Modeling the Effect of Air Temperature and Pressure on the Reliability of a Passive Containment Cooling System

Yu YU[a], Francesco DI MAIO[b], Enrico ZIO[b,c], Bin WANG[a], Shengfei WANG[a], Zhangpeng GUO[a], Xuefeng LYU[a], and Fenglei NIU[a]
[a] School of Nuclear Science and Engineering,
Beijing Key Laboratory of Passive Safety Technology for Nuclear Energy
North China Electric Power University, Beijing, China
[b]Energy Department, Politecnico di Milano, Milan, Italy
[c] Chair on System Science and Energetic Challenge, European Foundation for New Energy – EDF, Ecole Centrale de Paris and Supelec, Paris, France

Abstract: Passive systems safety is a key design aspect of new generation Nuclear Power Plants (NPPs). The Passive Containment Cooling System (PCCS) of the AP1000 NPP is a typical passive safety system, by which the heat produced in the containment is transferred to the environment through natural circulation and atmosphere is used as ultimate heat sink, making the climatic conditions of the plant location influencing the system reliability. In this paper, the effect of air temperature and pressure on the system reliability is analyzed by the variance decomposition sensitivity method. Results show the importance of considering the joint effect of the air pressure and temperature for the system reliability assessment.

Keywords: Passive Systems Reliability, Sensitivity Analysis, Variance Decomposition Method, Passive Containment Cooling System, Nuclear Power Plant.

1. INTRODUCTION

The Passive Containment Cooling System (PCCS) of the AP1000 NPP is a typical passive safety system in which the heat produced in the containment is transferred to the environment through natural circulation [1,2,3]. The atmosphere is the ultimate heat sink [4], so that the climatic conditions of the NPP geographical location may influence the system reliability [5]. In this paper, the effect of air temperature and pressure on the system reliability is analyzed by means of a Thermal-Hydraulic (T-H) model, which describes the evolution of safety parameters (e.g., the containment inner pressure) along an accident progression. After a Loss of Coolant Accident (LOCA) or Steam Line Break (SLB), the steam injected into the steel vessel makes the values of the inner pressure and temperature escalate towards the upper safety thresholds. If the inner pressure peak value exceeds the threshold defined by structural constraints, the PCCS failure occurs.

Being the atmosphere the heat sink, the air temperature and pressure may have an important effect on the natural circulation within the PCCS. Therefore, they need to be considered in the modelling of the T-H accident progression. For this, it is necessary to evaluate the relationship between the air temperature and pressure, and its effect on the system reliability. To this aim, we implement a variance decomposition method [6,7,8] to analyze the sensitivity of the T-H model to two alternative assumptions, i.e., independent or correlated air pressure and temperature. The results will allow taking a decision regarding the most appropriate modelling alternative to be adopted for the reliability assessment of the PCCS of the AP1000.

The remainder of the paper is as follows. In Section 2, we describe the PCCS and the accident progression considered, in Section 3, we introduce the variance decomposition method, and in Section 4 conclusions are drawn. We will see that it is important to account for the correlation between air temperature and pressure in the reliability assessment of the PCCS of the AP1000.

2. SYSTEM DESCRIPTION

2.1 The PCCS of the AP1000

The PCCS is one of the most important safety systems in the AP1000 NPP, whose function is to transfer through natural circulation the heat produced in the containment to the atmosphere [1,9]. When the steam is injected into the vessel drawing an accident, such as a LOCA and SLB, it is cooled and condensed because the heat is transferred to the environment through the vessel to avoid the containment overpressure (whose safety threshold is 0.5 MPa) [4], while the cooling water is sprayed on the outer side of the steel vessel to enhance the heat transfer. A sketch of the PCCS process is shown in Fig.1 [9].

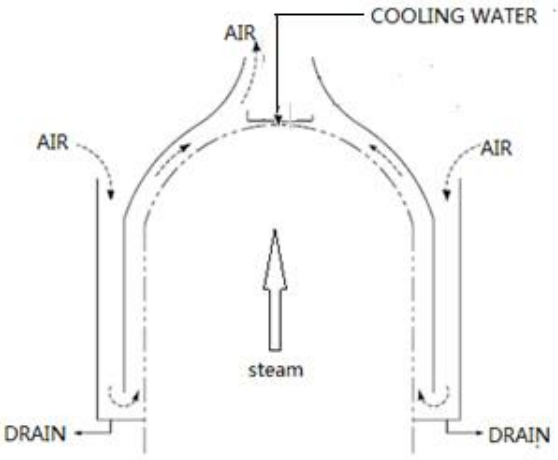

Fig.1 Sketch of the PCCS

2.2 The T-H Model

A T-H model is developed to simulate the system behavior drawing an accident. The list of the N=10 input parameters that must be fed to the T-H model to provide in output the inside pressure and temperature is give in Table 1, with their uncertainties.

Table 1: Input parameters and uncertainties

Parameter	**Interval**	**Distribution**	**Source**
Air pressure	[0.09,0.11]	Uniform	Historical data
Air temperature	0.47×[5.0,4.3] +0.53×[20.7,4.3]	Bi-Normal	Historical data
Steam mass flow	1~1.02	Uniform	Measuring error
Containment diameter	Design value* ±0.1m	Uniform	Construction error
Cylinder height	Design value* ±0.06m	Uniform	
Free volume in the containment	Design value* ±3.2⁎ 10^{-3} m^3	Uniform	
Up head height	Design value*±0.06m	Uniform	
Mass flow of the cooling water	Design value* ±10%	Uniform	Measurement error
Film covering ratio at the beginning	[0.75,0.9]	Uniform	Experimental data
Wind speed	[1,5]	Uniform	Historical data

* *confidential*

The physical process modeled proceeds as follows [5]: upon a LOCA or a SLB, the steam is injected into the steel vessel, the air in the containment is heated, and its temperature and pressure rise, the steam and hot air move upwards until the steel vessel is reached, where they are cooled down because the heat is transferred into the air tunnel outside the steel vessel where cooling water is sprayed, heating the air that is returned to the atmosphere through the chimney at the top the containment. The amount of the heat transferred to the environment that equals the heat removed from the inside of the containment and the resulting inner pressure and temperature are determined by the outer climatic conditions (air temperature and pressure), being the atmosphere the only available heat sink. As an example, Fig. 2 and Fig. 3 show the evolution of the inner pressure and temperature, respectively, along the progression of a generic SLB accident.

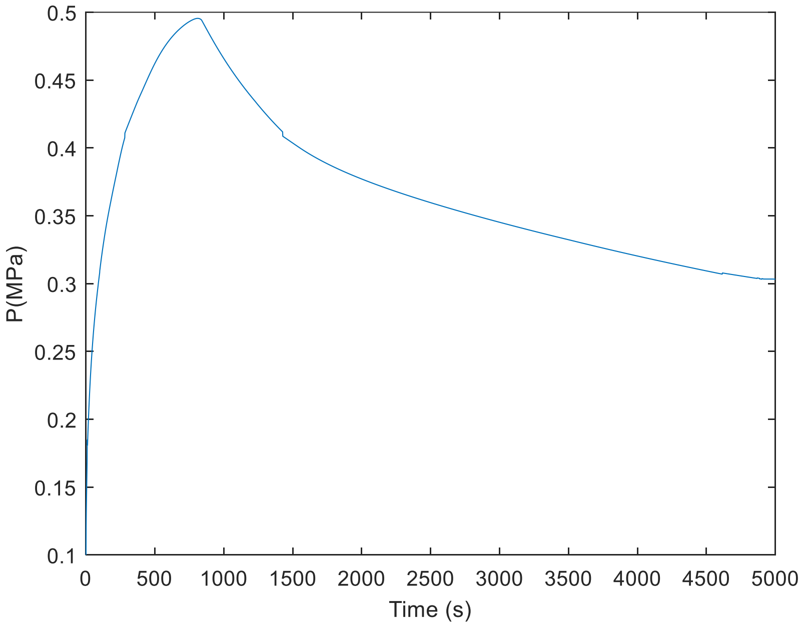

Fig.2 Inner pressure curve after a SLB accident

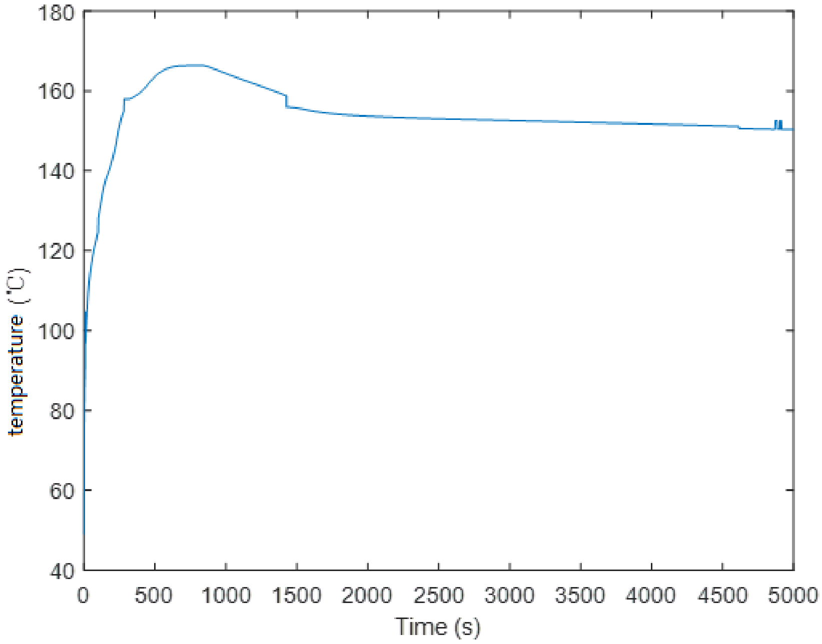

Fig.3 Inner temperature curve after a SLB accident

In Fig. 2 and Fig. 3 we can see that the pressure and temperature rapidly increase in a short time after the accident occurs, since a large amount of steam is suddenly injected into the steel vessel upon SLB; then, the natural circulation is established and the heat transfer is enforced as long as allowed by the temperature difference between the fluid temperature and the air temperature; then, when the heat produced in the containment balances the heat transferred to the atmosphere, the temperature reaches its maximum, and starts slowly decreasing when the heat transferred exceeds that produced due to a reduction of the steam flow.

It is clear that air temperature and pressure have effects on the accident progression and, eventually, on the PCCS reliability. In what follows, we test two alternative hypotheses (i.e., independent and correlated air temperature and pressure) on the T-H model capability of simulating the accident progression and the reliability of the PCCS, by a variance decomposition method.

The assumed correlation between air temperature and pressure is plotted in Fig.4 [4, 10].

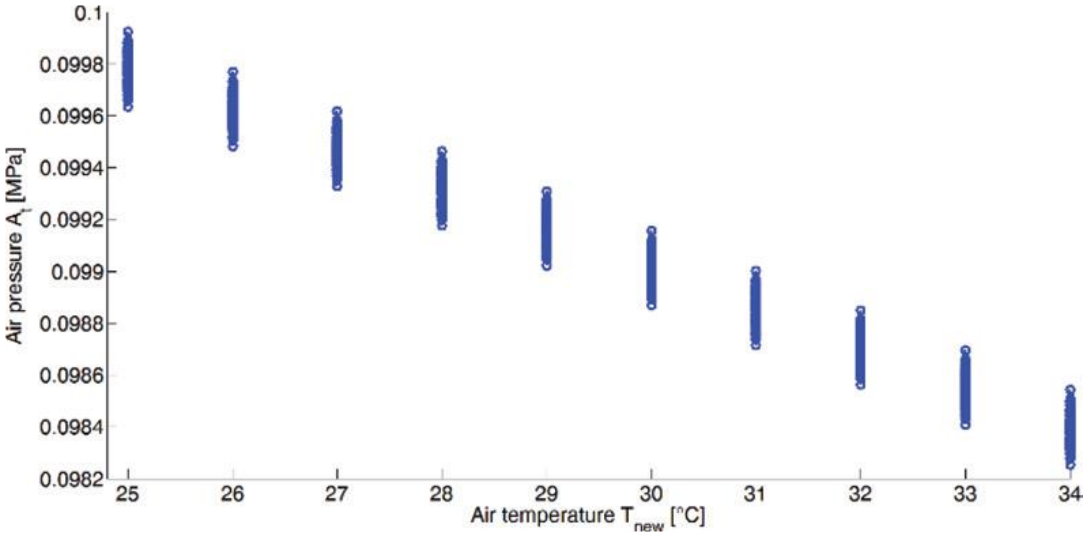

Fig.4 Correlation between air pressure and temperature [4]

3. SENSIVITITY ANALYSIS

Let us assume Y to be the output of the T-H model with $X_1, X_2, \ldots, X_N$ inputs [11,12]:

$$Y=f(X_1, X_2 \ldots X_N) \tag{1}$$

In our case, Y is the pressure in the containment and $X_1 \sim X_N$ are the $N=10$ inputs listed in Table 1. To calculate the sensitivity index η_l^2 for each of the l-th input parameters, we proceed as follows:

- Sample s values of x_l from its probabilistic distribution, that is $\{x_l^1, x_l^2, \ldots, x_l^s\}$;
- For each value x_l^j, sample r values of all the variables except x_l, $x_1 \sim x_N$, that is $\{x_1^1 \sim x_N^1, x_1^2 \sim x_N^2, \ldots, x_1^r \sim x_N^r\}$ from the conditional distribution $f_{x1\sim xN \mid xl}(x_1 \sim x_N \mid x_l^j)$;
- Calculate the T-H model output $y^{jk}=f(x_l^j, x_{1\sim N\neq l}^k)$, $j=1,2,\ldots,s$, $k=1,2,\ldots,r$, obtaining an output matrix of order (s,r);
- For each row $j=1,2,\ldots,s$ of the matrix, calculate:

$$\hat{y}(x_l^j) = \frac{1}{r}\sum_{k=1}^{r} y^{jk} \cong E_{X_1\sim X_{N\neq l}}[Y|x_l^j] \tag{2}$$

- Calculate the expected value of *Y*:

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

- Calculate the variances:

$$\hat{V}_{X_l}\left[E_{X_1\sim X_{N\neq l}}(Y|x_l)\right] = \frac{1}{s-1}\sum_{j=1}^{s}[\hat{y}\,(x_l^j) - \bar{y}]^2 \tag{4}$$

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

- Calculate the importance factor:

$$\boldsymbol{\eta_l}^2 = \frac{\hat{V}_{X_l}\left[E_{X_1\sim X_{N\neq l}}(\boldsymbol{Y}|\boldsymbol{x_l})\right]}{\hat{V}[\boldsymbol{Y}]} \tag{6}$$

4. RESULTS

4.1 Results of the sensitivity analysis considering independent air temperature and pressure

When air temperature and pressure are assumed to be independent as in Table 1, we obtain the results of the sensitivity analysis as reported in Table 2.

Table 2: Results -- independent air temperature and pressure

Parameter	η^2
Air pressure	1.03
Air temperature	0.065
Steam mass flow	0.051
Containment diameter	0.033
Cylinder height	
Free volume in the containment	
Up head height	
Mass flow of the cooling water	0.032
Film covering ratio at the beginning	0.039
Wind speed	0.029

It can be seen that air pressure is the most crucial parameter, and the air temperature and steam mass flow are more important than all others that have negligible importance. Since the atmosphere is the heat sink and the hot steam injected to the containment is the heat source, this result is reasonable. This would suggest an accurate modelling of air temperature and pressure.

4.2. Results of the sensitivity analysis considering correlated air temperature and pressure

Assuming the air temperature and pressure correlation of Fig.4 [4], we obtain the results listed in Table 3.

Table 3: Results -- Considering Air Temperature and Pressure Relationship

Parameter	η^2
Air pressure and temperature	0.13
Steam mass flow	0.99
Containment diameter	0.071
Cylinder height	

Free volume in the containment	
Up head height	
Mass flow of the cooling water	0.036
Film covering ratio at the beginning	0.031
Wind speed	0.045

We can see that the air pressure and temperature are still among the key parameters, but the steam mass flow is the most crucial one. The different results with respect to that obtained considering independent air temperature and pressure can be explained by the negative air pressure and temperature correlation of Fig.4, that weakens the negative effects of high air temperature on the PCCS reliability. Neglecting the correlation would have incorrectly driven the analyst to consider the steam mass flow less important than air temperature and pressure.

5. CONCLUSIONS

In this paper, the effects of air temperature and pressure modelling assumptions on passive safety system modelling is analyzed by the variance decomposition method. Results show the importance of considering the correlation between the air pressure and temperature. The study suggests high priority should be given to properly address the climate parameters (e.g. air temperature and pressure).

Acknowledgements

This work is supported by "The National Natural Science Foundation of China (91326108), (51306057), (11705058)", "National Science and Technology Major Project (2015ZX06002007)" and "The Fundamental Research Funds for the Central Universities (2018ZD10)".

References

[1] L. T. Schulz, "*Westinghouse AP1000 advanced passive plant*", Nuclear Engineering and Design, vol.236, pp1547 – 1557, (2006).
[2] J. Oh and W. G. Michael, "*Methods for comparative Assessment of Active and Passive Safety Systems with respect to Reliability, Uncertainty, Economy, and Flexibility*", Proc. 9th Conference on Probabilistic Safety Assessment and Management (PSAM9), Hongkong, China, (2008).
[3] L. Burgazzi, "*Comparative assessment of passive and active systems for the development of advanced reactors*", Report for the frame of LP1, Objective B (Safety assessment and accident consequences evaluation), task B2-2 of PAR 2015, ADP ENEA-MSE, (2016).
[4] Y. Yu, F. L. Niu, SH. F. Wang, "*One-dimensional model for containment in AP1000 nuclear power plant based on thermal stratification,* Applied Thermal Engineering, Vol.70, pp25-32, (2014).
[5] U. Sahlin, F. Di Maio, M. Vagnoli and E. Zio, *"Evaluation the impact of climate change on the risk assessment of Nuclear Power Plant"*, Safety and Reliability of Complex Engineering Systems, Taylor & Francis Group, London, pp2613-2621, (2015).
[6] F. Di Maio, G. Nicola, E. Borgonovo and E. Zio, *"Invariant methods for an ensemble-based sensitivity analysis of a passive containment cooling system of an AP1000 nuclear power plant"*. Reliability Engineering and System Safety, Vol. 151, pp. 12-19, (2016).
[7] F. Di Maio, G. Nicola, E. Zio and Y. Yu, *"Finite mixture models for sensitivity analysis of thermal hydraulic codes for passive safety systems analysis"*, Nuclear Engineering and Design, Vol. 289, pp144-154, (2015).
[8] Y. Yu, T. Liu, J. J. Tong, J. Zhao, F. Di Maio, E. Zio and A. L. Zhang. *"Variance Decomposition Sensitivity Analysis of a Passive Residual Heat Removal System Model"*, Procedia Social and Behavioral Sciences, Vol.2, pp7772-7773, (2010).
[9] L. J. Foret. "*AP1000 Probabilistic Safety Assessment. Report*". Westinghouse Electric Company LLC, Pittsburgh, PA, USA.. Report no. APP-GW-GL-022, DCP/NRC1548, (2003).

[10] M. Vagnoli, F. Di Maio, E. Zio, “*Ensembles of climate change models for risk assessment of nuclear power plants*”, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, DOI: 10.1177/1748006X17734946.

[11] F. Di Maio, G. Nicola, E. Zio and Y. Yu, “*Ensemble-based sensitivity analysis of a Best Estimate Thermal Hydraulics Model: Application to a Passive Containment Cooling System of an AP1000 Nuclear Power Plant*”, Annals of Nuclear Energy, Vol. 73, pp. 200-210, (2014).

[12] E. Zio. *Computational Methods for Reliability and Risk Analysis*. World Scientific, Singapore, (2008).