NGHIÊN CỨU ĐỘ NHẠY CÁC MÔ HÌNH VẬT LÝ SỬ DỤNG TRONG CODE TÍNH TOÁN THỦY NHIỆT RELAP5 DỰA TRÊN SỐ LIỆU THỰC NGHIỆM CỦA HỆ THỰC NGHIỆM FEBA

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Tóm tắt: Trong phân tích an toàn thủy nhiệt, kết quả mô phỏng của các phần mềm tính toán thủy nhiệt phụ thuộc rất lớn vào mô hình hóa các hiện tượng vật lý được xây dựng trong các phần mềm đó. Những mô hình này là các phương trình, công thức thực nghiệm được phát triển dựa trên việc làm khớp chúng với dữ liệu thực nghiệm. Nghiên cứu độ nhạy được thực hiện để khảo sát ảnh hưởng của các mô hình vật lý đến kết quả tính toán trong quá trình làm ngập lại các thanh nhiên liệu sau khi xảy ra sự cố LOCA. Trong nghiên cứu này chúng tôi đã thực hiện phân tích độ nhạy của các mô hình vật lý trong phần mềm tính toán thủy nhiệt RELAP5/mod 3.3 dựa trên các số liệu thực nghiệm được đo đạc trên hệ FEBA. Có 16 mô hình vật lý đã được chọn cho phân tích độ nhạy để tìm ra các mô hình có ảnh hưởng nhất đến kết quả tính toán. Dựa trên hai tiêu chí là nhiệt độ cực đại của nhiên liệu và thời gian cần thiết để nhiên liệu dính ướt (quench time), kết quả phân tích độ nhạy chỉ ra rằng có bốn mô hình vật lý có ảnh hưởng lớn nhất đến kết quả tính toán độ nhạy. Bốn mô hình vật lý này sẽ được dùng để đưa vào phân tích độ bất định cho các mô hình vật lý này sinh ra.

Từ khóa: *mô hình vật lý,* FEBA*, độ nhạy, độ bất định, thời gian dính ướt, nhiệt độ cực đại của nhiên liệu.*

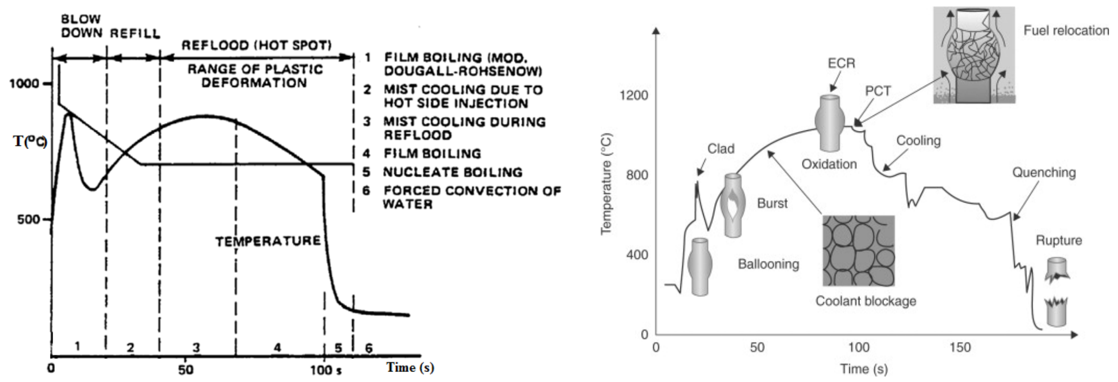
A sensitivity study of physical models using in RELAP5 code based on FEBA experimental data

Abstract: In the thermal-hydraulic safety analysis, the simulation results of thermal-hydraulic codes depend mainly on modeling the physical phenomena built into these codes. These models are the equations, empirical formulas that were developed based on matching them to experimental data. The sensitivity study is performed to investigate the influence of physical models on the calculation results during the reflood phase after the LOCA incident. In this study, we conducted a sensitivity analysis of physical models in RELAP5 / Mod 3.3 code based on experimental data measured on the FEBA test facility. 16 physical models have been selected for sensitivity analysis to find the most important models that have the most influence on the calculation results. Based on two criteria, the maximum temperature of the fuel rod and the quench time, the sensitivity analysis results show that four physical models have the most significant impact on the calculation result. These four physical models could be considered further in the next step of their uncertainty evaluation.

Keywords: *physical model,* FEBA*, sensitivity, uncertainty, quench time, PCT.*

1. INTRODUCTION

In the large break of loss of coolant accident (LBLOCA), the change of the cladding temperature could be divided into four main phases such as blowdown, refill, reflood, and long-term cooling as shown in Figure 1a. Reflood phase of LBLOCA occurred from the 40s to 250s after the initiation of the accident when the lower plenum of the reactor vessel has filled, and the core begins to refill. The quenching of fuel rods follows the refilling of the lower plenum. Steam is formed in the core because of the entering of water, and it carries with many drops. During this phase, the fuel rod cladding experiences steam cooling, dispersed droplet flow, the quench front, and finally, they submerge in water without boiling. Fuel rod rapidly cooled to saturated temperature, and its cladding surface becomes wetted from bottom to the top because of the injection of the emergency core cooling system (ECCS). The reflood phase is an important period in which the fuel rod could be ballooned, be bust, be oxidized, or even be melt if the fuel rods could not be cooled adequately, as shown in Figure 1b. This reflood phase is a complex transient in both the heat transfer mechanism and flow regimes due to the existence of a two-phase mixture [1, 2, 3, 4].



(a) Main phases during LBLOCA.

(b) Typical cladding temperature profile

Figure 1. The main phases and the cladding temperature profile during LBLOCA.

Thermal hydraulic (T/H) calculation codes such as RELAP5, MARS, TRACE, or CATHARE have widely used in the reactor safety analysis. These codes are also named Best-Estimate codes (BE) because of their capability of analyzing an accidental scenario as realistically as possible. RELAP5 is also a tool authorized by the US Regulatory Authority (NRC) for use in rulemaking, licensing audit calculations, evaluation of operator guidelines, and as a basis for a nuclear plant analyzer [4, 5]. In this software, along with initial and boundary conditions, physical models (PMs) are often used in simulations. These models were generally built theoretically or experimentally. The first group of models that were developed based on theories uses assumptions, simplifications, and ideal processes to solve. The second one was developed based on specific experimental systems with defined boundary conditions and initial conditions. It means that there would be some limitations existed in T/H codes because of their built-in PMs. Prediction accuracy in simulations is always a challenging problem that software developers need to deal with and find ways to improve. RELAP5 can be used to compute the transient of reflood but with limited accuracy. Choi and No showed in their work [4] that calculated PCT (Peak Cladding Temperature) was mainly under-predicted, and the fuel rods were quickly quenched in comparison with experimental data for low flooding rate conditions.

Researchers have carried out considerable works to understand the T/H mechanism and phenomena occurring during the reflood phase to evaluate further and improve the code prediction capability. Experiments have been conducted to investigate the T/H characteristics during reflood phase. Full-Length Emergency Cooling Heat Transfer (FLECHT [6]) Separate Effects and Systems-Effects Test (FLECHT-SEASET) programs was conducted focusing on the heat transfer mechanism at high flooding flow rate with variating of the power [7]. These tests, however, were not sufficient to quantify the phenomena relevant to a detailed reflood mechanism due to some uncertainties generated in the experiment [8]. RBHT (The Rod Bundle Heat Transfer) program [9] was proposed to improve previous experimental limitations. This program was conducted to investigate the bottom heat transfer at changing flooding flow rate from 2.54 to 15.54 cm/s with the upper plenum pressure variating from 1.38 to 4.14 bar using constant power. FEBA (Flooding Experiments with Blocked Arrays) [10] were carried out to was to study heat transfer mechanism, grid spacers effect, and ballooning effect during reflood phase for the development and assessment of improved T/H models [10]. The other experimental works [11] have also done using different geometries and flow regimes to explore the T/H process of reflood to improve the prediction of numerical simulation.

Recent researchers have performed plenty of simulations to evaluate the prediction capability of the RELAP5 code for the T/H process during reflood [12, 13, 14, 15]. They have shown that calculated results using RELAP5 for the reflood phase have limitations that need to be improved. The simulation result is influent by many input parameters such as the initial and boundary conditions, initial conditions, boundary conditions, material properties, power, and in particular, the PMs, as mentioned in [16]. The indirectly measured parameters of PMs, which relate to the empiricism of the closure laws, are determined indirectly using expert judgment with subjective decisions. These personal decisions usually induce uncertainties in the BE code. Kovtonyuk et al. [16] has also indicated that PMs have a strong influence on the simulated result that needs to have further evaluations.

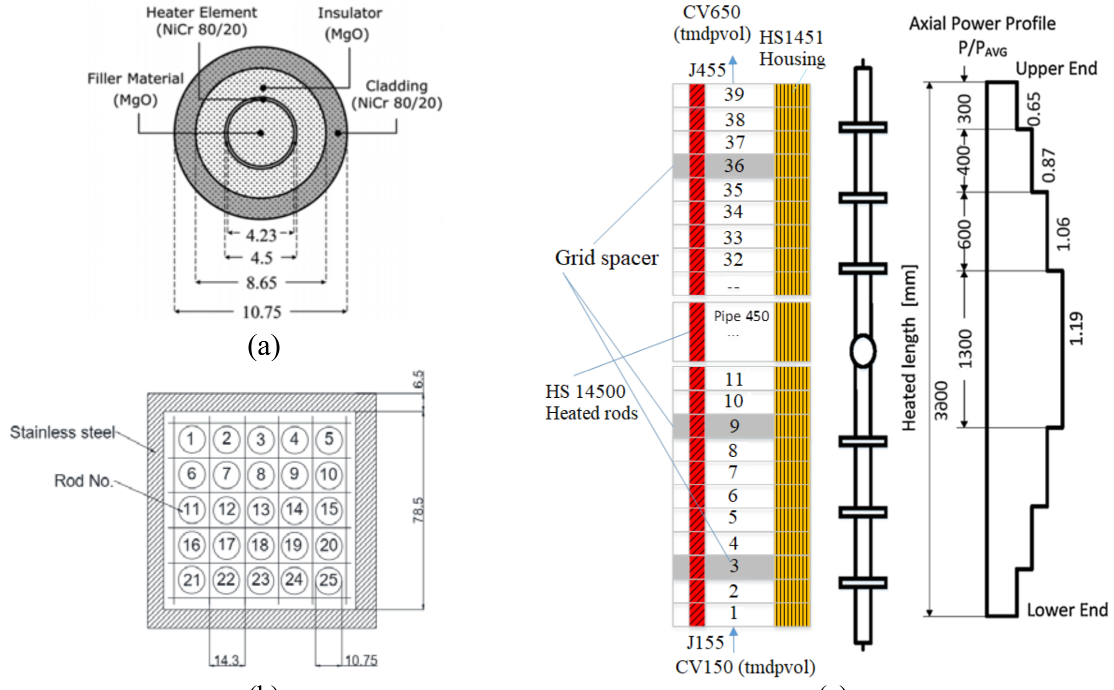
The aim of this paper is focused on the influence of PMs on the simulating results for reflooding phase. Series I of FEBA (Flooding Experiments with Blocked Arrays) experiment was chosen in this study as the representative reflooding experiment with relatively low inlet flow rate conditions [9]. The sensitivity study of PMs is carried out to find the most influential parameters. The results of this study will be used for further work on the uncertainty evaluation of chosen PMs.

2. TOOLS AND FEBA MODELING IN RELAP5

2.1. Description of FEBA facility

Karlsruhe designed the FEBA experiment to investigate the thermal-hydraulic behavior, including the grid spacers and blocked ratio effect relating to a LOCA in a PWR study, the heat transfer mechanisms to broaden the database for development and assessment of improved code accuracy. The test section contains a full length 5x5 rod bundle of PWR fuel rod dimension (Fig. 2a), which are surrounded by a square housing made of stainless steel. The housing keeps a role as an insulator to reduce heat losses from the test section to the environment (Fig. 2.b). Electrically heated rods are used to simulate the nuclear fuel rods. The cosine power of the fuel rods is approximated by seven steps of different power density in the axial direction. Seven grid spacers are located in the bundle the same with those used in the PWR core. The axial view of a heater rod and power profile is shown in Figure 2c.

The rod bundle was first heated at low nominal power (200 kW) to achieve a specified initial cladding temperature before simulating the transition. The test runs start by ramping up the power bundle is given according to 120% American National Standard (ANS) decay heat power curve about the 40s after the reactor shut down. The subcooled liquid was injected from the bottom of the test section. The cladding temperature, the outer surface of the heater rods, were measured at different axial locations during each transient test.



(b) (c)

Figure 2. (a) Cross-section of fuel rod simulators used in FEBA test. (b) Cross-section of FEBA test bundle with rectangular housing. (c) Heater rod with its axial power profile and its nodalization in RELAP5 together with locations of grid spacers [10].

2.2. Model of FEBA in RELAP5

The nodalization diagram of the FEBA facility in RELAP5 is illustrated in Figure 2c. The time-dependent volume (TDV) 150 and single junction (SJ) 155 represent for the cooling water inlet system, the TDV 650 and SJ 455 represent for the water outlet system. The flow channel was model by pipe 450 with 39 nodes (length of one node is 0.1 m) and connect to the heat structure 14500 and 14501, which simulate rod bundle and housing. The seven grids spacer are located at corresponding nodes (3, 9, 14, 20, 25, 30, and 36), and the proper loss coefficients, K_{loss}, have been allocated at a similar junction to simulate the pressure loss due to flow restriction.

The FEBA test number 216 was chosen for analysis. The initial and boundary conditions of this test number are shown in Table 1. Before starting the test run, the power was increased to the required level simulating decay heat according to 120% ANS - Standard about 40 s after reactor shutdown. The feedwater was injected into a low part of the system.

Table 1: Initial and boundary conditions of FEBA test 216 [10]

Pressure (bar)	Inlet velocity (cm/s)	Feedwater temperature (°C)		Bundle power (kW)	
		0-30 (s)	end	0 s	end
4.1	3.8	48	37	200	120% ANS

3. RESULTS AND DISCUSSIONS

The reference case is the case that all PMs are set in default values of 1.0. The first part of this section presents the reference case result in comparing with FEBA experimental data. The minimum and maximum values in the variation range of each physical model are considered for sensitivity study. Based on this study, the most influential parameters are selected for further work on uncertainty evaluation.

3.1. Reference case

The reference case was prepared using the initial and boundary conditions given in Table 1. Following the performing procedure of the FEBA experiment, the calculation is first for a steady-state. After reaching this stable state for 1000s, the flooding flow rate is injected from the inlet at the bottom of the test section to simulate the transient state. The initial temperatures of both housing and cladding are first evaluated by comparing them with that taken from the FEBA test [17]. Figure 3 shows the comparison of the calculated and experimental initial temperatures for both cladding and housing. We could conclude that the calculated results are similar to experimental data. This comparison indicated that the establishment of the initial state of simulation calculation is close to the experimental conditions. For the transitional period, the cladding temperature at three different elevations (at the bottom, in the middle, and at the top of the test section) is calculated and compared with experimental data, as shown in Figure 4.

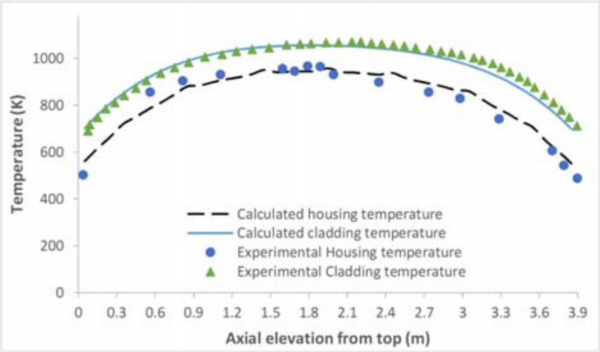


Figure 3. Comparing initial temperature for the reference case

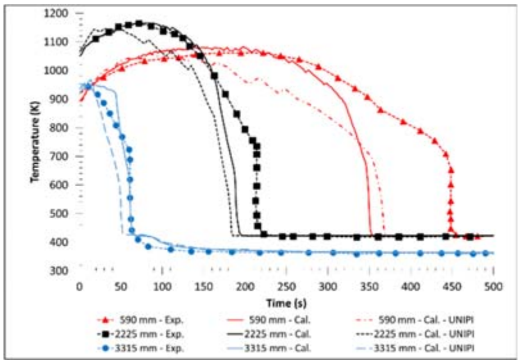


Figure 4. Cladding temperature at various elevations

As can be seen in Figure 4, the bottom of the test was firstly quenched, then the middle, and finally, the top was. The simulated results of the reference case give similar PCT at each elevation but underpredict the quenching time in comparing with measured data. The same predictions are found in [16] calculated by UNIPI using RELAP5. Our reference case gives better predictions for PCT and similar quenching times with the results of UNIPI. It was found in our reference case result that PCT along the heated rod occurred at 1500 (mm) corresponding to node 26 in our FEBA model. The reference elevation of 1500 mm (node 26) is selected for sensitivity calculations. Other researchers [14, 15] experienced this early quenching situation. They pointed out that the reflood model, such as wall to fluid or wall to vapor heat transfer correlations or the interfacial friction models, needs to be improved. Based on their researches, together with the opinion given in [16] by Kovtonyuk et al., the sensitivity study for physical models is conducted to find the most influential ones.

3.2. Sensitivity Study

In this study, based on the available physical models built-in RELAP5 [18], sixteen PMs were chosen. Each physical model is varied in the range from minimum to maximum values based on its given probability distribution function (PDF), which was selected by experts' decision as given in Table 2. Two cases of minimum and maximum values of each parameter are considered as two inputs for this study. It means that thirty-two cases are taken into account for the sensitivity work. The PCT and quenching time at reference elevation (node 26) are calculated for thirty-two cases and compared with their values obtained from reference case.

The chosen criteria for our sensitivity study are based on the given criteria [16]. For T/H evaluation and licensing process, the PCT is the main criterion to be selected. Together with this criterion, quenching time is a typical one, which is the reflood dominant characteristics. Therefore, two main criteria were chosen for our study are PCT and quenching time:

- The criterion for cladding temperature is defined as the absolute value of variation in rod surface temperature: $\Delta T_{ref} = 100$ (°C).
- The criterion for quenching time is the variation in rewet time: $\Delta t_{quench} = 30\ \%$

Table 2: Chosen PMs and their PDF using in the sensitivity study

Notation	Physical models	PDF	Range of Variation
PM1	Chen correlation of nucleate boiling wall heat transfer	Log-Normal	[0.4 – 2.8]
PM2	**AECL Lookup table CHF**	Normal	[0.20 – 1.80]
PM3	Zuber CHF correlation	Log-N	[0.50 – 2.00]
PM4	Transition boiling wall heat transfer	Normal	[0.50 – 1.50]
PM5	Film boiling heat transfer	Normal	[0.50 – 1.50]
PM6	Dispersed film boiling heat transfer	Normal	[0.50 – 1.50]
PM7	Wall heat transfer transition criteria of steam flow Reynold number 3000	Normal	[0.50 – 1.50]
PM8	Wall heat droplet enhancement factor of steam flow	Normal	[0.50 – 1.50]
PM9	Interfacial drag for bubbly flow	Log-Normal	[0.50 – 2.00]
PM10	**Liquid entrainment**	Log-Normal	[0.50 – 2.00]
PM11	**Droplet We number for reflood**	Log-Normal	[0.50 – 2.00]
PM12	**Interfacial heat transfer of IANN/ ISLG**	Log-Normal	[0.50 – 2.00]
PM13	**Surface roughness of IANN/ISLG**	Log-Normal	[0.50 – 2.00]
PM14	Dry/wet wall criteria 30 deg-C	Log-Normal	[0.50 – 2.00]
PM15	Liquid chunk flow regime	Normal	[0.50 – 1.50]
PM16	Droplet interfacial heat transfer	Normal	[0.80 – 1.20]

Figures 5 and 6 present the calculated results of the sensitivity study. The most influential PMs are PM11, PM12, and PM13, which were chosen by using the temperature criterion. If the quenching time criterion is applied, we could see that two parameters of PM2, and PM10, are the most influential PMs to the quenching time. Five chosen PMs as in bold in Table 2.

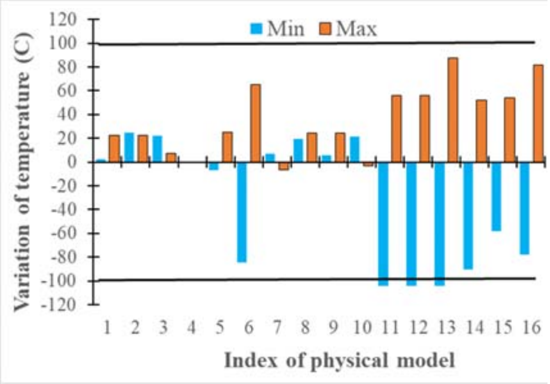


Figure 5. Sensitivity study for calculation of rod surface temperature.

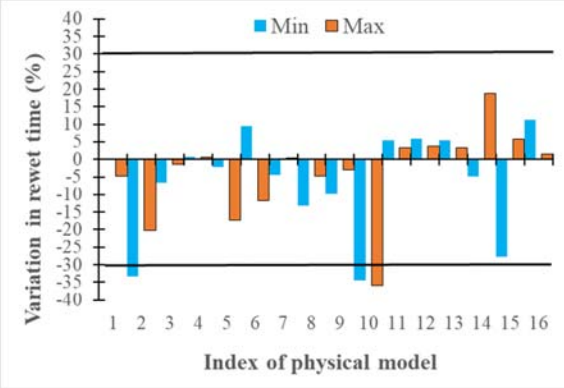


Figure 6. Sensitivity study for calculation of rewet time.

Based on the temperature criterion, five influential PMs have been selected for our sensitivity study. Three parameters are selected by using temperature criterion and two more PMs are chosen by using quenching time criterion.

4. CONCLUSIONS

The PMs which have built-in BE codes are the main focus in uncertainty evaluation. This study focuses on the sensitivity work related to PMs to have a better understanding of T/H mechanism during reflood phase, in which the most complex two-phase flow behavior happens. The sensitivity study has conducted based on built-in PMs in RELAP5 code using FEBA experimental data. The simulation of FEBA test facility is based on the initial and boundary conditions, together with the test performance procedure. The reference case in our study gives similar results to the initial temperatures of cladding and housing of test 216 in FEBA data. Its predictions give a faster quenching time in the transient period for all elevations along the heated rod. UNIPI obtained similar quenching time predictions. In comparison with UNIPI work, our reference case shows better predictions for PCT.

It was pointed out that the PMs are the influential parameters that could contribute a considerable uncertainty to the final simulating results. Therefore, further research on evaluating PMs is needed. Our work, thus, focused on studying PMs influence to give a better understanding of T/H behavior during the reflood phase. The sensitivity study for PMs built-in RELAP5 code has performed using temperature criterion. The final results show that among sixteen considered inlet parameters, five PMs of PM2, PM10, PM11, PM12, and PM13, as listed in bold in Table 2, are the most influential PMs to the final simulation results.

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