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

Tran Thanh Tram[1*], Hoang Tan Hung[2], Doan Manh Long[1], Vu Hoang Hai[1]

[1]*Nuclear Training Center, 140 – Nguyen Tuan, Thanh Xuan, Ha Noi*

[2]*Institute for Nuclear Science and Technology, Vietnam Atomic Energy Institute, 179 Hoang Quoc Viet street, Cau Giay district, Hanoi 100000, Viet Nam*

Email: tttram80@yahoo.com*

Abstract: In the thermal-hydraulic safety analysis, simulation results using thermal-hydraulic codes depend mainly on modeling the physical phenomena built-in the codes. These models are the equations, and empirical formulas developed based on matching them to experimental data or based on the assumptions, simplifications for solving theoretical equations. Therefore, it is recommended that these physical models need to take into account the uncertainty they cause. The sensitivity study is performed to investigate the influence of physical models on the calculation results during the reflood phase after the loss of coolant accident. It is allowable to choose the physical models that have the most significant influence on the calculation results. This study conducted a sensitivity analysis of physical models in RELAP5 code based on experimental data measured on the FEBA test facility. Sixteen physical models have been selected for sensitivity analysis to find the most important models that influence the calculation results. Based on two criteria, the maximum cladding temperature and the quench time, the sensitivity analysis results show that four physical models significantly impact the calculation result. Four chosen physical models are considered further in the next step of their uncertainty evaluation.

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

I. INTRODUCTION

In the large break of loss of coolant accident (LBLOCA), the cladding temperature change could be divided into four main phases: blowdown, refill, reflood, and long-term cooling shown in Figure 1a. Reflood phase of LBLOCA occurred 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. The vertical flow regime map is used in thermal-hydraulic codes for simulating the reflood phase. This map is modeled as nine regimes (four for pre-CHF heat transfer, four for post-CHF heat transfer, and one for vertical stratification) [1] in which heat transfer coefficients are the built-in correlations in the code. The flow regimes change from one to the others. A film boiling heat transfer is established when the cladding temperature is higher than the surface rewetting temperature. A two-phase flow regime, either a dispersed flow regime or an inverted-annular, may occur depending upon the liquid and vapor flow rate. The cladding temperature is then reduced by film boiling. The flow regime then becomes a transition

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boiling, and finally, a nucleate boiling in single-phase liquid. Fuel rods rapidly cooled to saturated temperature, and their cladding surface becomes wetted from bottom to the top thank to the injection of the emergency core cooling system (ECCS). Because of the change in flow regimes, heat transfer correlations alter correspondingly based on built-in heat transfer correlations such as Chen, Dittus-Boelter, Bromley, Zuber CHF, or CHF Look-up table [1], [2]. Typical physical phenomena during the reflood phase are the exiting of parameters such as droplets and quenching front. Although these parameters have a strong influence on heat transfer coefficients [3], knowledge of their effects is insufficient.

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 and flow regimes due to a two-phase mixture [4], [5].

Thermal hydraulic (T/H) codes, RELAP5, MARS, TRACE, or CATHARE, have been widely used in the reactor safety analysis. Among them, RELAP5 code is the preferable tool for use in rulemaking, licensing audit calculations, evaluation of operator guidelines, and as a basis for a nuclear plant analyzer [1], [5]. In this software, together with initial and boundary conditions, PMs are often used in simulations. These PMs were generally built theoretically or experimentally. The theoretical ones use assumptions, simplifications, and ideal processes to solve, while the experimental ones were developed based on specific experiments with defined boundary conditions and initial conditions. It means that 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.

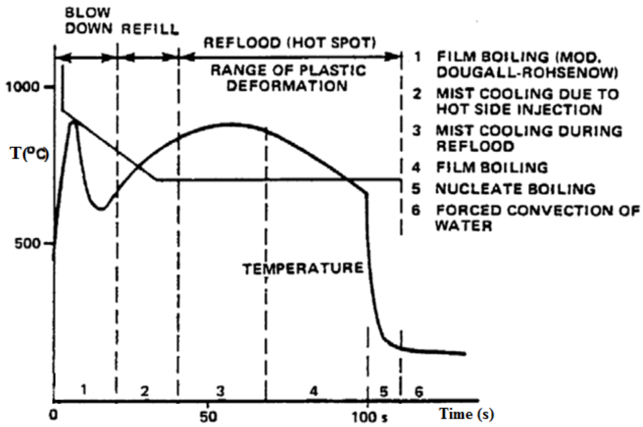
Researchers have carried out considerable experimental works to understand the T/H mechanism and phenomena occurring during the reflood phase to evaluate further and improve the code prediction capability. Full-Length Emergency Cooling Heat Transfer (FLECHT [7]) Separate Effects and Systems-Effects Test (FLECHT-SEASET) programs was conducted focusing on the heat transfer mechanism at high flooding flow rate with variating of the power [8]. However, these tests were insufficient to quantify the phenomena relevant to a detailed reflood mechanism due to some uncertainties generated in the experiment [9]. RBHT (The Rod Bundle Heat Transfer) program [10] was proposed to improve previous experimental limitations. This test was conducted to investigate the bottom heat transfer at changing the flooding flow rate with the upper plenum pressure variant. Like the RBHT test, FEBA (Flooding Experiments with Blocked Arrays) [11] was carried out to study the heat transfer mechanism. More effects of grid spacers and ballooning during the reflood phase were considered for FEBA tests to develop and assess improved T/H models [10].

The simulation results based on RELAP5 code are influenced by many input parameters, such as the initial and boundary conditions, initial conditions, boundary conditions, material properties, power, and the PMs [12]. PMs are suggested as vital influent parameters that need to have further evaluations [12].

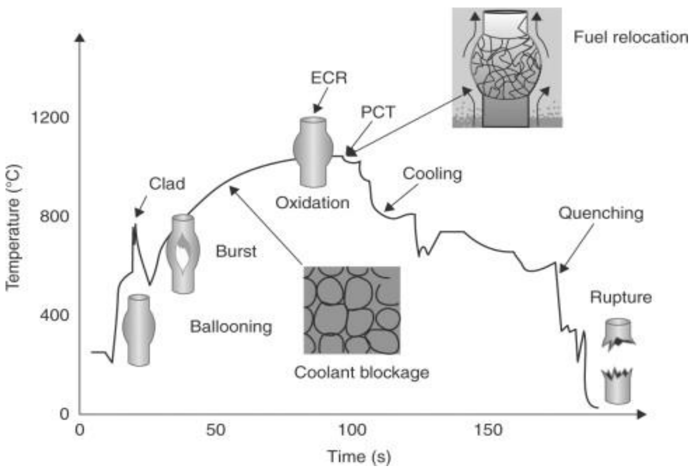
A sensitivity analysis (SA) shows how different values of an independent input variable affect a particular dependent output variable using a set of assumptions. Among all input parameters for the SA, some parameters have little effect on the calculation result, while others significantly impact. Through the SA process, the most influential input parameters are selected.

The SA method could be a useful tool to reduce the numbers of calculations by reducing the considered input parameters, while the calculated accuracy remains unchanged. As a result of the SA process, a significant reduction of input parameters from twenty to hundreds of original input parameters to less than ten parameters [12], [13], [14]. Only five influential input parameters related to PMs were selected through the SA process for the FEBA test using different codes [12] from seventy-two input parameters.

This paper focuses on the sensitivity analysis of PMs used in simulating the reflooding phase. Series I of the FEBA test was chosen for our simulation as the representative reflooding experiment at relatively low inlet flow rate conditions [11]. The sensitivity study of PMs is carried out to select the most influential parameters on the output. The obtained results are used for further work on the uncertainty evaluation of chosen PMs.



a) Main phases during LBLOCA [[4]].



(b) Typical cladding temperature profile [[6]].

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

II. TOOLS AND FEBA MODELING IN RELAP5

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 FEBA facility description and its model in RELAP5 will be given in detail in this part.

A. Description of FEBA facility

The FEBA main test section contains a full-length 5x5 rod bundle of pressurized water reactor (PWR) fuel rod dimension (Fig. 2a), surrounded by a square housing made of stainless steel. 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 as those used in the PWR core. The heater rod nodalization in RELAP5, its grid spacer positions, and its power profile are shown in Figure 2c. The FEBA test section is modeling in three different parts, inlet volume (150), main test section including heater rod (4500, 4501), and outlet volume (650) are the lower plenum, heater rod, and the upper plenum in corresponding. The heated rod length is 3900 mm. It should be noted in Fig. 2a that the chosen origin is on the top of the heated rod in a downward direction. The test was first heated at low nominal power (200 kW) to achieve a required initial cladding temperature before simulating the transition. According to the 120% American National Standard (ANS) decay heat power curve, the test runs start using the power bundle about the 40s after the reactor shut down. The subcooled liquid was injected from the bottom of the test section to simulate the reflood phase. During the test, the cladding and housing temperatures were measured at different axial locations along their axial surfaces.

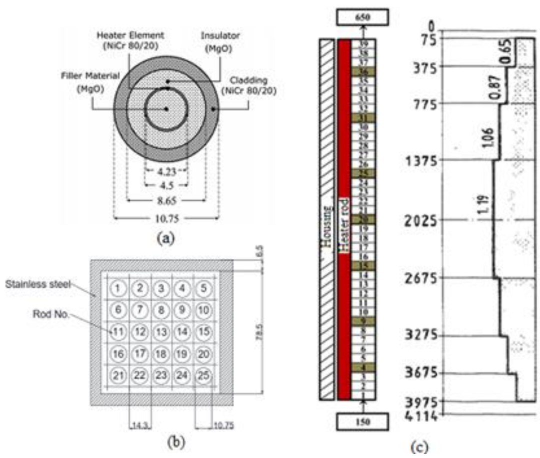


Fig. 2. (a) Cross-section of fuel rod simulators used in the FEBA test. (b) Cross-section of FEBA test bundle in a square housing. (c) Nodalized heater rod in RELAP5 and its axial power profile [[11]]

B. Model of FEBA in RELAP5

The nodalizated diagram of the FEBA facility in RELAP5 is illustrated in Figure 2c. The time-dependent volume (TDV) represents the inlet volume, and the TDV 650 defines the outlet plenum. The flow channel was modeled by pipe 450, divided into 39 equalized lengths of 0.1

m. It connects to the heat structure 14500 and 14501, which simulate rod bundle and housing. The seven grids spacers are set at corresponding nodes as designed in the experiment.

Test number 216 of the FEBA test was chosen for analysis. Its initial and boundary conditions are shown in Table I. As the experimental process, after reaching the required steady-state, the power was changed to simulate the decay heat power according to 120% ANS - Standard about 40 s after reactor shutdown. Together with that, the feedwater was injected into the inlet plenum at the bottom of the test.

III. RESULTS AND DISCUSSIONS

The reference case needs to be defined to perform a sensitivity analysis for test 216 conducted on the FEBA experiment. The first part of this section presents the reference case result in comparing it with FEBA experimental data. The sensitivity study is then performed for selected PMs to find the most influential parameters on the output results. Based on this study, the selected parameters could be used for further work on uncertainty evaluation.

A. Reference case

The reference case is the case that all considered PMs are set in default values of 1.0. The reference case was prepared using the initial and boundary conditions of test 216, as given in Table I.

Table I. Initial and boundary conditions of FEBA test 216 [[11]]

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

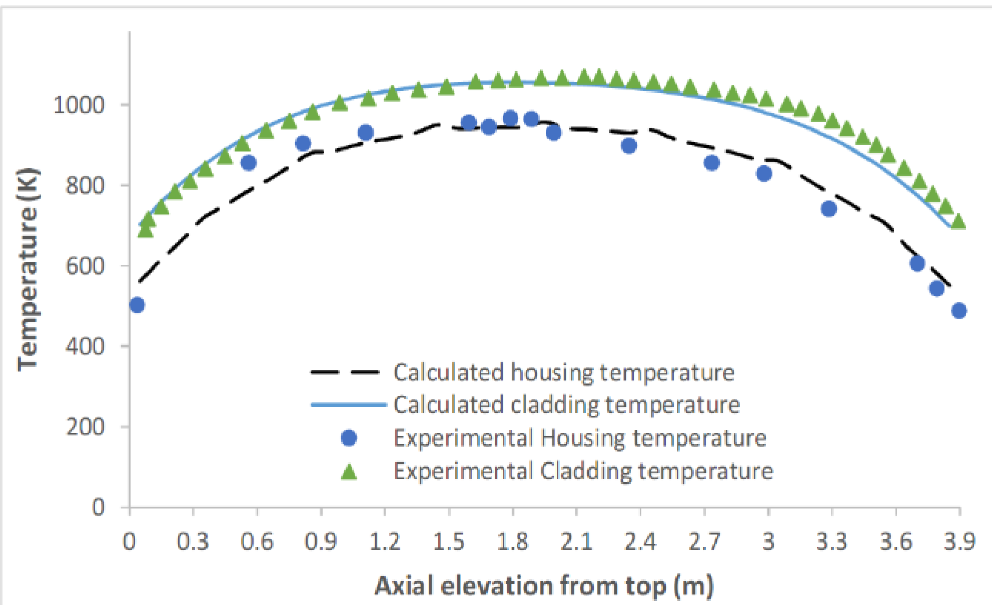


Fig. 3. Comparing the initial temperature for the reference case

Following the FEBA experimental procedure, the calculation is first for a steady-state for about 1000s. When reaching the designed temperature, the initial temperatures of cladding and housing are compared with corresponding experimental data, as shown in Figure 3.

We could conclude that the calculated results are similar to experimental data. It means that the heating process using prepared input data for test 216 is identical to the testing procedure and gives a good result. The input data, therefore, can be used for further work.

The next step for sensitivity analysis activates all PMs in the input with a default value of 1.0. The results need to be the same during this activation step. Figure 4 shows that the same cladding temperature at nine different elevations, 02, 07, 12, 18, 20, 23, 26, 29, and 34 nodes correspondingly, has been obtained before (no) and after (with) the activation. In our reference case calculated results, the PCT occurred at node 26 chosen for reference elevation. So the PCT and quenching time at reference elevation (node 26) are computed for thirty-two calculations for sensitivity study and compared to their values obtained from the reference case. After reaching the steady-state, the power curve was changed using the decay heat power according to 120% ANS-Standard. The feed water was then injected into the test section from the bottom to simulate the reflood phase.

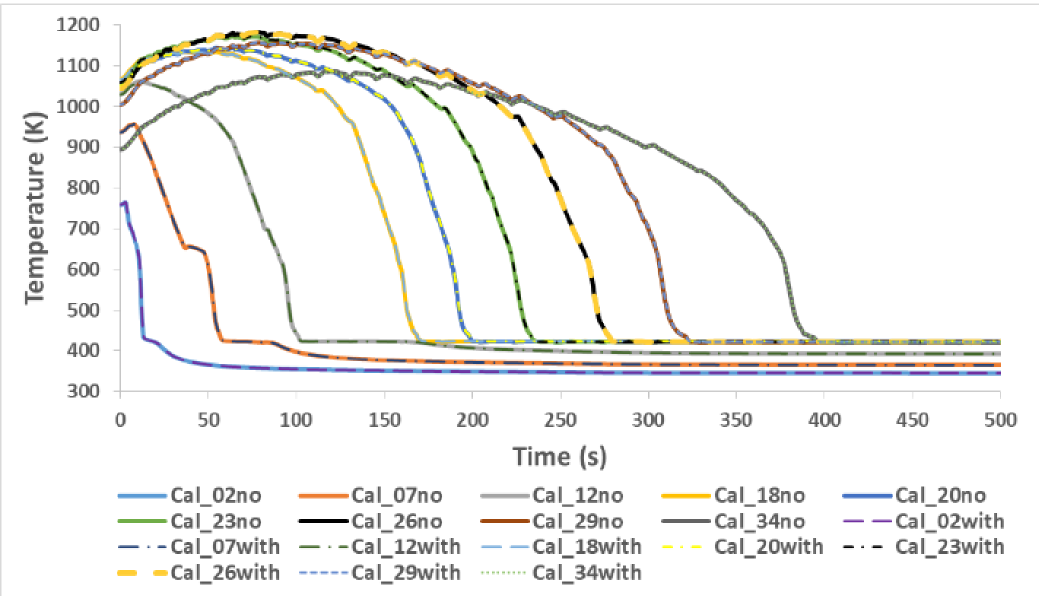


Fig. 4. Cladding temperature at various elevations

For the transitional period, the cladding temperatures at three different heights (at the bottom, in the middle, and at the top of the test section) are calculated and compared with experimental data and other calculations using MARS-3D (KAERI [12]), RELAP5 (UNIPI [12]) as shown in Figure 5 and Figure 6.

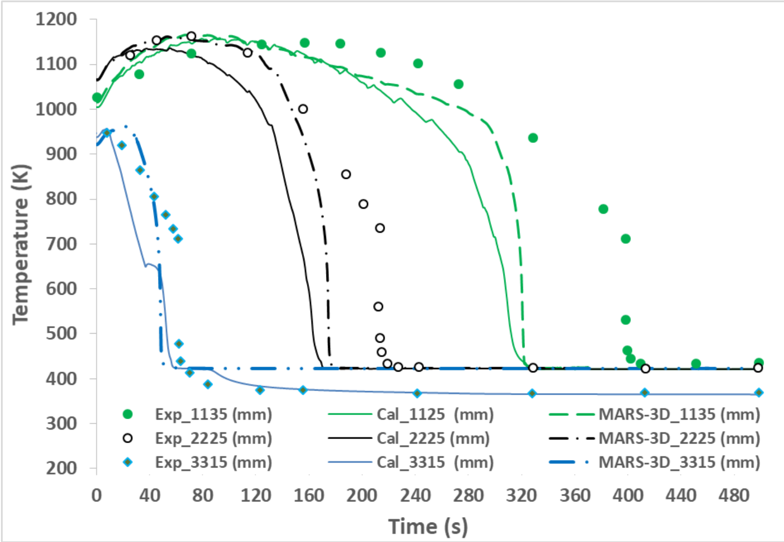


Fig. 5. Comparison between calculated cladding temperature and experimental data at three elevations [12]

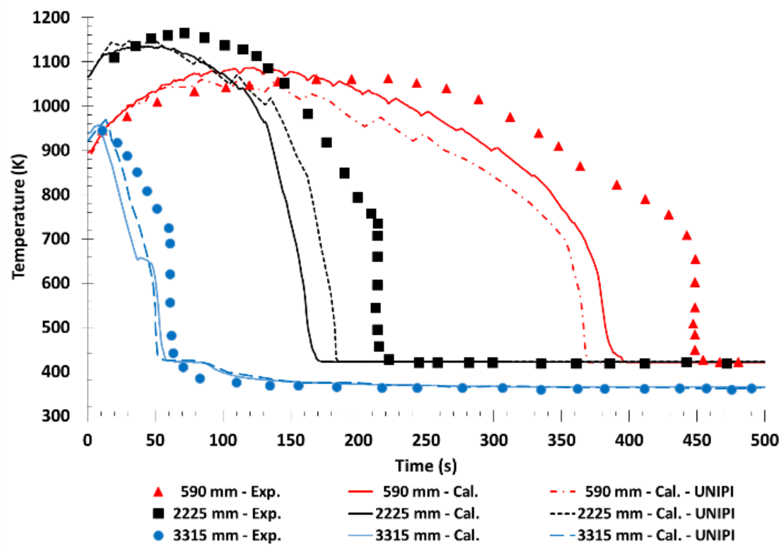


Fig. 6. Comparison between cladding temperature and experimental data at three elevations [12]

As shown in these figures, the bottom of the test was first quenched, then the middle, and finally, the top of the heater parts. The reference case results give similar PCT at each elevation but underpredict the quenching time. The heater rods were quickly quenched for all calculated results using codes compared to experimental data for low flooding rate conditions. This phenomenon has been stated by Choi and No [5] as the limitation of the RELAP5 code simulation. Similar predictions are found in [12] calculated by UNIPI using RELAP5. Our reference case gives better predictions for PCT and similar quenching times with the results of UNIPI. Our reference case result shows that PCT along the heated rod occurred at 1400 (mm), corresponding to node 26 in our FEBA model. The reference elevation of 1400 mm (node 26) is selected for sensitivity calculations. Other researchers [15],

[16], [17], [18] 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 improvement. Based on their researches, together with the opinion given in [12] by Kovtonyuk et al., the sensitivity study for PMs was performed to find the most influential parameters.

B. Sensitivity Study

Based on the available physical models built-in RELAP5 [2], sixteen PMs were chosen for SA. Main PMs are related to heat transfer coefficients for interfacial and wall heat transfers for each flow regime during the reflood phase. They can be listed as Chen, Dittus-Boelter, Bromley, Modified Bromley, Forslund-Rohsenow, Ishii-Mishima, Modified Bestion, Zuber CHF, and CHF Look-up table correlations. Other PMs are droplets, and quenching parameters, which are typical in reflood physical phenomena. Appendix A shows those PMs in more detail.

Each PM varied in the range from minimum to maximum values based on its given probability distribution function (PDF) selected by the expert, as shown in Table II. Two cases of minimum and maximum values for each parameter are considered as two inputs for this study. It means that thirty-two cases are calculated for the sensitivity work, the plot of cladding temperature at the elevation PCT occurred (node 26), as shown in Figure 7.

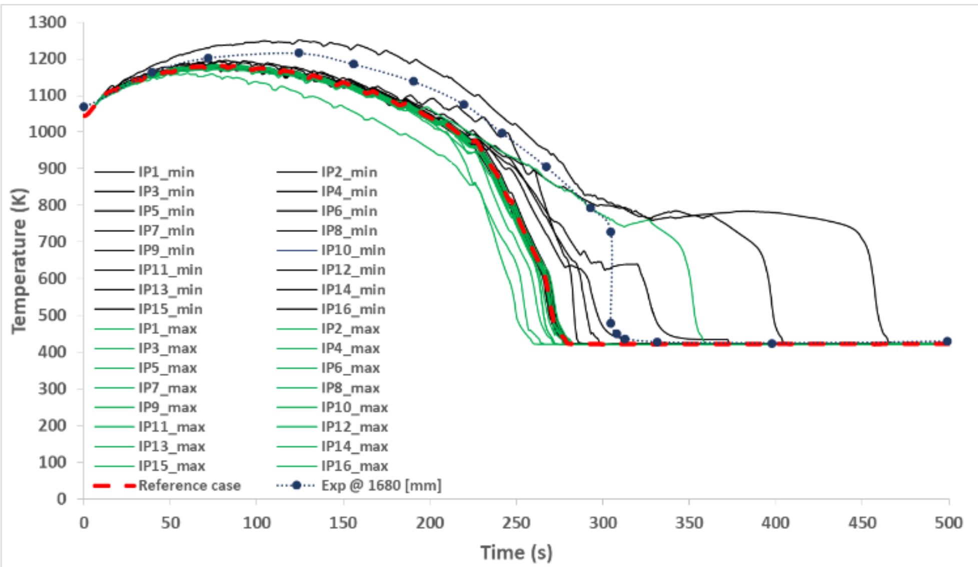


Fig. 7. Sensitivity result for 16 physical models

Because there is no measured data at the point PCT occurred (1400 mm), the available data (at 1680 mm) closest to this point, PCT occurrence, was selected for comparison. The obtained results show a reasonably good temperature distribution compared with the reference case (the dashed line) and the experimental data. However, the quench time has fluctuated significantly. Two phenomena usually occur during the quenching process, the sudden quench and slow down the quenching process. In our results of this sensitivity, prolonging the quenching process has happened in some calculations, as shown in Figure 7.

Table II. Chosen PMs and their PDF for the sensitivity study

Index	Physical models (PM)	PDF	Range of Variation
1	Chen correlation of nucleate boiling wall heat transfer	L-N	[0.4 – 2.8]
2	AECL Look-up table CHF	N	[0.20 – 1.80]
3	Zuber CHF correlation	L-N	[0.50 – 2.00]
4	Transition boiling wall heat transfer	N	[0.50 – 1.50]
5	Film boiling heat transfer	N	[0.50 – 1.50]
6	Dispersed film boiling heat transfer	N	[0.50 – 1.50]
7	Wall heat transfer transition criteria of steam flow Reynold number 3000	N	[0.50 – 1.50]
8	Wall heat droplet enhancement factor of steam flow	N	[0.50 – 1.50]
9	Interfacial drag for bubbly flow	L-N	[0.50 – 2.00]
10	Liquid entrainment	L-N	[0.50 – 2.00]
11	Droplet We number for reflood	L-N	[0.50 – 2.00]
12	Interfacial heat transfer of IANN/ ISLG	L-N	[0.50 – 2.00]
13	The surface roughness of IANN/ISLG	L-N	[0.50 – 2.00]
14	Dry/wet wall criteria 30 deg-C	L-N	[0.50 – 2.00]
15	Liquid chunk flow regime	N	[0.50 – 1.50]
16	Droplet interfacial heat transfer	N	[0.80 – 1.20]

The chosen criteria for our sensitivity study are based on the given criteria [12]. For the T/H evaluation and licensing process, the PCT is the main criterion to be selected. With this criterion, quenching time is a typical one, which is defined as the time required for heater rod temperature to reach a temperature at 30°C higher than the saturation temperature, $T_q = 30 + T_s$, is the reflood dominant characteristics. Therefore, the two chosen criteria for our study are PCT and quenching time:

- The criterion for PCT is defined as the absolute value of variation in PCT: $\Delta T_{ref} (= PCT_i - PCT_{ref}) = 10$ (°C) where i is the index of the calculation case.

- The criterion for quenching time is the variation in rewet time: $\Delta t_{quench} (= t_{q,i} - t_{q,ref}) = 50$ (s).

Based on two chosen criteria, the PCT and quenching time are calculated for each case at reference elevation and then compared with reference results.

Figures 8 and 9 present the computed results of the sensitivity study. It can be seen that for both the sensitivity criteria, the PMs with corresponding index of 1 to 5 and 11 to 13 do not affect the calculation results of the fuel rod temperature or quenching time. Among 16 PMs, we could see that PM with its index of 6, 14, and 15 is selected as the most influential PMs using the PCT criterion (Fig. 8). By applying the quenching time criterion, two PMs with their index of 6 and 9 are chosen (Fig. 9).

Based on the sensitivity study using the PCT and quenching time criteria, four influential PMs have been selected as summarized in Table III.

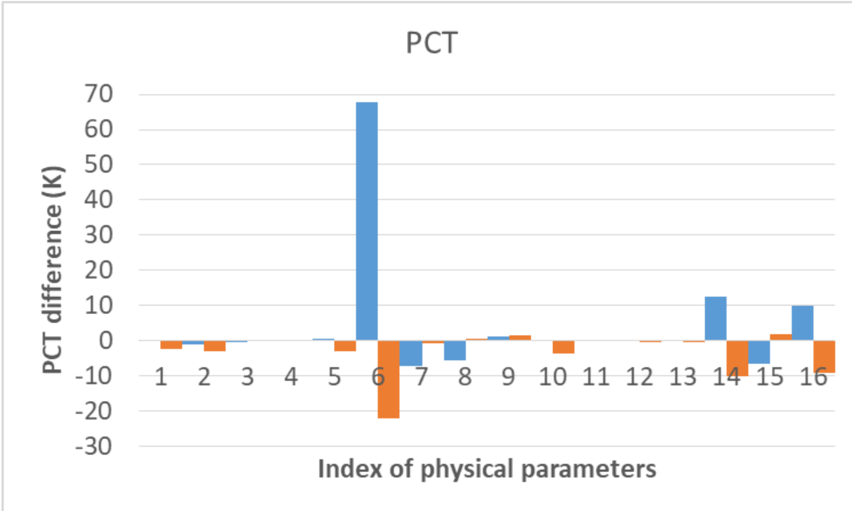


Fig. 8. Sensitivity study for calculation of rod surface temperature

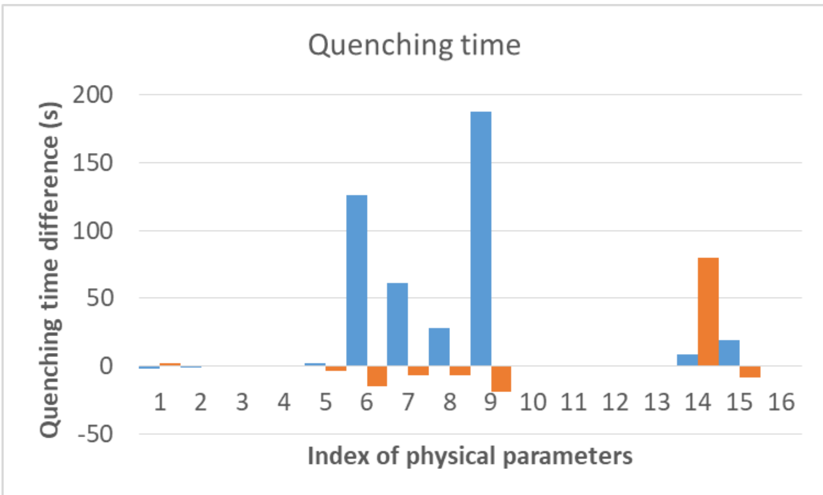


Fig. 9. Sensitivity study for calculation of rewet time

Table III. Four chosen PMs based on the SA

IP Index	Chosen PMs
6	Dispersed film boiling heat transfer
9	Interfacial drag for bubbly flow
14	Dry/wet wall criteria 30 deg-C
16	Droplet interfacial heat transfer

It can be seen that all four chosen physical models influencing the PCT and quenching time results in our sensitivity analysis are essential physical phenomena during reflood. The film boiling coefficient (IP6) is a dominant phenomenon in the heat transfer process during the reflood phase. Steam flow in the vapor phase with entrained droplets (IP9) of various sizes, and velocities, strongly influences these droplets to exert many essential flow and heat transfer processes [19] during reflood.

Experts recommend judging whether the wall is dry or wet at a temperature 30°C above the saturated temperature (IP14). However, two associated phenomena in this process, the sudden wetting and the delayed wetting process, exit during reflood. The phenomenon of slowing down the wetting process appears quite a lot in our sensitivity calculation, as shown in Figure 7, which indicates that the wetting criterion also needs to be further considered. The last chosen physical model, the heat transfer at the droplet-steam interface (IP16), contributes significantly to the heat transfer, especially during the reflood phase. The number of water droplets carried by the steam and the size of droplets partly determine the overall heat transfer capacity, leading to a decrease in the heater rod temperature. These factors cause quick or slow rewetting. Therefore IP16 is also a parameter that needs to be considered as uncertainty generated parameter.

IV. CONCLUSIONS

Among the inlet conditions such as initial, boundary conditions, and PMs, the PMs are suggested to be the most influential parameters on the calculation results. Therefore, PMs which have built-in BE codes are the main focus in uncertainty evaluation. Sensitivity analysis for PMs is the main focus of this study to better understand the T/H mechanism during the reflood phase in which the most complex two-phase flow phenomena happens. This analysis has performed for built-in PMs in RELAP5 code using FEBA experimental data to select the most influential parameter for further work.

The reference case was selected and evaluated, which proved the same heating process as the experiment has obtained. Comparing the reference results with those calculated by UNIPI (using RELAP5) and KAERI (using MARS-3D), similar quenching time predictions have been received.

Sixteen PMs were chosen for the sensitivity study. Two criteria of PCT and quenching time have been used for finding the influential PMs on the output result. The final results show that among sixteen considered inlet parameters, four PMs with the corresponding index of 6, 9, 14, and 16 have been selected, as listed in Table III. For our sensitivity study results, while the most influential parameter is the dispersed film boiling heat transfer (IP6) using the PCT criterion, the interfacial drag for bubbly flow (IP9) is the most significant parameter the quenching time criterion. They are the most influential PMs, which will be used for further work on uncertainty evaluation.

NOMENCLATURE

ECCS	Emergency Core Cooling System
LBLOCA	Large Break Loss Of Coolant Accident
IP(s)	Input Parameter(s)
PMs	Physical Models
PDF	Probabilistic Density Function
CHF	Critical Heat Flux
PCT	Peak Cladding Temperature
BE	Best Estimate
A	Area
D_H	Hydraulic diameter
D_{drop}	Diameter of droplet
h_l	Heat transfer coefficient for liquid
h_{FZ}	Nucleate boiling heat transfer coefficient
h_{FR}	Forslund - Rohenow coefficient
h_{FBGR}	Modified Bromley correlation coefficient

h_{DB}	Dittus-Boelter heat transfer coefficient
a_{gf}	Interfacial area per unit volume
c_l	Specific heat capacity of liquid
C_l	interfacial drag coefficient
k_l	Thermal conductivity for liquid
ρ_l	Liquid density
α	Void fraction
Gr	Grashof number
Re	Reynold number
We	Weber number

APPENDIX A. THE CONSIDERING PHYSICAL MODELS

Many parameters are used in the input to simulate the FEBA experimental facility, such as initial condition, boundary condition, and physical models. Physical models have been recommended in the PREMIUM project as parameters that significantly impact the output calculation results. The considered physical models are listed in Table II. They are often selected based on the conditions related to flow regime, void fraction, or phase transition. The physical models are described in detail in this part.

IP1: Chen's boiling correlation multiplier coefficient

In 1963, Chen [20] proposed the first flow boiling correlation for evaporation in vertical tubes. Chen's correlation included both the heat transfer coefficient due to nuclear boiling and the forced convection mechanism. It should be noted that the heat transfer coefficient varies significantly with the flow rate in cases of slightly high vapor fractions. Under these conditions, the flow at the center of the flow will be very high, resulting in a highly turbulent flow. This heat transfer mechanism is called forced convection evaporation. Chen proposed a correlation where the heat transfer coefficient is the sum of a forced convection component and a nucleate boiling component. The nucleate pool boiling correlation of Forster and Zuber [21] is used to calculate the nucleate boiling heat transfer coefficient, $h_{FZ.}$ and the turbulent flow correlation of Dittus-Boelter [2], [22], [23], [24] is used to calculate the liquid-phase convective heat transfer coefficient, h_l:

$$h_{tp} = h_{FZ}S + h_l F \qquad (A.1)$$

Where:

$$h_{FZ} = \frac{k_l^{0.79} c_l^{0.45} \rho_l^{0.49} \Delta T_s^{0.24} \Delta p^{0.75}}{\sigma^{0.5} \mu_l^{0.29} H_{fg}^{0.24} \rho_g^{0.24}} \qquad (A.1a)$$

$$h_l = 0.023 \frac{k_l}{D_H} (Re_l)^{0.8} (Pr_l)^{0.4} \qquad (A.1b)$$

Where:

- S is the nuclear boiling suppression factor, the ratio of the effective superheated to the wall superheated. It accounts for reduced boiling heat transfer because the effective overheating across the boundary layer is smaller than a superheater based on wall temperature. S=0.00122 for Forster and Zuber correlation;

- F is the two-phase multiplier as a function of the Martinelli flow parameter, $F = (X_{tt}^{-1} + 0.213)^{0.736}$;

- k_l, c_l, ρ_l, μ_l is the coefficient of thermal conductivity, specific heat capacity, density, and viscosity of the liquid, respectively;

- Δp is the difference in saturation and superheated wall pressures;

- H_{fg} is the vaporization enthalpy and D_H is the equivalent diameter;

- Re_l and Pr_l are Reynolds and Pranlt numbers for the liquid phase.

IP2: AECL CHF Look-up table

The CHF look-up table is widely used to predict CHF. The CHF look-up table is basically a normalized data bank for a vertical 8 mm water-cooled tube. The 2006 CHF look-up table is based on a database containing more than 30,000 data points, in the ranges of 0.1–21 Mpa pressure, 0–8000 kg.m–2.s-1 (zero flow refers to pool-boiling conditions) mass flux and –0.5 to 1 vapor quality (negative qualities refer to subcooled conditions) [2], [25].

Table A.1. CHF Table Lookup Multipliers [[2]]

k	Description
k1 = hydraulic diameter effect	$k1 = \left(\frac{0.008}{D}\right)^{0.33}$ for D < 0.016 m $k1 = \left(\frac{0.008}{0.016}\right)^{0.33}$ for D > 0.016 m D = heated equivalent diameter =4A/chu vi gia nhiệt
k2 = bundle effect	$k2 = \min[0.8, 0.8\exp(-0.5(Xe)^{0.33})]$ for rod bundles k2 = 1.0 for other surfaces
k3 = Grid spacer effect	$k3 = 1 + A\exp(-B{*}Lsp/D)$; $A = 1.5(Kloss)^{0.5}(G*0.001)^{0.2}$; B = 0.1, Kloss is the grid pressure loss coefficient
k4 = Heated length effect	$k_4 = \exp\left\{\left(\frac{D}{L}\right)[\exp(2.alp)]\right\}$; $alp = \frac{xlim}{[xlim + (1 - xlim)]}\frac{\rho_g}{\rho_f}$, $xlim = \min[1, \max(0, X_e)]$
k5 = Axial flux profile	k5 = 1 for , $X_e < 0$ $k5 = \frac{q_{local}}{q_{bla}}$; q_{bla} = average flux from the start of boiling at the survey point
k6 = Horizontal flow factor	k6 = 1 if vertical k6 = 0 if horizontal straitified k6 = 1 if horizontal high flow k6 = interpolate if medium flow
k7 = vertical flow factor	a. k7 = 1 for G < -400 or G > 100 kg/s-m^2, b. For -50 < G < 10 kg/s-m^2: k7 = (1-alp) for alp < 0.8 for alp > 0.8, table value of CHF is evaluated at G = 0, Xe = 0 c. For 10 < G < 100 kg/s-m^2 or -400 < G < -50 kg/s-m^2: interpolate
k8 = pressure out-of-range	$k8 = \frac{prop\ (out)}{prop\ (border\ )}$, $prop = \rho_g{}^{0.5}h_{fg}[\rho_f - \rho_g]^{0.25}$

CHF values are interpolated from experimental data based on the matrix of pressure p, mass flow, G and quantity, X, for the vertical pipe of 8 mm in diameter, then corrected for the other pipe diameters to be calculated through the correction factor [2]:

$$\mathrm{CHF} = \mathrm{CHF}_{table}\mathrm{chfmul} \qquad (A.2)$$

Where: $\mathrm{chfmul} = k_1.k_2.k_3.k_4.k_5.k_6.k_8$

These coefficients are listed in detail, as in Table A.1 below. The coefficient k7 applied to low mass flowrate, G = -50 to 10 kg / s.m^2 in which the critical flux unsteady varies with the change of mass flux [2].

IP3: The CHF boiling pool boiling Zuber multiplier

The reflood model in the RELAP5 code uses the modified Zuber CHF correlation instead of using the Groeneveld Lookup Table for low mass flow. RELAP5 calculates the wall heat flux for both liquid and vapor phases and calculates the heat flux for both film boiling and transition boiling. The "Look-up table" value is used when the mass flux is over 200 kg/ m2s. Under a mass flux of 100 kg / m2s, a modified Zuber correlation was used [2]:

$$CHF_{pb} = Kh_{fg}\left[\delta g(\rho_f - \rho_g)\right]^{0.25}\rho_g^{0.5} \qquad (A.3)$$

K, δ, and g are the number of hydrodynamic boiling stability, the surface tension of the liquid, and the gravitational constant. In the RELAP5 code, the value of K is:

$$K = 0.13\ \max\left[0.04, 1 - \alpha_g\right].$$

IP4: Modified Weismann multiplier

This is the correlation used to replace Chen's boiling-transition correlation for the fuel bundle configuration in the reflood [2], [20]:

$$h_w = h_{max}e^{-0.02\Delta T_{wchf}}$$
$$+4500\left(\frac{G}{G_R}\right)^{0.2} e^{-0.012\Delta T_{wchf}} \qquad (A.4)$$

Where: $h_{max} = \frac{0.5CHF}{\Delta T_{chf}}$ for CHF is the critical heat flux,

$\Delta T_{wchf} = \max\left[3, \min\left(40, T_w - T_{spt}\right)\right]$, and $\Delta T_{chf} = \max\left(0, T_w - T_{spt}\right)$, with T_{spt} is the saturated temperature calculated using total pressure, and T_w is the wall temperature.

PSI (Paul Scherrer Institute in Switzerland) model developed to improve the quench front behavior during the reactor core reflood process concerning shear force to replace the Chen transition boiling correlation. The transition boiling heat transfer coefficient to liquid use of the Weismann correlation depends on the distance from the point in question to the quench front position, less than 0.1 m and higher than 0.2 m. Its interpolated values are for the other elevations [2]:

$$h_{fTB} = \begin{cases} \max(h_{max}, h_w) & z_{QF} \le 0.1\text{ m} \\ h_{low} & z_{QF} \ge 0.2\text{ m} \\ \text{interpolate} & 0.1\text{m} \le z_{QF} \le 0.2\text{ m} \end{cases}$$

Where, z_{QF} is the distance from the considered point to the bottom quench front, $h_{low} = 0.0001 W/m^2K$

IP5: Modified Bromley correlation multiplier

The film boiling heat transfer coefficient to liquid, h_{fTB}, uses the maximum of a film coefficient, h_{FTB} and Forslund - Rohenow coefficient, h_{FR} , [2]:

$$h_{fTB} = \left[1400 - 1800\min\left(0.05, z_{QF.}\right)\right]\min\left(0.999 - \alpha_g, 0.5\right) + h_{FBGR}(1 - \alpha_g)^2$$

The first part of h_{fTB} is an empirical length-dependent expression. The second part includes a modified Bromley correlation coefficient, h_{FBGR}, which uses z_{QF} for the length in the denominator instead of the wavelength, as does the normal RELAP5 Bromley correlation. The modified Bromley correlation coefficient used here is given by:

$$h_{FBGR} = 0.62\left[\frac{g\rho_g {k_g}^3(\rho_f - \rho_g)[h_{fg} + 0.5(T_w - T_{spt})C_{pf}]}{\max(0.05, z_{QF.})\,\mu_g(T_w - T_{spt})}\right]^{0.25} \qquad (A.5)$$

IP6: Forslund-Rohsenow coefficient multiplier

The film boiling heat transfer coefficient to liquid, h_{fTB}, uses the maximum of a film coefficient, h_{FTB} and Forslund-Rohenow coefficient, h_{FR}. Forslund-Rohsenow correlation is determined as follows [2]:

$$h_{FR.} = h1\left\{\frac{g\rho_g\rho_f h_{fg}k^3}{\mu_g d\left(T_w - T_{spt}\right)\left(\frac{\pi}{6}\right)^{\frac{1}{3}}}\right\}^{0.25} \qquad (A.6)$$

Where:

$$h1 = 0.4\left(\frac{\pi}{4}\right)\left[\frac{6(0.999-\alpha_g)}{\pi}\right]^{\frac{2}{3}}$$

$$d = \min\{0.003, \max[0.0004, 3\frac{\sigma}{\rho_g}\max(0.01, (v_f - v_g)^2)]\},$$

Where v_f and v_g are the liquid and vapor velocities.

IP7: Single phase Vapor flow

The empirical correlation of Dittus-Boelter [22] has gained widespread acceptance for prediction of the Nusselt number with turbulent flow in the smooth surface tubes:

$$Nu = 0.023 Re^{\frac{4}{5}} Pr^n \qquad (A.7a)$$

Where $\begin{cases} n = 0.4 \text{ for heating} \\ n = 0.3 \text{ for cooling} \end{cases}$

The Dittus-Boelter correlation is only correct if:

$$0.7 \le Pr \le 160, Re \text{ “}10{,}000, \frac{L}{D} \ge 10$$

The Dittus-Boelter is used for both liquid and vapor phases in RELAP5/MOD3 [2]:

$$h_{DBv} = 0.023\frac{k_v}{D_H}\left(\frac{G_v D_H}{\mu_v}\right)^{0.8}(Pr_v)^{0.4} \quad (A.7b)$$

$$h_{DBl} = 0.023\frac{k_l}{D_H}\left(\frac{G_v D_H}{\mu_l}\right)^{0.8}(Pr_l)^{0.4} \quad (A.7c)$$

IP8: Wall heat droplet enhancement factor

A similar correlation is used in code TRACE as improved heat transfer coefficient:

$$\Psi_{2\phi} = \left[1 + 25\frac{(1-\alpha)Gr_{2\phi}}{Re_g^2}\right] \qquad (A.8)$$

Where:

$Gr_{2\phi} = \frac{\rho^2 g\beta(T_w - T_b)L^3}{\mu^2}$, $Re_g = \alpha_g\rho_g v_g\frac{D}{\mu_g}$ are the Grashof number and Reynolds Number. Here coefficients were obtained experimentally by a factor of 25 for this entire correlation coefficient multiplication uncertainties considered.

IP9: Modified Bestion drag model multiplication factor

The modified Bestion correlation is used for interfacial drag in vertical bubbly-slug flow at pressures below 10 bars in place of the EPRI correlation. Above 20 bars, the EPRI correlation is used. Between 10 and 20 bars, the interfacial drag is interpolated. The modified Bestion correlation for the code interfacial drag coefficient, C_i, is determined as [2]:

$$C_i = \frac{65\alpha_g\rho_g(1-\alpha_g)^3}{D} \qquad (A.9)$$

This correlation coefficient of C_0 =0.124 for the multiplication factor is considered as an uncertainty.

IP10: Ishii-Mishima correlation multiplier

In the annular-mist flow regime, the calculation of wall-to-coolant heat transfer requires the proper apportioning of the liquid in the wall region as an annular film and in the vapor region as droplets. The code uses the Ishii and Mishima correlation for the entrainment fraction as a basis for calculating the liquid volume fraction in the film region and the liquid volume fraction in the vapor region. The correlation determines the fraction of liquid flux flowing as droplets by the following expression [2]:

$$E = \tanh(7.25 \times 10^{-7}\, We^{1.25}\, Re_f^{0.25}) \quad (A.10)$$

Where effective Weber number for entrainment:

$We = \frac{\rho_g(\alpha_g v_g)^2 D}{\alpha}\left(\frac{\rho_f - \rho_g}{\rho_g}\right)^{\frac{1}{3}}$; the total liquid Reynold number: $Re_f = \alpha_f\rho_f v_f\frac{D}{\mu_f}$.

IP11: Weber number multiplier

Before calculating the diameter of the droplets, We_{crit} value for droplets, as well as for the biggest bubbles, must be determined. In RELAP5/MOD3 [2], the critical droplet value, We_{crit}, at pre CHF, post CHF, and the maximum bubble are 3, 12, and 10, correspondingly. In the code RELAP5 / MOD3, the PSI reflood model uses numbers with a value of 12.0. However, the new reflood model in TRACE5.0 uses a Weber value of 4.0. Therefore, the Weber number needs to take into account the uncertainty of the multiplier due to the variation of droplet diameter, $d_o = \frac{1}{2} d_{max}$. Weber number is defined by:

$$We_{crit} = \frac{\rho_c (v_f - v_g) d_{max}}{\sigma} \qquad (A.11)$$

Where ρ_c is the density of the continuous phase.

IP12: Slug flow interfacial heat transfer coefficient factor

In slug flow, interfacial heat transfer can be divided into two distinct parts [2]:

(a) the heat transfer between the large Taylor bubbles and the liquid surrounding them, and (b) the heat transfer between the small bubbles in the liquid slug and their host liquid:

$$Q_{ip}^{B} = H_{ip,Tb}\,\Delta T + H_{ip,bub}\,\Delta T$$

Thus, the coefficient of heat transfer in this slug flow is calculated as the total component heat transfer coefficient:

$$H_{ip} = H_{ip,Tb} + H_{ip,bub} \qquad (A.12)$$

IP13: Slug flow interfacial heat transfer area factor

The Taylor bubble frontal area per unit volume is α_b/L, where L is the cell length. Consequently, the interfacial area per unit volume, a_{gf}, là [2]:

$$a_{gf} = \frac{\alpha_b}{L} + \frac{3.6\alpha_{gs}}{d_o}(1 - \alpha_b) \qquad (A.13)$$

Where α_{gs}, α_b be the average void fraction in the liquid film and slug region and the void fraction of a single Taylor bubble:

$$\alpha_b = \frac{\alpha_g - \alpha_{gs}}{1 - \alpha_{gs}}$$

To provide a smooth transition into and out of slug flow, α_{gs}, in the above equation is considered as the free parameter which varies from α_{BS} at the bubbly-to-slug flow regime transition to nearly zero at the slug-to-annular-mist flow regime transition. The variation is represented by the exponential expression:

$$\alpha_{gs} = \alpha_{BS.} \exp\left[-8\left(\frac{\alpha_g - \alpha_{BS.}}{\alpha_{SA.} - \alpha_{BS}}\right)\right]$$

IP14: Dry/wet criteria for Liquid chunk flow regime

A wall is considered dry when its temperature is at least above saturation temperature 30 oC, $T_w > T_s + 30 = T_q$ [2]. If its temperature is at or below this temperature, Tq, the wall is considered to be wet. The uncertainty of 30°C related to the flow regime should be considered. While heat transfer on the drywall is dominated by film boiling, it is affected by transitional boiling, nuclear boiling, and forced convection on wet walls. This conversion standard is used to help code select wet wall surface values close to the quench front. The 30°C reduction value is constructed by comparing calculation results with the experiment [2].

IP15: Transition criteria for liquid chunk flow regime

The transition from bubbly flow to slug flow is based on Taitel, Bornea, and Dukler

(TBD) [2]. The bubbly-to-slug transition void fraction used in the code varies from 0.25 to 0.5, depending on the mass flux. The lower limit of 0.25 is based on a postulate of TBD that coalescence increases sharply when bubble spacing decreases to about half the bubble radius, corresponding to about 25% void. TBD then cites three references as supporting this approximate level. However, the indication of this limit is uncertain because TBD quotes are based on some other authors whose lower and upper bound values are not the same. Therefore, it is necessary to evaluate the uncertainty of this coefficient.

IP16: Droplet Interfacial Heat Transfer Coefficient

The heat transfer coefficient for interface to droplets based on the works of Andersen [2], [27] in the form: $H_{id} = h_{id} A_{i6}$

Where, $A_{i6} = 6\frac{1-\alpha_{dc}}{D_{drop}}$; $h_{id} = 1.8\pi^2 \frac{k_f}{D_{drop}}$

Where, $D_{drop} = \frac{2.7\sigma}{\rho_g \max\left(v_{drop}^2 j_{mt}^2\right)}$, $v_{drop} = 1.14\left[\frac{g\sigma\Delta\rho}{\rho_g^2}\right]^{0.25}$, j_{mt} is the total mass flux.

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