Uncertainty Quantification on Critical Flow for an IBLOCA Application

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1. Introduction

During the progression of an Intermediate-Break Loss-Of-Coolant Accident (IBLOCA), complex thermal-hydraulic phenomena occur simultaneously, including two-phase flow, core heat transfer, system pressure transients, and reflooding induced by safety injection. Therefore, securing the predictive reliability of thermal-hydraulic computer codes used for analysis is essential. This paper focuses on quantifying the uncertainty of the critical flow, which is one of the key thermal-hydraulic correlations required to develop a realistic evaluation methodology (best-estimate methodology) for IBLOCAs.

Deriving the uncertainty distribution through a comprehensive review of the application range, prediction errors relative to experimental data, and the representativeness of prediction results for critical flow correlations serves as a vital foundation for ensuring the reliability of IBLOCA safety analysis results. Quantifying the uncertainty of physical models and thermal-hydraulic correlations requires an experimental database capable of validating the target phenomena.

The uncertainty quantification methodology applied in this paper is based on the SAPIUM methodology [1], which was established through the OECD/NEA ATRIUM joint international research project [2]. The SAPIUM methodology provides a systematic approach to evaluating the uncertainties of physical models and correlations used in safety analysis through comparisons with experimental data. It quantifies uncertainties while accounting for data suitability, phenomenon representativeness, and statistical procedures, enabling reasonable uncertainty estimations that reflect dominant drivers per phenomenon and the coverage of the experimental database.

Previously Lee et al. [3] investigated the effect of the critical flow model in the MARS-KS code on the uncertainty quantification of a Large-Break Loss-Of-Coolant Accident (LBLOCA). Additionally, uncertainty quantification for the IBLOCA LSTF Test No.1 was performed based on the SAPIUM guideline [4].

In this paper, uncertainty quantification on critical flow has been conducted for an IBLOCA application. The modified Henry–Fauske critical flow model implemented in the SPACE code [5] was employed. Following the SAPIUM guidelines, the critical flow model in the SPACE code is confirmed to be appropriate for evaluating discharge flow and depressurization during an IBLOCA scenario.

2. SAPIUM and ATRIUM

2.1 The SAPIUM Methodology

Over the past few decades, Best Estimate Plus Uncertainty (BEPU) methodologies have been extensively developed for nuclear power plant (NPP) safety analysis under the framework of the OECD/NEA. A series of OECD/NEA BEPU programs have been conducted, including UMS (Uncertainty Methods Study; 1995-1997), BEMUSE (Best-Estimate Methods Uncertainty and Sensitivity Evaluation; 2004-2010), PREMIUM (Post BEMUSE REflood Models Input Uncertainty Method, 2012-2015), and SAPIUM (Systematic AProach for Input Uncertainty quantification Methodology, 2017-2019).
In this context, systematic approaches for quantifying and managing uncertainties have become increasingly important to improve the reliability and credibility of simulation results. Therefore, the SAPIUM methodology [1] was developed to establish guidelines containing recommendations and best-practices for performing Inverse Uncertain Quantification (IUQ). The outline of the SAPIUM guideline is shown in Fig. 1.

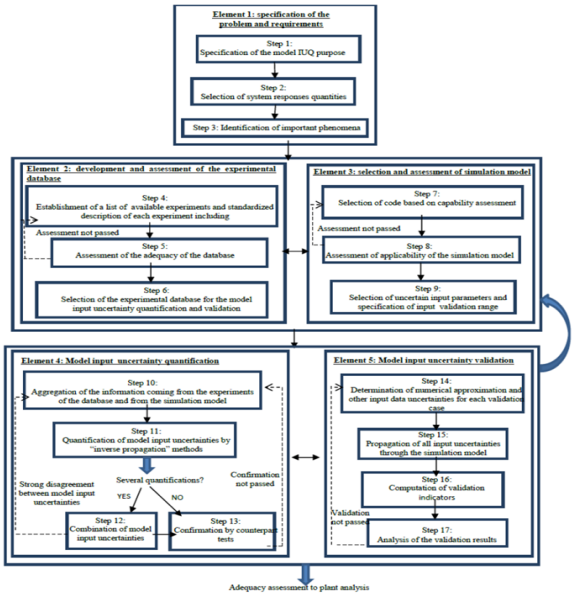


Fig. 1. The outline of the SAPIUM guideline.

2.2 The ATRIUM Project

The ATRIUM (Application Tests for Realization of Inverse Uncertainty Quantification and Validation Methodologies in Thermal-Hydraulics) project was proposed in 2022 and completed in 2025 [2]. The primary objective of the ATRIUM project is to perform a practical IUQ exercise to demonstrate the applicability of the SAPIUM framework.

The goals of the ATRIUM activities are to demonstrate the applicability of the best-practices, resolve some identified open issues, identify potential new issues, summarize lessons learned among participants, and update recommendations based on activity outcomes. The target application is an IBLOCA, with three exercises focusing on critical flow, post-CHF heat transfer, and overall IBLOCA behavior. Within this framework, the Korean participants utilized SPACE [5], a system thermal-hydraulic code, coupled with PAPIRUS [6], an uncertainty quantification tool.

2.3 The First Exercise on Critical Flow

The first exercise of the ATRIUM project focuses on critical flow, for which the critical mass flow rate is defined as the Figure of Merit (FoM). Following the SAPIUM guideline, the ATRIUM activities comprise 5 elements and 17 steps, as shown in Fig. 1.

In Element 1, Step 3, critical flow is identified as a dominant phenomenon. In Element 2, Step 4, a list of available experiments and standardized description of each experiment are established. The experimental database of critical flow for ATRIUM are summarized in Table I.

Table I: Summary of the Experimental Database of Critical Flow for ATRIUM

		D [mm]	L/D	N° tests	p_{in} [bar]	x_{in}	G [kg/m^2/s]
Sozzi - Sutherland	N2	12.7	0 – 140	358	56.0 – 71.3	-0.0044 – 0.0065	17528 - 75824
	N3	12.7	0	58	42.7 – 69.0	-0.0059 – 0.0060	33161 - 61226
	N4	19	0	23	56.0 – 66.3	-0.0003 – 0.0099	29295 - 51266
SMD	Div.	20.13	18	27	20.0 – 120.1	< 0	15300 - 62200
	Exp.	20.0	20	12	20.0 – 120.1	< 0	16100 - 61800
Marviken	13	200	3	1	~ 50 (transient)	< 0 ($DT_{sub,in}$ ~ 31 °C)	< 89200
	17	300	3.7	1			< 61700
	24	500	0.33	1			< 59750

The experimental database (ED) used for this exercise encompasses a wide range of critical flow experiments, including the Sozzi–Sutherland tests with three different nozzles and various L/D ratios [7], the Super Moby-Dick (SMD) experiments with divergent and expanded nozzles [8], and the transient Marviken (MVK) tests Nos. 13, 17, and 24 [9], as summarized in Table I. An adequacy analysis was performed to evaluate data suitability, and the database was subsequently divided into subsets for uncertainty quantification and validation.

In Element 2, Step 6, the experimental databases for IUQ and validation is selected, as shown in Table II.

Table II: Experimental Database for IUQ and Validation on Critical Flow for ATRIUM

Quantification database	Validation database
- Sozzi-Sutherland Nozzle 2 (358, steady-state) - Sozzi-Sutherland Nozzle 4 (23, steady-state) - Super Moby-Dick, Divergent (27, steady-state)	- Super Moby-Dick, Expansion (12, steady-state) - Marviken Test No. 13, 17, and 24 (3, transient)

In Element 3, Step 7, the SPACE 3.2 code is selected based on a capability assessment, utilizing the Henry-Fauske model.

In Element 3, Step 9, uncertainty-related input parameters and their ranges are selected. Based on expert judgment, 12 parameters were chosen. These include 3 operating parameters, such as inlet pressure, inlet temperature and inlet void fraction (with 1% uncertainty), and 9 modeling parameters, such as discharge coefficients for liquid, two-phase and vapor regimes, non-equilibrium factor, and interfacial heat transfer for bubble flow, slug flow, bubbly-to-annular transition, bubbly-to-slug transition and flashing (with 30% uncertainty).

In Element 4, Step 11, the model input uncertainty or its probability distribution are estimated by evaluating the IUQ results from both statistical and physical perspectives. In the ATRIUM project, Bayesian methods combined with Markov Chain Monte Carlo (MCMC) sampling with over 2,000 samples were used [10].

In Element 4, Step 12, the model input uncertainty is combined. In Element 4, Step 13, consistency between the estimated probability distribution (or ranges) and the experimental database is verified through a forward uncertainty propagation step using the quantification database. The experimental data are enveloped by the simulation results within a specified tolerance interval and confidence level (95% two-side tolerance interval and min and max values).

Finally in Element 5, Step 17, the validation results were analyzed using the validation database.

3. Uncertainty Quantification on Critical Flow for IBLOCA Application

Uncertainty quantification was performed on critical flow for an IBLOCA application. The selected elements and steps are detailed and discussed in the following subsections.

3.1 Review of Experimental Database by Target Phenomenon (Element 2, Step 4)

The critical flow validation experimental database is summarized in Table I.

Sozzi-Sutherland experiments: Conducted by GE in 1975, these critical flow experiments tested three nozzle geometries (N2, N3, N4). Tests for the N2 nozzle were performed across various L/D ratios, whereas the N4 nozzle tests evaluated varying diameters (D) [7].

Super Moby-Dick (SMD) Experiments: Conducted by CEA in 1982, these experiments evaluated critical flow using Expansion and Divergent nozzle geometries [8].

Marviken (MVK) Tests: Performed in 1978, consisting of 27 critical flow tests across 9 nozzle geometries, 4 distinct diameters (200, 300, 500, and 509 mm), and L/D ratios ranging from 0.33 to 3.7. Because the maximum break size for an IBLOCA is up to 8.5 inches, this validation incorporated experimental DBs from Test Nos. 13 and 17, which feature relevant diameters [9]. Detailed descriptions of all listed experiments are elaborated in the previous validation matrix evaluation report.

3.2 Selection of IUQ Methodology (Element 4, Step 11)

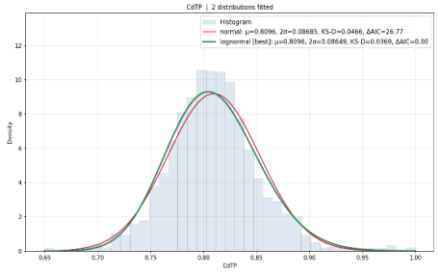
The PAPIRUS uncertainty quantification software was employed for both IUQ and UQ analyses. Developed in-house by KAERI, this tool offers diverse capabilities, including sensitivity analysis and uncertainty quantification [6]. Within PAPIRUS, the IUQ feature is designated as 'data assimilation probabilistic'. Fundamentally a Bayesian inference-based approach, it updates a priori knowledge (prior distributions) of input parameters using new experimental data to produce refined a posteriori distributions.

Ultimately, the goal is to identify a parameter distribution that fits the experimental data well without straying excessively from prior information. Because the probabilistic approach explores this posterior distribution directly through sampling rather than analytical solutions, non-linear or discontinuous system behaviors yield non-Gaussian posteriors. Thus, MCMC simulation using the Metropolis algorithm [10] is utilized to efficiently compute the a posteriori parameter distributions via random sampling. This evaluation method has been verified through numerous assessments and was applied to the IUQ computations in this methodology.

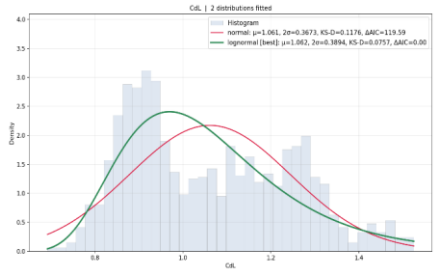
3.3 IUQ Analysis Results and Evaluation (Element 4, Steps 12-13)

IUQ computations were performed up to a total of 2,300 samples. The initial 200 samples were discarded to allow error fluctuations to stabilize, and uncertainty results were calculated based on the remaining 2,100 samples. The Sozzi-Sutherland test and the Super Moby-Dick (SMD) Divergent test were used for IUQ calculations. The results indicate that the input parameters with high sensitivity are, in order of importance: two-phase discharge coefficient, liquid discharge coefficient, slug/bubble interfacial heat transfer, and vapor discharge coefficient.

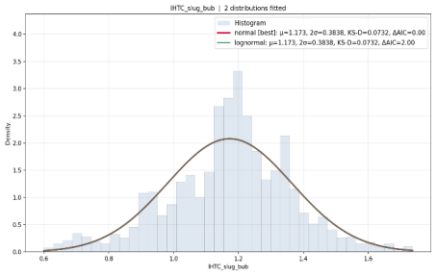
Fig. 2 illustrates the histograms and extracted uncertainty distributions for key input parameters determined via IUQ analysis.



(a) two-phase discharge coefficient (Normal μ=0.809 σ=0.043)



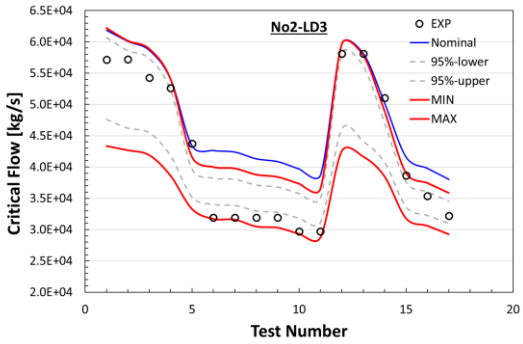
(b) liquid discharge coefficient (Normal μ=1.061 σ=0.1837)



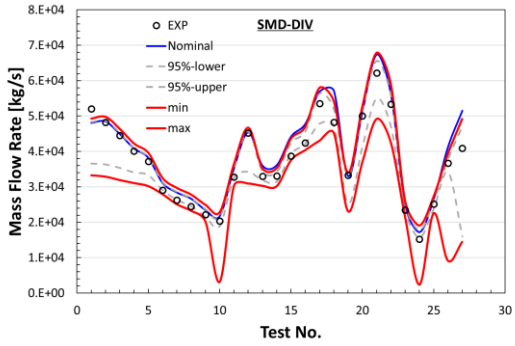
(c) interfacial heat transfers for bubbly-slug transition (Normal μ=1.173 σ=0.192)

Fig. 2. Histograms and uncertainty distributions of key input parameters for critical flow.

Fig. 3 summarizes representative results evaluating coverage by comparing IUQ predictions against experimental data. Analysis results display nominal, maximum, minimum, and 95% confidence level limits. It was confirmed that most experimental data points fell within the uncertainty bounds.



(a) Sozzi-Sutherland N2 L/D=3



(b) SMD-Divergent

Fig. 3 Experimental data coverage of critical flow IUQ analysis results.

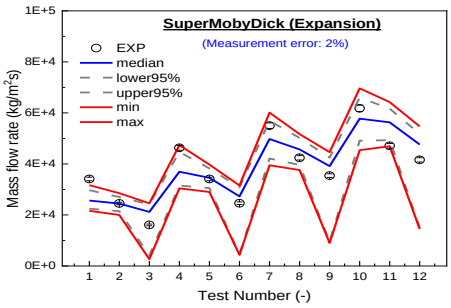
3.4 UQ Confirmation Analysis Results and Evaluation (Element 5, Steps 14–17)

The Super Moby-Dick (SMD) Expansion test and Marviken Test Nos. 13 and 17 were utilized for UQ confirmation calculations. Sensitivity evaluations were performed using the Morris methodology on sensitive parameters obtained from the IUQ results. The two-phase discharge coefficient, liquid discharge coefficient, slug/bubble interfacial heat transfer, and initial pressure and temperature were selected as sensitive variables for UQ. Selected sensitive variables and their distributions are summarized in Table III.

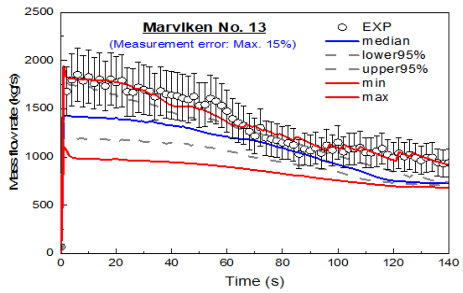
Table III: Input Parameters for Critical Flow UQ Analysis

No	Input parameter	ID	Distribution	Uncertainty
1	inlet pres.	P	Uniform	μ=1.0 ± 0.3%
2	inlet temp.	T	Uniform	μ=1.0 ± 1.0%
3	discharge coefficient for liquid	cdliq	Normal	μ=1.061, σ=0.1837
4	discharge coefficient for two-phase	cdtwoph	Normal	μ=0.809, σ=0.0430
5	IHT for bubbly-slug	ihtbs	Normal	μ=1.173, σ=0.1919

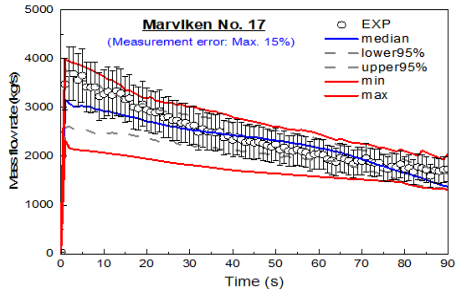
A total of 124 simulation runs were executed. Experimental data coverage of the critical flow UQ analysis was analyzed, during which some data points from Marviken Test No. 13 were initially missed. Multiple sensitivity calculations were performed to resolve this, demonstrating that increasing the uncertainty (standard deviation) of the liquid discharge coefficient from 0.1837 to 0.3000 resulted in excellent coverage of all experimental data as shown in Fig. 4. However, it is noted that the coverage of Marviken Test No. 13 against the median values acquired from simulation results needs further enhancement.



(a) SMD-Expansion



(b) Marviken No. 13

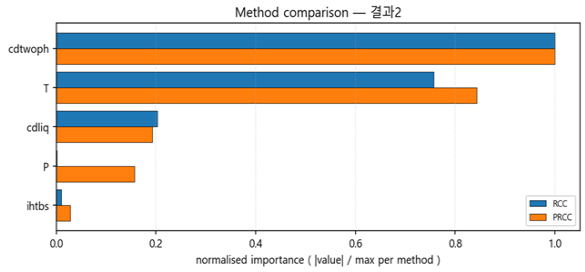


(c) Marviken No. 17

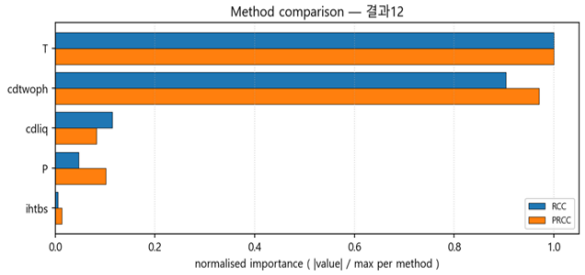
Fig. 4 Experimental data coverage of critical flow UQ analysis results.

Sensitivity and validation metric evaluations were performed for Cases 2 and 12 among the Super Moby-Dick (SMD) Expansion test results, representing typical steady-state critical flow conditions. As shown in Fig. 5,

while slight differences existed between RCC and Partial Rank Correlation Coefficients (PRCC) methodologies, parameter sensitivities were ranked in the following order: two-phase discharge coefficient, temperature, liquid discharge coefficient, pressure, and slug/bubble interfacial heat transfer.



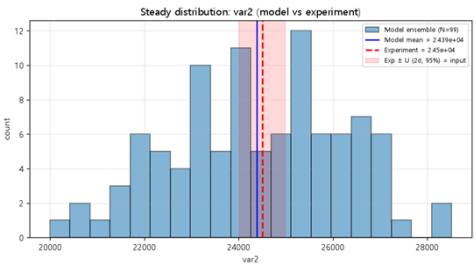
(a) SMD-Expansion, Case 2



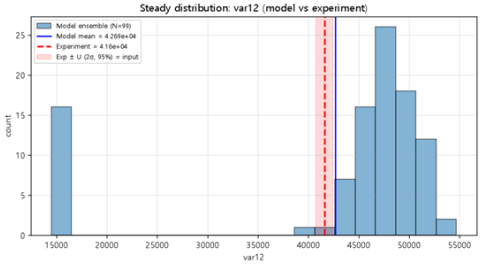
(b) SMD-Expansion, Case 12

Fig. 5 Sensitivity evaluation results for SMD-Expansion test.

Additionally, Fig. 6 demonstrates that the distribution of analysis results well envelopes the experimental data taking measurement error bounds (up to 2%) into account.



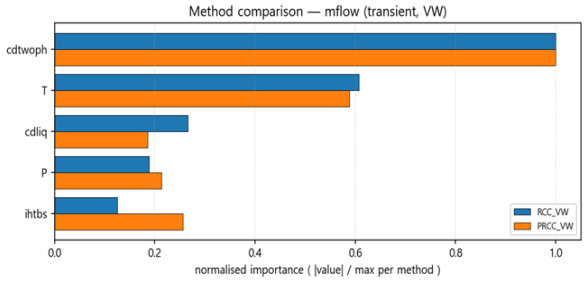
(a) SMD-Expansion, Case 2



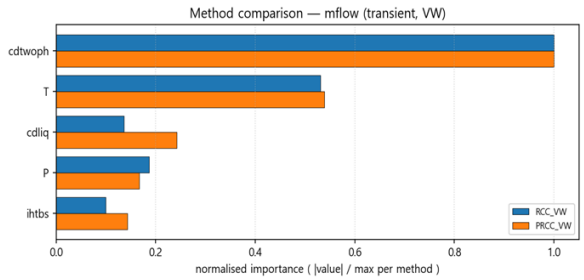
(b) SMD-Expansion, Case 12

Fig. 6 Validation Metric evaluation results for SMD-Expansion test.

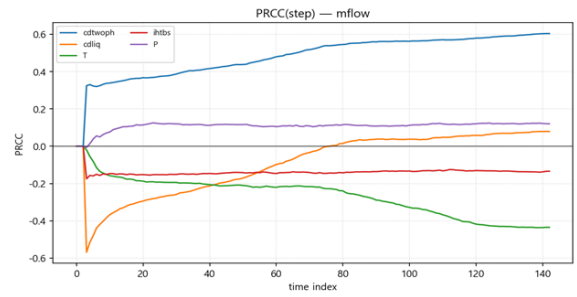
Sensitivity and validation metric evaluations were similarly performed for Marviken Test Nos. 13 and 17, representing typical transient critical flow conditions for IBLOCA application. As shown in Figs. 7(a) and 8(b), minor variations appeared between the RCC and PRCC methods, but the sensitivity ordering remained similar to the steady-state results: two-phase discharge coefficient, temperature, liquid discharge coefficient, pressure, and slug/bubble interfacial heat transfer. Figs. 7(c) and 8(d) plot time-dependent PRCC values of critical flow rates for Marviken Test Nos. 13 and 17. During the early phase of the test (0–20 seconds), sensitivities of the two-phase and liquid discharge coefficients predominated, whereas in the later phase (100–140 seconds), sensitivities of the two-phase discharge coefficient and temperature became dominant. Furthermore, Fig. 8 demonstrates that the analysis result distributions adequately envelope the experimental data considering error margins (up to 15%) for Marviken Test Nos. 13 and 17.



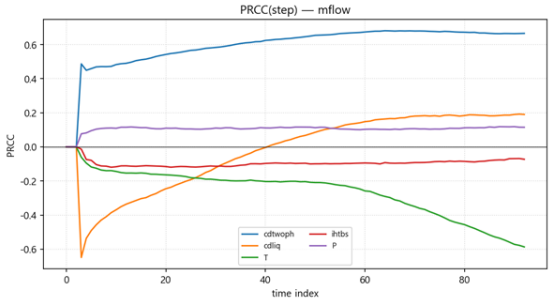
(a) Marviken Test No. 13



(b) Marviken Test No. 17

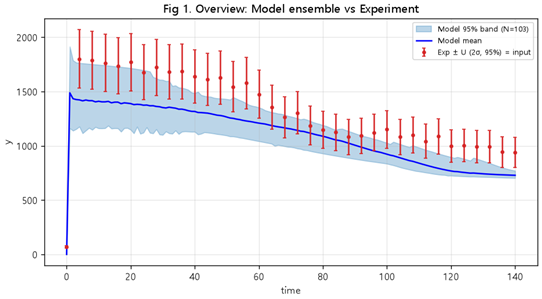


(c) Marviken Test No. 13 (temporal evaluation)

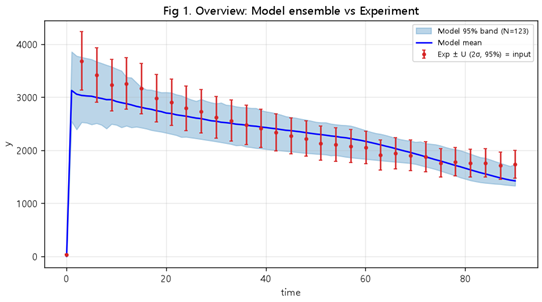


(d) Marviken Test No. 17 (temporal evaluation)

Fig. 7. Sensitivity evaluation results for Marviken tests.



(a) Marviken Test No. 13



(b) Marviken Test No. 17

Fig. 8. Validation metric evaluation results for Marviken tests.

4. Conclusions

In this paper, uncertainty quantification on critical flow was performed for an IBLOCA application. First, IUQ was conducted for the primary input parameters based on the selected experimental database, enabling the re-evaluation of parameter uncertainties and the identification of dominant contributing factors. It was confirmed that most experimental data points fell within the uncertainty bounds.

Second, the uncertainty distributions derived from IUQ were applied to the UQ of the critical flow. Parameter sensitivities were ranked in the following order: two-phase discharge coefficient, liquid discharge coefficient and slug/bubble interfacial heat transfer. UQ results demonstrate that the distributions of analysis results adequately envelope the experimental data, taking error margins into account for SMD-Expansion, Marviken Test Nos. 13 and 17.

This study provides a technical foundation for developing IBLOCA safety analysis methodologies based on the SAPIUM framework.

ACKNOWLEDGEMENT

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