An application of data assimilation to improve the prediction of the reflood tests

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1. Introduction

Predicting the heat transfer modes and flow phenomena under the reflooding phase is crucial. Many efforts have focused on comprehensive experimental and analytical research, primarily concentrating on rod bundle reflood experiments [1]. Nevertheless, acquiring sufficiently accurate estimation outcomes for the reflood tests is still challenging, although applying the advanced methods and computer codes such as RELAP5/MOD3.3 [2], MARS [3], and COBRA-TF [4]. Consequently, STARU was developed to enhance the prediction of the SPACE code for the reflood tests [5]. However, in our previous study, only a single reflood test was investigated, which may be insufficient to fully understand the system behaviors. Therefore, in this research study, we aimed to enhance the SPACE code [6] prediction for many FLECHT SEASET tests using STARU data assimilation.

2. Methods and Results

2.1 STARU data assimilation and sampling algorithms

Data assimilation applications are so diverse that were depended on the system behaviors, characteristics of parameters and responses, and the range of parameter uncertainties. However, the core characteristic of data assimilation is identifying the optimal candidates for the specific system and depends on the linearity of the system behaviors.

Table I. The selected FLECHT SEASET reflood tests

No.	Flooding rate (mm/s)	Power (kW/m)	Initial clad temperature at 1.83m (K)	Pressure (MPa)
F-S 31021	38.6	1.3	1153	0.28
F-S 31302	76.5	2.3	1142	0.28
F-S 31504	24.0	2.3	1136	0.28
F-S 33849	25.9	1.9	1018	0.28
F-S 34103	38.1	2.4	1158	0.28
F-S 34316	25.0	2.4	1162	0.28
F-S 34420	38.9	2.4	1392	0.27
F-S 34711	17.0	1.4	1161	0.13
F-S 35050	25.9	1.6	1031	0.14

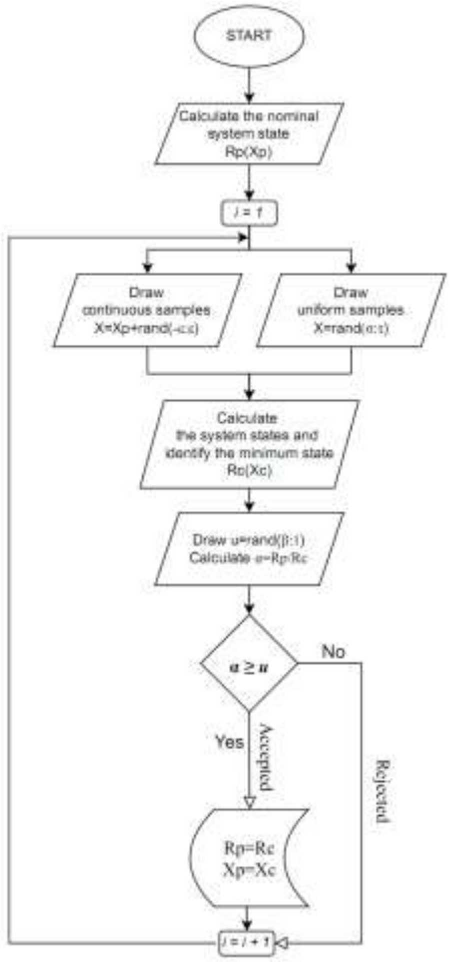

Figure 1. STARU sampling algorithm

Consequently, STARU was developed to analyze the highly non-linear system, and many parameters in which implementing the Monte Carlo sampling methods is crucial. Based on the characteristics of parameters and system responses, the adjusted multipliers and their uncertainties ranges can be justified along with the acceptance probability β and step size ε; the STARU sampling algorithm in this study was displayed in Fig. 1

In particular, the system states that indicated the accuracy of prediction can be estimated by:

$$R = \sum_{j=1}^{m} \sum_{i=1}^{n} \left| \frac{V_{C_i}^j}{V_C^j + V_E^j} - \frac{V_{E_i}^j}{V_C^j + V_E^j} \right| * k^j \qquad (1)$$

where $V_C^j = \sum_{i=1}^{n} V_{C_i}^j$ is the summation of the calculation values $V_{C_i}^j$, $V_E^j = \sum_{i=1}^{n} V_{E_i}^j$ is the summation of the experimental values $V_{E_i}^j$; k^j is the weighting factor of each response that can be adjusted based on its behaviors during the assimilation process. It was revealed that the value of R can be investigated based on the adjusted parameters by using the SPACE code simulation. Furthermore, it is revealed that the smaller value of R, the better improvement of the predicted responses.

The STARU sampling algorithm is displayed in Fig. 1. There were two types of random sampling techniques: (1) uniform sampling and (2) continuous sampling. The uniform sampling technique characterized that the new candidates were sampled randomly within the parameter's uncertainty ranges, and there was no relationship between the current candidate and the subsequent candidates. Nonetheless, in the continuous sampling technique, the following system state was strongly correlated with the previously accepted state within a justified step size. The term 'system state' refers to the R-value (see equation 1), which was evaluated based on the ARD method and the *a posteriori* parameter. It should be clarified that the main objective of the STARU data assimilation is to find the lowest value of R, which represents the global minimum value in the entire system.

2.1 The selected tests and responses

The investigations of the quenching time were crucial in the reflood simulations. Therefore, in this investigation, we selected five responses that involved the cladding temperatures at two different elevations, the steam temperature near the top of the test section, the pressure drop, and the quenching time. Table I presented the selected FLECHT SEASET unblocked reflood test cases.

The crucial step in data assimilation is the selection of the physical models, which directly impacts the assimilation results. Due to the wide range of heat transfer modes in the reflood phenomena, the selected parameters were the form loss coefficients, the interfacial friction factors, the interphase heat transfer coefficients, and the entrainment/de-entrainment models, and the convective heat transfer coefficients. These physical models were judiciously selected by experiences and well-illustrated in [6]. Accordingly, the standard deviation (STD) distributions for all physical models were estimated by:

$$STD_T = \sqrt{\frac{\sum_{i=1}^{T}(x_i - \overline{x_T})^2}{T-1}} \quad (2)$$

where T is the total accepted samples; x_i is the multipliers of accepted sample i-th; and $\overline{x_T}$ is the averaged value of multipliers of all accepted samples. Estimating the STD is identifying the most sensitive physical models in the reflood simulation. Note that if the value of the parameter’s STD is small, that parameter has a significant contribution to the predictions. Because the STD values reflect the deviations from the mean value of the specific parameter, therefore, within a given physical model, if the STD is high while the change of the system is small, it means that this physical model will insignificantly affect the predictions and vice versa.

2.2 STARU data assimilation results

Fig. 2 presents the evolution of the system states for the FLECHT SEASET tests. The system state dramatically reduced after a few iterations illustrating that the predictions were enhanced. Fig. 3 illustrates the STD distributions for all the physical models. As a result, the multiplier of entrainment, the interphase friction factor for inverted slug flow, and the wall heat transfer coefficients for saturated film boiling were the most sensitive physical models for the FLECHT SEASET tests.

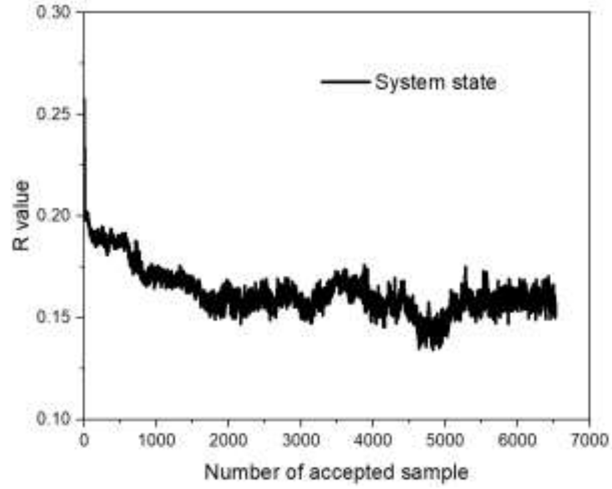

Figure 2. The system state evolution of the FLECHT SEASET tests

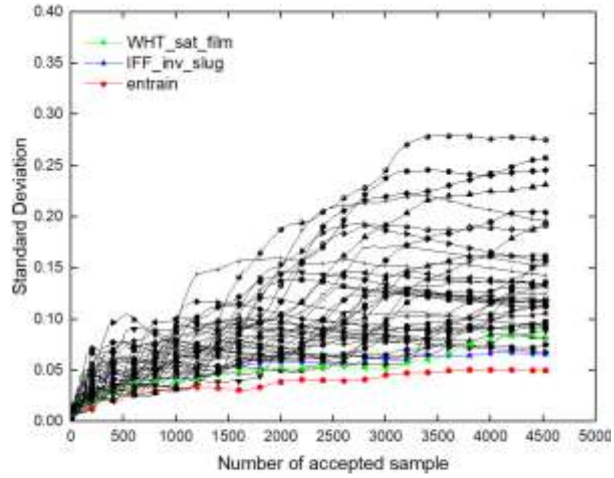

Figure 3. STD distribution for the FLECHT SEASET tests

However, due to the system's complexity, which included many reflood test data, the system state slowly approached the global minimum (see Fig. 2). We found that the improvements were archived in almost all the test cases. In particular, it can be seen that the a posteriori responses, such as cladding temperatures and quenching time, rapidly approximated the experimental data (see Figs. 4, 5&6). These improvements can reinforce the efficiency of the STARU sampling algorithm that rationally found the better candidates.

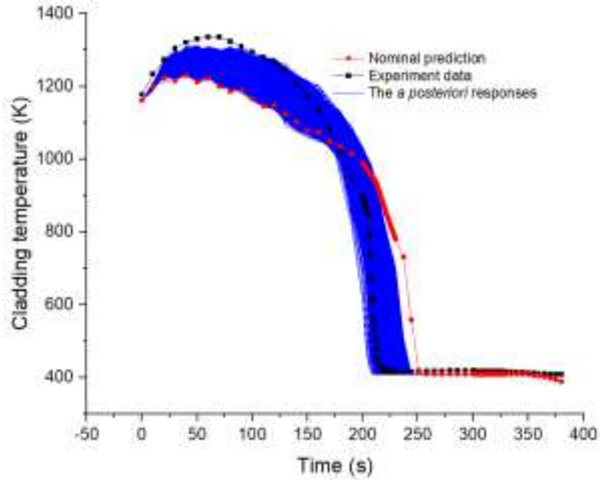

Figure 4. The cladding temperature at 1.83m improvements (FS-34103)

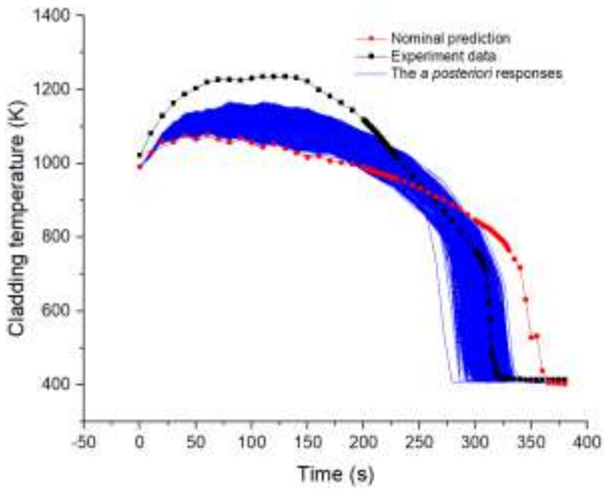

Figure 5. The cladding temperature at 2.44m improvements (FS-34103)

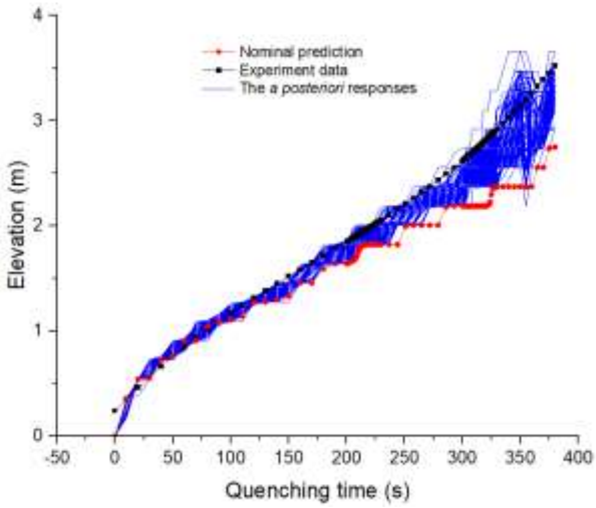

Figure 6. The quenching time improvements (FS-34103)

3. Conclusions

The predictions for the FLECHT SEASET tests of the SPACE code were enhanced using the STARU data assimilation code. We found that all the test case predictions were improved and rapidly approximated the experimental data. Moreover, the obtained most sensitive physical models were consistent with the result of the previous study [6, 7]. This outcome can reinforce the efficiency of STARU data assimilation that rationally found the better candidates. However, because of the complexity, the system state slowly approached the global minimum. Therefore, future studies should focus on enhancing the performance of the sampling algorithm and justified parameters of STARU data assimilation.

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Nomenclature

Acronyms:

ARD	Absolute Relative Difference
COBRA-TF	Coolant-Boiling in Rod Arrays - Two Fluid
FLECHT SEASET	Full-Length Emergency Core Cooling Heat Transfer-Separate Effects Tests And System-Effects Tests
MARS	Multi-dimensional Analysis of Reactor Safety
RELAP5	Reactor Excursion and Leak Analysis Program
SPACE	Safety and Performance Analysis CodE for nuclear power plants
STARU	Sampling meThod for highly non-lineAR system Uncertainty analysis
STD	STandard Deviation

Symbols:

V^j	Response j
V_C^j	Calculated values of response j
V_E^j	Experimental values of response j
k^j	Weighting factor of response j
R	Absolute value of difference
T	Total accepted samples
x_i	The multipliers of accepted sample i
$\overline{x_T}$	The averaged value of multipliers of all accepted samples