An Efficient Method of Key Parameter Screening for PCCS under SLB Accident in AP1000

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Abstract: Variance decomposition is an effective sensitivity analysis method to screen the key parameters influencing passive safety system operation based on the uncertainties of thermal-hydraulic (T-H) model inputs. However, such method needs a large number of samples gained from T-H model running with the inputs sampled randomly from their probabilistic distributions, and the T-H model always takes quite long time to run once, then it will be a heavy calculation burden to do the analysis. In this paper, we propose a method to improve the analyzing efficient: based on the system T-H characteristics, the system behavior in a short time after an accident happening can represent the system T-H performance and be used to do the sensitivity analysis.

Passive Containment Cooling System (PCCS) in AP1000 is used as a case study in our analysis, by which the heat produced in the containment can be transferred to the atmosphere through natural circulations. After steam line break (SLB) accident, the peak value of pressure in the containment appears within 1000s, we do the sensitivity analysis to screen key parameters in two ways: firstly, we screen the key inputs with variance decomposition method directly, 100 samples are gained from T-H model simulating 1000s, the inputs are sampled based on their probabilistic distributions, and the results show that air pressure is the most important parameter and the others don't have enough differentiation degrees. Then we get more 100 samples under the condition that air pressure is supposed as 0.1MPa, here air temperature and steam mass flow are important ones besides air pressure. In another way, we analyze the correlation between pressure in the containment in a short time after SLB and the peak value according to the system T-H behavior, and get 600 samples from T-H model simulating 50s, the results are in accordance with that from T-H model simulating 1000s, air pressure, air temperature and steam mass flow are important parameters, and it just needs 1.55h to calculate the important factor for one input.

Key words: Passive Safety System, Key Parameters Screening, Thermal-Hydraulic Characteristics, Variance Decomposition

1. Introduction

Passive safety concept [1] is widely used in new generation nuclear power plant design to improve the safety, since such systems do not need any external power supply for operation and some of them operate based on natural circulation. The driving force of natural circulation is from density difference of the hot and cold fluids, which can be comparative with the resistance force, so uncertainties influencing the driving and resistance forces may have important effect on system operation reliability [2,3]. The system behavior is always described by the Thermal-Hydraulic (T-H) model, and uncertainties [4] include input parameters' uncertainties [2,5] and model uncertainty [5,6], then system physical process failure may occur if the real operating state deviates from the design condition because of such uncertainties [1].

There are always dozens of input parameters for T-H model, evaluating the effects of their uncertainties on system operation one by one is a heavy calculation burden, so, it is necessary to screen the important ones [7,8] to be analyzed in detail. Variance decomposition [8,9] is an effective method for screening key factors for influencing passive system operation, however, such method needs the T-H model to run hundreds or even thousands of times for calculating the important factor for one input parameter, with the inputs sampled randomly from their probabilistic distributions. So, it needs several to dozen hours to get the important factor for one parameter even if the T-H model describing the accident development needs several minutes to run once, which will be a heavy calculation burden.

Never the less, the purpose of sensitivity analysis is to screen key parameters, it is no need to simulate the whole accident scenario. In this paper, we purpose that for screening key parameters, we just focus on the variation trend of T-H model output depending on inputs, based on the system T-H characteristics, the system behavior in a short time after an accident happening can represent the system T-H performance and be used to do the sensitivity analysis. Thus, the calculation efficiency can be improved. Here, Passive Containment Cooling System (PCCS) in AP1000 after steam line break (SLB) accident is used as a case study to evaluate the influences of input parameters on the system behavior.

2. Case Study

2.1 System Operation

Passive Containment Cooling System (PCCS) in AP1000 [10] is a typical passive safety system, the heat produced in containment can be transferred to the atmosphere by natural circulations inside and outside the steel vessel during accident. When the steam with high temperature [10,11] injects into the containment from primary or secondary loop during loose of coolant accident (LOCA) or main steam line break (SLB), it will rise to the upper head mixed with hot air in the containment. The hot mixed gas will be cooled and go down when it arrives at inside surface of the steel vessel, and the condensed water will return to the containment. The heat can be transferred to the steel vessel through such natural circulation in containment.

Outside the steel vessel there is an air tunnel, the cold air will go down to the bottom of the tunnel, and when the air arrives at outside surface of the steel vessel it will be heated and rise, then return to the atmosphere through chimney at the top of containment. The cooling water will be sprayed to outside surface of the vessel from the tank on the top, which will be helpful to transfer the heat to the environment. The flowchart of the system is shown in Fig.1[10].

2.2 T-H Model Characteristics

The initial value of pressure in the steel vessel can be supposed as the atmosphere pressure, then it will increase because of steam injecting into containment and of temperature rising induced by hot steam after some accidents such as SLB. Fluid state in the containment will be determined by heat produced and that transferred to the atmosphere, and the amount of heat produced depends on the mass flow of hot steam injecting into the vessel, while amount of heat transferred to the environment is decided by natural circulations and heat conductivity of the steel vessel.

The system failure is defined as:

$$\text{Pressure peak value in the containment} > \text{threshold (0.5 MPa)} \quad (1)$$

In the beginning of accident the heat produced in the containment is more than that transferred to the atmosphere, the fluid pressure and temperature will increase. Then the heat produced will decrease with steam mass flow dropping, while the heat transferred to the atmosphere will increase because of the following phenomena:

- Natural circulation in the containment will be established and strengthened since the density difference between hot and cold fluids will increase, the steam and hot air will float up, then be cooled and condensed at inside surface of the steel wall. More over the temperature difference between the hot fluid and the steel wall will increase, then the heat transferred to the steel wall from the fluid in the vessel will increase.
- The heat amount conducted by steel vessel will increase since temperature difference between inside and outside of the wall will enlarge.
- With steel wall temperature increasing, the air outside the containment will be heated more rapidly and the natural circulation outside the steel vessel will be strengthened, then more heat will be transferred to the atmosphere.

When heat amount produced and transferred to the atmosphere are in balance, the temperature and pressure in the containment will arrive at their peak values, then drop since the heat transferred to the environment exceeds that produced. The T-H model has 10 input parameters listed in Table.1 and pressure in the containment is the output.

The main steam line break is one of the accidents threatening the containment integrity, in this paper we do the sensitivity analysis based on the system T-H behavior after such accident. The steam mass flow rate injecting[10,11] into the steel vessel is very high in a quite short time after the accident happens, then it will drop sharply and keep at a quite low level for a long term (shown in Fig.2), which is used as design base, and the air temperature is 49℃ (condition1 in Fig.3). Result (condition1) in Fig.3 shows that pressure in the containment arrives at peak value within 1000s, which is the balance between heat produced and transferred to the atmosphere.

3. Methodology Development

3.1 Variance Decomposition

Variance decomposition [8,9,12] is an effective method to screen key factors influencing passive system operation, however, to get important factor (η^2) for one input parameter, such method needs at least hundreds of samples from T-H model running, and the inputs are sampled randomly based on their probabilistic distributions. The sketch of the method is summarized as follow:

It can be supposed the T-H model as [8,9,12]

$$Y=f\,(X_1, X_2) \tag{2}$$

- Sample s values of x_1, that is $\{x_1^1, x_1^2, \dots, x_1^s\}$;
- For each value x_1^j, sample r values of x_2, that is $\{x_2^1, x_2^2, \dots, x_2^r\}$ from the conditional distribution $f_{x2\mid x1}\,(x_2\mid x_1^j)$;
- Calculate the T-H model output $y^{jk}=f\,(x_1^j, x_2^k)$, here, $j=1,2,\dots,s$, $k=1,2,\dots,r$, so we can get an output matrix of order (s,r);
- For each row $j=1,2,\dots,s$ of the matrix, calculate

$$\hat{y}*\left(x_1^j\right)=\frac{1}{r}\sum_{k=1}^{r}y^{jk}\cong E_{X_2}[Y|x_1^j] \tag{3}$$

- Calculate the expected value of Y:

$$\bar{y}=\frac{1}{s}\sum_{j=1}^{s}\hat{y}*\left(x_1^j\right)\cong E[Y] \tag{4}$$

- Calculate the variances:

$$\hat{V}_{X_1}\left[E_{X_2}(Y|x_1)\right]=\frac{1}{s-1}\sum_{j=1}^{s}[\hat{y}*\left(x_1^j\right)-\bar{y}]^2 \tag{5}$$

$$\hat{V}[Y]=\frac{1}{sr-1}\sum_{j=1}^{s}\sum_{k=1}^{r}(y^{jk}-\bar{y})^2 \tag{6}$$

- Calculate the important factor:

$$\eta^2=\frac{\hat{V}_{X_1}[E_{X_2}(Y|x_1)]}{\hat{V}[Y]} \tag{7}$$

3.2 Parameter Evolution Pattern Identification

For PCCS, pressure in the containment is the output of T-H model, and system failure is defined as its peak value exceeding the threshold. To screen key parameters, we just care how the input parameters influencing the output. After SLB accident, hot steam injecting into the containment is the heat source, and atmosphere is the cold source, so we analyze the system behavior under different operating conditions: Condition 1 is the design condition (see section 2.2), and the other conditions have different steam mass flow and air temperature, the detailed description is shown in Table.2.

Fig.3(a) shows that the pressure increases more quickly, the pressure peak value is higher. That is, the influence of input parameters on pressure increasing rate can reflect the effect of those on pressure peak value. This can be explained as that the pressure peak value is determined by steam mass flow and heat transfer capacity of the system, and system heat transfer capacity is related to the fluid state (pressure, temperature) and the properties of the material (e.g. heat transfer conductivity of the steel), moreover, the fluid state is decided by the physical process. If the steam mass flow is higher (condition 3 to 5 in Fig.3), more steam injects into the containment, which results in higher pressure and temperature in the vessel, so the pressure increases more rapidly, then the heat transfer capacity is also higher because of higher temperature difference between the hot fluid and the steel wall, and the pressure peak value will be arrived at a higher balance level of heat produced and transferred. On the other hand, if the system heat transfer capacity is lower induced by higher air temperature (condition 2 and 5 in Fig.3) or some other causes, the heat in the containment accumulates more quickly, then the pressure in the vessel increases more rapidly and the peak value is also higher.

Results in Fig.3(a) and (b) show that input parameters' influences on the pressure peak value and on the pressure increasing trend are in accordance, that is, the condition having higher pressure peak value will induce more rapidly pressure increasing. In the beginning of the accident, a great amount of steam injects into the containment and pressure in the vessel grows sharply, in this period the steam mass flow has more important effect. Then the steam mass flow drops quickly to a quite low and steady level, and the natural circulations inside and outside the containment establish at the same time, so the pressure increasing process trends to be steady. Fig.3 (b) shows that pressure in the containment has such order after 20s, as well as the peak value shown in Fig.3 (a) :

$$P_{condition5} > (P_{condition4} \sim P_{condition2}) > P_{condition1} > P_{condition3} \quad (8)$$

the results for condition2 and condition4 are very similar, and they almost have the same peak values. Then we analyze the pressure increasing speeds from local values at 20s,30s,40s and 50s to the peak values under different conditions, the results are shown in Table.3. We can see that the pressure increasing rate gradually drops along with the time, since the steam mass flow decreases quickly in the beginning of the accident and the heat transfer process establishes. However, such increasing speeds have different orders for 20s,30s,40s and 50s analysis:

pressure increasing speed from value at 20s to the peak value :

$$\text{condition5} > \text{condition2} > (\text{condition1} \sim \text{condition4}) > \text{condition3} \quad (9)$$

pressure increasing speed from value at 30s to the peak value :

$$\text{condition5} > \text{condition2} > \text{condition1} > \text{condition4} > \text{condition3} \quad (10)$$

pressure increasing speed from values at 40s and 50s to the peak value :

$$\text{condition5} > (\text{condition2} \sim \text{condition4}) > \text{condition1} > \text{condition3} \quad (11)$$

Our purpose is to screen key parameters influencing the system operation, then calculating efficiency can be improved by shortening the mission time of accident simulation. Here the pressure increasing speed from values at 40s and 50s to the peak value have the same order as the peak value itself, so we do the sensitivity analysis for such partial simulation periods: 0 to20s, 0 to 30s, 0 to 40s and 0 to 50s.

4. Results

4.1 Results of Different Sampling Methods

There are 10 input parameters for T-H model describing passive containment cooling system behavior, the probabilistic distributions are listed in Table.1. Here construction errors are expressed by uniform distributions since the sampled values are most widely distributed under such suppose, that is, if the parameters don't have important effect on the output based on such distribution, they will not be the key influence factors under other distributions, and the construction parameters are set in one group and analyzed together. From Fig.3 we can see that the pressure peak value is arrived within 1000s after the accident happening.

It is very complicated to determine the suitable sample size for variance decomposition, and trial method is always used based on the overall consideration of calculation accuracy and efficiency. Here T-H model simulating 1000s needs about 87s to run once, and we have 7 input parameters (Construction parameters are analyzed as one group) to be analyzed. We try 100 samples ($s=10$, $r=10$) firstly, it needs about 2.4h to get the important factor for one parameter, so 17h is necessary for the completed analysis, the results are shown in Table.4.

It can be seen that the important factor of air pressure is about 1 and those of others are all around 0.1, then the air pressure is an important one, but the others are difficult to be screened, so more samples are needed and we need to find a more efficient sampling method, here we try in two ways:

1) Since air pressure is much more important than other parameters and its important factor is 1, we get more *100* samples (also $s=10$, $r=10$) to calculate the important factors for others under the condition that air pressure is 0.1MPa, the results are shown in Table.4. The important factor of steam mass flow is 0.9 and that of air temperature is 0.2, and the others are also around 0.1.

2) Based on the analysis in section 3.2, the pressure gotten from partial simulation period can be used to predict the trend of pressure peak value, then we do the sensitivity analysis again based on T-H model simulating the accident up to just 20s, 30s, 40s and 50s respectively, even we simulate the accident up to 50s, the time for T-H model running once is only 9.3s, so we can get more samples easily.

In variance decomposition method, we get a matrix including s rows and r columns (see section 3.1), here the difference between s rows represents the effect of parameter analyzed (i.e. x_1 in section 3.1) on the result, while difference between r columns reflects the influences of other parameters (i.e. x_2 in section 3.1). Since air pressure is the most important one and the other parameters' effects will be concealed, we need to increase s to have more samples of analyzed parameter, meanwhile it is more necessary to increase *r* to have more samples of other parameters except the analyzed one, thus the influence of air pressure can be decreased when we calculate important factors for others. Here we increase the samples to 600 (*s=20, r=30*) for 20s, 30s, 40s and 50s simulating and the results are also shown in Table.4, we can see that parameters have different important factors, in 40s and 50s analysis the air pressure is the most important one, then steam mass flow and air temperature are comparative and more important than others, especially the results from 50s analysis are more clear. Nevertheless results from 20s and 30s analysis show the different important factor order, since they have different pressure increasing speed orders (formula (9) ~ (10)). At the beginning of the accident a lot of steam injected into the containment inducing the pressure increasing, the local value can describe the state at the moment, and it needs some time to establish the heat transfer process. The peak value is determined by the balance of heat produced and transferred, which can be described by the increasing rate from local value to the peak value. So the 40s and 50s analysis can get the results in accordance with those of simulating the accident up to 1000s.

In order to compare the results with those of simulating the accident up to 1000s, we also run the T-H model simulating 50s 100 times (*s=10, r=10*), the results are shown in Table.3, which are similar with the results of 1000s: important factor of air pressure is 1 and the others are around 0.1.

The results of simulating 1000s and 50s are in accordance: air pressure is the most important input and steam mass flow and air temperature are important ones. The results are reasonable from system's T-H characteristics, air pressure can influence the peak pressure value directly since it is supposed as the initial value of pressure in the containment.

The hot steam injecting into the containment and the atmosphere are heat and cold sources of system respectively, which have the crucial effects on the establishment and the operation of natural circulations, so they are also the important ones.

4.2 Efficiency of Different Sampling Methods

We can get the important input parameters by sampling method in section 4.1, however, if we run 100 times of the T-H model simulating accident for 1000s owing to calculation efficiency consideration, it is difficult to get the results directly, since air pressure has crucial effect on the result, the effects of other parameters will be concealed because of a limited number of samples. So, we have to fix the air pressure as 0.1 MPa and calculate the important factors for other parameters again. If we run the T-H model simulating accident just for 50s and increase the samples to 600, the important factor order can be gotten directly. The running time is shown in Table.5.

That can be explained as the sampled parameters' values have randomness, and air pressure is much more important than others, so the mean value of output for each row ($\hat{y}$) and the variances $\hat{V}_{X_1}\left[E_{X_2}(Y|x_1)\right]$ and $\hat{V}[Y]$ are influenced by the value of air pressure more greatly when samples are less, for example, if an extreme value (very high or very low) is sampled for air pressure, the mean value of such row ($\hat{y}$) will be higher or lower, however, the mean value of matrix ($\bar{y}$) is averaged by total number of samples ($s \times r$), so the influence of extreme value on ($\bar{y}$) is much lighter than that on ($\hat{y}$). Hence the effect of extreme value of air pressure on $\hat{V}_{X_1}\left[E_{X_2}(Y|x_1)\right]$ is higher than on $\hat{V}[Y]$, in result the important factors (η^2) of other parameters are very similar and higher than their real effects on the output. With the sample number increasing such influence of extreme value of air pressure will decrease, the important factors of others can reflect their real influences better, and the parameter important order can be gained directly.

Moreover the steam mass flow is much more important than air temperature when we have 100 samples, but they are comparative and the air temperature is a little more important than mass steam flow when 600 samples are gotten, which can be explained that the distribution interval of air temperature is much wider than that of steam mass flow, that is, the extreme value of air temperature is very high, however, the probabilistic density distribution of air temperature is bi-normal but that of steam mass flow is uniform, so the high value of air temperature is easier to be sampled when sample number increases. From Fig.3 we can also see the temperature has more important influence than steam mass flow, since in Fig.3 the extremely values of parameters are used.

5. Conclusions

Air pressure has absolute predominance among the inputs, however, the results are determined by the system T-H characteristics and also by the probabilistic density distributions and variation intervals of input parameters, and such attributes are influenced by the system conditions, for example, air pressure and temperature are decided by the local climate of plant site, so we consider steam mass flow and air temperature as the important ones as well as air pressure.

The pressure in the containment at short time (e.g. 50s for SLB) can be used to replace the peak value when

- the local values and the peak values in different conditions have the same orders,

- the pressure increasing speeds from local values to the peak values have the same order as the peak values themselves.

The input parameters of T-H model describing the system behavior after accident can be grouped as: environment parameters (air temperature, air pressure, wind speed), construction parameters, initial parameters (cold water mass flow, film ratio) and steam mass flow. The environment parameters, construction parameters and initial parameters are not influenced by the accident development, however steam mass flow will drop quickly to a low level and be steady in long term, so the fluid state in a short time can reflect its variation trend with the accident development.

In this paper, SLB is analyzed as a case study, and the results of simulating 50s and 1000s after such accident are in accordance, never the less, getting 100 samples and simulating 1000s needs 2.4h while getting 600 samples and simulating 50s needs 1.55h, more over the results cannot be gotten directly if we just have 100 samples. Simulating shorter time and getting more samples is an efficient way to do the sensitivity analysis since it is just needed to get the important factors of parameters.

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