Research Article

Assessment of TRACE CCFL Model with SBLOCA Experiment of IIST Facility

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In this paper, the TRACE model for IIST facility is developed and verified with the Small Break loss of coolant accident (SBLOCA) experiment of IIST (Institute of Nuclear Energy Research Integral System Test) facility. By using the Wallis and Kutateladze correlations of countercurrent flow limitation (CCFL) model, the TRACE analyses results, such as break flow rate, primary pressure, and the temperature of cold-leg and hot-leg, are consistent with the IIST data. The results show the Kutateladze correlation of CCFL model can well predict the SBLOCA behavior and present good agreement with IIST experiment data in this paper. Besides, the sensitivity study results of Kutateladze correlation in CCFL model are verified and compared with the IIST data.

1. Introduction

A reduced-height and reduced-pressure IIST facility has been established for safety studies of the Westinghouse three loops pressurized water reactor (PWR) since 1992. The research purposes of the IIST facility are enhancement of understanding of thermal hydraulics phenomena during the accidents [1–3], contributing to evaluate and develop the safety computer codes [4, 5], and validation of EOP during the accidents of PWR [6]. The IIST facility has three loops as well as all the systems associated with Westinghouse PWR plant system transients. The maximum operating pressure of the IIST facility is 2.1 MPa. CCFL is an important phenomenon in a reactor system. In a PWR, countercurrent flow (CCF) may occur in both the hot-leg and the entrance to the steam generator during LOCA. CCF also occurs during blowdown as the Emergency Core Cooling Systems (ECCSs) fill water into the downcomer. When the CCFL occurs, the mass and heat transfer between gas and liquid phases reduces, and a water pool forms. This phenomenon

prevents the core from cooling such that the fuel temperature rapidly increases [7]. Therefore, studies on CCF and CCFL are essential for proper nuclear reactor safety.

The codes used in this paper are TRACE v 5.0p2 and SNAP v 2.0.3. TRACE (TRAC/RELAP Advanced Computational Engine) is an advanced and best estimate reactor systems code for analyzing thermal hydraulic behaviors in light water reactors [8]. TRACE consolidates the capabilities of the four codes, TRAC-P, TRAC-B, RELAP 5, and RAMONA, into one modernized code. One of the features of TRACE is its capability to model the reactor vessel with 3D geometry. It can support a more accurate and detailed safety analysis of nuclear power plants. TRACE has a greater simulation capability for loss of coolant accident. Furthermore, a graphic user interface program, SNAP (Symbolic Nuclear Analysis Package), which is being under development by Applied Programming Technology, Inc. for conveniently creating and editing the input decks.

According to the best LOCA simulation capability of TRACE, this paper focuses on the development of TRACE

FIGURE 1: The TRACE model for IIST facility.

IIST model and analysis of the SBLOCA with the IIST experiment data. The results of different form of CCFL model, such as Wallis correlation and Kutateladze correlation, are also verified with the IIST data in this study. Furthermore, the sensitivity studies of CCFL model in water level and core cladding temperature are discussed.

2. IIST Facility and SBLOCA Experiment

Figure 1 shows the TRACE model of IIST facility. IIST facility is established in order to simulate the thermal hydraulics phenomena of Maanshan NPP, which is a Westinghouse three loops PWR. The IIST facility consists of a pressure vessel and three loops. Each loop has a steam generator (SG) and a coolant pump [9]. Except that there is a pressurizer in the loop 1, the three loops are identical. The scaling factors of height and volume in the RCS are approximately 1/4 and 1/400, respectively. Scaled safety injection systems (include HPI and accumulators) inject cooling water into the cold-leg of each loop. During the SBLOCA experiment [10], a catch tank is simulated to collect and measure the effluent from the simulated break. The comparison of major parameters between IIST facility and the Maanshan NPP is shown in Table 1.

The experiment of IIST facility was performed in order to simulate a 2% cold-leg break (the break area is 2% of the scaled cold-leg cross-section area) with total HPI failure [11]. This break is located in loop 2 of IIST facility, which is one of the two loops that do not have a pressurizer. In this experiment, the core power decay and pump coastdown

during the SBLOCA experiment were not simulated. The initial condition of the experiment is shown in Table 2.

3. CCFL Model in TRACE

CCFL is an important issue related to the safety analysis of PWRs. CCFL phenomenon determines the maximum velocity of one phase relative to the other one when the velocity of neither of the two phases can increase further without flow regime change [12]. CCFL may occur in the downcomer, the upper core tie plate, the hot legs, the entrance of the SG inlet plenum, and the pressurizer surge line, where the flow direction or flow area changes. The TRACE code has the ability to calculate the CCF and predict the CCFL by applying the CCFL model at the flow path. The CCFL correlation can be applied at specific locations in the 3D component and in the 1D vertical component. The CCFL correlations can be represented as Wallis form [13], Kutateladze form [14], and Bankoff form [15]. In TRACE, the CCFL model basically uses the Bankoff correlation, because the correlation reverts to the Wallis form by setting the scaling constant $\beta = 0$, and reverts to the Kutateladze form by setting $\beta = 1$.

Equations (1) and (2) show the Wallis correlation and Kutateladze correlation, respectively,

$$J_g^{1/2} + m_w J_l^{1/2} = C_w, \quad (1)$$

$$K_g^{1/2} + m_K K_l^{1/2} = C_K, \quad (2)$$

TABLE 1: The comparison of major parameters between IIST facility and the Maanshan NPP.

Parameter	IIST	Maanshan PWR	IIST/PWR
Design pressure (MPa)	2.1	15.6	1.35×10^{-1}
Maximum core power (MW)	0.45	2775	1.62×10^{-4}
Primary system volume (m ³)	5.37×10^{-1}	2.15×10^2	2.50×10^{-3}
Number of loops	3	3	1
Core			
Height (m)	1.0	3.6	2.77×10^{-1}
Hydraulic diameter (m)	1.08×10^{-1}	1.22×10^{-2}	8.85
Bypass area (m ²)	7.2×10^{-5}	1.54×10^{-2}	4.67×10^{-3}
Hot leg			
Inner diameter, D (m)	5.25×10^{-2}	7.35×10^{-1}	7.13×10^{-2}
Length, L (m)	2.0	7.28	2.75×10^{-1}
$L/\sqrt{D}$ (m ^{0.5})	8.72	8.48	1.03
U-tube in one SG			
Number	30	5626	5.33×10^{-3}
Average length (m)	4.08	16.85	2.24×10^{-1}
Inner diameter (mm)	15.4	15.4	1.0
Volume (m ³)	2.28×10^{-2}	18.44	1.23×10^{-3}
Cold leg			
Inner diameter, D (m)	5.25×10^{-2}	7.87×10^{-1}	6.67×10^{-2}
Length, L (m)	5.0	15.7	3.18×10^{-1}
$L/\sqrt{D}$ (m ^{0.5})	21.8	17.69	1.22
Downcomer			
Flow area (m ²)	0.0185	2.63	7.03×10^{-2}
Hydraulic diameter (m)	4.12×10^{-2}	4.8×10^{-1}	8.58×10^{-2}
Pressurizer			
Volume (m ³)	9.32×10^{-2}	39.64	2.35×10^{-3}
Surge-line flow area (m ²)	3.44×10^{-4}	6.38×10^{-2}	5.39×10^{-3}

where J_k and K_k are dimensionless mass flux (k : gas or liquid). The m and C are constants determined from the experiments

$$J_k = j_k \left[\frac{\rho_k}{gd(\rho_f - \rho_g)} \right]^{1/2}, \quad (3)$$

$$K_k = j_k \left[\frac{\rho_k^2}{g\sigma(\rho_f - \rho_g)} \right]^{1/4}.$$

Here, j_k and ρ_k are the superficial velocity and the density of phase (k : gas or liquid), d is the hole diameter, and σ is the surface tension.

4. Results and Discussions

4.1. Analysis Results of CCFL Model. In this study, the CCF may occur in the hot leg, the entrance to the steam generator, and the pressurizer surge line in IIST SBLOCA experiment. In order to verify the SBLOCA prediction of TRACE CCFL model, the comparisons of the results among Wallis correlation, Kutateladze correlation, and IIST data are considered in this paper. From (3), the hydraulic diameters

TABLE 2: The initial condition of the IIST SBLOCA experiment.

Parameter	IIST test data
Primary coolant system	
Core power (kW)	126
Pressurizer pressure (MPa)	0.958
Pressurizer water level (m)	1.459
Loop flow rate (kg/s)	0.217
Hot-leg temperature (K)	450
Cold-leg temperature (K)	409
Secondary coolant system	
Secondary-side pressure (MPa)	0.295
Secondary-side fluid temperature (K)	407

of pipe from 2.5 to 200 mm are calculated for the Wallis correlation and Kutateladze correlation of CCFL model, as shown in Figures 2 and 3. The pipe hydraulic diameter of reactor coolant system is 52.5 mm in IIST facility, so it is chosen the 50 mm results for the IIST CCFL model analysis in this study. Figure 2 shows the Wallis correlation plotted against the data. The constant m_w and C_w are both set to 1 from the results of Figure 2. The Kutateladze correlation

FIGURE 2: The Wallis correlation comparison with data (pipe diameter = 2.5–200 mm).

FIGURE 3: The Kutateladze correlation comparison with data (pipe diameter = 2.5–200 mm).

plotted against the data is shown in Figure 3. The constant m_k and C_k are set to 0.6 and 1, respectively.

Figure 4 shows the comparison of break flow rate and primary system pressure among Wallis form, Kutateladze form, and IIST data. The break flow rate and primary system pressure trends of Wallis form, and Kutateladze form are similar with the IIST data. Asymmetric natural-circulation flow rates were observed in the three loops during the IIST SBLOCA experiment. Figure 5 shows the comparison of loop 1 and loop 3 flow rate among Wallis form, Kutateladze form, and IIST data in the SBLOCA experiment. The trends of Wallis form and Kutateladze form are similar to the IIST

FIGURE 4: The comparison of break flow rate and primary pressure among Wallis form, Kutateladze form, and IIST data.

FIGURE 5: The comparison of loop 1 and loop 3 flow rate among Wallis form, Kutateladze form, and IIST data.

data. For loop 1, the IIST data show the inlet and outlet plenum of SG1 to empty after 500 s, as shown in Figure 6. Figure 6 indicates the Wallis form of CCFL model results compared with the IIST data are overpredicted during 400~1600 s. The Kutateladze form predictions of water level in the SG1 inlet plenum are the same trends with IIST data, except at 100~700 s. Figure 6 also shows the Wallis form and Kutateladze form overpredicted water level in the SG1 outlet plenum at 300~800 s. Figure 7 shows the comparison of the liquid holdup in the SG2 inlet plenum and SG3 outlet among Wallis form, Kutateladze form, and IIST data. There are the similar trends in this parameter. However, the water level of Wallis form and Kutateladze form predicted are lower than IIST data after 300 sec. According to the results of SG3 outlet plenum liquid level predicted by Wallis form and Kutateladze

FIGURE 6: The comparison of SG1 inlet and outlet water level among Wallis form, Kutateladze form, and IIST data.

FIGURE 8: The comparison of SG3 hot leg and cold leg temperature among Wallis form, Kutateladze form, and IIST data.

FIGURE 7: The comparison of SG2 inlet and SG3 outlet water level among Wallis form, Kutateladze form, and IIST data.

FIGURE 9: The comparison of core water level and cladding temperature among Wallis form, Kutateladze form, and IIST data.

form, the trends compared with IIST data are generally consistent in 0~700 s and overpredicted after 700 s. Figure 8 shows the fluid temperatures of the cold-leg and hot-leg in loop 3. The TRACE predicted the loop 3 fluid temperature to be in good agreement with the IIST experiment data. Figure 9 shows the comparison of the core liquid level and cladding temperature among Wallis form, Kutateladze form, and IIST data. The trends of their curves are similar. Besides, the TRACE can predict the time to reach the core uncover, which caused the core cladding temperature increase, as shown in Figure 9. The results show that the core cladding temperatures of Kutateladze form predicted are the same trends with IIST data. The core cladding temperature begins to increase when the core uncovered. Comparing to IIST

data and Kutateladze form, the trends of core cladding temperature predicted by Wallis correlation do not increase.

4.2. Sensitivity Studies of Kutateladze Correlation. From the results of Section 4.1, it is indicated using Kutateladze form of CCFL model in the IIST that TRACE model has a good SBLOCA behaviors prediction capability. Furthermore, the sensitivity studies of Kutateladze correlation for the water levels and core cladding temperature are verified and discussed in this paper. According to the results of Figure 3, the base values of C_k and m_k are 1 and 0.6, respectively. The sensitivity studies for Kutateladze correlation are setting the difference value for m_k and C_k . The first method is to maintain the constant C_k , and set the value of m_k for 1.0,

FIGURE 10: The CCFL sensitivity study of m_k for SG1 inlet water level.

FIGURE 12: The CCFL sensitivity study of C_k for SG1 inlet water level.

FIGURE 11: The CCFL sensitivity study of m_k for core cladding temperature.

FIGURE 13: The CCFL sensitivity study of C_k for core cladding temperature.

0.8, 0.6, and 0.4, respectively. The other one is to maintain the constant m_k and set the value of C_k for 1.2, 1.0, 0.8, and 0.6, respectively. Figure 10 shows the sensitivity study of m_k for SG1 inlet water level. The results of $m_k = 1.0$ case overpredicted the water level after 400 s. By the way, the trends are almost the same without CCFL model. The results of $m_k = 0.8$ are different from the $m_k = 0.6$ and $m_k = 0.4$ between 600~800 s. It also indicates that the results of $m_k = 0.6$ and $m_k = 0.4$ are consistence. Figure 11 shows the sensitivity study of m_k for core cladding temperature.

The results of $m_k = 0.6$ and $m_k = 0.4$ show to predict the same times to reach the core uncover and to increase the core cladding temperature. The time of $m_k = 0.8$ predicted is later than $m_k = 0.6$ and $m_k = 0.4$. The core cladding temperature curve of $m_k = 1.0$ does not increase. Figure 12 shows the sensitivity study of C_k for SG1 inlet water level. The results of $C_k = 0.6 \sim 1.2$ are almost the same. It indicates that the different values of C_k follow the same trend. The results are also shown in Figure 13. The different values of C_k predict

FIGURE 14: Animation of the IIST facility TRACE model for SBLOCA analysis.

the same times to reach the core uncover, and to increase the core cladding temperature.

For the 50 mm pipe of the reactor coolant system analysis, the above sensitivity studies of CCFL in IIST TRACE model indicate that using the values of $m_k = 0.6$ and $C_k = 1$ for Kutateladze correlation can well predict the SBLOCA behavior and the results present good agreement with IIST SBLOCA experiment data.

Furthermore, the animation of the IIST TRACE model is presented using the animation function of TRACE/SNAP interface with analysis results, such as primary pressure, break flow rate, and core cladding temperature. The animation model of IIST is shown in Figure 14.

5. Conclusions

By TRACE/SNAP code, the TRACE model for IIST facility is developed and verified with the SBLOCA experiment of IIST facility. In TRACE code, the CCFL model includes the Wallis correlation and Kutateladze correlation. In order to verify the SBLOCA prediction of TRACE CCFL model, the comparisons of the results among Wallis correlation, Kutateladze correlation, and IIST data are considered in this paper. The TRACE analyses results, such as break flow rate, primary pressure, the temperature of cold leg and hot leg, and core cladding temperature, are consistent with the IIST data. It also indicates that the results of Kutateladze form predicted can best represent the results of IIST data. Besides,

the sensitivity studies of Kutateladze correlation are verified and discussed in this paper. The best values of m_k and C_k for IIST TRACE model are 0.6 and 1, respectively. In summary, since our current paper has shown good agreements between IIST data and TRACE results using Kutateladze correlation of CCFL model, future applications of this model are highly recommended for SBLOCA analysis.

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