Uncertainty of the Thermal-Hydraulic Model Analysis

Yu YU[*], Yingqiu HU, Junchi CAI, Shengfei WANG, Fenglei NIU
School of Nuclear Science and Engineering
Beijing Key Laboratory of Passive Nuclear Safety Technology
North China Electric Power University, Beijing, China, 102206

Abstract: Passive containment cooling system is innovatively used in AP1000 to improve the safety of nuclear power plant. By this system the steam produced in the containment can be condensed through natural circulation and independent of outside power. However, since the system is a new design, the uncertainty exists in the thermal-hydraulic (T-H) model especially in the correlations of heat and mass transfer. In this paper, the effect of uncertainties of such correlations on the output of T-H model is analyzed. Since the uncertainty of the correlations is within 20% based on the experiments, at different operation conditions such as different air temperature, we run the T-H model with the heat and mass transfer coefficients 5%, 10%, 15% and 20% higher and lower than their calculation value respectively and compare the results with the result of exact value by correlations. Then the amplitude of variation of the T-H model output and the safety margin of the system can be gained for different operation conditions, from the results, it is illustrated that the uncertainties of heat and mass transfer correlations may have important effect on the system reliability in some operation conditions and should be considered in the system reliability model.

Keywords: Passive containment cooling system, natural circulation, thermal-hydraulic model uncertainty

1. INTRODUCTION

Passive system [1] is widely used in new generation reactor design to improve the safety especially under disaster such as earthquake, flooding and so on. However since the system operates depending on natural circulation but not on outside power, uncertainties in physical model and input parameters [2] have important effect on system performance. In past years, more attention is paid to evaluate the influence of parameter's uncertainty, and some methods are developed to analyze the physical process failure [3-8].

Passive cooling containment system (PCCS) [1,9] is innovatively used in AP1000 nuclear power plant, since it's a new design, the thermal-hydraulic process such as heat and mass transfer way is firstly used, and the heat transfer and mass transfer process are described by empirical correlations fitted based on experiment data [10], uncertainty in thermal- hydraulic model should be considered in the system reliability analysis. For this system the model uncertainty is mainly induced by the heat and mass transfer correlations at inside and outside surfaces of the steel vessel, in this paper, we calculate the pressure and temperature in the containment at 5%, 10%, 15% and 20% lower and higher of the heat and mass transfer coefficients than the exact calculation values, then we evaluate the influence of thermal- hydraulic model uncertainty on the system performance based on the results by calculating the safety margin of the system under different uncertainties of heat and mass transfer correlations.

2. THERMAL – HYDRAULIC MODEL UNCERTAINTY

2.1. System description

The passive containment cooling system in AP1000 [10] is an important safety-related system that functions to reduce containment temperature and pressure following a loss-of-coolant accident (LOCA)

[*] E-mail: yuyu2011@ncepu.edu.cn

accident, a main steam line break (MSLB) accident inside containment, or other events that cause a significant increase in containment pressure and temperature. The system achieves this by removing thermal energy from the containment atmosphere to the environment via the steel containment vessel. The simplified flow chart of the system based on the design is shown in Figure.1.[10]

Surrounding the containment, there are the steel containment vessel and the concrete shield building. After LOCA, MSLB or other transient accident, steam rising from break or from the In-Containment Refueling Water Storage Tank (IRWST) injects to containment and be condensed at the inside surface of the steel vessel. The passive containment cooling system is composed of following major components: air baffle, located between the steel containment vessel and the concrete shield building, which defines the cooling air flow path; air inlets composed of three rows of holes in the concrete shield building, and air exhaust which is also incorporated into the shield building structure. In order to enhance the heat transfer, the passive containment cooling water storage tank (PCCWST) which is incorporated into the shield building structure above the containment, and a water distribution system, mounted on the outside surface of the steel containment vessel, which functions to distribute water flow on the containment.

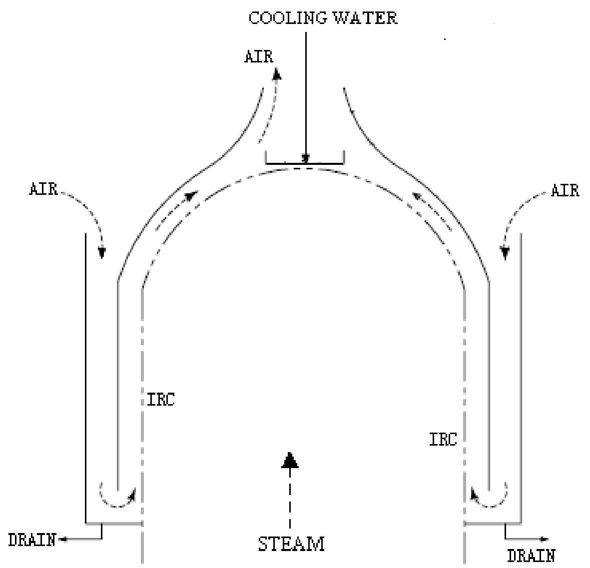


Fig.1 Flow chart of passive containment cooling system

2.2. Thermal-hydraulic model analysis

The steam injected to the steel vessel is the heat source in our analysis, and the heat is transferred to the steel wall when the steam is condensed, then the air in the air flow path will be heated by the hot steel wall and bring the heat to the heat sink—atmosphere. The thermal- hydraulic model is based on the conservative equations (mass, momentum, energy and constituent) to describe the natural circulation inside and outside the steel vessel, and the heat and mass transfer capacity is described mainly by the experiential correlations [11] which are fitted based on experiment data:

$$\mathbf{G = k_G \cdot M_A \cdot (p_{Ai} - p_{AG})} \quad (1)$$

$$\mathbf{Q = \alpha \cdot A \cdot \Delta t} \quad (2)$$

Here formula (1) is the mass transfer correlation and formula (2) is the heat transfer correlation, G is the condensing or evaporating mass flux, k_G is the mass transfer coefficient, M_A is the molecular weight of gas A and p_{Ai} and p_{AG} are the partial pressure of gas A at the interface and at the bulk gas mixture respectively. Q is the heat transfer amount, α is the heat transfer coefficient, A is the heat transfer area and Δt is temperature difference between the surface of the steel vessel and the flux. Mass transfer coefficient (k_G) and heat transfer coefficient (α) are fitted based on experiment data.

The T-H performance of the system is described by the conservative equations and the correlations above. The conservative equations are deduced from the heat transfer theory and can be considered no uncertainty existing. The model uncertainty is mainly aroused by two parts: model hypothesis including boundary conditions, initial conditions and some hypothesis to simplify the physical model as well as the correlations describing the physical process. Some of uncertainty in the model hypothesis can be reflected by the input parameters' probabilistic distributions. Here we focus on the uncertainty of correlations, and heat and mass transfer correlations are fitted from the experiment data, which are two of the important factors influencing the output of the model, while the differences of coefficients (k_G and α)between experiment data and calculation values are always within 20%.

The function of the passive containment cooling system in AP1000 is to decrease the temperature and pressure in the containment, and one of the main failure modes of containment is overpressure, so the output of the T-H model is pressure in the containment.

3. RESULTS

Since the uncertainties of correlations are within 20%, we calculate the pressure in the containment with 5%, 10%, 15% and 20% correlation uncertainties. In our analysis, input parameters are set as their design values, some parameters such as diameter of steam source, steam temperature, steam mass flow rate are related to the accident, in this paper MSLB is analyzed as an example because this accident is one of the most challenging ones to the containment. In the T-H model, the heat and mass transfer correlations are used for heat transferred from mixture of air and steam to the steel vessel and steam condensed at the inside surface of the vessel, and heat transferred from steel vessel to the air in the air flow path and cooling water evaporated at the outside surface of the vessel. The heat and mass transfer correlations are in accordance for the same location, that is, the uncertainty of heat and mass transfer are highly correlated so we use the same uncertainty for the two correlations, and the 81 combination states of the correlations with 9 values of heat and mass transfer coefficients (0, ±5%, ±10%, ±15% and ±20%) as well as the results are listed in Table1. From the results, it can be seen that the difference between the max and minimum values of the pressure in the containment is 0.013MPa induced by the uncertainties of thermal-hydraulic model.

Since the design value of containment pressure is 0.5 MPa, the safety margin is:

$$\Delta \mathbf{P} = \mathbf{0.5} - \mathbf{P_{containment}} \qquad \text{(MPa)} \qquad (1)$$

Here, $\Delta\mathbf{P}$ is the safety margin and $P_{containment}$ is the pressure in the containment calculated by the thermal-hydraulic model.

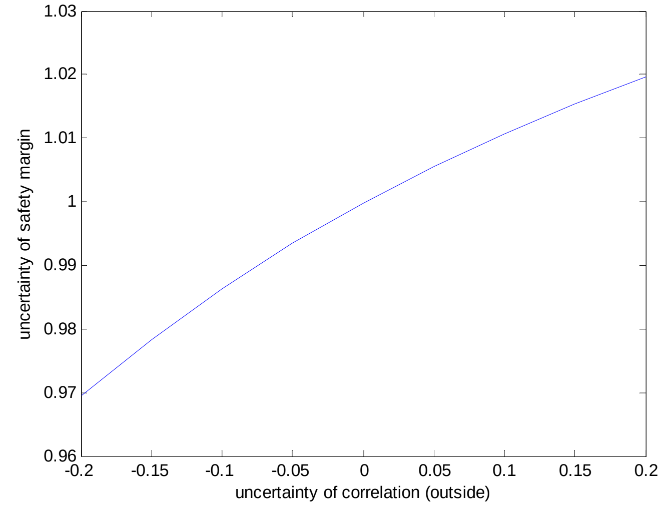
Table 1: Correlation Uncertainties and results

Uncertainties of correlations		Pressure in the containment (MPa)
Heat and Mass transfer (inside surface of the vessel)	Heat and Mass transfer (outside surface of the vessel)	
0	0	0.4062
-20%	-20%	0.4138
-20%	-15%	0.4131
-20%	-10%	0.4124
-20%	-5%	0.4118
-20%	0	0.4113
-20%	5%	0.4108
-20%	10%	0.4103
-20%	15%	0.4099
-20%	20%	0.4096
-15%	-20%	0.4125
-15%	-15%	0.4117
-15%	-10%	0.4110
-15%	-5%	0.4104
-15%	0	0.4098
-15%	5%	0.4093
-15%	10%	0.4089
-15%	15%	0.4085
-15%	20%	0.4081
-10%	-20%	0.4112
-10%	-15%	0.4105
-10%	-10%	0.4097
-10%	-5%	0.4091
-10%	0	0.4085
-10%	5%	0.4080
-10%	10%	0.4075
-10%	15%	0.4071
-10%	20%	0.4067
-5%	-20%	0.4101
-5%	-15%	0.4093
-5%	-10%	0.4086
-5%	-5%	0.4079
-5%	0	0.4073
-5%	5%	0.4068
-5%	10%	0.4063
-5%	15%	0.4059
-5%	20%	0.4055
0	-20%	0.4091
0	-15%	0.4082
0	-10%	0.4075
0	-5%	0.4068
0	5%	0.4057
0	10%	0.4052
0	15%	0.4048
0	20%	0.4044
5%	-20%	0.4081
5%	-15%	0.4072
5%	-10%	0.4065
5%	-5%	0.4058
5%	0	0.4052
5%	5%	0.4047

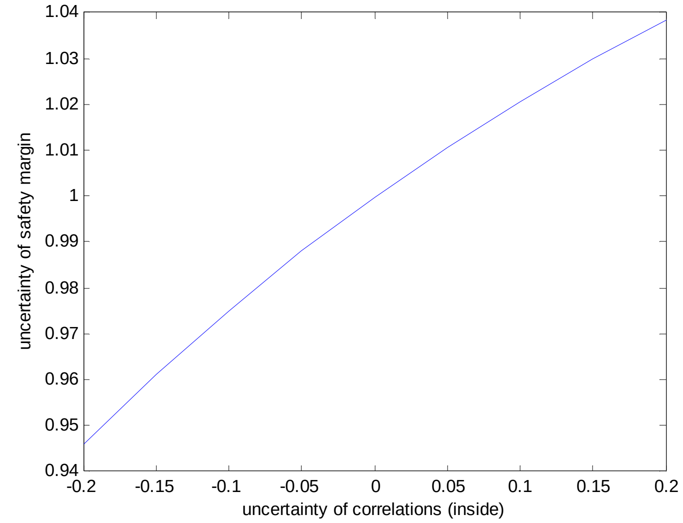
5%	10%	0.4042
5%	15%	0.4037
5%	20%	0.4033
10%	-20%	0.4072
10%	-15%	0.4063
10%	-10%	0.4056
10%	-5%	0.4049
10%	0	0.4043
10%	5%	0.4037
10%	10%	0.4032
10%	15%	0.4027
10%	20%	0.4023
15%	-20%	0.4063
15%	-15%	0.4055
15%	-10%	0.4047
15%	-5%	0.4040
15%	0	0.4034
15%	5%	0.4028
15%	10%	0.4023
15%	15%	0.4019
15%	20%	0.4014
20%	-20%	0.4056
20%	-15%	0.4047
20%	-10%	0.4039
20%	-5%	0.4032
20%	0	0.4026
20%	5%	0.4020
20%	10%	0.4015
20%	15%	0.4010
20%	20%	0.4006

The variations of safety margin uncertainties along with the uncertainties of correlations are shown in Fig.2 and Fig.3. In the figures, the horizontal ordinate is the uncertainty of correlations, while the longitudinal coordinates is the uncertainty of the safety margin. From the figures it can be seen that the uncertainty of safety margin induced by uncertainties of correlations is within ±10%.

Fig.2 shows the uncertainty of safety margin variation along with the uncertainties of correlations inside and outside respectively, from which we can see that when uncertainty of correlations inside is zero the uncertainty of safety margin induced by uncertainty of correlations outside is from -3% to 2%, while the uncertainty of safety margin induced by uncertainty of correlations inside is from -6% to 4% when uncertainty of correlations outside is zero. From the results it can be seen that the amplitude of safety margin variation induced by the uncertainties of correlations is lower than the variation amplitude of correlations itself, the reason can be analyzed as: the heat transfer correlation influences the total heat transfer amount, it influences the temperature in the containment directly and then affects the pressure in the containment, the heat transfer coefficient is lower, the temperature and pressure in the containment are higher. While the influence of mass transfer correlation can be analyzed from two aspects: on the one hand, if the mass transfer capacity decreases, the amount of steam condensed reduces and then more steam will retain in the containment and the pressure in the containment will increase; on the other hand, the energy by which the air in the containment will be heated is mainly from the latent heat when steam is condensed, so if the amount of steam condensed decreases, the heat to the containment will be lower and then the temperature and pressure increasing velocity will decrease. The influence of correlations' uncertainties on the system pressure is synthesized result of the above two ways.



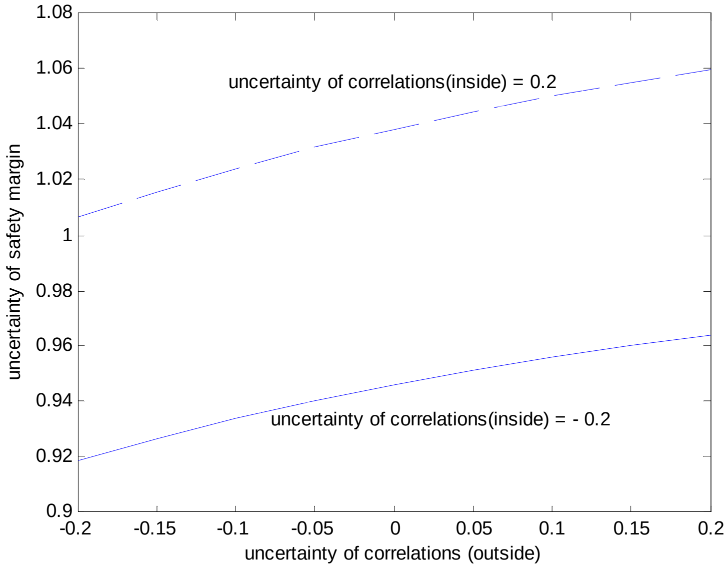
(a) Uncertainty of correlations (inside) = 0



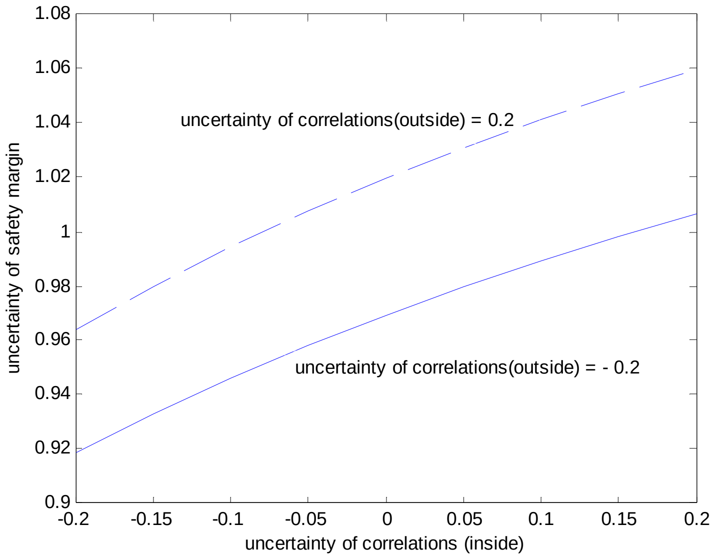
(b) Uncertainty of correlations (outside) = 0

Figure.2 Influence of correlations' uncertainties

From the results it can be also seen that influences of uncertainties of heat and mass transfer correlations at inside and outside of the containment are difference, Fig.3 shows the influence of correlations inside and outside when the other one are -20% and 20% respectively, the influence of uncertainties of correlations inside is more important than the influence of uncertainties of correlations outside, since the correlations inside affect the heat and mass transfer synthetically as described above, while for correlations outside, mass transfer correlation affects the cold water evaporating process primarily, and heat transfer process is affected by more complex factors such as air speed and so on.



(a) Influence of correlations' uncertainties (outside) at different uncertainties of correlations for inside



(b) Influence of correlations' uncertainties (inside) at different uncertainties of correlations for outside

Figure.3 Influence of correlations' uncertainties

4. CONCLUSIONS AND DISSCUSSION

In this paper we analyze the effect of correlation uncertainties on the system thermal-hydraulic performance, and the uncertainty of safety margin induced by uncertainties of correlations is about 10% for MSLB accident in AP1000, which may influence the system failure probability and should be considered in the system reliability analysis. From the results it can be concluded that the influence of the T-H model uncertainty on the system reliability is affected by thermal- hydraulic performance, so it will be affected by other factors such as accident (e.g. MSLB, LOCA or other accidents), uncertainties of input parameters, equipment state and so on. Since the T-H model is a complicated non-linear system and there are numerous factors influencing the system characteristic, so the uncertainties of correlations may need to be considered in the system reliability model combined with the uncertainties of input parameters and the equipment fault.

Acknowledgements

This work was supported by The National Natural Science Foundation of China [grant number: 51206042, 91326108]

References

[1] T.L.Schulz. "*Westinghouse AP1000 advanced passive plant*", Nuclear Engineering and Design, 236, pp1547-1557, (2006).
[2] J. Oh, W. G. Michael. "*Methods for comparative Assessment of Active and Passive Safety Systems with respect to Reliability, Uncertainty, Economy, and Flexibility*", Proceedings of 9th Conference on Probabilistic Safety Assessment and Management (PSAM9). Hongkong, China,2008.
[3] E. Zio, N. Pedroni. "*Estimation of the functional failure probability of a thermal-hydraulic passive system by Subset Simulation*", Nuclear Engineering and Design, 239, pp580-599, (2009).
[4] L.Burgazzi, V. Kopustinskas, VL.Lumia, et al. "*Recommendations for the integration of passive system reliability in PSA*". Report, the 5th EURATOM framework programme 1998-2002 key action nuclear fission, 2004.
[5] Y. YU, J.J. TONG, T. LIU, et al. "*A MODEL FOR PASSIVE SYSTEM RELIABILITY ANALYSIS*", Proceedings of 18th International Conference on Nuclear Engineering (ICONE18), Xi'an, China, 2010.
[6] Y. Y, T. LIU, J. J. TONG,et al. "*Variance Decomposition Sensitivity Analysis of a Passive Residual Heat Removal System Model*", Social and Behavioral Sciences, 2, pp7772-7773, (2010).
[7] Y. Yu , T. LIU, J.J. TONG, et al. "*Multi-Experts Analytic Hierarchy Process for the Sensitivity Analysis of Passive Safety System*", Proceedings of the 10th International Probabilistic Safety Assessment & Management Conference(PSAM10), Seattle, USA, 2010.
[8] E. Zio, F. D. Maio, J. J. Tong. "*Safety margins confidence estimation for a passive residual heat removal system*", Reliability Engineering and System Safety. 95, pp828-836, (2010).
[9] Foret LJ. "*AP1000 Probabilistic Safety Assessment*", Report, Westinghouse Electric Company LLC, Pittsburgh, PA, USA. Report no. APP-GW-GL-022, DCP/NRC1548, 2003.
[10] J. G. Sun, T. H. Chien, J. Ding, et al. "*Validation of COMMIX with Westinghouse AP-600 PCCS Test Data*", Proc. of the 21th Water Reactor Safety Information Meeting, Bethesda, MD, 1993.
[11] A.L.Hines. "*Mass Transfer and Applications*", Englewood Clifs: Prentice-Hall, Inc., 1985.