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Uncertainty Analysis of Thermal-Hydraulic in Simulation of AP1000 Steam Generator

Xiaoyu Zhang, Zhaofei Tian, Gangping Shang

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory: Nantong Street/Number 145, Harbin, China, 150001, einshane@163.com

Abstract - *Uncertainty quantification and sensitivity analysis is an important part of best-estimate safety analysis for nuclear power plants. In this paper, the AP1000 steam generator (SG) is used as the object of research, and the SG water level is chosen as the target parameter, and the sampling statistical method is used to carry out the uncertainty analysis of thermal-hydraulic in SG. Through the uncertainty quantification, SG thermal-hydraulic calculation uncertainty input parameters and their variation range are determined, and the uncertainty range of SG water level is obtained. Sensitivity analysis is used to quantify the impact of input parameters on the target parameter. The results show that SG water level meets the safety requirements when AP1000 is in full power operation, and the primary inlet coolant temperature contributes the most to the uncertainty of SG water level.*

I. INTRODUCTION

Uncertainty is a reasonable representation of the distribution of target parameters in the form of confidence intervals or standard deviations with a certain confidence level, which gives more information than safety analysis using conservative assumptions. In 1988, the US Nuclear Regulatory Commission (NRC) proposed to allow the use of best-estimate method instead of conservative model method, at the same time, the regulatory requirements for uncertainty assessment must be included in the best estimates [1]. The International Atomic Energy Agency (IAEA) has identified three major sources of uncertainty for nuclear thermal engineering calculations: uncertainty in procedures or models, uncertainty in simulation representations and manufacturing uncertainty [2], where the uncertainty of the input parameters of procedures is the research of this paper.

In this paper, the AP1000 steam generator is used as the object of research. The input parameters with water level as the target parameter are determined and randomly sampled. Based on RELAP5, the steady state operation condition under rated power is modeled. Subsequently, the combined samples are input into RELAP5 program to get the simulated target parameter results. And the results are statistically calculated to obtain the uncertain values of the target parameter, such as mean and variance. At the same time, sensitivity analysis is conducted to analyze the correlation direction and sensitivity between the input parameters and the target parameter. Finally, the mathematical expression of the input parameters and the target parameter is determined by regression analysis.

II. DESCRIPTION OF THE ACTUAL WORK

1. RELAP5 SG Simulation Model

In this paper, the AP1000 SG is simulated by RELAP5. RELAP5 is an advanced thermal-hydraulic calculation program developed by the Idaho National Engineering Laboratory with the assistance of the US Nuclear Regulatory (NRC) for engineering review. It is mainly used to simulate pressurized water reactor accident process. One-dimensional transient, two-fluid, six-equation hydrodynamics and one-dimensional heat conduction and point reactor dynamics models are used in RELAP5 [3]. Nowadays, RELAP5 is widely used in the field of nuclear industry. In this paper, the model component division of the AP1000 SG is shown in Fig. 1. The model component description is shown in Table I. The operating parameter values of the AP1000 SG are listed in Table II.

2. Choices Of The Target Parameter And Input Parameters

The uncertainty analysis method adopted in this paper is based on the statistical uncertainty and sensitivity analysis method. The analysis flow of this method is shown in Fig. 2.

First, the key target parameter needed to be selected to reflect the uncertainty of the SG. For a SG, there will be a certain range of fluctuations in the water level. If the water level is too high, the steam separator will be drown and the steam wetness will increase; If the water level is too low, heat transfer tubes will be exposed, which will aggravate the corrosion of heat transfer tubes and deteriorate the heat transfer efficiency. Therefore, the SG water level is chosen as the key target parameter.

The input parameters should be judiciously chosen based on those that are expected to have the greatest epistemic uncertainty or the most influence on the target parameter for sensitivity analysis [4]. The direct factors affecting the water level uncertainty are the heat transfer between the primary side and the secondary side in SG and the feed water flow. The parameters in Table III have direct effects on these processes, and they also have practical input uncertainties, so they could be used as input parameters. (The flow rates chosen in Table III are best-estimate flow rates.) The third column in Table III is the expected range of each parameter.

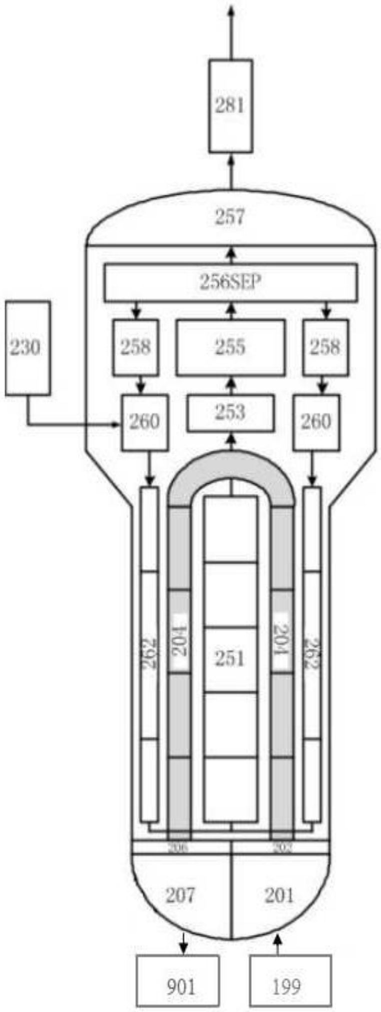

Fig. 1. The AP1000 SG RELAP5 simulation model.

Table I. AP1000 SG RELAP5 Component Description

Number	Type	Description
201	BRANCH	Primary coolant inlet chamber
207	BRANCH	Primary coolant outlet chamber
204	PIPE	U-shaped heat transfer tubes
262	PIPE	Feed water downward section
252	PIPE	Heated upward section
253	SNGLVOL	The lower part of unheated upward section
255	SNGLVOL	The upper part of unheated upward section
258	SNGLVOL	The upper part of downward section
260	BRANCH	The lower part of downward section
256	SEPAARATE	Steam-water separator
257	SNGLVOL	SG upper head
281	TMDPVOL	Steam outlet boundary
230	TMDPVOL	Feed water inlet boundary
199	TMDPVOL	Primary coolant inlet boundary
901	TMDPVOL	Primary coolant outlet boundary

Table II. AP1000 SG Operating Parameters Value

Parameter	Value
Primary inlet temperature (K)	594.25
Primary part pressure (MPa)	15.5
Feed water temperature (K)	499.85
Secondary part pressure (MPa)	5.76
Primary inlet mass flow rate (kg/s)	7592.8
Secondary inlet mass flow rate (kg/s)	944.35

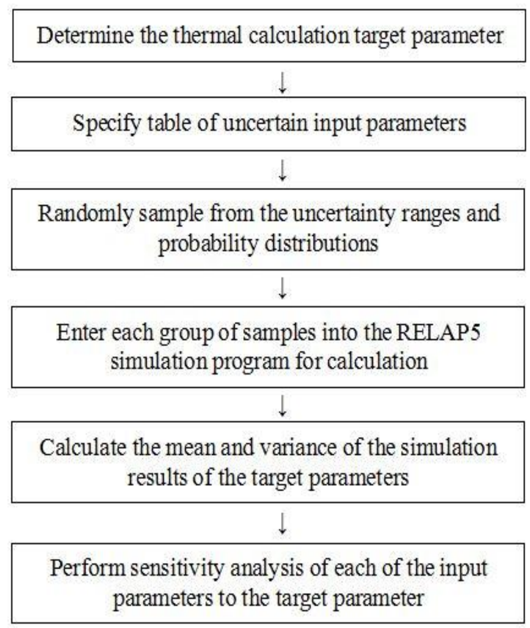

Fig. 2. The statistical uncertainty and sensitivity analysis method process summary.

Table III. Input Parameters Information

Input Parameter	Nominal Value	Uncertain Range
Primary inlet temperature (K)	594.25	±4.16
Feed water temperature (K)	499.85	±19.994
Primary inlet mass flow rate (kg/s)	7592.8	±37.96
Secondary inlet mass flow rate (kg/s)	944.35	±4.7

The data comes from AP1000 Design Control Document (AP1000 DCD) [5]. In order to ensure the comprehensiveness and credibility of subsequent sampling, the uniform distribution is chosen as the parameter distribution function. In addition, the heat transfer coefficient of heat transfer tubes also has an effect on the heat transfer process, however, the tube wall resistance and the fouling resistance are constant, and the small change of the coolant flow rate is not sufficient to affect the exothermic coefficient inside heat transfer tubes and the boiling exothermic coefficient outside tubes is a function of the steam pressure and the heat load which has little effect on the heat transfer coefficient [6]. Therefore, this paper ignores the impact of the heat transfer coefficient.

3. The SG Input Parameters Sampling Method

The statistical uncertainty analysis method needs enough samples to carry out calculations. The sampling method used in this paper is Latin hypercube sampling (LHS) [7]. LHS is a statistical method for extracting a reasonable subset of parameters from multidimensional parameters sets and it has an efficient hierarchical extraction characteristic. The obvious advantage of LHS is that a large amount of uncertainty and sensitivity assessment information can be obtained by sampling a small number of samples.

The number of samples in the thermal-hydraulic program is determined by the confidence which target parameters need. The minimum number of samples could be calculated by the Wilks formula [8]:

$$
\begin{aligned}
&1\text{-}a^{n} \geq b \\
&(1-a^{n})-n(1-a)a^{n-1} \geq b.
\end{aligned}
\tag{1}
$$

This formula shows that under confidence b, the probability that the program computations will not exceed the maximum exact value is a%. The Wilks formula has only one assumption: all parameters are independent of each other [8]. And in this paper, the input parameters are mutually independent boundary parameters in the RELAP5 program.

According to “95/95 Statistical Statement” put forward by NRC, it is required that the uncertainty assessment must ensure that at least 95% of the computations are within the safety margin at 95% confidence level [9]. From the Wilks formula, the minimum sampling frequency is 93 times under the 95% confidence level. The number of samples selected in this paper is 100, and the sampling results for each input parameter are shown in Fig 3-6.

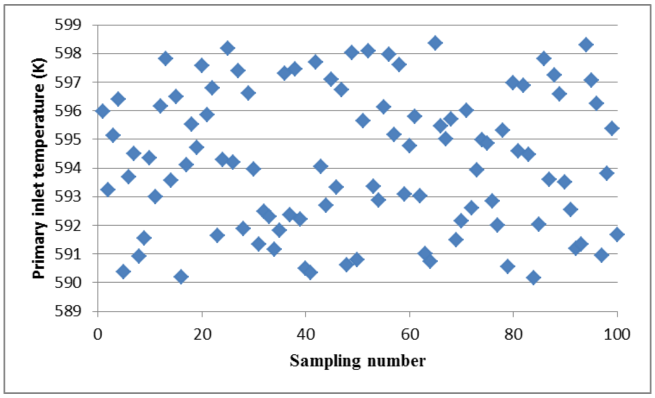

Fig. 3. The primary inlet temperature sampling results.

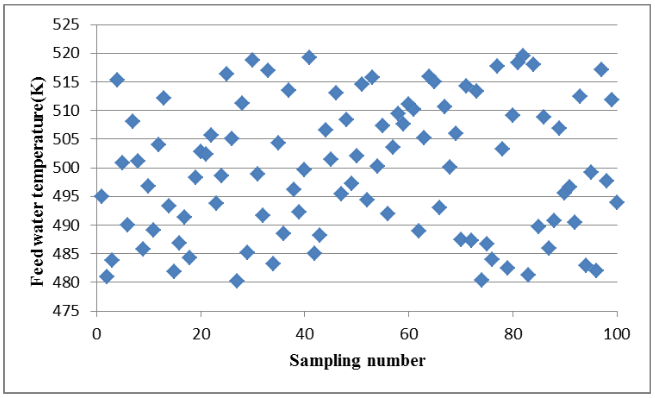

Fig. 4. The feed water temperature sampling results.

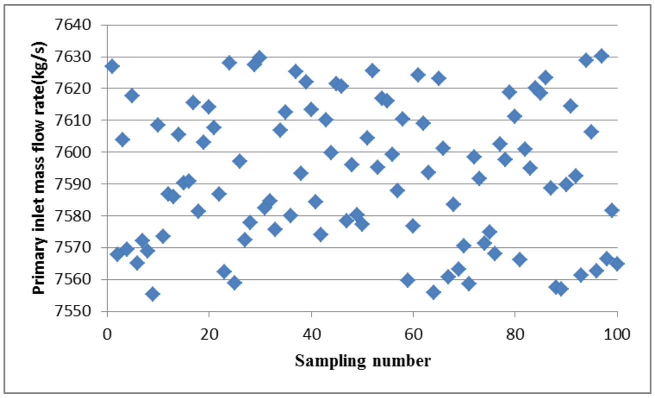

Fig. 5. The primary inlet mass flow rate sampling results.

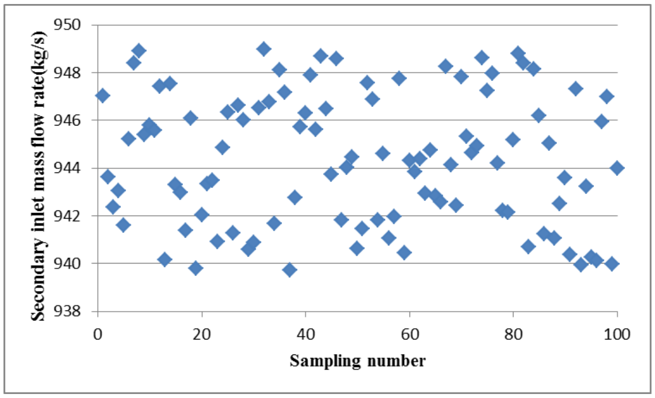

Fig. 6. The secondary inlet mass flow rate sampling results.

4. Uncertainty Quantification And Sensitivity Analysis Of The Water Level In SG.

The samples were combined randomly and taken into the RELAP5 software to compute the results of 100 SG water levels which are shown in Fig 7.

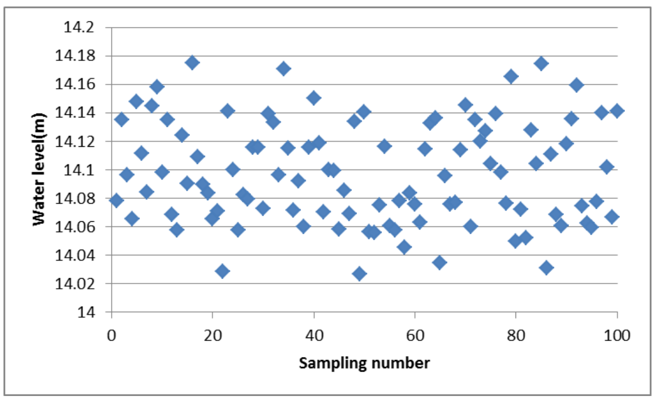

Fig. 7. The SG water level results.

Then the mean and standard deviation of 100 results were calculated to obtain the uncertainty information (Table IV). At the same time, the K-S test can be used to determine the distribution function [10].

In the sensitivity analysis, the correlation coefficient can be used to accurately describe the correlation between the input parameters and the target parameter, so that the impact of the input parameters on the target parameter is obtained. In this paper, the Pearson correlation coefficient between the SG water level and each input parameter is calculated, as shown in Table V, which can be used to compare the input parameters and find the one with the greatest contribution to the water level of SG.

Through the regression analysis, the mathematical expression between the input parameters and the target parameter can be given. It can illustrate the specific impact of changes in parameter values. Table VI and Table VII show the results of the regression analysis.

III. RESULTS

Table IV. The SG Water Level Uncertainty Quantification Information

Samples Number	100
Mean Value (m)	14.09734
Maximum (m)	14.1749
Minimum (m)	14.0268
Standard Deviation	0.035534
Uncertainty Range	±0.55%
Distribution Function	Normal

The results given above show that the uncertainty of the AP1000 SG water level is 14.09734±0.07756 m. From the AP1000 DCD [5], the reference value of AP1000 SG water level under full power steady operating conditions is 14.10 m. So the mean of the water level in this paper which is very close to the reference value is within reasonable limits. In addition, the water level fluctuations are very small, within ±0.55%, which are difficult to threaten the safety of the AP1000 SG, so the experimental results meet the safety requirements.

Table V. The Pearson correlation coefficient between each input parameter and the target parameter.

The Input Parameter	The Correlation Coefficient
The primary inlet temperature	-0.8431104
The feed water temperature	-0.3885025
The primary inlet mass flow rate	-0.0634999
The secondary inlet mass flow rate	0.1237918

If the correlation coefficient is positive, the input parameter and the target parameter have a positive correlation; if the correlation coefficient is negative, the input parameter is negatively correlated with the target parameter. The greater the absolute value of the correlation coefficient which is less than 1, the stronger the correlation. Therefore, as shown in Table V, the absolute value of the correlation coefficient between the primary inlet temperature and the water level is largest and greater than 0.8, so the coolant temperature fluctuations contribute the most to the SG water level and the two are highly correlated. The correlation between the feed water temperature and the SG water level is the second highest. But the fluctuations of the primary and secondary inlet mass flow rates have little impact on the water level. Although theoretically both temperature and flow rate could affect the heat transfer, however, the heat transfer temperature difference could directly change the heat transfer and the impact of the flow rate is mainly achieved by changing the heat transfer coefficient. And under steady operating conditions, the tiny fluctuations of the flow rate hardly change the heat transfer coefficient. So the correlation coefficient absolute values of the flow rates are very small. In addition, the feed water inlet mass flow rate could directly affect the water level without the heat transfer process, so the correlation coefficient absolute value of the secondary inlet mass flow rater is larger than the primary inlet mass flow. And this is also the reason why the correlation coefficient value between the secondary inlet mass flow rate and the water level is positive (the larger the mass flow rate, the higher the water level).

Table VI. Regression Equation Coefficients.

Parameter term	Coefficient Value
Constant term	21.61736
The primary inlet temperature	-1.2646829E-02
The feed water temperature	-1.2995549E-03
The primary inlet mass flow rate	2.2157310E-05
The secondary inlet mass flow rate	5.0485338E-04

Table VII. Evaluation Parameters Of The Regression Equation Fitting Degree.

Residual sum of squares Q	1.4071958E-02
Average standard deviation S	1.1862529E-02
Multiple correlation coefficient V	0.9426314

From the calculation results in Table VI, the regression equation between the target parameter and the input parameters is obtained:

$$\begin{aligned} Y &= 21.61736 - 0.012646A - 0.0012996B \\ &+ 0.000022157C + 0.00050485D \end{aligned} \tag{2}$$

In the equation, A = the primary inlet temperature (K), B = the feed water temperature (K), C = the primary inlet mass flow rate (kg/s), D = the secondary inlet mass flow rate (kg/s), Y = the SG water level (m).

When the regression equation is used to describe the statistical relations between variables, the regression equation predicted value is not exactly the same as the true value and the regression equation can be evaluated by the values of Q、S、V in Table VI. Among them, the residual sum of squares indicates the degree of uncertainty in the target parameter could not be interpreted by the input parameters, and the closer the value is to 0, the more closely the correlation is. The average standard deviation indicates the degree of deviation of the regression equation and the smaller its absolute value, the lower the deviation degree. The multiple correlation coefficient indicates the degree of the linear correlation between a dependent variable and multiple independent variables. The closer the value is to 1, the closer the linear correlation is. From the calculation results, it can be clearly seen that the absolute values of Q and S are very close to 0, and the value of V is very close to 1, so it can be concluded that there is a good linear correlation between the input parameters and the target parameter in this paper.

IV. CONCLUSIONS

Different from the conservative models for the SG thermal-hydraulic computations, this paper adopts the uncertainty quantification and sensitivity analysis based on the random sampling method, and chooses the AP1000 natural circulation SG as the research object. The main conclusions are as follows:

(1). Under the AP1000 full power steady-state operating conditions, the mean value of the SG water level is 14.09734 m, and the uncertain range is ±0.55%.

(2). Among four input parameters chosen in this paper, the primary inlet temperature has the strongest impact on the SG water level, and the primary inlet mass flow rate has the weakest impact.

The above results not only verify the inherent safety of AP1000 SG, also have great significance in reducing the excessive conservative margin and improve the economy of nuclear power plant. However, the RELAP5 simulation program used in this paper has a certain degree of conservatism, and its computation results will inevitably have a certain conservative margin. Therefore, through the future model uncertainty research, the threshold of the results obtained in this paper may has space to narrow.

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