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International Agreement Report

Uncertainty Analysis of Main Steam Line Break Accident for Maanshan PWR with RELAP5/DAKOTA

Prepared by:
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ABSTRACT

In our previous study, the RELAP5/SNAP model of Maanshan PWR nuclear power plant is established. This model was used to perform the analysis of Main Steam Line break (MSLB) inside-containment transient. The analysis results of RELAP5/SNAP are consistent with the FSAR data. In this study, the main purpose is to perform an uncertainty analysis for Maanshan MSLB by using RELAP5/SNAP model and DAKOTA code. Total 21 parameters which include initial power, accumulator volume, injection water temperature, injection flow, rod material thermal conductivity, discharge coefficient for break, slug flow drag, etc. are evaluated in this analysis. According to the uncertainty analysis results, discharge coefficient for break, slug flow drag, and annular-mist flow drag have larger effect in the calculation of break flow, and slug flow drag and annular-mist flow drag have larger effect in the calculation of void fraction.

FOREWORD

RELAP5 is a thermal hydraulic analysis code and has been designed to perform best-estimate analysis of LOCA, operational transients, and other accident scenarios for nuclear power plants. Traditionally, RELAP5 models were developed by ASCII files, which was not intelligible for the beginners of computer analysis. A graphic input interface code-SNAP is developed by Applied Programming Technology Inc. and can process the establishment of the RELAP5 models more conveniently.

Taiwan and the United States have signed an agreement on CAMP to obtain the authorization of these codes. NTHU is the organization in Taiwan responsible for the application RELAP5 and SNAP in safety analysis of nuclear power plants. Hence, the RELAP5/SNAP model of Maanshan PWR nuclear power plant has been developed. To expand the applicability of the RELAP5/SNAP model, a thermal hydraulic analysis methodology of the postulated MSLB is established in our previous study. By comparing the RELAP5 results and FSAR data, it indicates that the RELAP5/SNAP model has a respectable accuracy. Hence, this model was used to perform an uncertainty analysis of MSLB to understand the parameters effects in this study.

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EXECUTIVE SUMMARY

RELAP5 which is MOD3.3 Patch05 code was developed by Idaho National Engineering Laboratory for light water reactor transient analysis. RELAP5 can simulate the operation of NPPs under normal operations and transients, provide an accurate and rapid analysis patterns for NPP systems, and provide transients analysis results to NPPs and regulatory commission. RELAP5/MOD3.3 code is featured with nonhomogeneous and non-equilibrium model for the two-phase system and is a one-dimensional thermal hydraulic analysis code which uses Semi-Implicit method numerical scheme. RELAP5/MOD3.3 code also includes some models to deal with some particular phenomenon, such as critical flow model, reflooding model, metal-water reaction model etc.

SNAP which is developed by Applied Programming Technology, Inc. is a graphic interface code and different from the traditional input deck in ASCII files. SNAP can help users to easily build the RELAP5 models in a graphic interface. Furthermore, SNAP has the animation function to present RELAP5 analysis results. Hence, RELAP5/MOD3.3 and SNAP codes were used in this study.

DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) is developed by Sandia National Laboratory. DAKOTA supplies a simple setting interface for researchers to perform different iteration method with the analysis code (ex: RELAP5). Therefore, uncertainty analysis can be determined by some simulations with different input parameters sets in RELAP5 and DAKOTA.

Maanshan NPP which is a PWR is located on the southern coast of Taiwan. The reactor coolant system of Maanshan NPP has three loops, each of which includes a reactor coolant pump and a steam generator. In addition, a pressurizer connects to the hot-leg piping in loop 2. In our previous study, to analyze the MSLB transient, the RELAP5/SNAP model of Maanshan NPP was established. The analysis results of RELAP5 were compared with the FSAR data. According to the compared RELAP5 results and FSAR data, it indicates that the RELAP5/SNAP model has the ability to predict the MSLB transient.

However, to understand the effects of parameters for MSLB transient, the uncertainty analysis by using the RELAP5/SNAP model and DAKOTA code was performed in this study. Total 21 parameters which include 13 parameters of NPP and 8 parameters of RELAP5 model are evaluated in this analysis. These parameters of NPP are initial power, accumulator volume, accumulator temperature, accumulator pressure, accumulator boron concentration, injection water temperature, high pressure injection flow, low pressure injection flow, rod material thermal conductivity, rod material heat capacity, RCP initial speed, RCP inertia, and pressurizer initial pressure. In addition, the parameters of RELAP5 model are discharge coefficient for break, two-phase friction, junction form loss, bubbly flow drag, slug flow drag, annular-mist flow drag, dispersed flow drag, and reflood drag. The number of samples was determined by Wilks' formula to generate the 95/95 confidence level and probability. Additionally, Pearson product-moment correlation coefficients were calculated to confirm the parameters correlation size in the MSLB. The uncertainty analysis results indicate that the discharge coefficient for break, slug flow drag, and annular-mist flow drag have larger correlation size in the break flow, and slug flow drag and annular-mist flow drag have larger correlation size in the void fraction.

ABBREVIATIONS AND ACRONYMS

ACC	Accumulator
CAMP	Code Applications and Maintenance Program
DAKOTA	Design Analysis Kit for Optimization and Terascale Applications
ECCS	Emergency Core Cooling System
FSAR	Final Safety Analysis Report
HHSI	High Head Safety Injection
kg	kilogram(s)
LHSI	Low Head Safety Injection
LOCA	Loss of Coolant Accident
MPa	Megapascal(s)
MSIV	Main Steam Isolation Valves
MSLB	Main Steam Line Break
MUR	Measurement Uncertainty Recapture
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRWL	Narrow Range Water Level
NSSS	Nuclear Steam Supply System
NTHU	National Tsing Hua University
PWR	Pressurized Light Water Reactor
RCS	Reactor Coolant System
RCP	Reactor Coolant Pump
RPV	Reactor Pressure Vessel
SG	Steam Generator
SI	Safety Injection
SNAP	Symbolic Nuclear Analysis Program
WRWL	Wide Range Water Level

1 INTRODUCTION

Maanshan NPP which located on the southern coast of Taiwan is the third NPP in Taiwan and the only one PWR. The NSSS of Maanshan NPP is built by Westinghouse and has three loops, which can be divided into primary side and secondary side. The original power of Maanshan NPP is 2775 MWt. After MUR finished, the power of Maanshan NPP is 2822 MWt. There is a RCP and a SG in each loop of the primary side. Pressurizer connects to the hot leg of the second loop, which can adjust the pressure of the RCS. In addition, each loop equipped with an ACC injection system, a HHSI and a LHSI.

RELAP5, DAKOTA and SNAP codes are used in this study. RELAP5 is a thermal hydraulic analysis code and can simulate and analyze NPP transients [1]. We use the MOD3.3 Patch05 version in our studies. DAKOTA can couple with RELAP5 to perform uncertainty analysis [2]. SNAP can process the input and output of RELAP5 and DAKOTA in thermal hydraulic analysis and uncertainty analysis [3].

In our previous study [4], the RELAP5/SNAP model of Maanshan PWR NPP for MSLB transient is established. The analysis results of RELAP5 were compared with the FSAR data. It indicates that the RELAP5/SNAP model has the ability to predict the MSLB transient. In this thermal hydraulic analysis, the values of parameters are constant which causes the only one result for RELAP5 calculation as Figure 1-1 [5]. However, the values of parameters have the variation in uncertainty analysis. This causes the different result for RELAP5 calculation as Figure 1-2 [5].

Therefore, to understand the variation effects of parameters in the RELAP5 calculation for MSLB transient, the uncertainty analysis by using the RELAP5/SNAP model and DAKOTA code was performed in this study. Total 21 parameters which include 13 parameters of NPP and 8 parameters of RELAP5 model are evaluated in this uncertainty analysis. The 13 parameters of NPP parameters are initial power, accumulator volume, accumulator temperature, accumulator pressure, accumulator boron concentration, injection water temperature, high pressure injection flow, low pressure injection flow, rod material thermal conductivity, rod material heat capacity, RCP initial speed, RCP inertia, and pressurizer initial pressure. The 8 parameters of RELAP5 model are discharge coefficient for break, two-phase friction, junction form loss, bubbly flow drag, slug flow drag, annular-mist flow drag, dispersed flow drag, and reflood drag. The distributions and ranges of the parameters are from the references [6-8]. In addition, the number of samples was determined by Wilks' formula [9-10] to generate the 95/95 confidence level and probability. Finally, to confirm the parameters correlation size in the MSLB transient, Pearson product-moment correlation coefficients [11] were calculated.

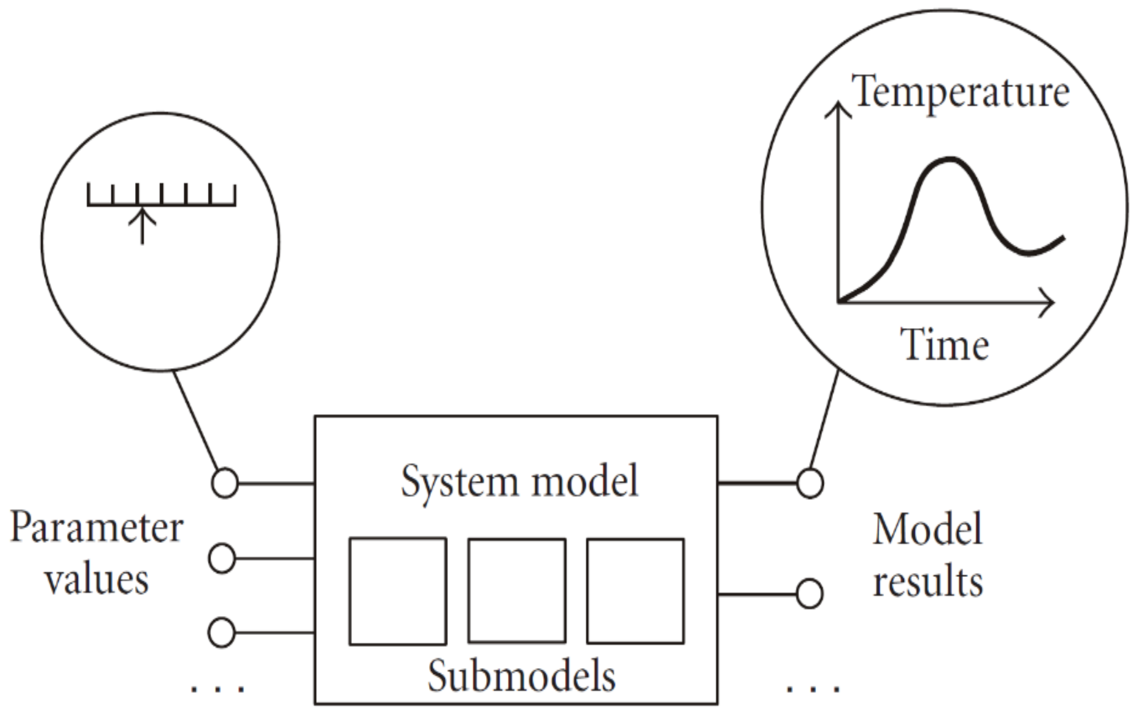

Figure 1-1 Thermal Hydraulic Analysis Schematic Diagram [5]

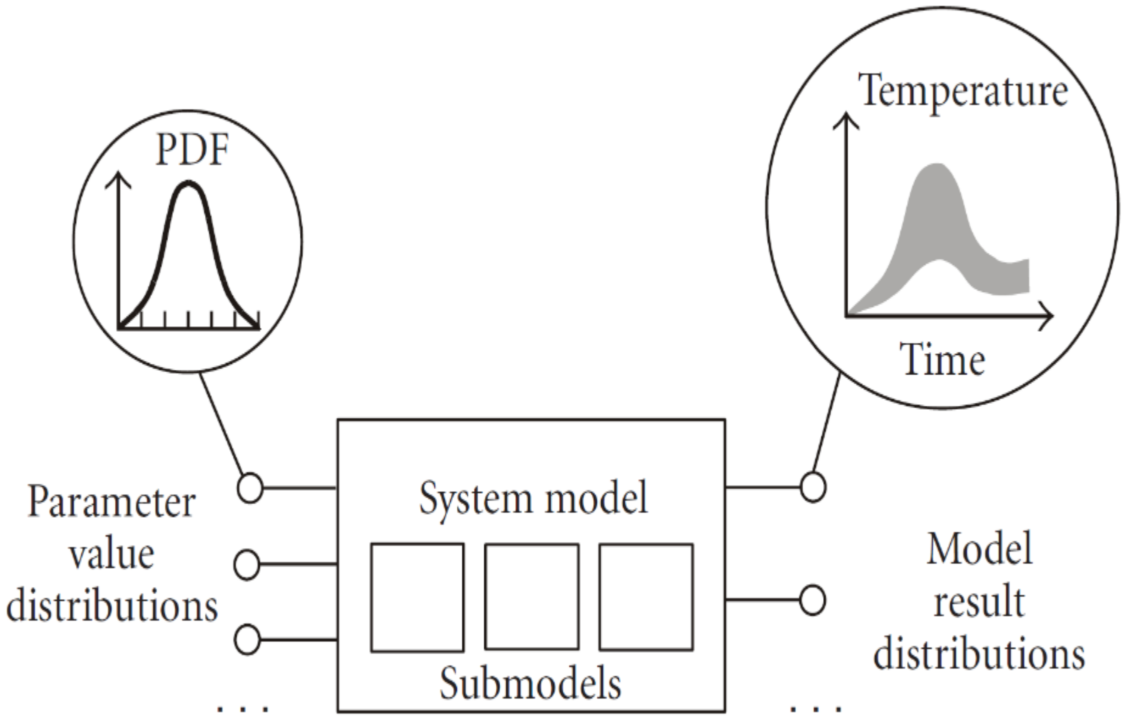

Figure 1-2 Uncertainty Analysis Schematic Diagram [5]

2 MODEL AND METHODOLOGY DESCRIPTION

2.1 RELAP5/SNAP Model Description

Figure 2-1 shows the RELAP5/SNAP model of Maanshan NPP. This model was established in our previous study [4]. This model can be divided into primary side loop, secondary side loop, and ECCS and established by using Pipe, Valve, Branch, Pump and Single Volume, and Time Dependent Junction components. There are three loops in this model. Every loop has a RCP and SG. A pressurizer which can adjust the pressure of RCS with the spray valves connects to the hot leg in the second loop. Some Branch components and heat structure components were used to simulate the reactor vessel and fuels channels. Table 2-1 presents the initial conditions of the model for MSLB transient. In addition, the sequence of MSLB transient is shown in Table 2-2.

2.2 Analysis Methodology Description

Figure 2-2 shows the analysis methodology of Maanshan NPP MSLB transient. The thermal hydraulic analysis was performed in our previous study [4] and the flow chart of analysis process is shown in Figure 2-2 green region. The main steps are as follows:

- The model is established.
- To perform the steady-state analysis and to confirm the analysis results of steady-state.
- After the steady-state analysis results is consistent with the FSAR data, the transient analysis is performed.
- To compare the transient analysis results with the FSAR data.

The compared results indicate that the RELAP5/SNAP model has a respectable accuracy [4]. Hence, this RELAP5/SNAP model is used to perform an uncertainty analysis in this study and the flow chart of analysis process is shown in Figure 2-2 red region. The main steps are as follows:

- To identify the parameters which are evaluated.
- To identify the distributions and ranges of parameters.
- To generate the sample number of code runs by using Wilks' formula.
- To input the above data in the DAKOTA code and the screen of uncertainty configuration is shown in Figure 2-3.
- To perform the uncertainty analysis by using DAKOTA and RELAP5/SNAP model.

Table 2-3 lists the distributions and ranges of parameters. Total 21 parameters which include 13 parameters of NPP and 8 parameters of RELAP5/SNAP model are evaluated in the uncertainty analysis. Table 2-4 presents the required minimum number of RELAP5 runs which is dependent of the values of confidence level and probability. Wilks' formula [9-10] was employed to determinate the minimum number of runs and as follows:

$$1-\alpha^n \geqq \beta \qquad \text{for one-side tolerance limit}$$

$$1-\alpha^n-n(1-\alpha)\alpha^{n-1} \geqq \beta \qquad \text{for two-side tolerance limit}$$

Where α is probability, β is the confidence level, and n denotes the number of code runs.

Hence, the required minimum number of RELAP5 runs for one-side tolerance limit is 59 to generate the 95/95 confidence level and probability in this study. Finally, to confirm the parameters correlation size in the MSLB transient, Pearson product-moment correlation coefficient [11] was calculated by using the analysis results and the equation is as follows:

$$\mathbf{r} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(y_i-\bar{y})^2}}$$

Where r is the Pearson product-moment correlation coefficient, n is the number of samples, and x and y denote two quantities.

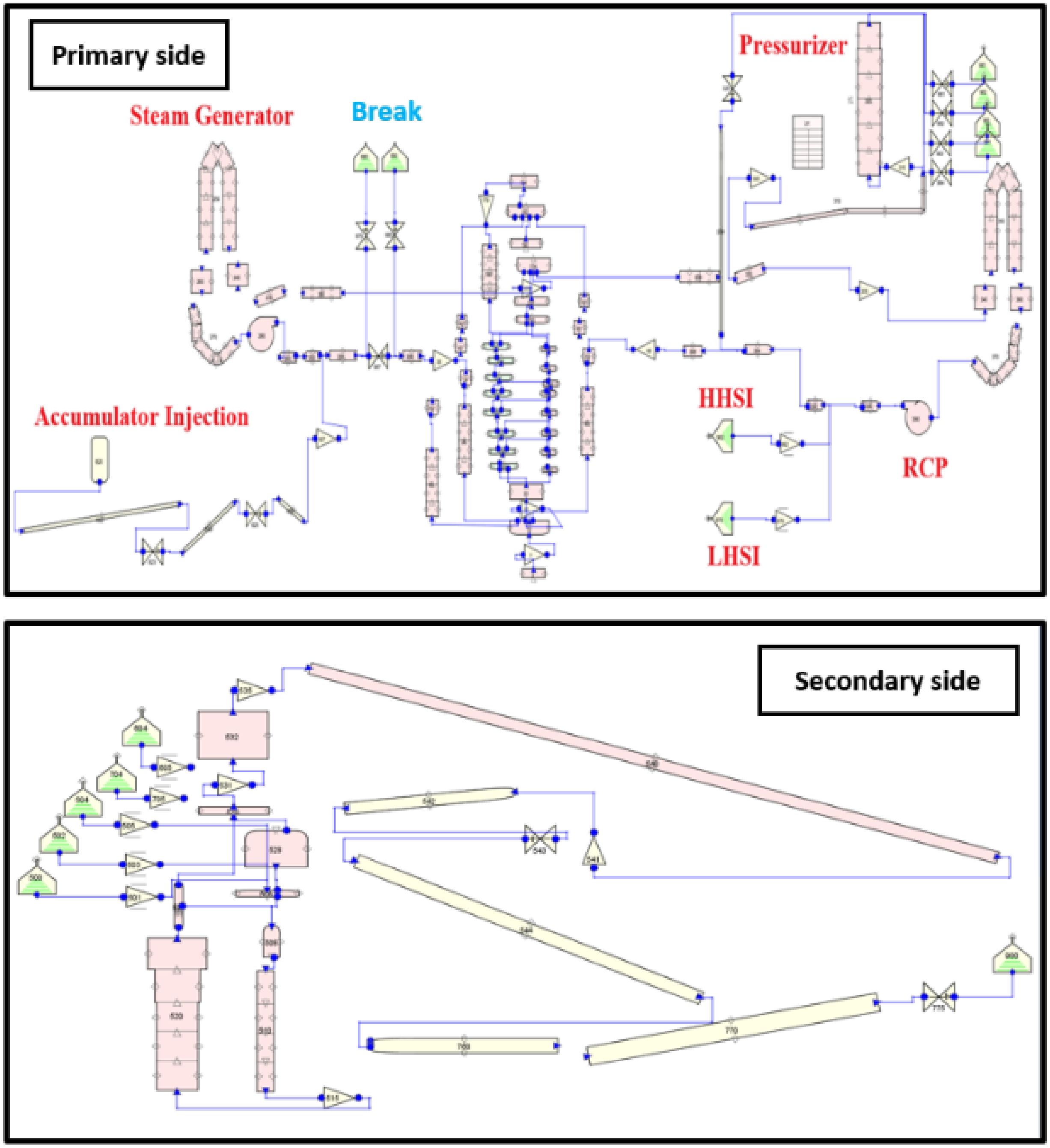

Figure 2-1 The RELAP5/SNAP Model of Maanshan NPP

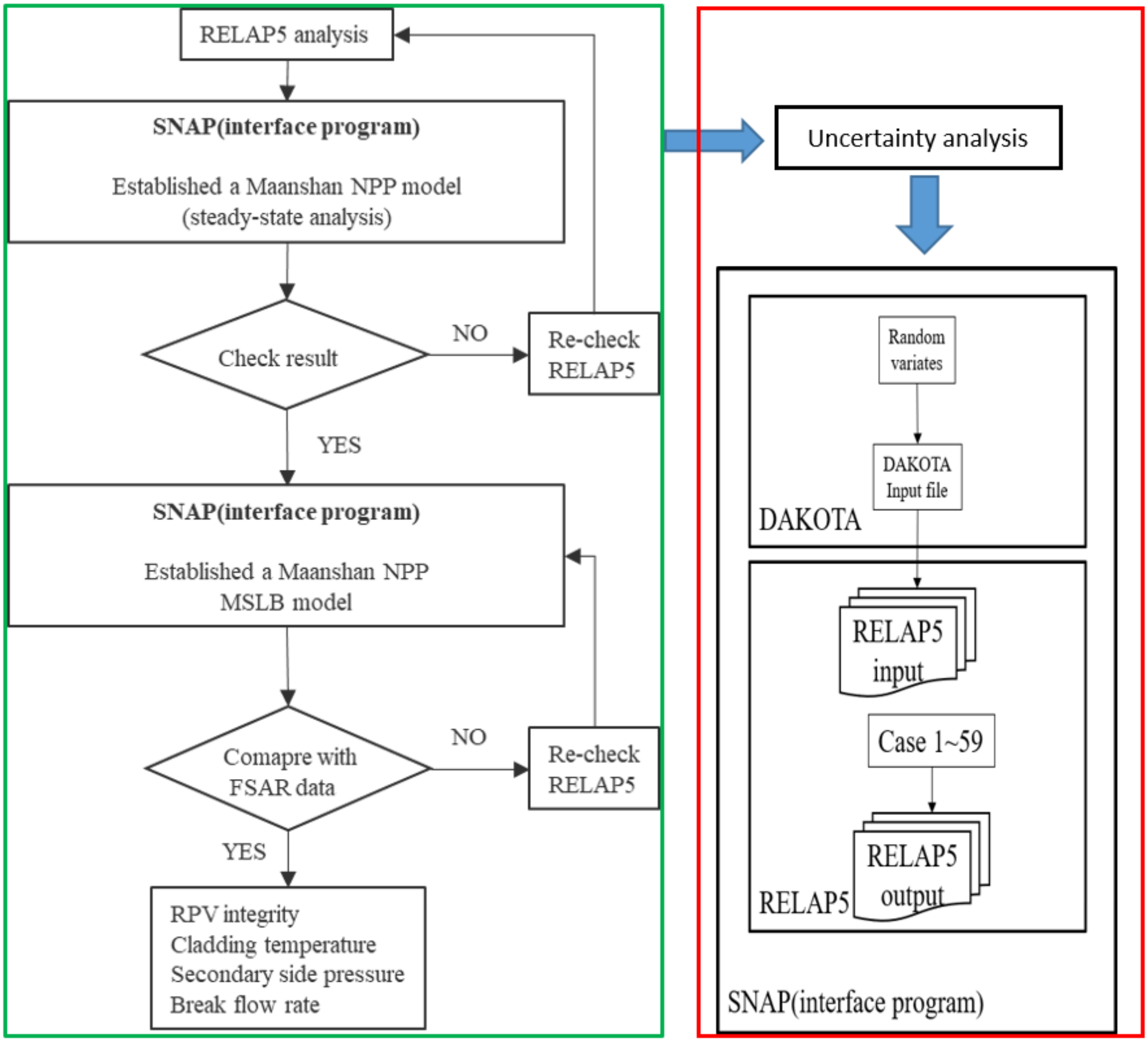

Figure 2-2 The Flow Chart of Analysis Methodology

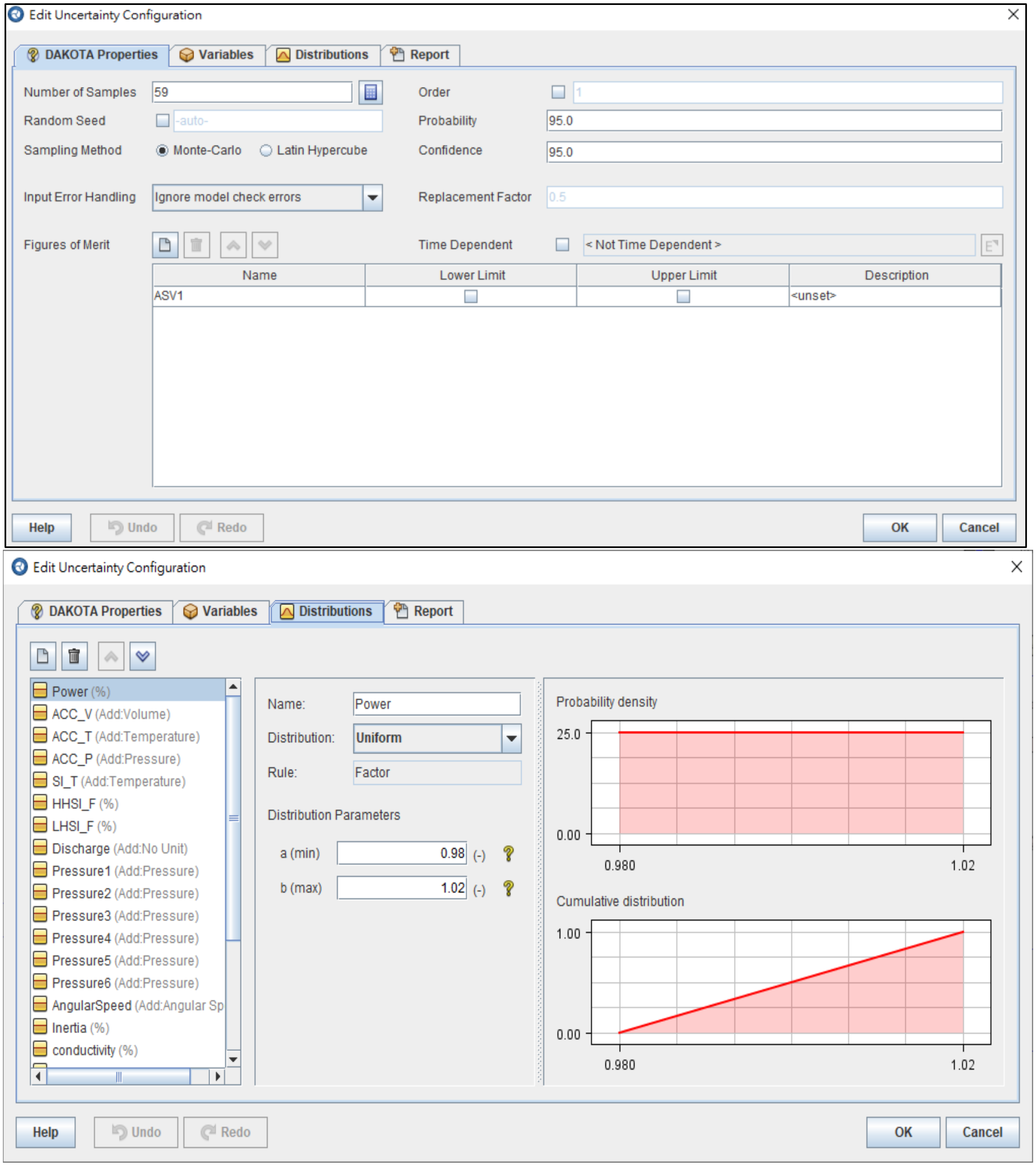

Figure 2-3 Uncertainty Configuration Interface

Table 2-1 Initial Conditions of Maanshan NPP

Parameters	RELAP5
Power (MW_t)	2900
RCS temperature (K)	582.97
Primary side pressure (MPa)	15.862
Secondary side pressure (MPa)	6.845
Scram setpoint (MPa)	12.8
SI signal setpoint (MPa)	11.8
ECCS electric delay time (s)	27
ACC pressure (MPa)	4.24
Auxiliary feedwater flow rate (kg/s)	7.965
Break size (m^2)	0.436

Table 2-2 Sequence of Events in MSLB

Events	Time (sec)
Steady-state	0
Pipe break	400
Reactor scram	418
SI signal	427
Auxiliary feedwater	446
HHSI	447
Accumulator injection	541
End of Accumulator injection	1219
Transient end	2000

Table 2-3 The Key Parameters of Uncertainty Analysis [6-8]

	Parameters	Distribution	Range
The parameters of NPP	Initial power	Uniform	-1.02% ~ 1.02%
	Accumulator volume	Uniform	985 ~ 1015
	Accumulator temperature	Uniform	100 ~ 150
	Accumulator pressure	Uniform	632 ~ 680
	Accumulator boron concentration	Uniform	2300 ~ 2500
	Injection water temperature	Uniform	70 ~ 130
	High pressure injection flow	Uniform	-5% ~ 5%
	Low pressure injection flow	Uniform	-5% ~ 5%
	Rod material thermal conductivity	Normal	-20% ~ 20%
	Rod material heat capacity	Normal	-10% ~ 10%
	RCP initial speed	Uniform	1180 ~ 1190
	RCP inertia	Uniform	-5% ~ 5%
	Pressurizer Initial pressure	Uniform	2200 ~ 2300
The parameters of RELAP5/SNAP model	Discharge coefficient for break	Uniform	-20% ~ 20%
	Two-phase friction	Uniform	0.5 ~ 1.5
	Junction form loss	Lognormal	ξ = 0.1 (0.05 ~ 0.2)
	Bubbly flow drag	Uniform	0.5 ~ 1.5
	Slug flow drag	Uniform	0.5 ~ 1.5
	Annular-mist flow drag	Uniform	0.5 ~ 1.5
	Dispersed flow drag	Uniform	0.5 ~ 1.5
	Reflood drag	Uniform	0.5 ~ 1.5

Table 2-4 Minimum Number of Code Runs for One-Side and Two-Side Tolerance Limits [9-10]

	One-side tolerance limits			Two-side tolerance limits		
β \ α	0.90	0.95	0.99	0.90	0.95	0.99
0.90	22	45	230	38	77	388
0.95	29	59	299	46	93	473
0.99	44	90	459	64	130	662

3 UNCERTAINTY ANALYSIS RESULTS

Figure 3-1~3-11 are the analysis results of uncertainty analysis in this study. In general, the safety analysis of transients focus on the PCT criteria which is 2200 ºF in 10 CFR 50.46. Figure 3-1 shows the PCT results. It indicates that the PCT results are lower than the criteria of 2200 ºF. Additionally, the variation of PCT results are more obvious after 600 sec. That is because HHSI injects water to the core in this duration (see Figure 3-2). This causes the variation of core water level (see Figure 3-3) which affects the variation of PCT.

Figure 3-4 and 3-5 present the results of primary side and secondary side pressure. By compared the results of primary side and secondary side pressure, it indicates that the variation of secondary side pressure results are more obvious in 600~1000 sec. This may be caused by the SG heat transfer coefficient. Figure 3-6 shows that the SG heat transfer coefficient has more variation in 600~1000 sec. Figure 3-7 presents the void fraction results which have larger variation than other parameters. Because the void fraction is also related to the water level, it also can see the similar symptom in the WRWL and NRWL (see Figure 3-8 and 3-9). In the analysis of MSLB transient, one of important parameters is the break mass flow rate. Figure 3-10 shows the results of break mass flow rate. It indicates that the variation of break mass flow rate results are more obvious in 600~1000 sec and after 3000 sec.

To confirm the correlation size of parameters in the void fraction and break mass flow rate, Pearson product-moment correlation coefficients were calculated. Figure 3-11 shows the results of Pearson product-moment correlation coefficient for break mass flow rate. It indicates that the maximum correlation size is the discharge coefficient. In addition, the slug flow drag and annular-mist flow drag also have the larger correlation size in the calculation of break mass flow rate. Therefore, the discharge coefficient, slug flow drag, and annular-mist flow drag may dominate the break mass flow rate. Figure 3-12 presents the results of Pearson product-moment correlation coefficient for void fraction. It indicates that the maximum correlation size is the slug flow drag. The second correlation size is the annular-mist flow drag. This indicates that slug flow drag and annular-mist flow drag may dominate the calculation of void fraction. In addition, it also can find that the parameters of RELAP5/SNAP model have the larger effects than the parameters of NPP in the void fraction and break mass flow rate.

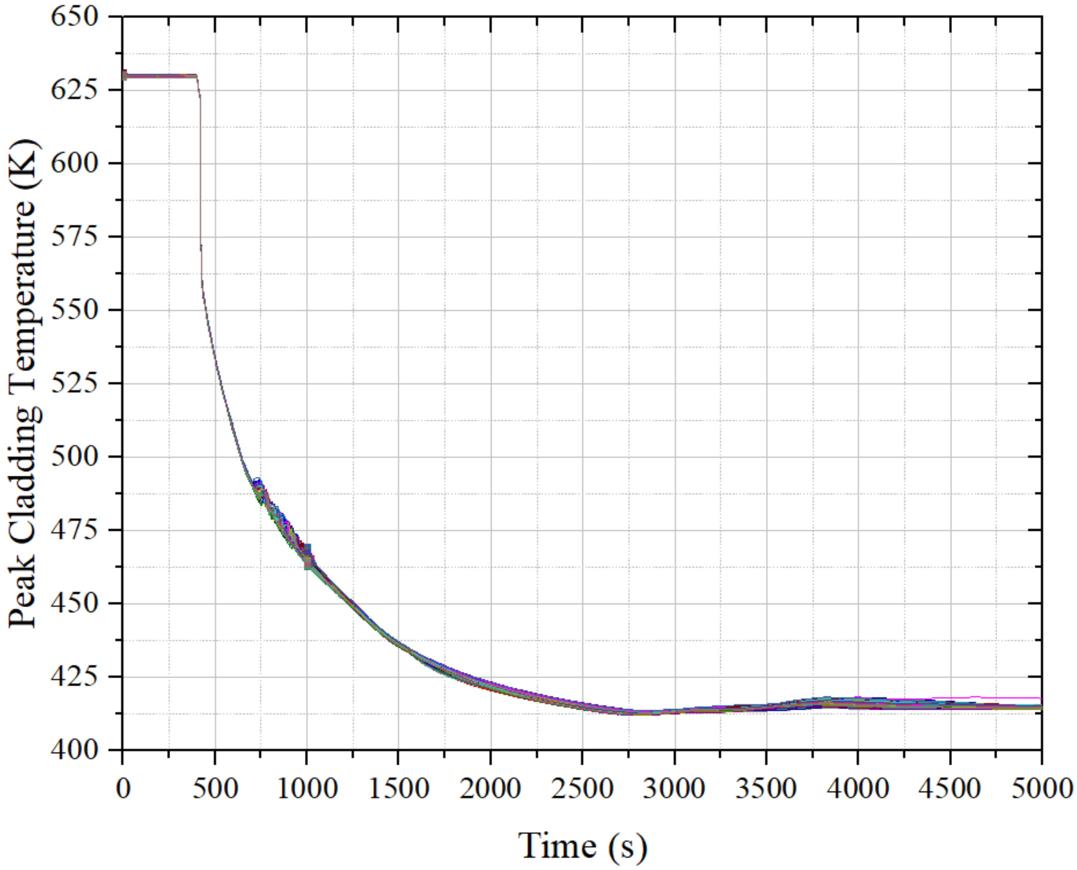

Figure 3-1 The Uncertainty Analysis Results of PCT

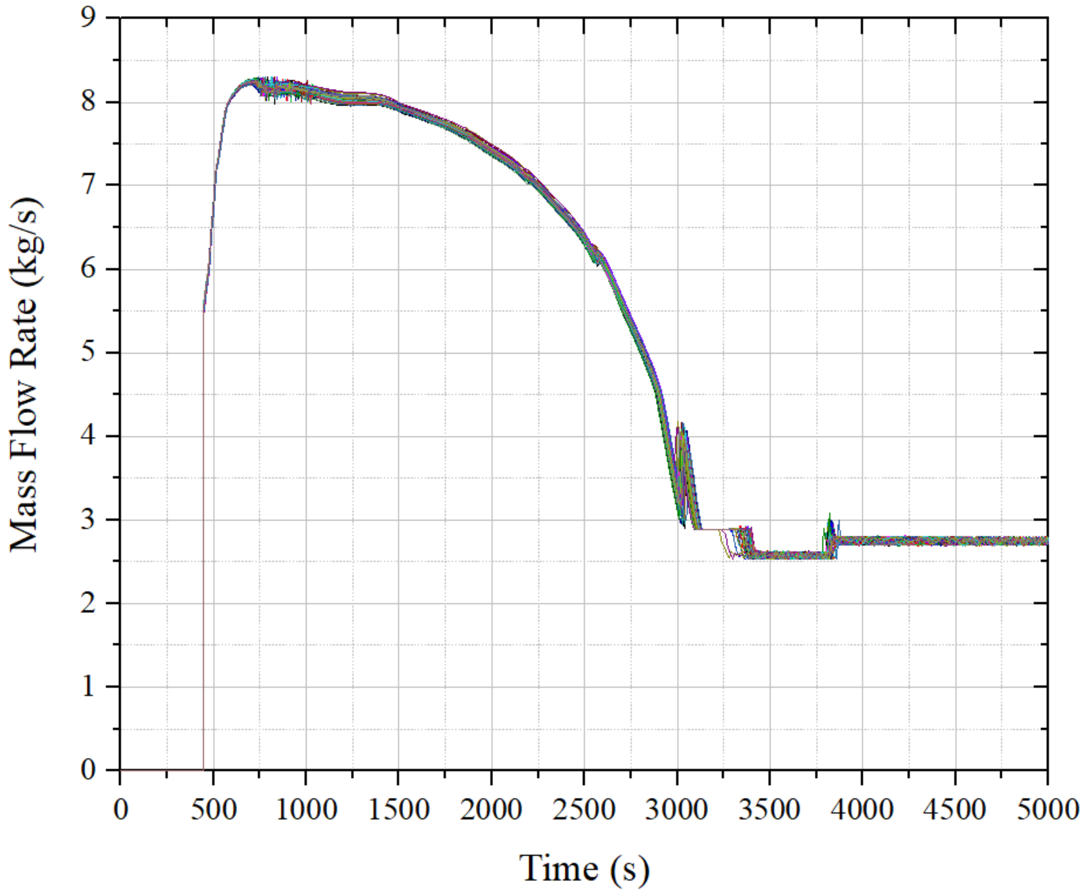

Figure 3-2 The Uncertainty Analysis Results of HHSI Mass Flow Rate

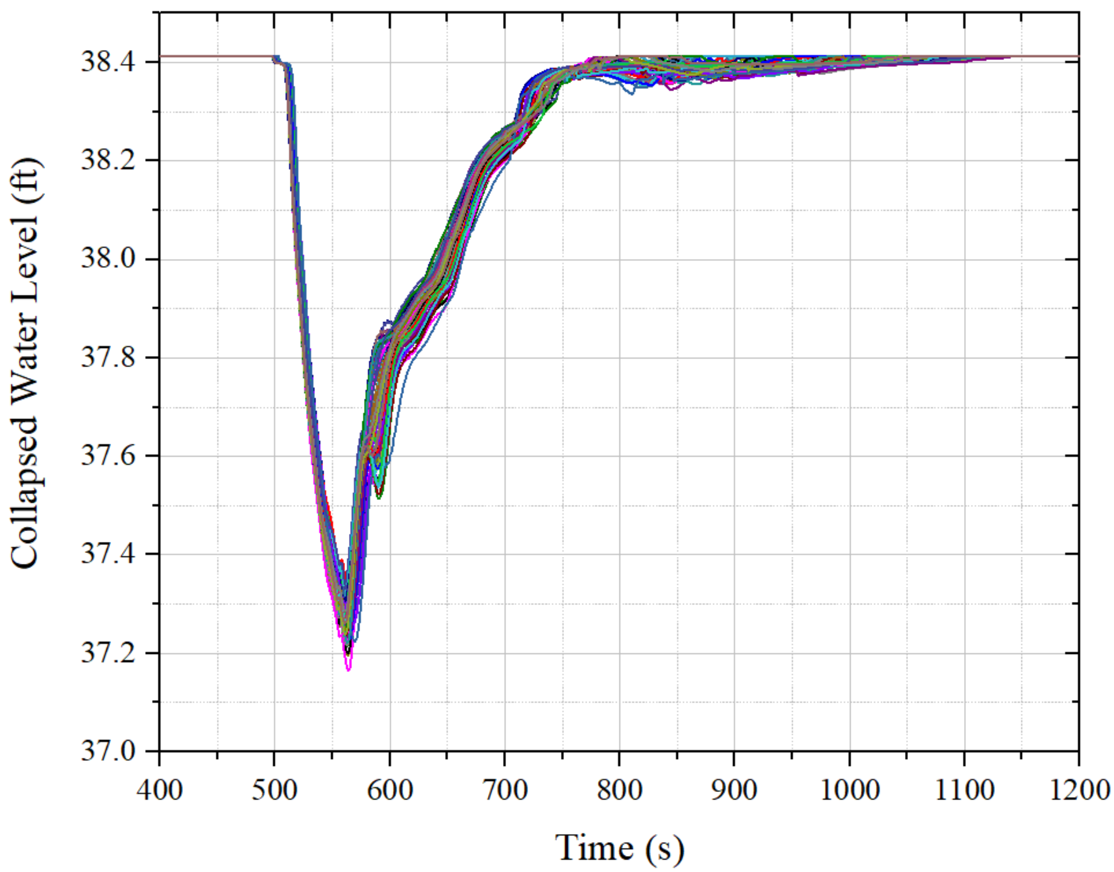

Figure 3-3 The Uncertainty Analysis Results of Core Collapsed Water Level

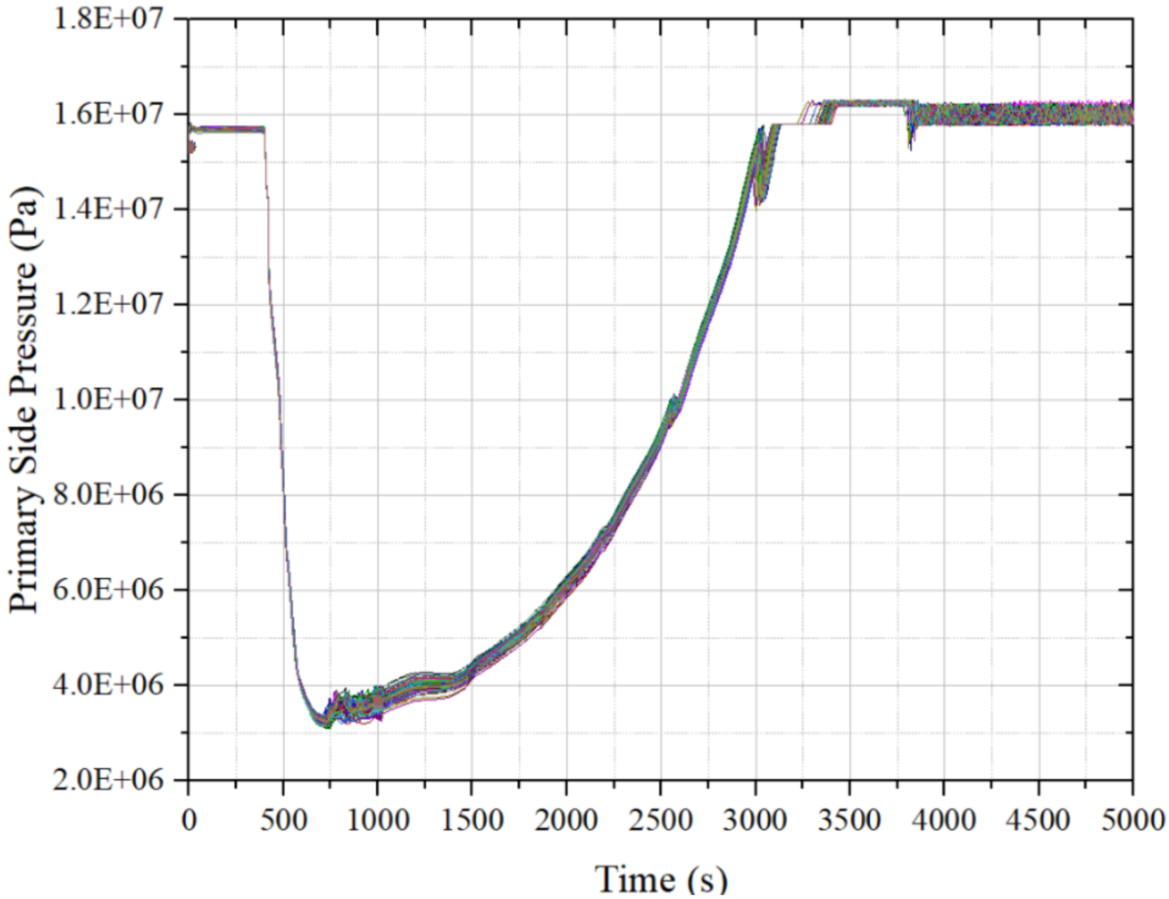

Figure 3-4 The Uncertainty Analysis Results of Primary Side Pressure

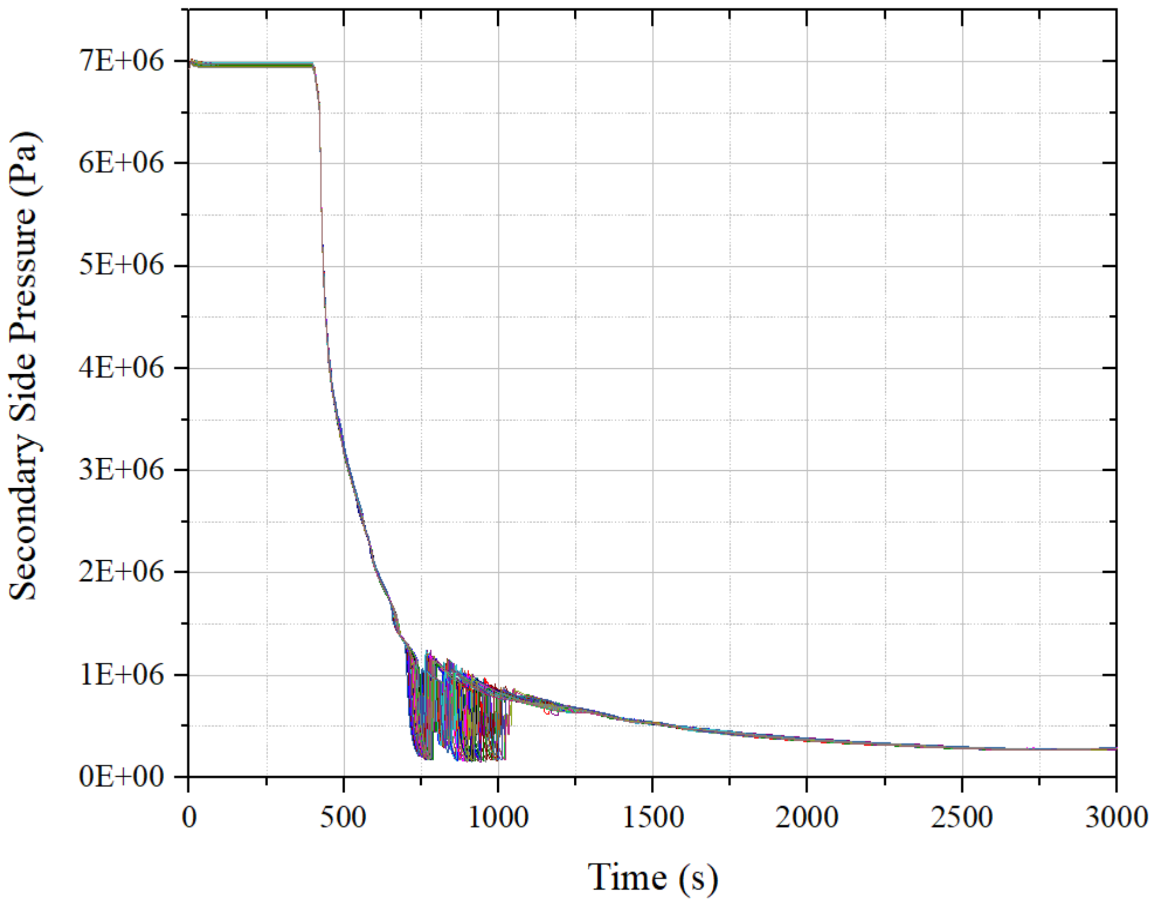

Figure 3-5 The Uncertainty Analysis Results of Secondary Side Pressure

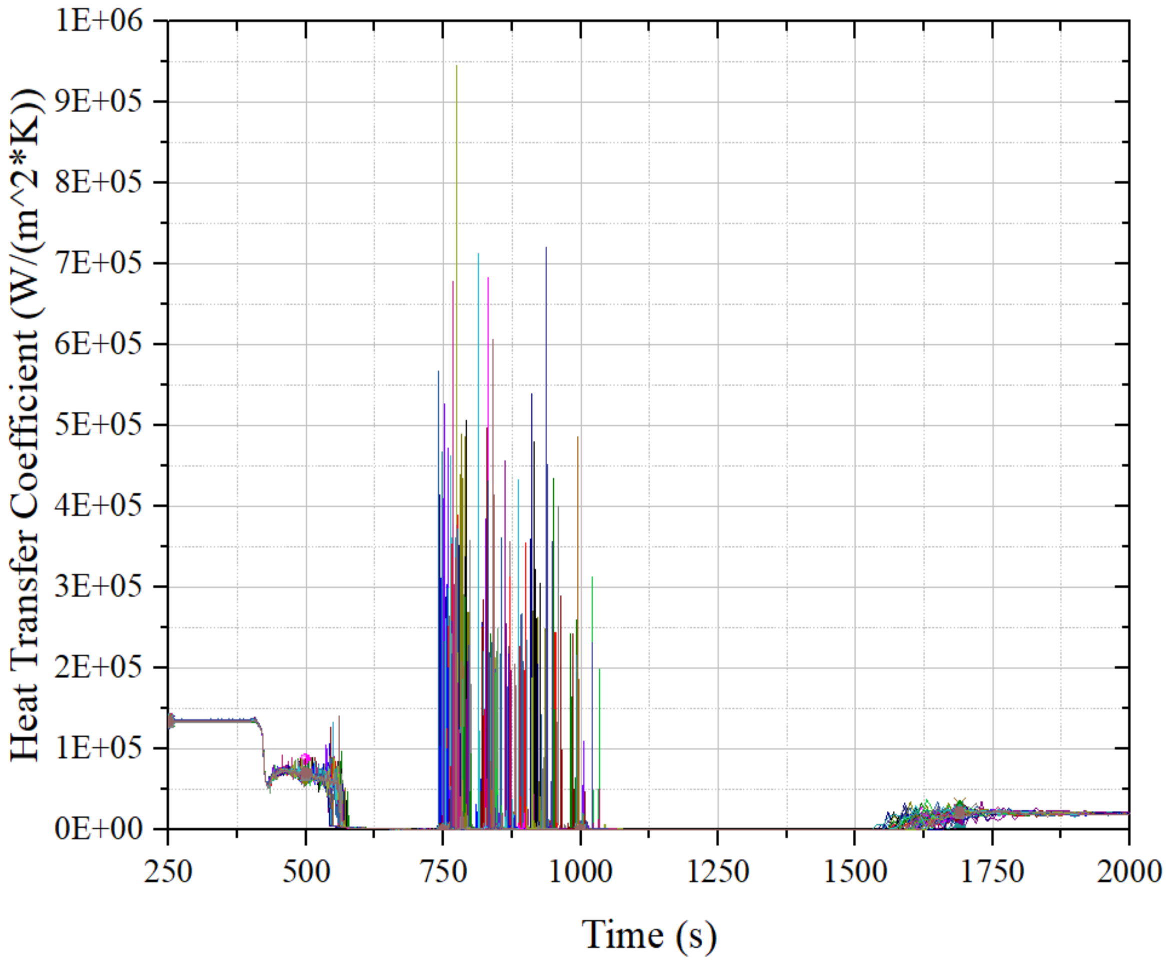

Figure 3-6 The Uncertainty Analysis Results of SG Heat Transfer Coefficient

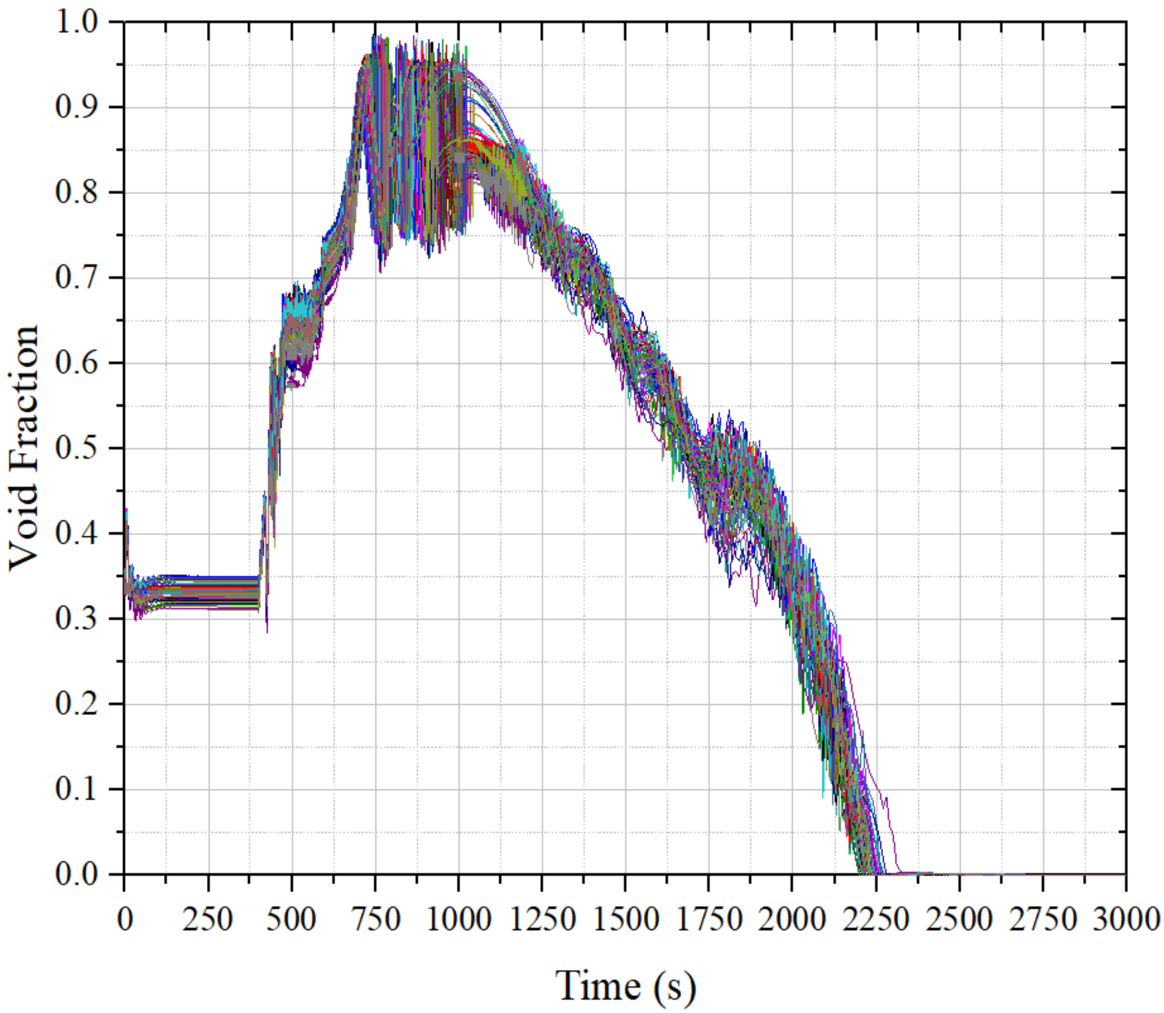

Figure 3-7 The Uncertainty Analysis Results of SG Void Fraction

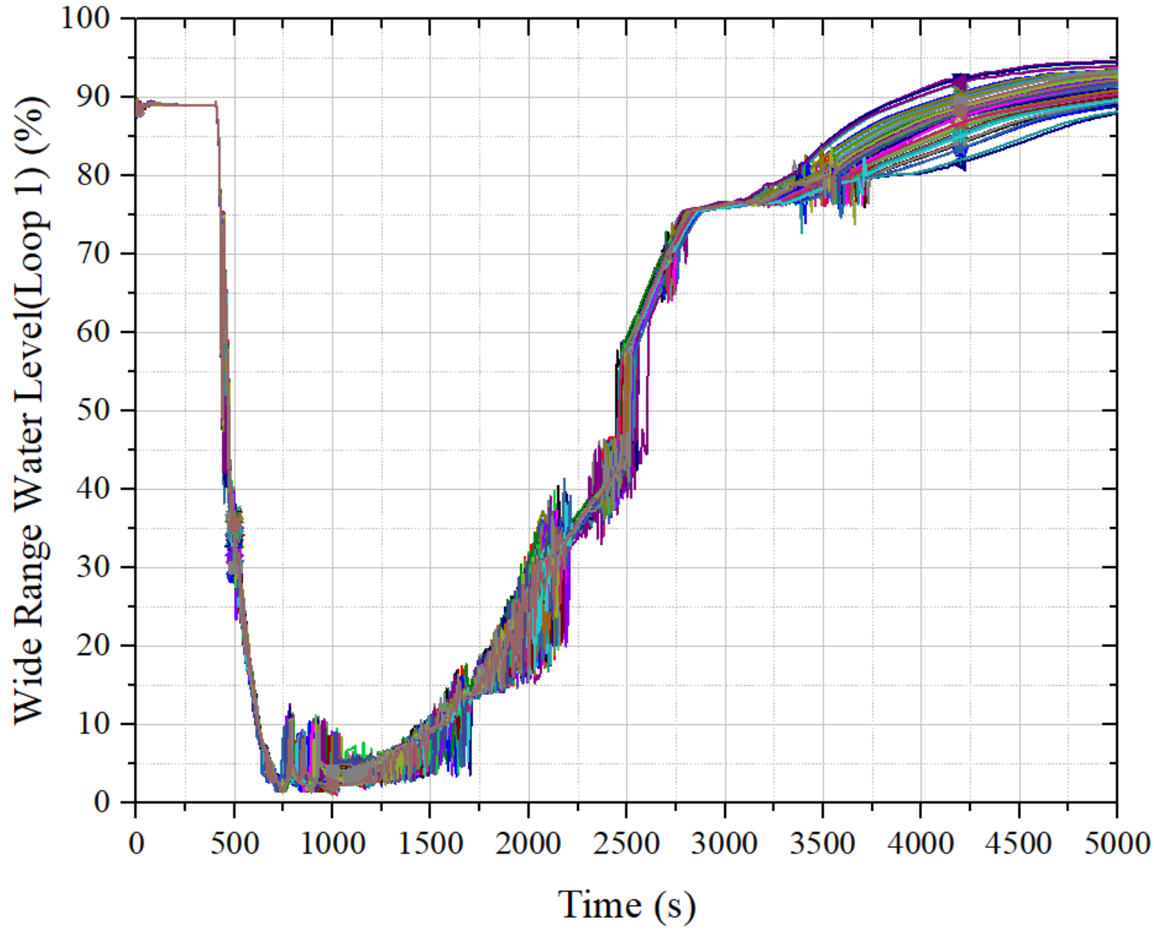

Figure 3-8 The Uncertainty Analysis Results of SG WRWL

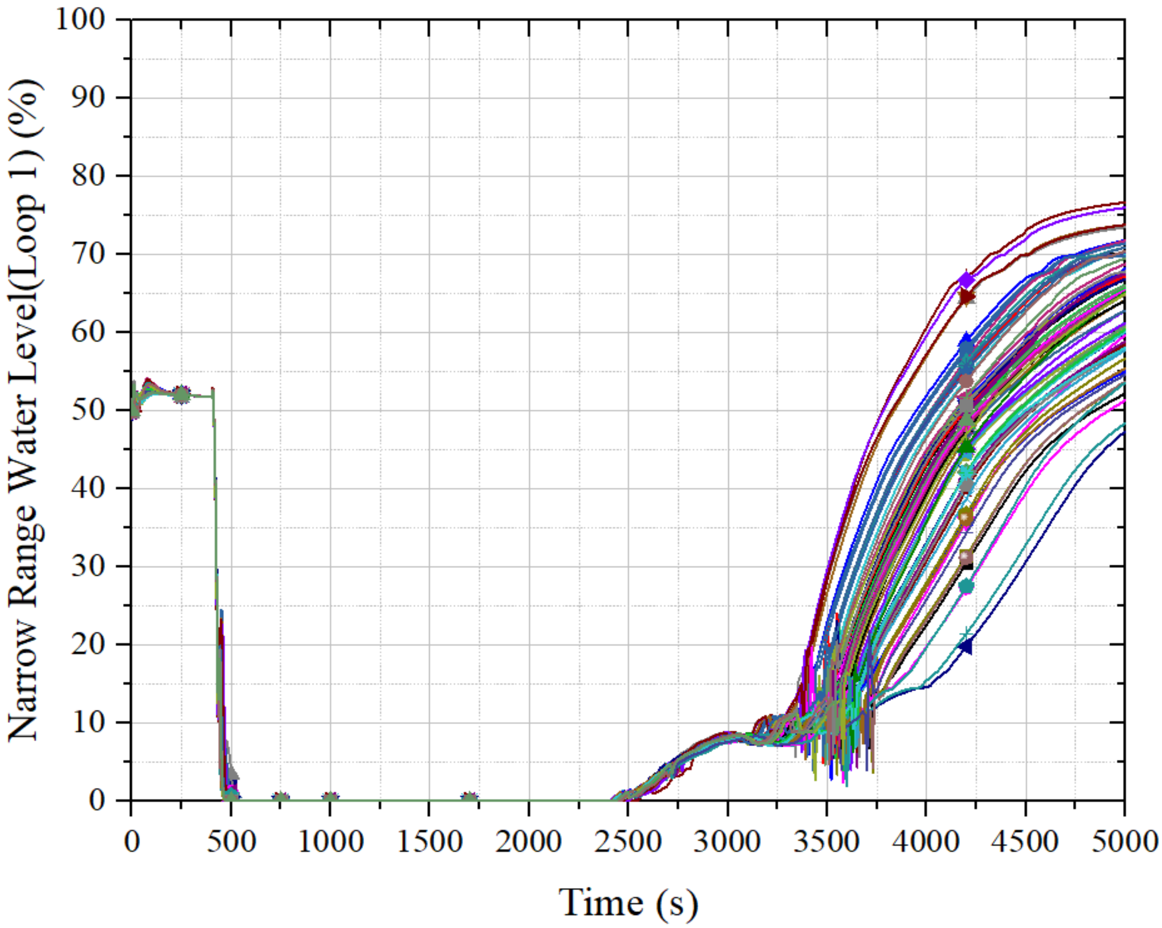

Figure 3-9 The Uncertainty Analysis Results of SG NRWL

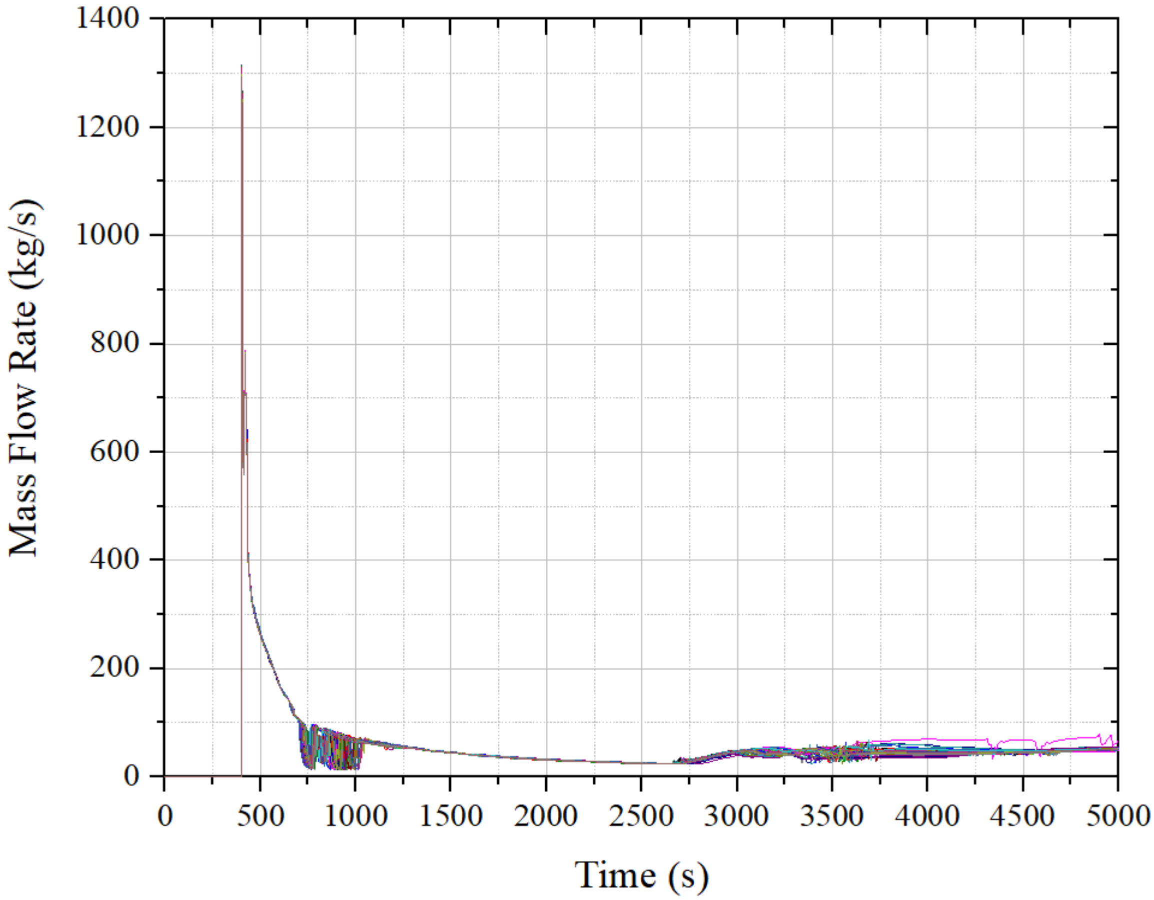

Figure 3-10 The Uncertainty Analysis Results of Break Mass Flow Rate

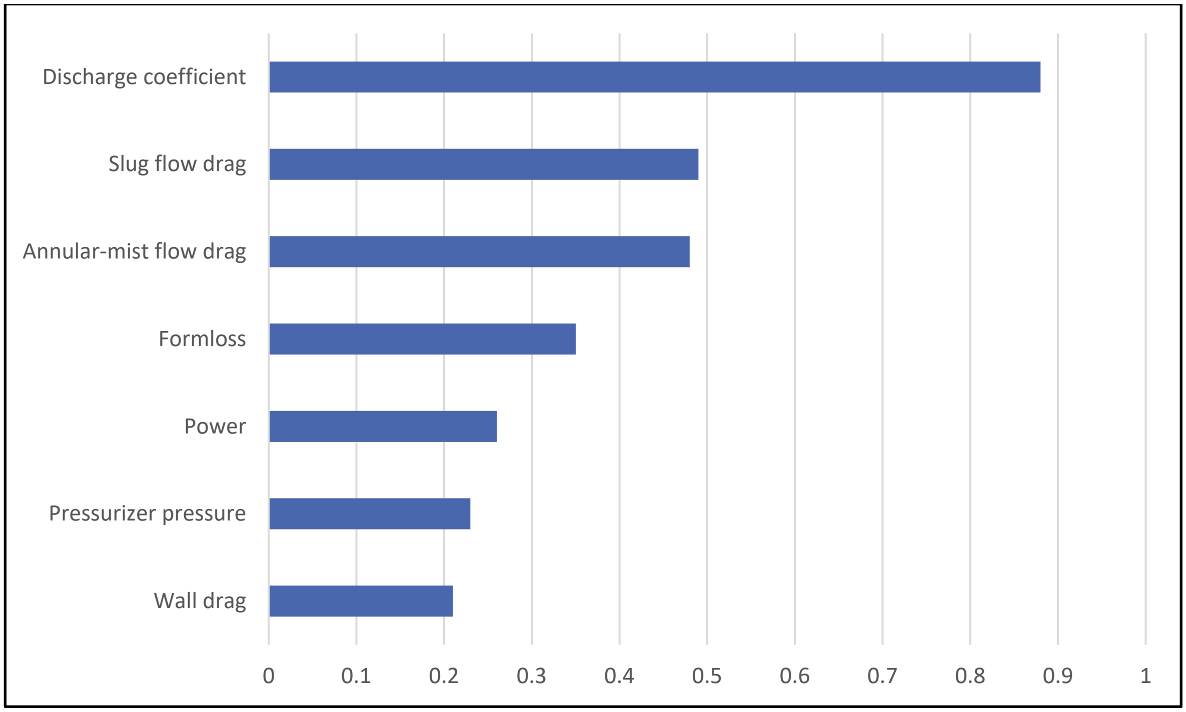

Figure 3-11 The Parameters Correlation Size in Break Mass Flow Rate

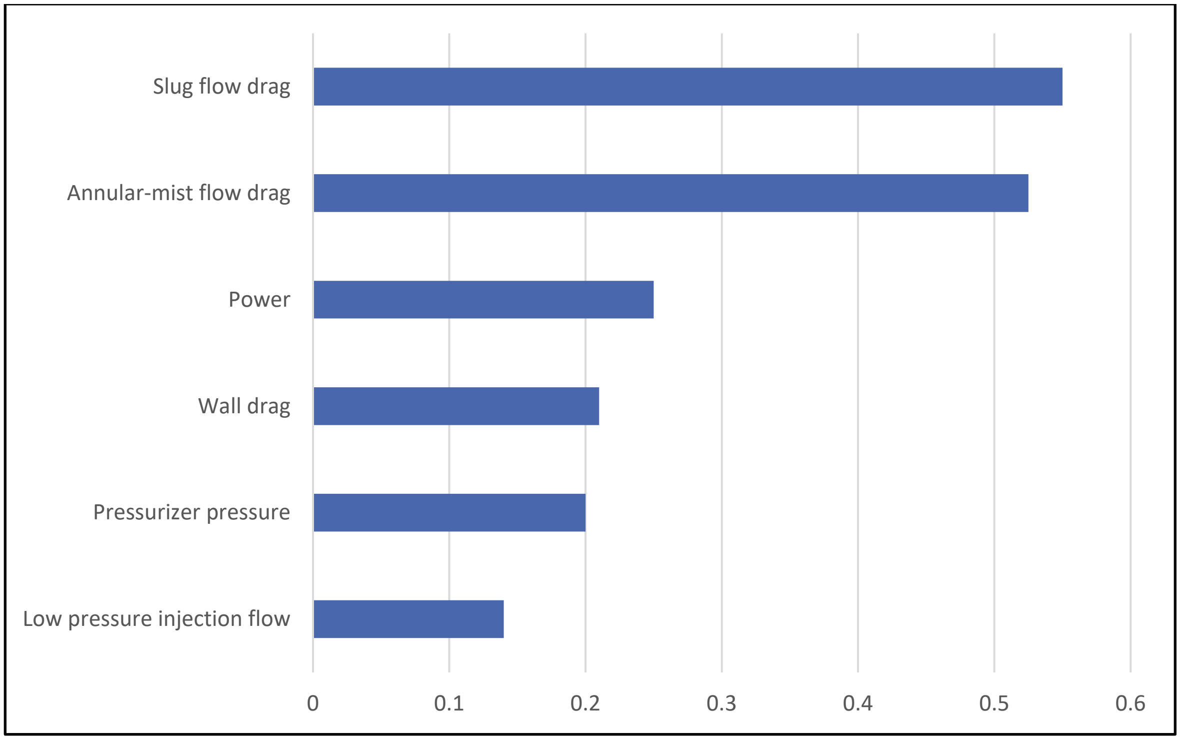

Figure 3-12 The Parameters Correlation Size in Void Fraction

4 CONCLUSION

The RELAP5/SNAP model of Maanshan PWR was used to perform a thermal hydraulic analysis for MSLB in our previous study [4]. The analysis results are similar to the FSAR data [6]. This indicates that the RELAP5/SNAP model has a respectable accuracy. Therefore, to understand the parameters effects for MSLB, an uncertainty analysis of Maanshan PWR MSLB by using RELAP5/SNAP model and DAKOTA code is performed in this study. This uncertainty analysis evaluates total 21 parameters which include initial power, accumulator volume, injection water temperature, injection flow, rod material thermal conductivity, discharge coefficient for break, slug flow drag, etc. According to the results of uncertainty analysis, in the calculation of break flow, discharge coefficient for break, slug flow drag, and annular-mist flow drag have larger effect. However, in the calculation of void fraction, slug flow drag and annular-mist flow drag have larger effect.

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11. ABSTRACT (200 words or less)

In our previous study, the RELAP5/SNAP model of Maanshan PWR nuclear power plant is established. This model was used to perform the analysis of Main Steam Line break (MSLB) inside-containment transient. The analysis results of RELAP5/SNAP are consistent with the FSAR data. In this study, the main purpose is to perform an uncertainty analysis for Maanshan MSLB by using RELAP5/SNAP model and DAKOTA code. Total 21 parameters which include initial power, accumulator volume, injection water temperature, injection flow, rod material thermal conductivity, discharge coefficient for break, slug flow drag, etc. are evaluated in this analysis. According to the uncertainty analysis results, discharge coefficient for break, slug flow drag, and annular-mist flow drag have larger effect in the calculation of break flow, and slug flow drag and annular-mist flow drag have larger effect in the calculation of void fraction.

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