EFFECT OF MODEL UNCERTAINTY ON THE SYSTEM PHYSICAL PROCESS FAILURE PROBABILITY

Yu YU, Cheng YANG, Guanyu LIU

School of Nuclear Science and Engineering, Beijing Key Laboratory of Passive Safety Technology Nuclear Energy North China Electric Power University, Beijing, China,102206
Email Address: yuyu2011@ncepu.edu.cn

ABSTRACT

Passive safety system is widely used in new generation reactor design, and physical process failure due to the uncertainties of input parameters and Thermal-Hydraulic(T-H) model is one of the important contributors to system failure. Some methods are developed for input parameters' uncertainties analysis, in this paper, the effect of T-H model uncertainty on the system physical process failure probability is studied. Passive Containment Cooling System (PCCS) in AP1000 nuclear power plant is a typical safety system, which is analyzed as an example in the work, and Monte Carlo (MC) simulation is used to evaluate the system physical process failure probability, and the contributions of T-H model uncertainty is estimated.

Keywords: Passive safety system, Thermal-Hydraulic model uncertainty, physical process failure, MC simulation

I. INTRODUCTION

Passive system is widely used in new generation reactor design to improve the safety of nuclear power plant, and functional failure of passive system (i.e., the system fails to implement its safety function since the system operational condition deviates from the design condition.) should be considered in Probabilistic Safety Analysis (PSA) [1,2] since the system operates based on natural circulation. The system behavior is always described by the Thermal-Hydraulic (T-H) model in the system design and safety analysis, so the uncertainties of input parameters and the T-H model itself can induce system functional failure in some extreme conditions.

Passive Containment Cooling System (PCCS) in AP1000 nuclear power plant [3,4] is a typical passive safety system, the heat produced in the containment after accident is transferred to the atmosphere by natural circulations inside and outside the steel vessel, a T-H model is established based on lumped-parameter method to verify whether the system can complete the safety function in accident condition. The input parameters of such T-H model have uncertainties and the key parameters are screened, also the T-H model has uncertainty itself, since the heat transfer correlation is gained by fitting from the experimental data. And the uncertainty of the correlation can be described by the ratio between theoretical value and experimental value,[5] such uncertainty can have important effect on the hear transfer process, then influence the system physical process failure probability.

In this paper, a method based on Monte-Carlo (MC) simulation is proposed to evaluate the system functional failure probability considering uncertainties of both input parameters and T-H model, and the PCCS in AP1000 is analyzed as an example.

II. SYSTEM DESCRIPTION

Passive Containment Cooling System (PCCS) in AP1000 nuclear power plant is a typical passive safety system, the heat produced in the containment is transferred to the atmosphere through the natural circulations inside and outside the steel vessel, as shown in FIGURE 1[3].

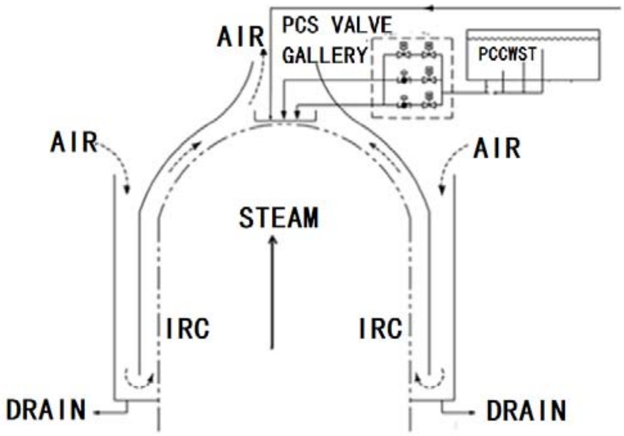

FIGURE 1: PCCS SYSTEM

The Thermal-Hydraulic (T-H) model is established based on lumped parameter method to describe the T-H behavior of the system, including the natural circulation and steam condensation inside the steel vessel, heat conduction through the steel wall and the natural circulation outside the steel vessel. The T-H model has dozens of input parameters including enviromental parameters, operation parameters and construction parameters, and the output is the curve of pressure in the containment varying with the time. The system failure can be judged if the peak value of pressure in the containment exceed 0.5 MPa, that is,

$$P\text{containment} > 0.5 \text{ MPa} \tag{1}$$

Based on the sensitivity analysis, air temperature, air pressure and uncertainty of the steam mass flow are screened as the key inputs affecting the peak value of pressure in the containment.

III. METHOD

For the passive containment cooling system, the system behavior is described by T-H model in section II, and in the model, the heat transfer process inside and outside the steel vessel is expressed by formula:

$$\boldsymbol{\alpha = N_u \frac{\lambda}{L}} \tag{2}$$

Here, α is the heat transfer coefficient, λ is the thermal conductivity which can be gotten by the physical properties of the fluid, and L is characteristic length. The Nusselt number (*Nu*) is gained by the correlation which is fitted based on the experimental data, so the uncertainty of such correlation can have effect on the system reliability evaluation.

In order to describe the uncertainty of the correlation, we use the ratio $Nu_{(e)} / Nu_{(c)}$ as the variable, $Nu_{(e)}$ is the Nusselt number value of the experiment, and $Nu_{(e)}$ is the Nusselt number value of calculation based on the correlation. The probabilistic distribution of such variable is shown in FIGURE 2 [5].

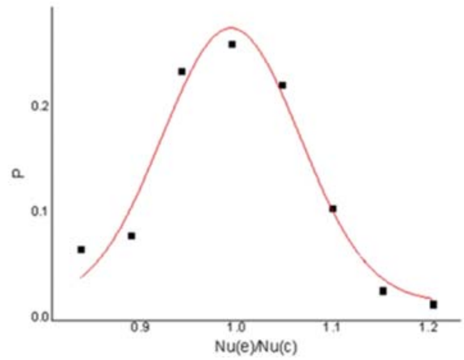

FIGURE 2 [5]. Distribution of ratio $Nu_{(e)} / Nu_{(c)}$

IV. RESULTS

The air temperature, air pressure and uncertainty of the steam flow are the key input parameters of the T-H model after Main Steam Line Break (SLB) accident, and the uncertainty distributions of the above parameters is shown in TABLE I:

TABLE I. Distributions of T-H model input parameters

Input Parameter	Uncertainty Distribution	Description
Air pressure /MPa	[0.09,0.11]	Fitting based on the historical data
Air temperature / ºC	Bi – Normal (FIGURE 3)	Fitting based on the historical data
Steam mass flow uncertainty	[0.98,1.02]	Design specification

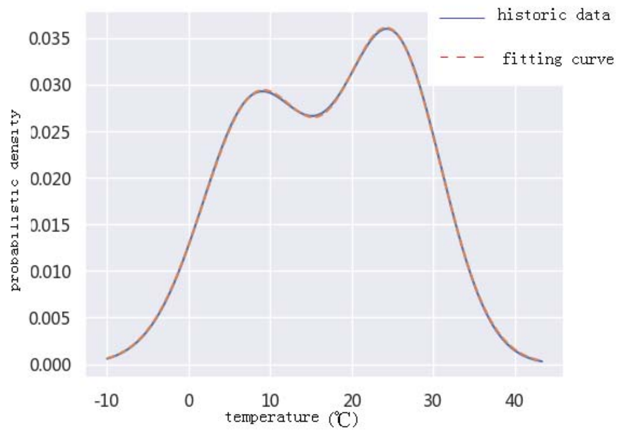

FIGURE 3. Distribution of air temperature

The Monte Carlo (MC) method is used to calculation the system reliability, in the simulation, uncertainties of both parameters and T-H model are considered, and the heat transfer correlation uncertainty is sampled based on FIGURE 2. And the 4.7×10^{-3} is gained for system failure probability, while 2.1×10^{-5} is gotten for without the effect of T-H model uncertainty.

V. CONCLUSIONS

From the results, it can be seen that the ratio $Nu_{(e)} / Nu_{(c)}$ can be used to describe the uncertainty of the heat transfer correlation, and such uncertainty can have important effect on the system physical process failure probability evaluation, based on the result, the failure probability may have increased about two orders.

REFERENCES

[1] IAEA, "Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants", DRAFT SPECIFIC SAFETY GUIDE (DS523), 2020.
[2] F.DI Maio, N. Pedroni, B.Toth, et al. "Reliability Assessment of Passive Safety Systems for Nuclear Energy Application State-of-the-Art and Open Issues", energies, Vol.14, 2021, 4688.
[3] L. T. Schulz, "Westinghouse AP1000 advanced passive plant", Nuclear Engineering and Design, vol.236, pp1547 – 1557, 2006.
[4] Y. Yu, F. Niu, SH. Wang, "One-dimensional model for containment in AP1000 nuclear power plant based on thermal stratification, Applied Thermal Engineering, Vol.70, pp25-32, 2014.
[5] Y. Yu, SH. Wang, F. Niu,etc. "Effect of Nu correlation uncertainty on safety margin for passive containment cooling system in AP1000", Progress in Nuclear Energy, Vol. 79, pp1-7, 2015,