Statistical Uncertainty Quantification of Physical Models during Reflood of LBLOCA

Deog Yeon Oh*, Kwang Won Seul and Sweng Woong Woo
Korea Institute of Nuclear Safety, 19 Gusong, Yuseong, Daejeon 305-338, KOREA
**Corresponding author: k392ody@kins.re.kr*

1. Introduction

The use of the best-estimate (BE) computer codes in safety analysis for loss-of-coolant accident (LOCA) is the major trend in many countries to reduce the significant conservatism. A key feature of this BE evaluation requires the licensee to quantify the uncertainty of the calculations[1]. So, it is very important how to determine the uncertainty distribution before conducting the uncertainty evaluation. Uncertainty includes those of physical model and correlation, plant operational parameters, and so forth. The quantification process is often performed mainly by subjective expert judgment or obtained from reference documents of computer code. In this respect, more mathematical methods are needed to reasonably determine the uncertainty ranges.

In PREMIUM (Post BEMUSE Reflood Models Input Uncertainty Methods) project[2], the methodology for quantification of uncertainties of the physical models in system thermal-hydraulic codes were suggested such as the statistical method CIRCÉ[3], and a sensitivity method based in an accuracy calculation by the FFTBM, and so on. In this study, CIRCÉ method was used to quantify the distribution of most influential parameters in MARS-KS thermal-hydraulic code[4].

FEBA experiment as main experimental data for the quantification of uncertainties is used in CIRCÉ method. The first uncertainty quantification are performed with the various increments for two influential uncertainty parameters to get the calculated responses and their derivatives.

However, in the uncertainty quantification using CIRCÉ method, the uncertainty ranges may be dependent on the selection of the code-calculated responses and their derivatives. So, the different data set with two influential uncertainty parameters for FEBA tests, are chosen applying more strict criteria for selecting responses and their derivatives, which may be considered as the user's effect in the CIRCÉ applications. Finally, three influential uncertainty parameters are considered to study the effect on the number of uncertainty parameters due to the limitation of CIRCÉ method.

With the determined uncertainty ranges, uncertainty evaluations for FEBA tests are performed to check whether the experimental responses such as the cladding temperature or pressure drop are inside the limits of calculated uncertainty bounds. A confirmation step will be performed to evaluate the quality of the information in the case of the different reflooding PERICLES experiments.

2. Uncertainty Quantification Methodology and Uncertainty Evaluation

In this section, the methodology for uncertainty quantification is introduced and applied for FEBA experiment. The obtained uncertainty ranges are used for uncertainty evaluation for FEBA and PERICLES tests to check the validity of CIRCÉ method.

2.1 Statistical Method for Quantification

CIRCÉ is an inverse method of quantification of uncertainty of the parameters associated to the physical models of the thermal-hydraulic system code. This tool has been developed by CEA in France for the CATHARE code[3]. CIRCÉ method uses the E-M (Expectation-Maximization) algorithm based on the principle of maximum of likelihood and Bayes' theorem to estimate the mean value (also called as bias) and the standard deviation of each parameter associated to the physical models.

To get these results, CIRCÉ combines the differences between the experimental results (R_j^{exp}) and the corresponding code results (R_j^{code}), and the derivatives of each code response ($\partial R_j^{code}/\partial \alpha_i$) with respect to each uncertainty parameter (α_i). The flowchart of CIRCÉ method is shown in Figure 1.

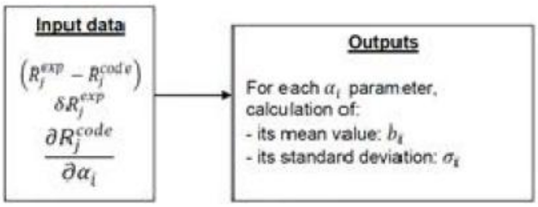

Fig. 1 Flowchart of CIRCÉ method.

2.2 Uncertainty Quantification

The purpose of the FEBA program was to obtain an insight into the most important heat transfer mechanisms during reflood phase of LOCA[5]. The test section in Figure 2 consists of a full-length 5x5 rod bundle of PWR fuel rod dimensions utilizing electrically heated rods with a cosine power profile approximated by 7 steps of different power density in axial direction.

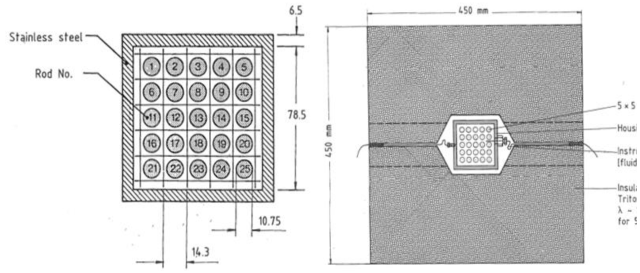

Fig. 2 Cross section of FEBA experiment

Figure 3 below shows the MARS-KS nodalzation for FEBA test facility.

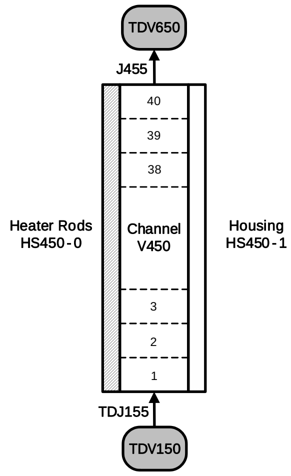

Fig. 3 Nodalization of FEBA Experiment

There are a lot of influential uncertainty parameters associated with reflooding phenomena possibly implemented in thermal-hydraulic codes. Uncertainty of parameters including their bias and standard deviation is quantified by CIRCÉ method. Since the CIRCÉ method restricts the number of parameters depending on the number of experimental data, two or three most-influential parameters sensitive to the cladding temperature and quenching time, are selected based on the sensitivity analysis for FEBA-216 test.

If the experimental data is not enveloped in the uncertainty evaluation, there may be several possible reasons; insufficient number of uncertainty related to reflood phenomena, even narrower uncertainty parameter ranges, and deficiency of reflood model in thermal-hydraulic code. So, three CIRCÉ calculations for uncertainty quantification were carried out how the data set of responses or the number of influential uncertainty parameters affect the quantified results.

For the 1st case, total 93 responses from the six FEBA tests as shown in Table 1 were selected, and the derivative for each response were determined by averaging all derivatives obtained from the various increments. The following rules are applied to exclude the responses and their derivatives as general recommendations by CEA[3]:

- Significant different responses
- Response with the high absolute value of residual (> 2.5)
- Derivative close to 0

Table 2 shows the final uncertainties of reflood models for two uncertainty parameters such as dry/wet wall criteria and interfacial heat transfer of drop-steam.

Table 1 Initial and boundary conditions of FEBA tests

Test No.	Inlet velocity (cold), cm/s	System pressure, Bar	Feed water temperature, °C		Bundle power, kW	
			0-30 s	End	0 s	Transient
223	3.8	2.2	44	36	200	120% ANS
216	3.8	4.1	48	37	200	120% ANS
220	3.8	6.2	49	37	200	120% ANS
218	5.8	2.1	42	37	200	120% ANS
214	5.8	4.1	45	37	200	120% ANS
222	5.8	6.2	43	36	200	120% ANS

Table 2 Input uncertainties quantified by CIRCÉ method

Uncertainty parameter	Type of PDF	Standard deviation	Bias value
Dry/Wet Wall Criteria	Normal	0.09956	0.691945
Interfacial Heat Transfer of Drop-Steam	Normal	0.45487	1.057595

For the 2nd case, the different set of responses in the calculated and experimental data of FEBA tests, were chosen to investigate the user's effect in the CIRCÉ applications. Here, for more restrictive selection, the different sign of derivative with respect to response, too small or large value of derivative, and responses near early transient were excluded in the CIRCÉ input

To get the derivatives of responses, ±0.1 increment for each two uncertainty parameter multiplier was used assuming the linearity between the code responses and uncertainty parameters. In accordance with the above data selection rule, total 100 responses at various measured locations were chosen for the six FEBA experiments. The new uncertainty ranges in Table 3 can affect the quenching time and cladding temperature behavior resulting in the wider uncertainty bounds.

For the final case 3, one more uncertainty parameter associated with interfacial drag, i.e., Weber number, was considered. The calculations with ±0.1 increment for each three parameter multiplier were conducted for six FEBA tests. The totally increased 208 responses including the responses near quenching time and their derivatives were used in CIRCÉ method. Table 3 summarizes uncertainties quantified for three cases. The results show that Weber number is influential parameter because the standard deviation of two other uncertainty parameters in case 2 are reduced, and that of Weber number has larger value for case 3.

Table 3 Summary of input uncertainties quantified

Parameter		Case 1	Case 2	Case 3
Dry/Wet Wall Criteria	Bias	0.691945	0.632516	0.918448
	Std.	0.09956	0.357499	0.175293
Interfacial Heat Transfer of Drop-Steam	Bias	1.057595	1.324723	1.264939
	Std.	0.45487	0.683672	0.458397
Weber number	Bias	-	-	0.336048
	Std.	-	-	0.533331

2.3 Uncertainty Evaluation for FEBA Experiment

200 calculations for each six FEBA test were performed, and 2.5% and 97.5% percentiles of 200 calculations for the cladding temperature were obtained.

For case 1, the calculated cladding temperatures at 2225 mm and 1135 mm for FEBA 223 (Figures 4 and 5) showed higher temperature prediction than experimental data, not enveloped by lower and upper limits. The cladding temperature at 1135 mm had the wider uncertainty band than at 2225 mm as shown in the above Figures. But the earlier quenching for FEBA 223 test were predicted that uncertainty calculation did not envelope the experimental data.

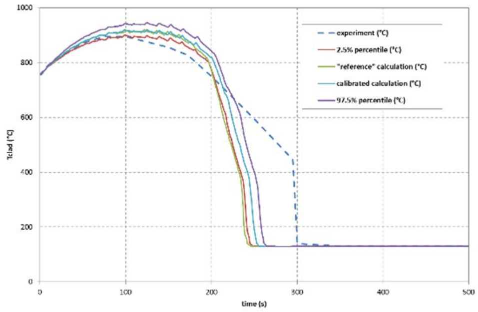

Fig. 4 Cladding temperature at 2225 mm for FEBA 223 test

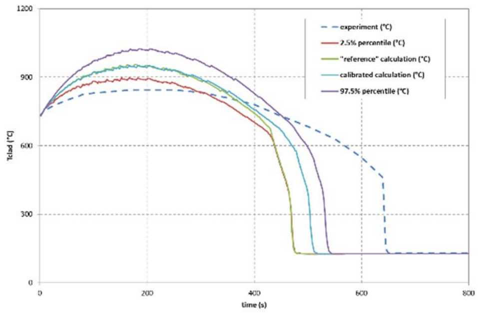

Fig. 5 Cladding temperature at 1135 mm for FEBA 223 test

So, the cladding temperatures at elevation 2225 mm and 1135 mm elevations were compared for three cases, and they were shown in Figure 6 and 7. The enveloped results with the wider uncertainty band for case 2 were improved in comparison with those of case 1. But the quenching time was not still covered. For case 3 considering three uncertainty parameters, the cladding temperature and quenching time were well enveloped within the lower and upper bounds.

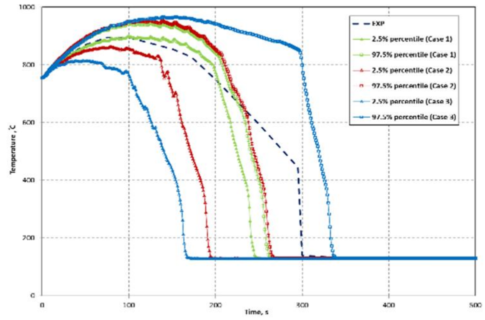

Fig. 6 Cladding temperature at 2225 mm for FEBA 223 test

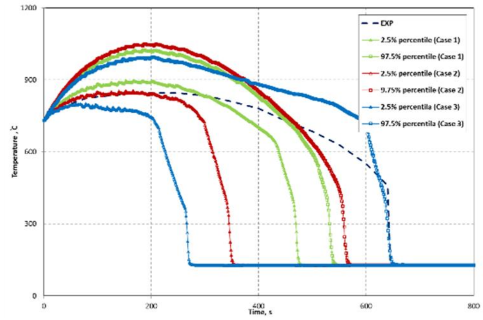

Fig. 7 Cladding temperature at 1135 mm for FEBA 223 test

2.4 Uncertainty Evaluation for PERICLES Experiment

The PERICLES experiment consists of three different assemblies, denoted here by A, B and C (Figure 8). These assemblies are contained in a vertical housing with a rectangular section. Each assembly contains 7*17 = 119 full length heater rods[6].

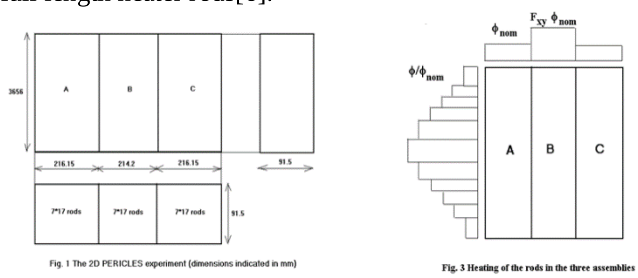

Fig. 8 PERICLES experiment

Figure 9 shows the MARS-KS nodalization for PERICLES test facility.

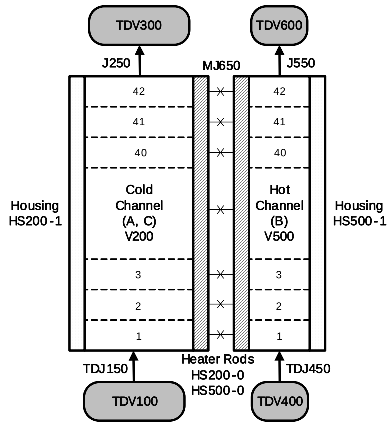

Fig. 9 MARS-KS Nodalization of PERICLES

There are six reflooding tests for PERICLES, four out of them with a radial power peaking equal to 1.435, and two others with a flat profile. The initial and boundary conditions for these six tests are given in Table 4.

Table 4 Initial and boundary conditions of PERICLES tests

Test No	Φ_{nom} (HA) W/cm²	Φ_{nom} (CA) W/cm²	F_{xy}	GO (HA) g/cm²s	GO (CA) g/cm²s	T_{wi} (HA) °C	T_{wi} (CA) °C	DT °C	P (bar)
RE0062	2.93	2.93	1	3.6	3.6	600	600	60	3
RE0064	4.2	2.93	1.435	3.6	3.6	600	475	60	3
RE0069	2.93	2.93	1	3.6	3.6	475	475	60	3
RE0079	4.2	2.93	1.435	3.6	3.6	600	475	90	3
RE0080	4.2	2.93	1.435	5	5	600	475	60	3
RE0086	4.2	2.93	1.435	3.6	3.6	600	475	60	4

200 calculations for each six PERICLES test were performed, and 2.5% and 97.5% percentiles for the cladding temperature in two assemblies were obtained.

For case 1, the cladding temperature of experiments at both 1828 mm and 2998 mm elevation were not enveloped by 2.5% and 97.5% percentile because of very narrow band during heat-up phase and over-prediction of maximum cladding temperature. Figures 10 to 11 show some results of those cladding temperatures behavior at two elevations in central assemblies for RE0062 test. And it is observed that quenching times at 2998 mm were bounded by lower and upper limit, but those at 1828 mm were not.

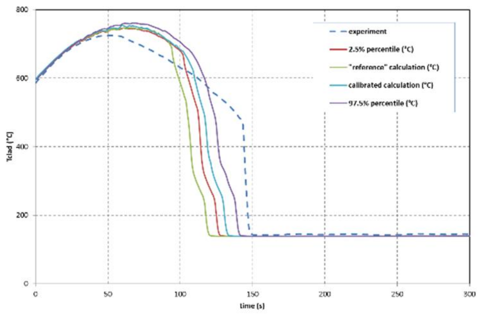

Fig. 10 Cladding temperature at 1828 mm in central assembly for RE0062 test

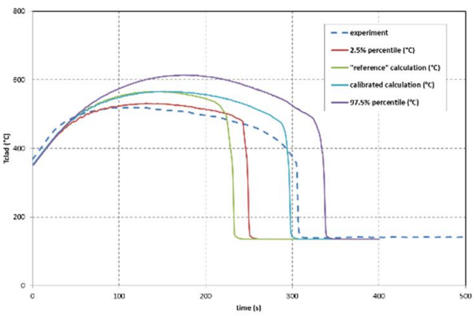

Fig. 11 Cladding temperature at 2998 mm in central assembly for RE0062 test

So, the cladding temperatures at elevation 1828 mm and 2998 mm elevation were compared for three cases. Figures 12 to 15 show the uncertainty evaluation for RE0062 and RE0064 tests at two elevations. For case 2 with the wider uncertainty band, the cladding temperature and quenching time were fully enveloped in comparison with those of case 1. For case 3, the 2.5% lower limits were slightly changed from those of case 2. Also, some uncertainty band for case 3 became even narrower, which means the better optimized uncertainty ranges if three influential uncertainty parameters are considered. Both case 2 and 3 showed that the cladding temperature and quenching time were well enveloped within the lower and upper bounds.

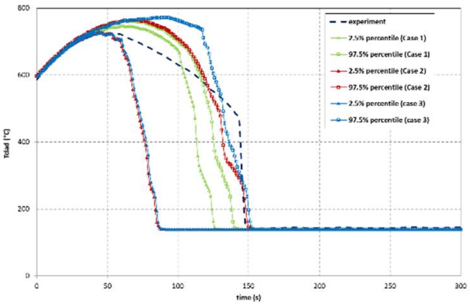

Fig. 12 Cladding temperature at 1828 mm in central assembly for RE0062 test

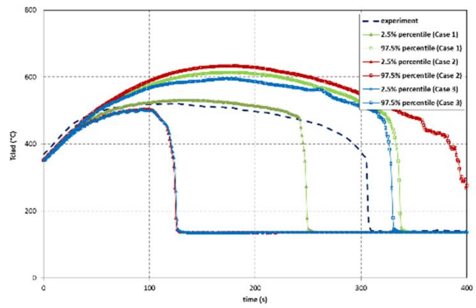

Fig. 13 Cladding temperature at 2998 mm in central assembly for RE0062 test

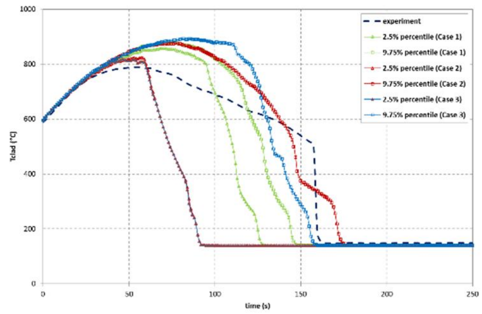

Fig. 14 Cladding temperature at 1828 mm in central assembly for RE0064 test

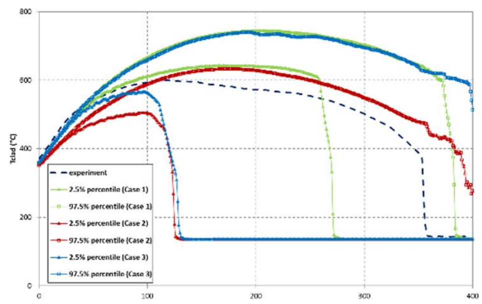

Fig. 15 Cladding temperature at 2998 mm in central assembly for RE0064 test

3. Conclusions

The uncertainty ranges of physical model in MARS-KS thermal-hydraulic code during the reflooding were quantified by CIRCÉ method using FEBA experiment tests, instead of expert judgment. Also, through the uncertainty evaluation for FEBA and PERICLES tests, it was confirmed whether the cladding temperatures of experiment were enveloped by the calculated upper and lower bounds.

For FEBA tests themselves, the result of uncertainty evalution such as cladding temperature or quenching front propagation was improved encompassing their corresponding measured values if the data set was selected properly. However, this is not always true for PERICLES tests, i.e., sometimes not applicable to extend the uncertainty ranges to the different experiment with scaled-up or 2-dimensional experiment.

Furthermore, it is not always desirable to unconditionally increase the uncertainty range for the sake of enveloping the experimental data. The maximum upper limit, for example, the maximum cladding temperature may exceed the acceptance criteria for licensing the nuclear power plant. Therefore, it is more important to correctly consider the number of uncertainty parameters influential to the reflood phenomena. Nevertheless, the statistical methods like CIRCÉ may supplement expert judgment to determine the uncertainty ranges.

Acknowlegement

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