Research on Sensitivity Analysis and Evaluation of cosCONT Software

Yichun Wang[1], Jiulong Yang[1], Yu Yu[1]

[1] *North China Electric Power University: No. 2 Beinong Road, Changping District, Beijing, 102206, and*
wangyc@ncepu.edu.cn, 120242212034@ncepu.edu.cn, *yuyu2011@ncepu.edu.cn*

ABSTRACT

Thermal-hydraulic analysis of reactors serves as a critical technical foundation for the safety analysis and evaluation of nuclear power plants. Currently, the use of simulation modeling software, coupled with partial experimental validation, has become an essential method for scientific research and engineering training. The cosCONT software, developed by the Nuclear and Nuclear Technology Research Institute of the National Electric Power Group's State Nuclear Power Research Institute, is a module within the COSINE software package dedicated to thermal response analysis of containment structures. This software is capable of simulating various thermodynamic conditions within the containment. Given the inherent uncertainties associated with computer simulation modeling and input parameters, conducting uncertainty analysis on the software's simulation results is imperative. As changes in containment pressure to a certain level can lead to failure behaviors under accident conditions, this paper focuses on containment pressure variations as the primary output. A ranking of parameter importance is established by employing variance analysis methods to screen significant input parameters and conducting sensitivity analysis of the software. This approach aims to assess the reliability of the software in predicting pressure and to analyze the key influencing factors, thereby providing recommendations for the rational application of the software.

Keywords: cosCONT; Sensitivity analysis; Containment pressure

I. Introduction

Nuclear power plant safety is paramount for the sustainable development of nuclear energy. Reactor thermal-hydraulic analysis provides essential technical support for safety assessments, primarily achieved through simulation modeling software for research and engineering training.

This study focuses on cosCONT, the containment thermal response analysis module within the COSINE software package developed by the State Power Investment Group. Using the Main Steam Line Break (MSLB) accident scenario in the CAP1400 reactor as a case study, an integrated platform was designed and large-volume case calculations were optimized. Variance decomposition was employed to achieve technical optimization for sensitivity analysis, enabling the filtering and ranking of key parameters that influence containment pressure predictions.

II. Sensitivity analysis methods

II.A. Latin hypercube sampling (LHS)

Key input parameters were sampled using the Latin Hypercube Sampling (LHS) method. LHS is a statistical technique for generating stratified random samples from multidimensional distributions [1]. It partitions the distribution range of each variable into equiprobable strata, ensuring exactly one sample is drawn from each stratum. This stratification enhances sample homogeneity and improves accuracy compared to simple random sampling. Consider a unit hypercube in p-dimensional space, $C^p = [0,1]^p$, divided evenly into n intervals along each axis (n is the sample size), the LHS can be represented as a $n \times p$ array$[x_{i,j}]$ （$i = 1, \dots, n$; $j = 1, \dots, p$）, where $x_{i,j} \in [0,1]$, such that $x_{i,j}$ in column j belongs to only one interval, we denote this matrix as $LHS(n, p)$[2].

The sampling procedure is as follows:

- Generate a random permutation π_j for each dimension j, where $\pi_j(i)$ denotes the interval number of the i^th^ sample in dimension j;
- For each sample in dimension j, calculate the sampling point:

$$x_j^i = \frac{\pi_j(i) - u_{ij}}{N} \tag{1}$$

Where u_{ij} is the random number obtained by sampling in U(0,1).

II.B. Parallel computing enables efficiency gains

A single simulation of the CAP1400 containment thermal-hydraulic response under the MSLB accident scenario using the cosCONT platform requires approximately 10 hours. This computational burden severely limits the efficiency of iterative analyses required for large-scale sensitivity studies involving numerous design basis accidents. To address this challenge, a computational acceleration strategy was implemented: a parallel-serial hybrid model was constructed leveraging multi-core CPUs to achieve efficient resource allocation.

Parallel computing, a branch of high-performance computing, aims to maximize resource utilization, accelerate computation, and enhance processing power [3]. For engineering computing scenarios lacking dedicated supercomputing resources, this study proposes a hybrid acceleration scheme based on multi-core processors, illustrated in Fig. 1. The scheme employs a parallel-serial thread scheduling strategy. Computational resources are fully utilized by enabling parallel processing of multiple threads within the core simulation code. This approach facilitates parallel scheduling of multiple threads while maintaining simulation functionality [4], effectively minimizing the overhead associated with thread context switching.

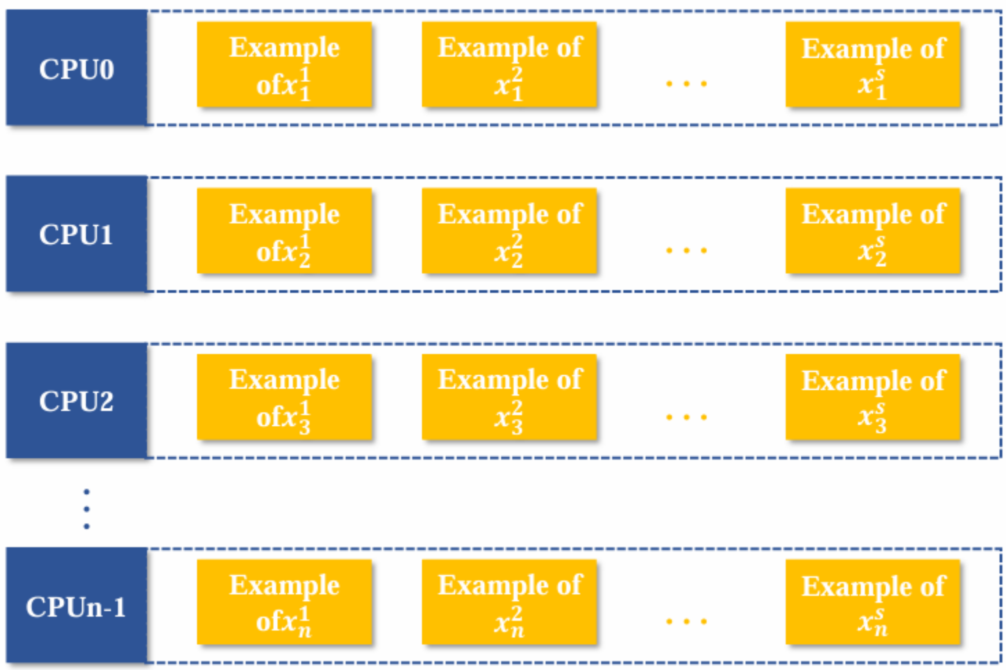

FIGURE 1. Multi-threaded parallel-serial architecture of a multi-core computer

II.C. variance decomposition

Following the execution of the T-H model hundreds of times via the parallel strategy, the variance decomposition method was applied to rank the importance of key input parameters based on the model outputs. Variance decomposition is an effective method for screening key inputs, yielding the significance factor ($\eta 2$) for each parameter. This method requires running the T-H model with inputs randomly sampled according to their probability distributions. The procedure is summarized as follows [5]:

First, assume a T-H model with n input parameters:

$$Y = f(X_1, X_2, \dots, X_n) \tag{1}$$

- X_1 of s samples, denoted as $\{x_1^1, x_1^2, \dots, x_1^s\}$;

- For each specific value x_1^j, sample r values for each of the remaining parameters $X_2,\dots,X_n$ from their conditional distribution $f_{(x_2,\dots,x_n|x_1^j)}$, yielding sets $\{x_2^1, x_2^2, \dots, x_2^s\}$, …, $\{x_n^1, x_n^2, \dots, x_n^s\}$;
- This forms an input parameter matrix of size $s\times r$ for the conditional runs;
- For each row j of the matrix(j=1,2,,...,s), calculate the conditional mean output:

$$\bar{y}(x_1^j) = \frac{1}{r}\sum_{k=1}^{r} y^{ik} = E_{X_{2,\dots,}X_n}[Y|x_1^j] \tag{2}$$

- Calculate the mean value of Y:

$$\bar{y} = \frac{1}{s}\sum_{j=1}^{s} \bar{y}(x_1^j) = E[Y] \tag{3}$$

- Calculate the variance:

$$\overline{V_{X_1}}[E_{X_{2,\dots,}X_n}(Y|x_1^j)] = \frac{1}{s-1}\sum_{j=1}^{s}\left[\bar{y}(x_1^j) - \bar{y}\right] \tag{4}$$

$$\bar{V}[Y] = \frac{1}{sr-1}\sum_{j=1}^{s}\sum_{k=1}^{r}(y^{ik} - \bar{y})^2 \tag{5}$$

Equation (4) represents within-group variance, and equation (5) represents between-group variance.

- Calculation of important factors:

$$\eta^2 = \frac{\overline{V_{X_1}}[E_{X_{2,\dots,}X_n}(Y|x_1^j)]}{\bar{V}[Y]} \tag{6}$$

By the above calculation, the important factors of parameter X1 can be obtained, and the calculation of the important factors of other parameters is the same as above.

III. Objects of analysis

III.A. Introduction to the software

The sensitivity analysis was performed on cosCONT, the containment thermal response analysis module within the COSINE software package for thermal-hydraulic analysis, developed by the State Nuclear Power Research Institute. The functional architecture of the COSINE program is depicted in Fig. 2. cosCONT primarily comprises three components: control inputs, hydrodynamic parameters, and output settings [6]. It is suitable for thermal-hydraulic analyses of containment structures in passive safety nuclear power plants. The software calculates key parameters such as pressure, temperature, and flow within the containment, simulates internal phenomena during accidents, and models the behavior of various nuclear power plant system components [6].

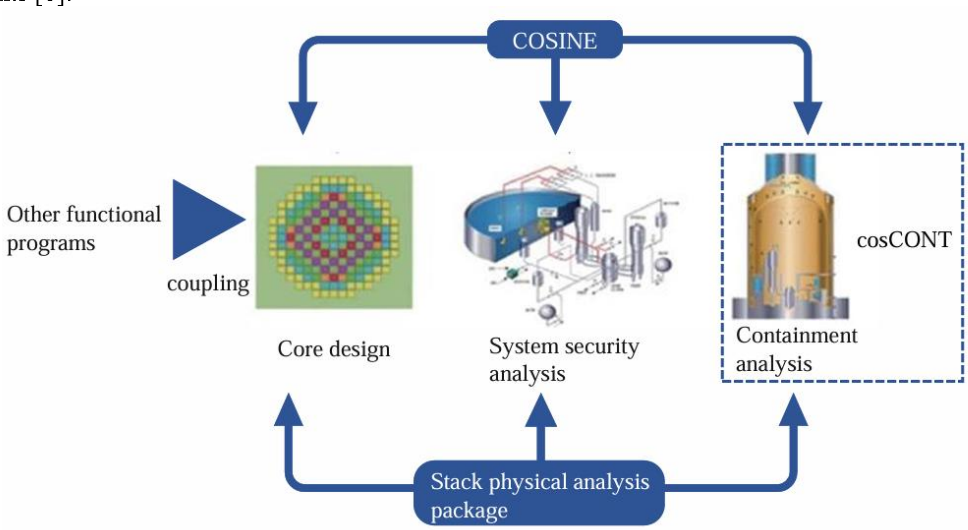

FIGURE 2. Functional block diagram of the COSINE software package system[7]

III.B. Modelling and working conditions

The CAP1400 containment design, shown schematically in Fig. 3, retains the Steel Containment Vessel (SCV) structure of the AP1000 design, which is based on passive containment cooling. The CAP1400 design features increased size and capacity compared to its predecessor.

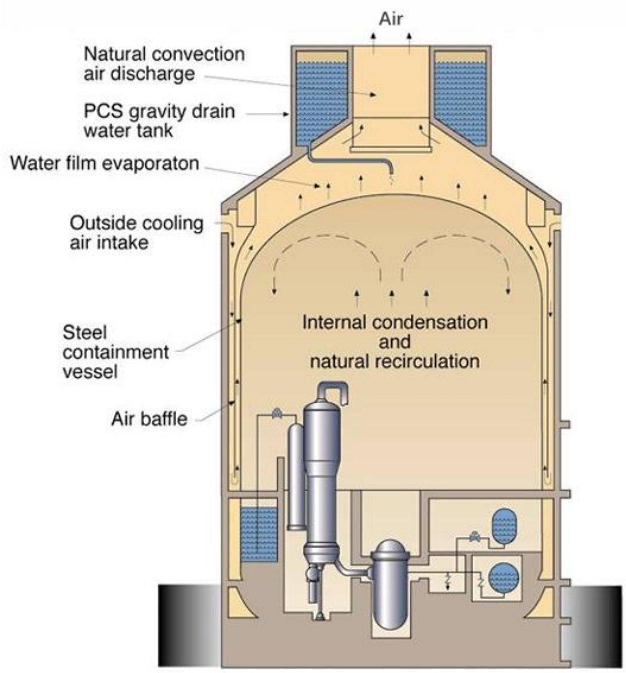

FIGURE 3. Overall schematic diagram of the CAP1400 containment vessel [8]

This study employs the self-developed cosCONT software to simulate the Main Steam Line Break (MSLB) accident for the CAP1400 reactor. This scenario serves as the basis for the software sensitivity analysis and the assessment of its applicability. In the hypothetical MSLB scenario, the pressure transient within the steel containment is illustrated in Fig. 4. Following the accident initiation (t=0), a large mass of steam is released into the containment, causing a rapid pressure rise. Pressure begins to decrease once the external Passive Containment Cooling System (PCS) water film is fully established, resulting in a distinct pressure peak. Maintaining containment pressure below its design value is critical for the success of the passive containment cooling system in preventing significant radioactive releases to the environment. Consequently, containment pressure is the primary focus of safety analyses related to containment integrity [8]

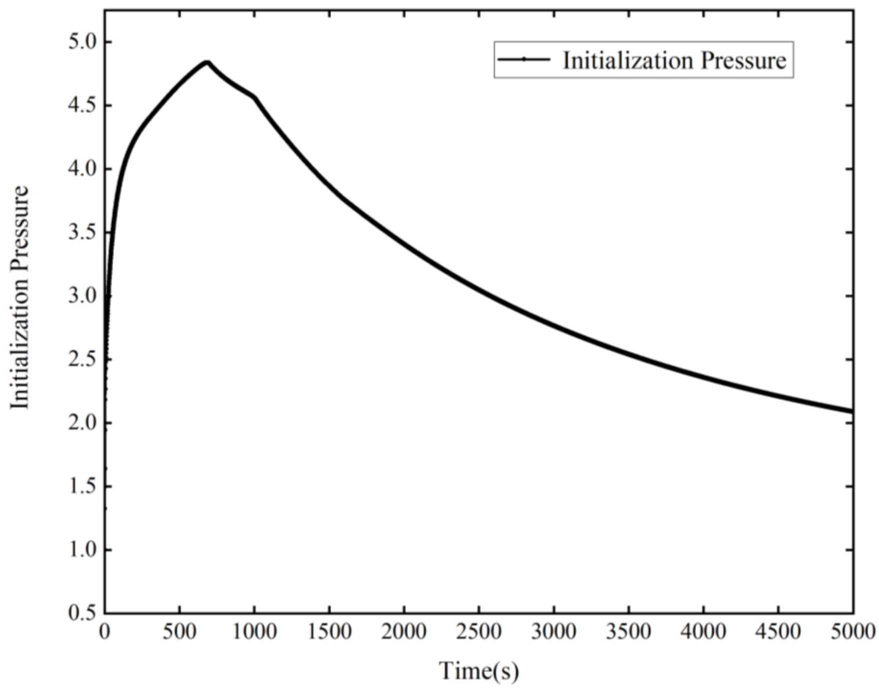

FIGURE 4. MSLB Process Pressure Change Curve (Since the model raw pressures are not publicly available, all raw data sections are initialised in this paper.)

IV. Analysis and discussion of results

IV.A Key Parameter Screening and Sampling

Seven key input parameters were identified, in order: atmospheric ambient temperature, condensation conservatism factor, evaporation conservatism factor, internal initial temperature, PCS water film initial temperature, internal initial pressure, and internal initial humidity, and the distribution ranges and characteristics of the parameters are demonstrated in Table 1.

TABLE I. Probability distribution of input parameters

Code	Parameter	Interval	Column Header Goes Here
X_1	Atmospheric environmental temperature	(30.4,8.44) (°C)	Normal
X_2	Condensation conservation factor	[0.5,1]	Uniform
X_3	Evaporation conservation factor	[0.6,1]	Uniform
X_4	Initial internal temperature	[283.15,323.15] (K)	Uniform
X_5	Initial temperature of PCS water film	[283.15,322.04] (K)	Uniform
X_6	Internal initial pressure	[0.09,0.11] MPa	Uniform
X_7	Internal initial humidity	[0,100%]	Uniform

Determining the appropriate sample size for variance decomposition is complex, and a trial algorithm is often employed based on a combination of computational accuracy and efficiency. We analysed seven input parameters. We took 100 samples (s = 10, r = 10) for each input parameter in the trial.

IV.B Analysis of variance decomposition

The importance factors ($\eta 2$) obtained from the variance decomposition for each parameter are listed in Table II and visualized in Fig. 5. The resulting parameter importance ranking is: X7 (Initial internal humidity) > X3 (Evaporation conservative factor) > X5 (Initial PCS water film temperature) > X6 (Initial internal pressure) > X2 (Condensation conservative factor) > X4 (Initial internal temperature) > X1 (Atmospheric environmental temperature).

TABLE II Importance factors for each parameter

Code	Parameter	Materiality factor η^2
X_1	Atmospheric environmental temperature	0.0047
X_2	Condensation conservation factor	0.0518
X_3	Evaporation conservation factor	0.0810
X_4	Initial internal temperature	0.0268
X_5	Initial temperature of PCS water film	0.0676
X_6	Internal initial pressure	0.0554
X_7	Internal initial humidity	0.5117

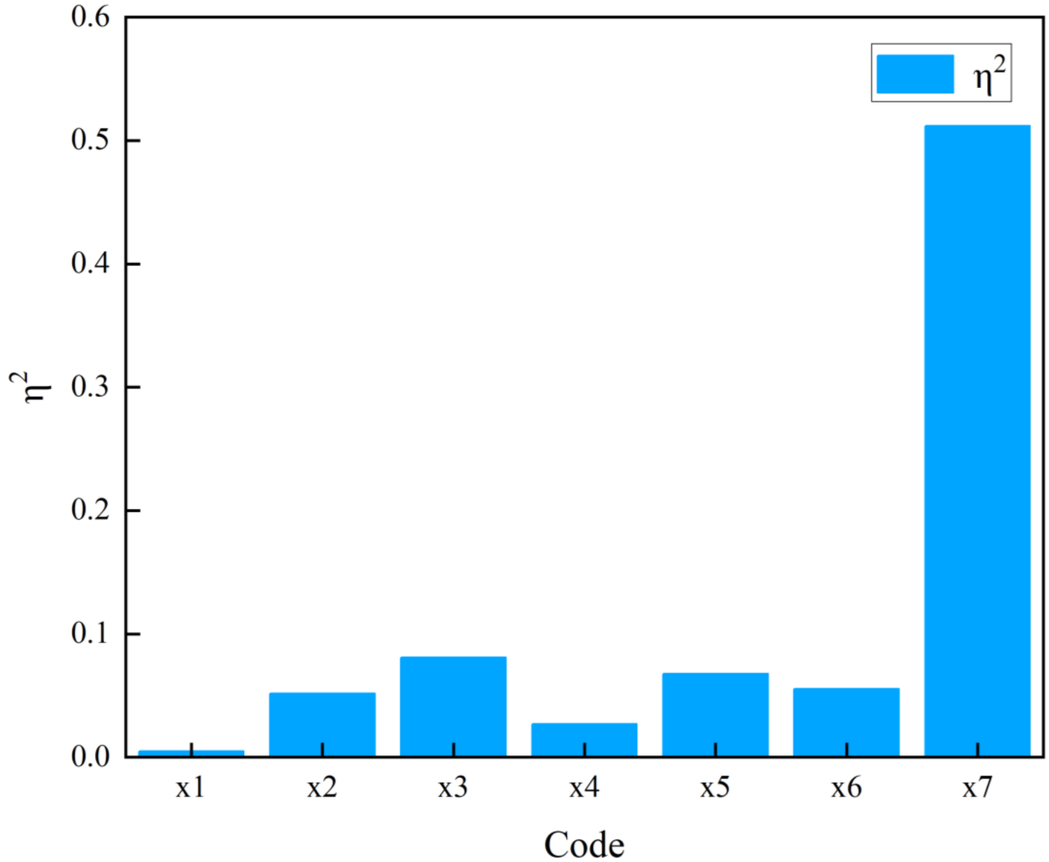

FIGURE 5. Graphical representation of the importance factor of each parameter

The initial internal humidity (X_7) exhibits a dominant influence (η2=0.5117), consistent with its direct impact on the partial pressure of non-condensable gases (NCGs) within the containment. Furthermore, studies indicate that NCGs accumulate near condensing surfaces, forming a gas boundary layer that impedes steam contact with the cold wall, thereby reducing the heat transfer coefficient [9]. This underscores the criticality of initial humidity.

The evaporation conservative factor (X_3) and initial PCS water film temperature (X_5) also show significant influence. The PCS water film is the primary heat transfer pathway from the containment shell. The evaporation factor directly relates to the heat transfer coefficient governing evaporation from the water film surface, while its initial temperature sets the initial driving temperature difference for heat removal.

Initial internal pressure (X_6) and the condensation conservative factor (X_2) demonstrate moderate importance. Pressure influences the saturation temperature and condensation rates, while the condensation factor scales the heat transfer coefficient for condensation on internal surfaces. Initial internal temperature (X_4) has a lesser, though non-negligible, effect, primarily setting the initial thermodynamic state. Atmospheric environmental temperature (X_1) exhibits the smallest impact, likely because it primarily affects the natural convection heat transfer on the outer containment surface, which may be less dominant compared to the internal PCS-driven heat removal in this specific scenario.

The observed ranking aligns with physical understanding: parameters directly governing the dominant heat transfer mechanisms (humidity affecting NCG resistance, evaporation factor and water film temperature affecting PCS performance) and initial state conditions significantly influencing the transient evolution (pressure, humidity) rank highest.

V. Summary and analysis

In this study, a global sensitivity analysis is conducted for the MSLB condition of a CAP1400 nuclear power plant, simulated using the containment thermal response software cosCONT, to assess the variance decomposition method. In the analysis process, due to the complexity of the T-H model, the long computation time leads to low analysis efficiency. In this study, the parallel computing method is employed to facilitate the simultaneous operation of the thermal model, thereby reducing the overall running time and enhancing analysis efficiency.

Through this study, we obtained the important ordering of key parameters under the MSLB condition of the cosCONT simulation of CAP1400, and provided an efficient and reliable analysis case for the sensitivity analysis of the thermal model through parallel computing. In the future, we will conduct further sensitivity analysis from x_1 to x_6, do a more detailed sequencing job.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the State Nuclear Power Research Institute for providing technical support and access to the cosCONT software platform. Special thanks to Prof. Yu from North China Electric Power University for valuable discussions on sensitivity analysis methodology, and to Kaixin Wu for the discussion of methods. The authors declare no conflict of interest.

REFERENCES

[1] Francesco Di Maio, Giancarlo Nicola, Enrico Zio, et al, Ensemble-based sensitivity analysis of a Best Estimate Thermal Hydraulics model: Application to a Passive Containment Cooling System of an AP1000 Nuclear Power Plant[J]. Annals of Nuclear Energy,73(2014).
[2] Curtis B. Storlie, Brian J. Reich, Jon C. Helton, et al. Analysis of Computationally Demanding Models with Continuous and Categorical Inputs.[J] Reliability Engineering & System Safety, 113(2013).
[3] Razi Sheikholeslami, Saman Razavi. Progressive Latin Hypercube Sampling: An Efficient Approach for Robust Sampling-based Analysis of Environmental Models[J].Environmental Modelling & Software, 93(2017).
[4] Xin Zhou, Xiaohan Shen, Zhaoru Liu, ET AL. A novel shadow calculation approach based on multithreaded parallel computing[J]. Energy and Buildings, 312(2024).
[5] Yu Yu , Shengfei Wang , Zhangpeng Guo ,et al. An Efficient Method of Key Parameter Screening for PCCS under SLB Accident in AP1000[J]. Progress in Nuclear Energy, 122(2020).
[6] Yi Yao, Dongxue Yang, Yu Yang. Containment Thermal Response Analysis Software cosCONT V2.0 User Manual[K]. Beijing: State Power Investment Group Science and Technology Research Institute Co., Ltd(2024).
[7] Xunyu Zhou. Validation of COSINE Containment Analysis Program and Parameter Sensitivity Study[D]. Harbin Engineering University(2015).
[8] Li, Dong, Penghao Jiang, Chen Hu, et al. Comparison of Local and Global Sensitivity Analysis Methods and Application to Thermal Hydraulic Phenomena[J]. Progress in Nuclear Energy 11,58(2023).
[9] Yu Yu , Shengfei Wang, Guanyu Liu, et al. Analysis of climatic conditions' effect on passive containment cooling system reliability in AP1000 for multi-unit nuclear power plant site[J]. Progress in Nuclear Energy, 170(2024).
[10] Zhao H, Peterson PF. An overview of modeling methods for thermal mixing and stratification in large enclosures for reactor safety analysis[R]. Idaho National Laboratory (INL) (2010).