reproducing the thermal-hydraulic behavior of the PAFS. Accordingly, the use of the improved condensation model is considered more appropriate for the analysis of PAFS performance in the i-SMR.

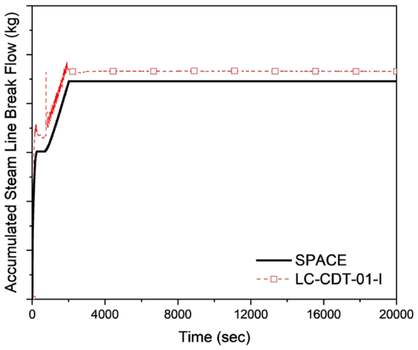


Fig. 3. Comparison of the accumulated break mass via main steam line break

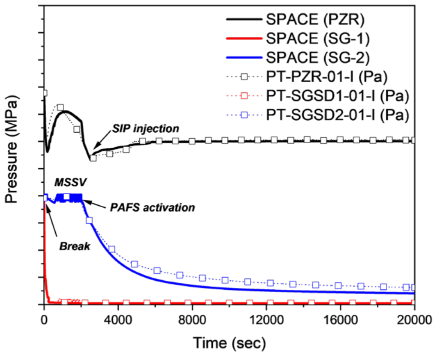


Fig. 4. Comparison of pressure behavior of ATLAS C2.3 test

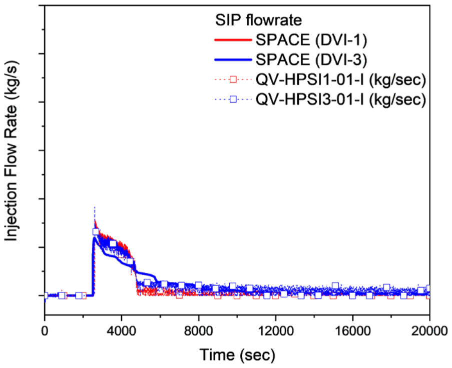
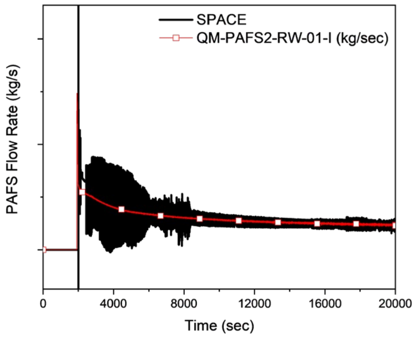
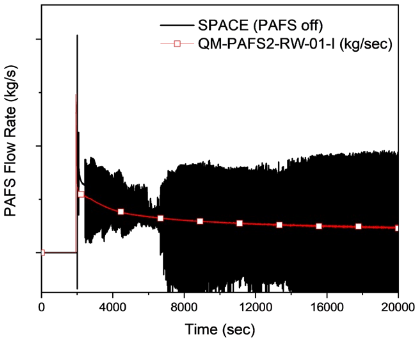


Fig. 5. Comparisons of HPSIs behavior



(a) with PAFS condensation model



(b) Without PAFS condensation model

Fig. 6. Comparison of the return line flow rate of PAFS

4. Conclusions

In this study, the applicability of the SPACE code to the analysis of the Passive Auxiliary Feedwater System (PAFS) was evaluated using the OECD/NEA ATLAS-3 C2.3 integral effect test data. The steady-state conditions and subsequent SLB transient behavior were reproduced with satisfactory agreement with the experimental results. Furthermore, the comparison of simulations with and without the improved PAFS condensation heat-transfer model confirmed that the incorporation of the enhanced condensation model significantly improves the prediction of return-line flow behavior and overall transient stability. The results indicate that accurate condensation modeling is essential for reliable analysis of PAFS performance. Overall, the SPACE code, when equipped with the improved PAFS condensation model, provides a reasonable predictive capability for simulating PAFS behavior under SLB conditions and can be considered applicable for the thermal-hydraulic analysis of passive safety systems in the i-SMR design.

Acknowledgements

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