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Preliminary Inverse Uncertainty Quantification of Post-CHF Phenomena Using SPACE Code

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Abstract

The SPACE code development team at KAERI recently participated in ATRIUM, a program organized by OECD/NEA, and conducted an applicability assessment of SAPIUM, a methodology for Inverse Uncertainty Quantification (IUQ) using the SPACE code. In the ATRIUM program, critical flow and post Critical Heat Flux (post-CHF), key phenomena in Intermediate Break Loss of Coolant Accident (IBLOCA) scenarios, were selected for study. For the Integrated Effect Test (IET), the LSTF (Large Scale Test Facility) test no.1 was chosen. According to the general guidelines of SAPIUM, the methodology consists of five main steps: Specification of the problem and requirements, Development and assessment of the experimental database, Selection and evaluation of the simulation model, Model input uncertainty quantification, and Model input uncertainty validation. Currently, the first phenomenon, critical flow, has been completed, and this paper discusses the study conducted on post-CHF phenomena. Five experimental databases relevant to post-CHF and 16 input parameters associated with post-CHF phenomena were selected. A Bayesian methodology-based Markov Chain Monte Carlo (MCMC) simulation was conducted with over 2,000 samples. The analysis results demonstrated an appropriate coverage of the selected experimental results. Additionally, the key model parameters and their correlations were identified. Future work will include validation evaluations to verify the final IUQ results. The improved uncertainty distributions of input parameters for the two phenomena will then be applied to the final IBLOCA simulation, LSTF Test No.1, to complete the uncertainty quantification and evaluate the SAPIUM methodology.

Keywords: Inverse Uncertainty Quantification (IUQ), Post-CHF, SPACE, ATRIUM

Introduction

The application of Best Estimate Plus Uncertainty (BEPU) methodologies in nuclear power plant safety analysis has steadily increased. To enhance the understanding of BEPU methodologies, multiple benchmark activities have been conducted under the NEA/CSNI/WGAMA framework: UMS (Uncertainty Methods Study, 1995-1997), BEMUSE (Best-Estimate Methods Uncertainty and Sensitivity Evaluation, 2004-2010), PREMIUM (Post BEMUSE Reflood Models Input Uncertainty Methods, 2012-2015), and SAPIUM (Systematic Approach for Input Uncertainty quantification Methodology, 2017-2019) [1, 2, 3, 4, 5, 6]. The ATRIUM project has a scope of performing practical IUQ exercise of demonstration of the SAPIUM approach to demonstrate the applicability of the best-practices, to resolve some identified open issues and identify possible new issues, and to summarize the lessons learned from the different participants and possibly update the recommendations based on the results of the activity. SPACE code team in Korea Atomic Energy Research Institute (KAERI) has participated in ATRIUM (Application Tests for Realization of Inverse Uncertainty quantification and validation Methodologies in thermal-hydraulics) project, which is organized by OECD/NEA [7].

SAPIUM approach has the logical flow for inverse uncertainty quantification as shown in Figure 1 [4]. In addition, the SAPIUM guideline proposes several steps for each element for a systematic IUQ process including clear specification of the problem, an efficient strategy to construct adequate experimental database and an assessment of the simulation methods, appropriate uncertainty ranges and distributions, IUQ methods, and validation. An intermediate break loss of coolant accident (IBLOCA) was selected as the application of ATRIUM. The two major phenomena are proposed for the transient during IBLOCA and defined as exercises for IUQ. The first exercise is critical flow (choked flow) and the related experimental database is composed of separated effect tests (SETs). The second exercise is post-CHF and related experimental database is composed of combined effect tests (CETs). Finally, the obtained input model uncertainties will be propagated on an integrated effect test (IET). In this project, OECD/NEA ROSA-2

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Project Large Scale Test Facility (LSTF) Intermediate Break Hot-break test no.1(IB-HL-01) is selected as the final IET. It can be SAPIUM guideline Element 1, which specifies the problem and requirement. Currently, the exercise 1 and 2 are completed. In this paper, the 2nd exercise of post-CHF results will be discussed based on the SAPIUM guideline.

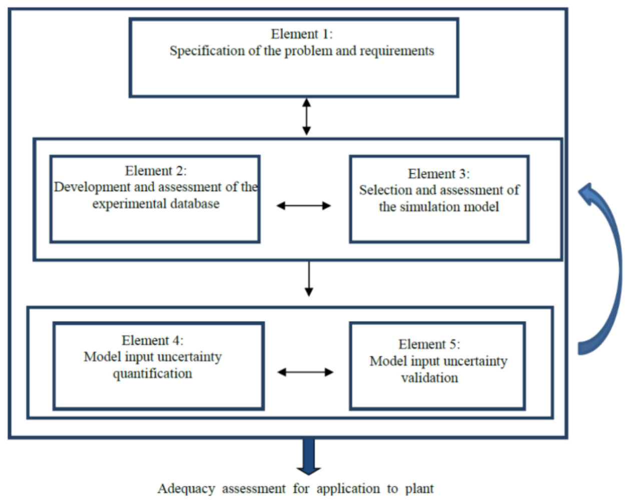

Figure 1 Major elements of the SAPIUM framework [4]

Experimental Database (ED)

Experimental database for post-CHF is summarized in Table 1 [8, 9, 10]. To evaluate the adequacy of the experimental database, adequacy analysis was conducted with SAPIUM guidelines Element 2. Based on the results, the Stewart experiment was excluded due to its limited ability to capture the physical phenomena required for simulation [11]. The Beker experiment [8], conducted at the Royal Institute of Technology (RIT), is sometimes referred to as the RIT test. They consist of a heated cylindrical tube delimited by two copper rings. It has three kinds of test sections with different diameter sizes and heated lengths. They measured flow rate, local wall and fluid temperatures, inlet and outlet pressure, and temperature. Based on wall temperature measurements, burn-out can be estimated when a significant temperature increase occurs. Figure 2 shows a schematic diagram of the Beker test facility and test section. The THTF (Thermal-Hydraulic Test Facility) is a heavily instrumented pressurized-water loop built at ORNL [10] to investigate the heat transfer phenomena during small and large break LOCA. Figure 3 shows a simplified THTF facility and bundle cross-section [10]. The test section consists of a cylindrical barrel containing 8x8 electrically heated rods enclosed in a shroud box. The 60 rods are heated structures, but 4 rods are used for instrumentation. The shroud box holds 6 grid spacers along the heated length and 1 grid spacer located before the beginning of the heated length. There are 14 axial measurement locations for rod temperature and fluid void fraction. In the experimental database, two kinds of types in THTF are considered. The first experiment is the Film Boiling (FB) test and the second experiment is the Uncovered Bundle (UB) test. In the film boiling tests, the bundle power was increased until the dry-out point was obtained at the desired level. A steady state was reached when pressure and rod temperature were stabilized. In the uncovered bundle tests, a certain collapsed level was obtained in the bundle thanks to the connection lines between the

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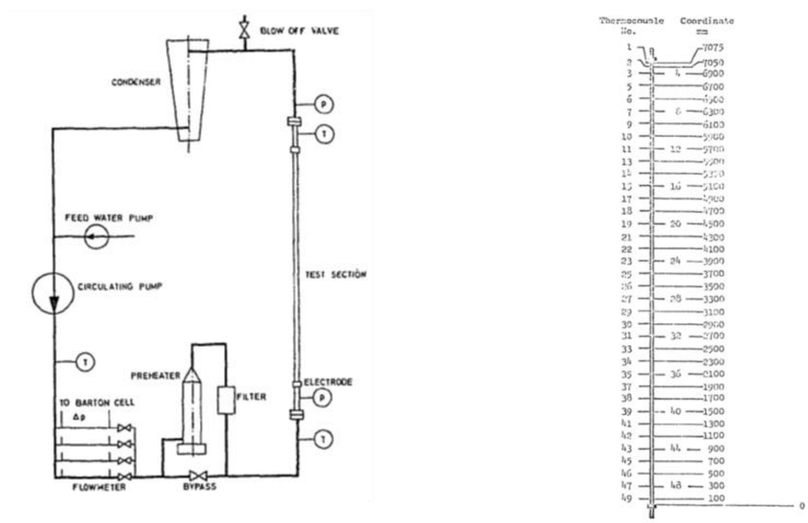
pressurizer and the annulus and the annulus and the outlet section. After stabilization, the power of the bundle increased to produce the peak cladding temperature safety limit of 740 °C.

Table 1. Summary of Post-CHF experimental database

ED	Type	No. tests	P [bar]	G [kg/m^{2}s]	q" [W/m^2]	$T_{sub,in}$[K]
Baker T/S 1	Tube	281	30-200	500-3000	100-1250	10
Baker T/S 2	Tube	102	30-200	500-3000	90-850	10
Baker T/S 3	Tube	38	150-200	780-2475	290-940	5-10
Stewart	Tube	312	20-90	115-2833	65-460	9-56
THTF FB	Bundle	22	40-130	226-806	320-940	8-46
THTF UB	Bundle	6	40-75	3-30	74-480	46-103
LSTF	**Bundle**	**1**	**20-50**	**0-600**	**500-2000**	**0**



(a) experimental loop (b) Test section

Figure 2. Becker's experimental facility [8]

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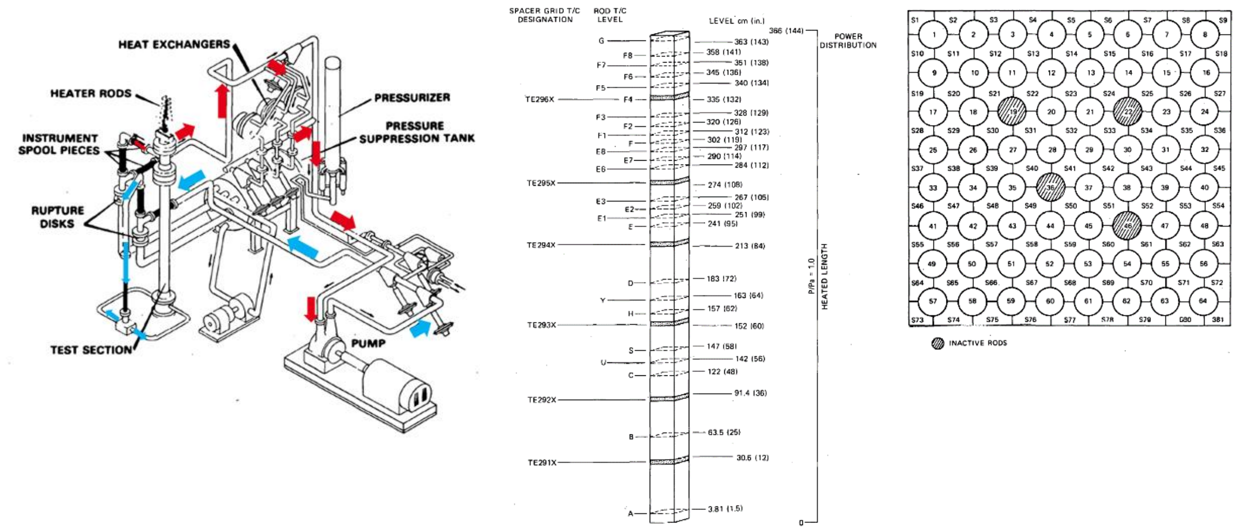

(a) experimental loop (b) test section (c) cross section

Figure 3. THTF experimental facility [10]

Models

Benchmark calculations are conducted using SPACE code version 3.2, which is a licensed safety analysis code for a nuclear power plant. Figure 4(a) shows nodalization of Becker's test section with 54 nodes. The node size is defined to match the locations of thermocouples. Inlet and outlet regions are modelled with additional 3 nodes. Inlet boundary conditions are defined with constant mass flow rate and temperature, and the outlet boundary condition is defined with pressure. The heat structure is modeled and connected to hydraulic cells to apply the power. Becker's different test sections are individually modelled with appropriate design parameters. Default all wall heat transfer models are applied and critical heat flux model of AECL 2006 CHF look-up table (LUT) and film boiling heat transfer of 2004 LUT are used. Figure 4(b) shows Nodalization of THTF test section with 29 nodes. In the same way, inlet and outlet regions are additionally modelled. THTF bundle heat structures are modelled with two kinds of heated and non-heated ones. The boundary conditions and heat transfer models are the same as those of the Becker's test. However, considering the bundle type, the Chexal-Lellouche interfacial drag model is applied [12]. Moreover, the grid spacer in the bundle has various physical phenomena during a post-CHF such as rewetting, radiation, droplet breakup, vapor heat transfer enhancement, etc. To consider this special effect from a grid spacer. SPACE code has interfacial area transport model (IAT), grid spacer (GS) model, and vapor enhancement (SP) model. Therefore, for the THTF tests, these models are applied for the better prediction of post-CHF phenomena.

Figure 5 shows typical results of wall temperatures for each test. Both results show reasonable prediction of wall temperature during CHF. Figure 5(b) shows results for various combinations of the grid spacer effect related models. Measured temperatures show temperature drops near the grid spacers due to enhancement of heat transfer. To obtain the better prediction of the wall temperature when the bundle has grid spacers, the grid spacer-related models are strongly recommended to use. Therefore, based on the SAPIUM guideline Element 3, the simulation model is selected and assessed.

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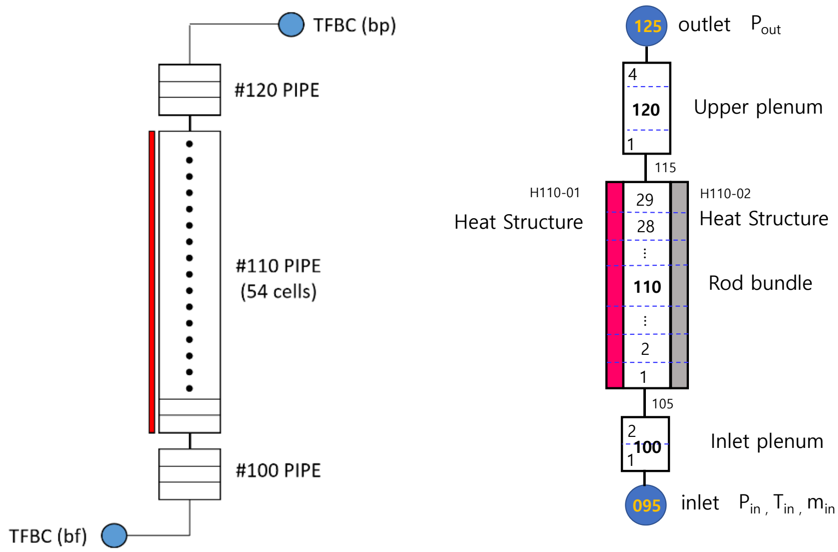
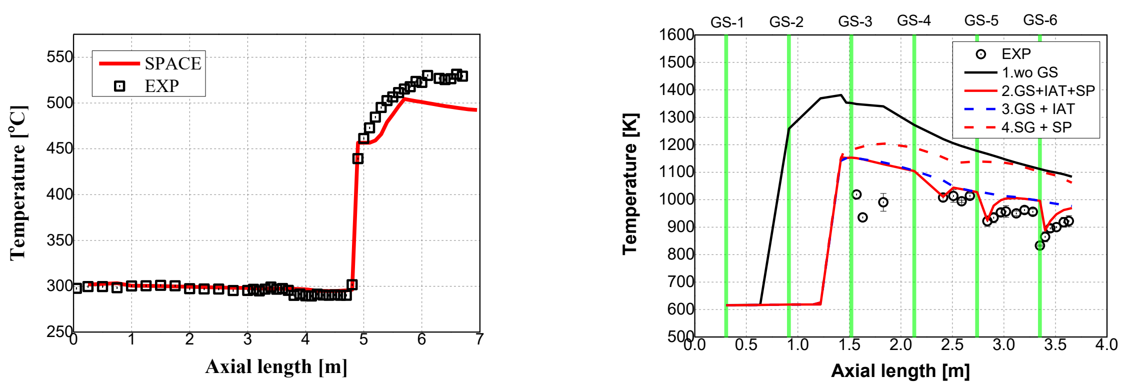


(a) Becker's test (b) THTF test

Figure 4. Nodalizations for SPACE code



(a) Becker's Test 2-No.439 (b) THTF test

Figure 5. Typical results of the wall temperatures

Inverse Uncertainty Quantification (IUQ)

In the SAPIUM guideline Element 4 and 5 are inverse uncertainty quantification (IUQ) and validation (forward uncertainty quantification, FUQ), respectively. During adequacy analysis for the experimental database, the experimental database for IUQ and FUQ are selected. Therefore, updated uncertainty distributions after the IUQ will apply to FUQ to check their validation. In this study, Baker test section 1 and 3 and THTF FB test are selected as the IUQ ED and all cases for Baker test section 2 and THTF UF tests are selected as the validation ED. The 16 input parameters for the post-CHF are selected with an

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engineering judgment (Table 2). The experimental measurement uncertainty is defined as 2%. For IUQ methodology, Bayesian analysis for the statistical inverse problem is used. Given experimental data and a priori distributions of the parameters, an inverse problem is solved adjusting the parameter values to achieve better agreement between measured and predicted values [13]. More than 2,000 samples were generated using the Markov Chain Monte Carlo (MCMC) method. All uncertainty quantification was conducted using the in-house tool, PAPIRUS [13].

Table 2. Summary of Post-CHF experimental database

No	Input Parameter	Index	Uncertainty	Distribution
1	Inlet mass flow rate lnet_M)	**Inlet_M**	±2%	Uniform
2	Inlet temperature	**Inlet_T**	±2%	Uniform
3	Outlet pressure	**Outlet_P**	±2%	Uniform
4	Total power	**Power**	±2%	Uniform
5	Interfacial friction (IF) for droplet	**IF_droplet**	±30%	Normal
6	IF for bubbly	**IF_bubbly**	±30%	Normal
7	IF for annular	**IF_annular**	±30%	Normal
8	IF for inversed slug	**IF_invSlug**	±30%	Normal
9	Wall heat transfer (WHT) for liquid	**HT_liquid**	±30%	Normal
10	WHT for subcooled nucleate boiling	**HT_subNB**	±30%	Normal
11	WHT for saturated nucleate boiling	**HT_satNB**	±30%	Normal
12	WHT for saturated film boiling	**HT_satFB**	±30%	Normal
13	WHT for vapor	**HT_Vapor**	±30%	Normal
14	WHT for CHF	**HT_CHF**	±30%	Normal
15	Interfacial heat transfer (IHT) for annular	**IHT_Annular**	±30%	Normal
16	IHT for inverted slug	**IHT_invSlug**	±30%	Normal

Figure 6 shows mismatch value for IUQ calculation. Initial 250 samples are neglected to evaluate the distribution of the input parameters. Figure 7 shows the standard deviation of all input parameters. The lower value means a more sensitive parameter. The most influential parameters are the film boiling heat transfer, saturated nucleate boiling, and subcooled nucleate boiling, in order. Figure 8 shows updated uncertainty distribution of input parameters. The most influential parameter of the film boiling heat transfer shows slightly higher mean values, which means the current model is under-estimated for heat transfer. And the nucleate boiling heat transfers are also under-estimated. Especially, the saturated nucleate boiling heat transfer shows large deviation. Figure 9 shows coverage of the wall temperatures for the Becker's tests. The lines indicate nominal, median, 95% confidence, minimum and maximum. Some results have a good coverage, but some results are not. It means that the current model needs improvement for specified conditions. For the THTF tests, their results are good coverage for most of the conditions (Figure 10). Using the updated distribution of the input parameters, the validation calculations (SAPIUM guideline element 5) are conducted. The coverage results for all experimental databases show a similar trend to the IUQ. It means the updated uncertainty distribution of the input parameters is well evaluated.

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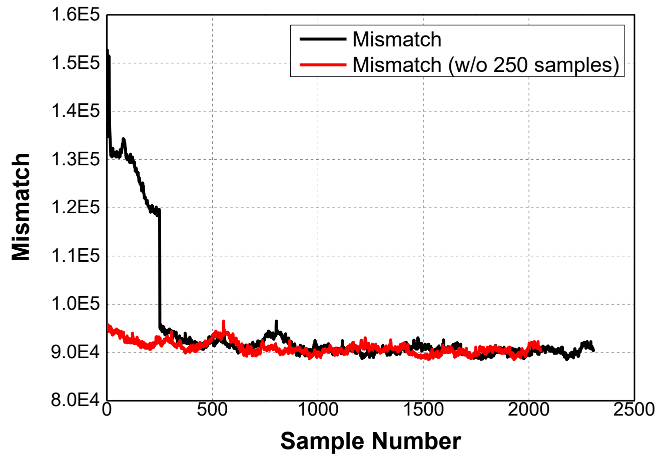


Figure 6. Mismatch values during IUQ calculation

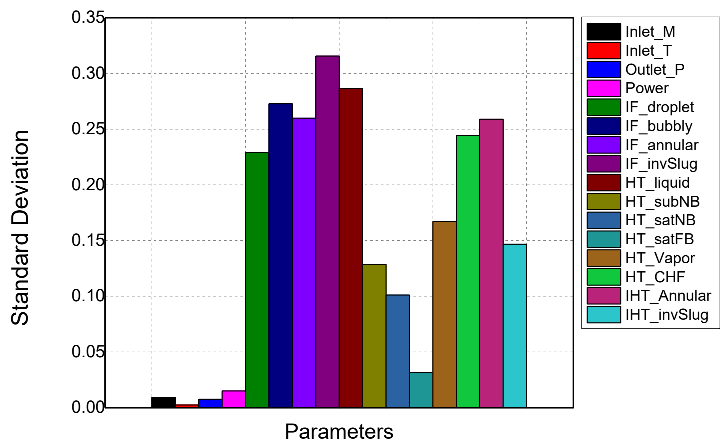
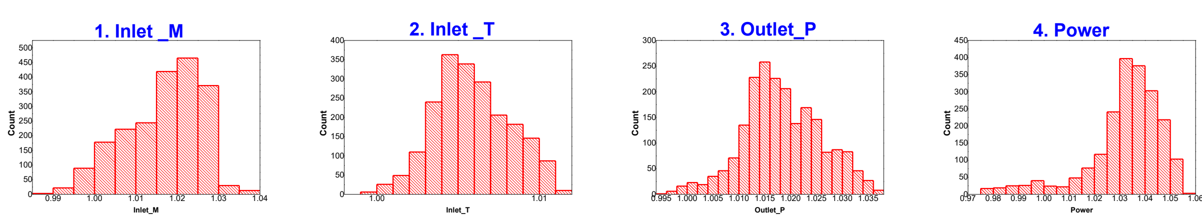


Figure 7. Standard deviations of input parameters



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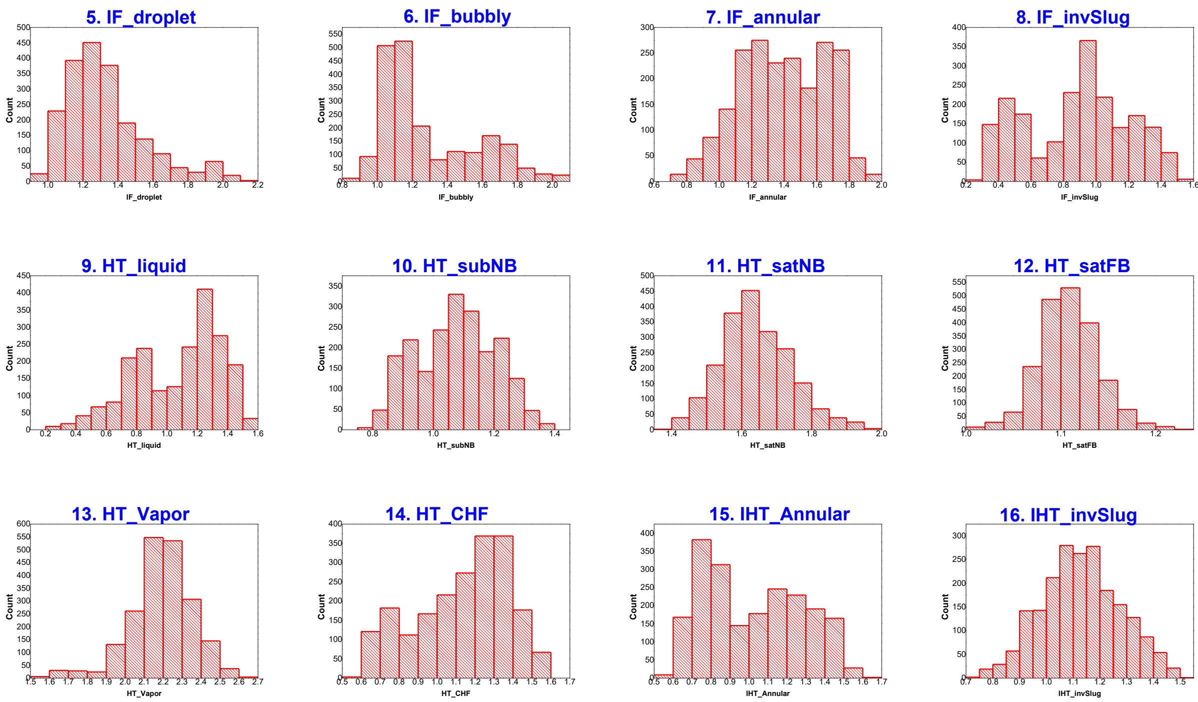

Figure 8. Distributions of uncertainty for the input parameters

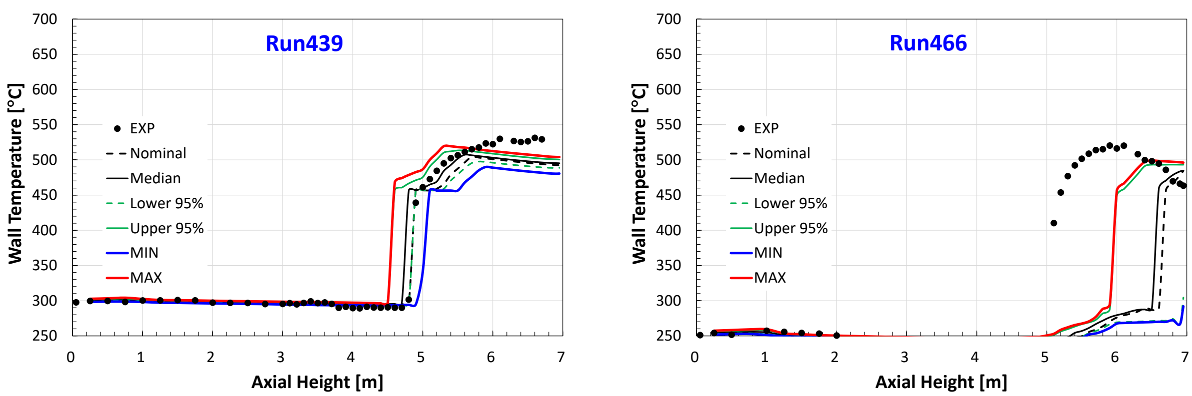

Figure 9. Coverage of the wall temperatures for Beker's tests

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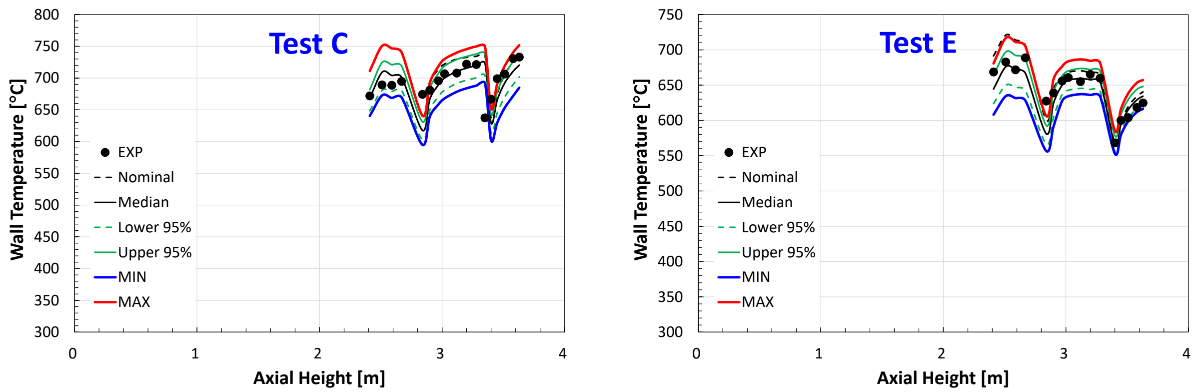

Figure 10. Coverage of the wall temperatures for THTF's tests

Summary

The ATRIUM project aims to apply the SAPIUM guideline to advance IBLOCA testing at the LSTF facility. The critical flow and post-CHF are defined as a major phenomenon during IBLOCA. In this study, the second exercise on post-CHF was conducted using the SPACE code. The candidates of experimental database are Becker and THTF tests. Based on the adequacy analysis results for the experimental database, the inverse uncertainty quantification and validation are selected. 16 input parameters, including boundary conditions, heat transfer, interfacial drag, interfacial heat transfer models, are selected. The inverse uncertainty quantification results show that the most influential parameters are film boiling and nucleate boiling heat transfers. And the updated uncertainty distribution shows good coverage for the wall temperatures. For the Becker experiments, some conditions exhibited poor predictive accuracy, suggesting that the current model may have limitations for in-tube CHF. It means the current model can be limited for in-tube CHF. Therefore, for the wider range validation, the post-CHF model needs to be improved. However, for the THTF experiments, all cases show acceptable results. Thus, the bundle-type post-CHF model demonstrates good predictive capability due to the inclusion of grid spacer-related models. In the next step, the updated uncertainty distributions of input parameters for the exercise 1 and 2 will apply to the final IBLOCA IET benchmark problem, LSTF Test No.1 to confirm the overall transient of IBLOCA phenomena.

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