Constitutive Equations Improvement Methodology of Reactor Safety Analysis Code using Experimental Data: Application to SUBO Experiment

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1. Introduction

In a nuclear power plant, stringent safety requirements have to be satisfied. Satisfying safety goal under a design basis accident (DBA) is one of the requirements, which is difficult to conduct experiments on a real scale. Therefore, this is evaluated with a well-validated safety analysis code, which means that the performance of the safety analysis code is very important. It has been striving to improve the performance of the safety analysis code for decades. In particular, numerous separate effect tests (SETs) were performed to improve the constitutive equations which are based on the experimental correlation.

Recently, integral effect tests (IET) are being conducted worldwide. In IET, which simulates many components of a nuclear reactor, inconsistency between simulation and experiment are reported. In this case, efforts were made to preemptively modify the constitutive equations based on empirical correlation. Much effort was required in this process, and in particular, the constitutive equation requiring the modification to match IET data is not easy to identify.

In this study, following methods are proposed to improve the reactor safety analysis code with the IET data directly. First, divide the range of constitutive equations with a machine learning based clustering method. In this process, a lot of data that can cover the whole design basis accident is necessary. Second, calculate the optimal multiplier coefficient for each group. In the previous study, data generation and clustering were conducted [1]. In this paper, multiplier coefficient optimization is conducted for SET experiment application as a preliminary study.

2. Data Clustering

Data clustering was conducted in the previous study [1]. The data to be clustered are various constitutive equations which are randomly generated within the range that can include DBA. Data generation process is explained in detail on reference [2]. Figure 1 shows the histogram of the constitutive equations.

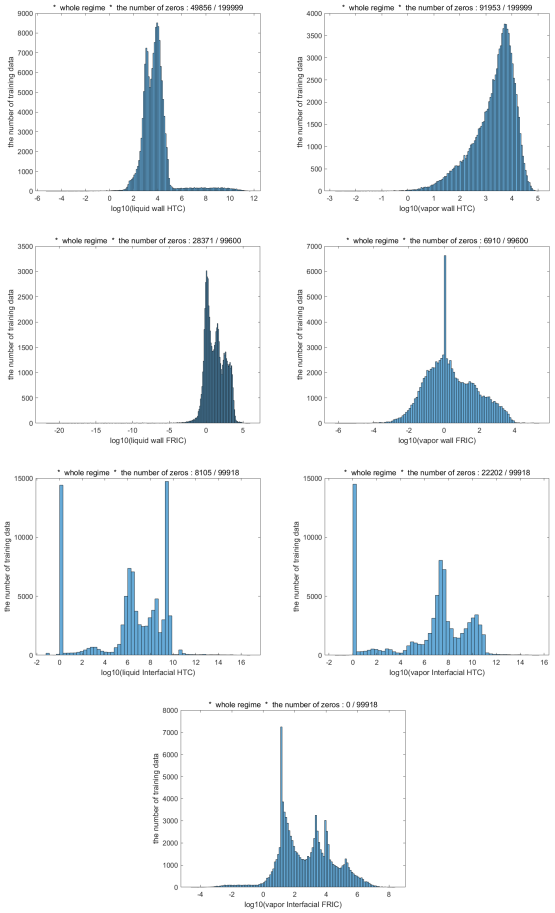


Fig. 1. Training data (a~g: coefficient of liquid wall HTC, vapor wall HTC, liquid wall FRIC, vapor wall FRIC, liquid interfacial HTC, vapor interfacial HTC, interfacial FRIC) [1]

For clustering this data, self-organizing map (SOM) method is used. It is an artificial neural network that performs both clustering and dimension reduction with a simple structure. In the clustering process, clustering number is prescribed. The optimal clustering number is calculated using the indices: silhouette coefficient and gap coefficient. A large value of the silhouette coefficient indicates the appropriateness of the selected clustering number. In terms of the gap coefficient, smaller k that satisfies equation 1 is appropriate.

$$\mathrm{Gap}(k) \geq \mathrm{Gap}(k+1) - s_{k+1} \qquad (1)$$

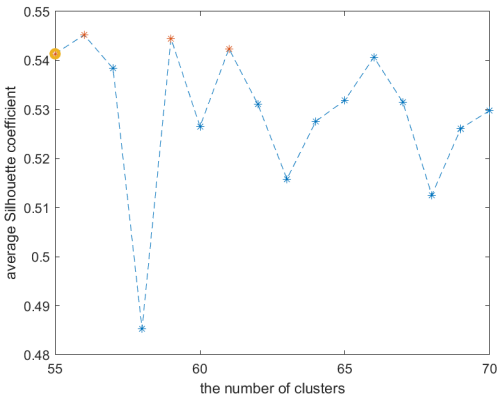


Fig. 2. Silhouette coefficient according to the number of clusters.

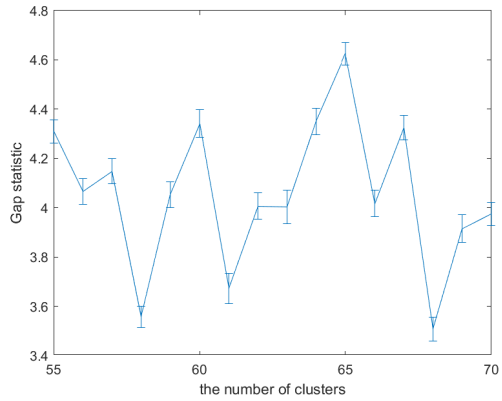
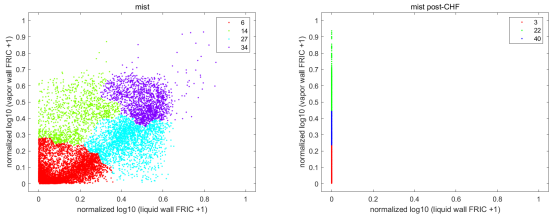


Fig. 3. Gap coefficient according to the number of clusters [2]

Table I: Minimum group number of clusters [2]

	Minimum clustering number	Optimum clustering number
Wall Heat Transfer	71	109
Wall Friction	55	55
Interfacial Heat Transfer	49	83
Interfacial Friction	51	60

Figures 2 & 3 show the silhouette coefficient and gap coefficient according to the number of clusters. Table 1 represents the number of optimal clustering from the silhouette coefficient and gap coefficient. The results of clustering of wall friction is shown in the following figures.



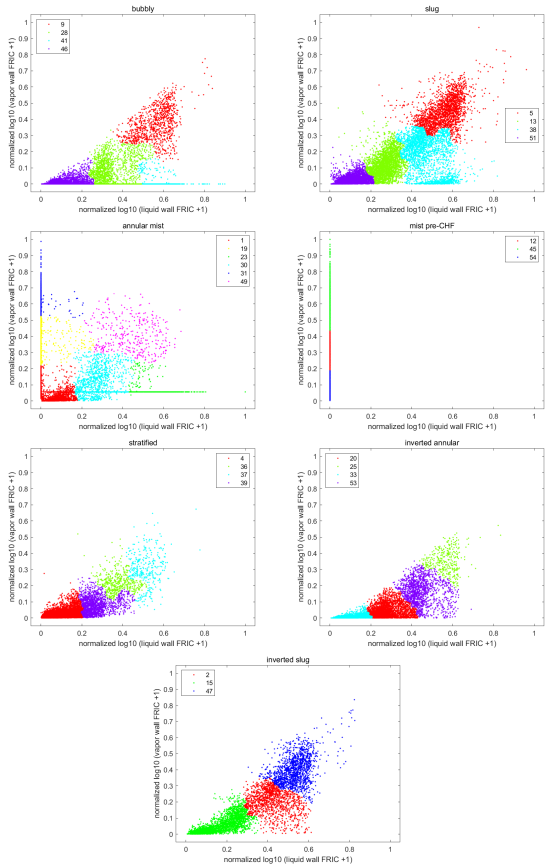


Fig. 4. Wall friction clustering results according to the flow regime [2]

3. Multiplier Coefficient Optimization

3.1 Multiplier Coefficient Optimization Method

In this process, MARS-KS code is modified by applying a multiplier coefficient to the 7 types of constitutive equations. The range of multiplier coefficient is between 0.8 – 1.2 based on the general constitutive correlation uncertainty. KREM method [3] is applied to calculate the 95% confidence level. By adjusting the MARS-KS source code, the constitutive equation is modified in every time step on all nodes and calculate the included sub-region defined by the SOM method.

When modifying the multiplier coefficient, there should be an indicator that the accuracy of the modified code. In this study, mean square error (MSE) between experiment and code result is used.

In optimizing process, KREM methodology is used. KREM (KEPRI Realistic Evaluation Model) is developed by the Korean nuclear industry. In the KREM methodology, a non-variable statistical technique is used to evaluate the confidence limit based on the binomial distribution. In order for the maximum of n randomly extracted values to exceed the p% of the population with

q% confidence, the number of extracted n satisfies the following inequality.

$$1 - \left(\frac{p}{100}\right)^n \geq \frac{q}{100} \qquad (2)$$

From the equation, n should be larger than 58.4 in order to have the confidence level of 95%.

Specific process of multiplier coefficient optimization is as follows: find the sub-regime that is included in the calculation. Using Latin hypercube sampling, determine the distribution of the multiplier coefficient within the range of 0.8 – 1.2, which is the uncertainty of the correlation equation of the constitutive equation. Execute the modified MARS-KS, and calculate the error. Find the case that has the minimum error. Re-calculate the sub-regime that is included in the calculation if the group of sub-regimes has changed, repeat the multiplier coefficient optimization process until it converges.

3.2 SUBO experiment

SUBO experiment is a subcooled boiling experiment conducted by KAERI [4].

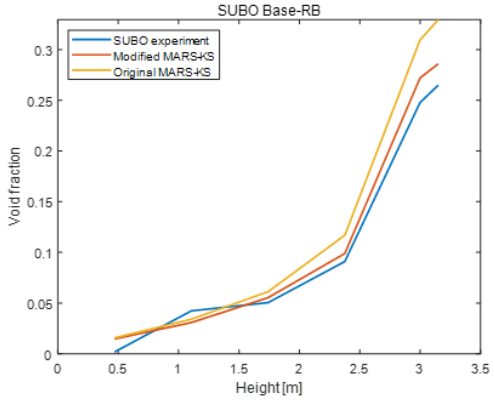


Fig. 5. Void fraction of SUBO experiments and MARS-KS prediction results

Table II: Error of the MARS-KS code results

	Original MARS-KS	Modified MARS-KS
Error	0.1852	0.0826

Figure 5 shows the experiment result, original MARS-KS result, and modified MARS-KS by multiplier coefficient optimization. Table 2 shows the error of MARS-KS code. The error of the modified MARS-KS has been reduced by more than a half.

Eight sub-regimes are included in the calculation of the SUBO experiment with MARS-KS code. The following figure and table show the regime number used in the MARS-KS code while simulating SUBO.

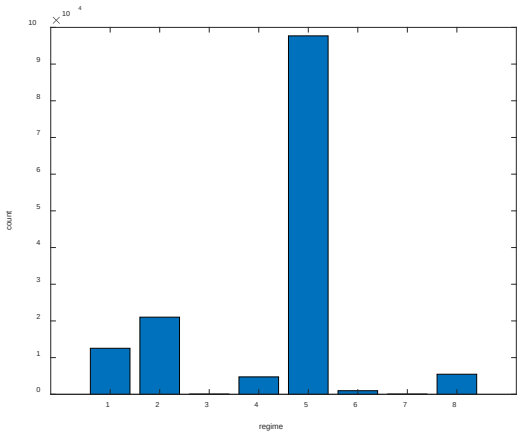


Fig. 6. Gap coefficient according to the number of clusters

Table III: The number of count in SUBO simulation

Regime	Regime Number	The number of count
1	2	12,546
2	10	21,025
3	11	18
4	21	4,750
5	35	97,691
6	40	979
7	71	19
8	79	5,472

In the MARS-KS code calculation process, 68.6% of the constitutive equations are included in the sub-regime No. 35. Sub-regime No. 35 is a part of the interfacial heat transfer slug regime. The multiplier coefficient of the regime 35 is optimized to 1.0434, which is higher than 1.0. Figure 7 shows the sub-regime number of slug regime.

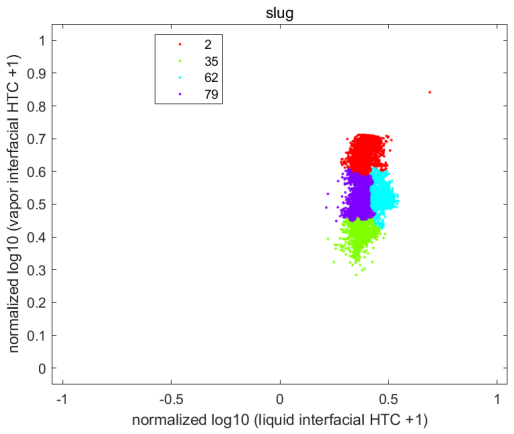


Fig. 7. Sub-regime number of slug regime

In order to enhance the effect of multiplier coefficient effect, optimization was performed by expanding the range of the multiplier coefficient from 0.1 to 10. Figure 8 shows the void fraction in the case of the multiplier coefficient from 0.1 to 10.

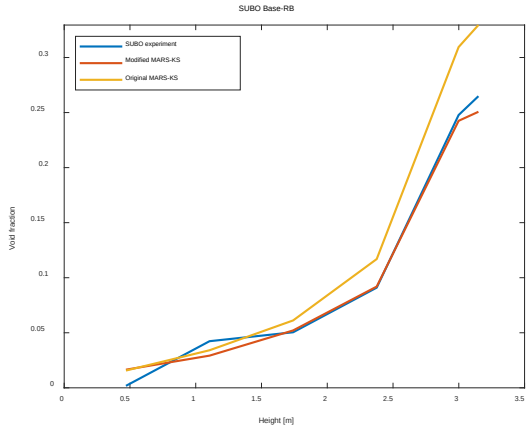


Fig. 8. Void fraction of SUBO experiments and MARS-KS prediction results – extreme case

Error of the modified MARS-KS error with wider range for optimization becomes 0.0498, which is also a half of the previous modified MARS-KS case with narrow range of optimization. In this case, the multiplier coefficient of the regime 35 becomes 3.5802.

Table IV: optimal multiplier coefficient in regime 35

	0.8 – 1.2 case	0.1 – 10.0 case
Multiplier Coefficient	1.0434	3.5820

From this result, the interfacial heat transfer coefficient of regime 35 was optimized in the direction of increasing the value to match SUBO better. Regime 35 in the original MARS-KS code is included in the slug regime. Therefore, it can be inferred that the interfacial heat transfer coefficient value of the slug region is evaluated to be small under the thermal hydraulic conditions given in the original MARS-KS code compared to SUBO experiment.

4. Summary and Further Works

In this study, the following method was proposed to increase the performance of the safety analysis code by directly utilizing the IET data: divide groups of the constitutive equation with a machine learning based clustering method, and optimize the multiplier coefficient in each group (sub-regime). In the previous paper [1], constitutive equation data were generated within the range that include DBA, and sub-regime were divided using this data. In this paper, multiplier coefficient optimization method is presented and a part of KREM methodology is utilized during the process. As for the preliminary study, SET, SUBO experiment, is selected to for the application of the method. The error of safety analysis code has been reduced more than a half within range of 0.8 – 1.2. The optimal multiplier coefficient of interfacial heat transfer in the sub-regime of slug regime is estimated to be 1.0434, which can be inferred that the accuracy of the MARS-KS can be further increased by increasing interfacial heat transfer in the part of slug regime. To check tendency of optimal multiplier coefficient, another optimization was performed for wider range of the multiplier coefficient searching. In this case, the multiplier coefficient of the corresponding sub-regime becomes 3.5820. By utilizing this method, it can directly contribute to improving the performance of constitutive equation with experiment data in the future.

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