Numerical and Experimental Study of Mixing and Thermal Stratification in Passive Containment

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Abstract

This research investigates the mixing and thermal stratification phenomenon caused by the plumes or buoyant jets in passive containment. The facility used in the study is one twentieth of the prototype passive containment of AP1000. The experiments are both conducted under non-adiabatic and adiabatic condition. In each condition, two key parameters, inlet temperature and flow rate are tested by controlling variables to identify their influence on the thermal stratification phenomenon. The experiment results are compared with the numerical computation and they reach a good agreement.

Keywords

Numerical simulation, mixing and thermal stratification, passive containment.

1. Introduction

The passive containment cooling systems (PCCS) [1,2] is an important part of the advanced PWR passive safety systems, which is one of the key features of AP series pressurized water reactor. Different from the pre-stress concrete containment of previous PWR, the containment of AP1000 has two independent layers, inside of which is a cylindrical steel container while the outside layer is reinforced concrete structure. The cylindrical steel container with elliptical upper and lower heads is the main heat-transfer surface. During the loss of coolant accident (LOCA) and main steam line break accident (MSLB), steam is cooled down on the inner wall of steel containment , and heat can be transferred to the outside of containment[3].Then the heat will be ultimately transferred to atmosphere though air convection, heat radiation and water spray liquid film evaporation in order to prevent pressure and temperature from exceeding the limits.

When developing PCCS during the process of designing AP600/AP1000, Westinghouse listed the important phenomena identification and ranking table (PIRT), in which the mixed layer and circulation score 9.0 means that the phenomenon is important. Limited by its own characteristic of WGOTHIC software in which the lumped parameter method is applied for the simulation, it cannot reflect mixing and thermal stratification. In the transient calculation process in MSLB, only the natural convection was taken into consideration, whereas the heat transfer and mass transfer phenomena during the forced convection were ignored. Instead, in the process of the LOCA simulation, after the end of discharge stage, condensation and convection in sealed compartment will not be taken into account, so this will compensate for the weakening of the heat transfer caused by thermal stratification. [4]

Professor Peterson demonstrated that the thermal stratification phenomenon can be determined by Fr [5]. By calculating the Fr of AP600/1000 and referring to other software calculation results, Westinghouse reached a conclusion that the thermal stratification phenomenon has little chance to happen in AP600/1000. However, in the process of developing CAP1400 and CAP1700, thermal stratification is likely to occur due to the change of the containment size and inner structure. Once it occurs, it will have a huge impact on the establishment of the natural circulation as well as steam condensation inside the containment, which may affect the performance of PCCS. So it is necessary to carry out the thermal stratification experiment combined with CFD numerical simulation to provide the basis theory for this phenomenon, and to get a better understanding of the heat transfer efficiency at different heights in containment.

In this paper, small scaling containment experiments with hot dry air injection are conducted to simulate the LOCA accidents. Two key parameters, i.e. injection temperature and flow rate are taken into consideration to identify their influence on the mixing and thermal stratification. The experiments are conducted under non-adiabatic and adiabatic condition.

2. Experimental details

The experimental facility concludes a steel passive containment, an air supply system and a temperature measure system. Figure 1 presents the schematic of the facility and the details of the distribution of the measuring points on the containment.

The size of experiment steel passive containment is one twentieth of the prototype AP1000 containment. It is made of the type 304 stainless steel with the height of 3.34m, diameter of 2m and thickness of 6mm. The containment has an ellipse shape dome and cylindrical side wall with its lower part embedded underground. There is a removable rectangle door at the side of the containment wall providing a convenient pass in and out for researchers and one pipeline is penetrated through it.

The air supply system produces constant hot dry air for the experiment with an air blower, an air heater, a volumetric flow meter, a steel corrugated pipe, an angle-adjust rack and a nozzle. There are two platinum resistance temperature sensors on the air heater so the temperature can be controlled by the feedback signal. The pipeline is wrapped by insulating materials to reduce the heat loss. The diameter of the nozzle is 25mm and the height of the nozzle is 60cm from the floor of the containment. The flow rate can be monitored by the volumetric flow meter and controlled by the valves.

Thermocouples are distributed in the interested area inside the containment to measure the temperature. They are connected to the Anilent multifunction switch/measure unit for data collection which will be processed by the bundled software Benchlink Data Logger for further analysis. The distribution of thermocouple spots for the thermal stratification measurement is also shown in Figure 1. Details of the distribution are as follows:

There are 7 layers (red lines) in the containment, their interval distance are described in Fig. 1.

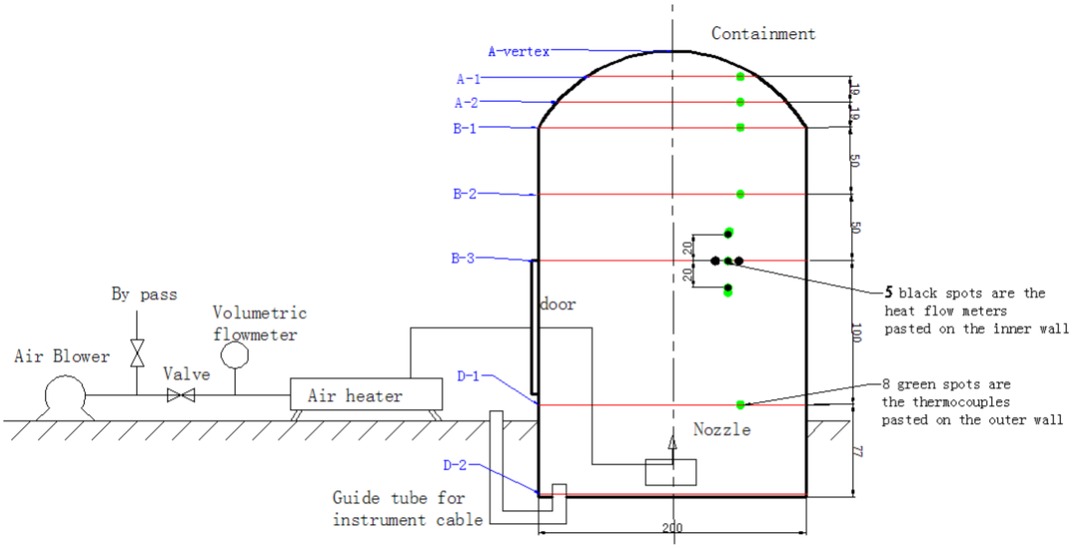

Fig. 1 Schematic of the experimental facility

(b) The thermocouples are placed at the center of the cross section, midpoint of the radius and 5cm away from the inner wall, including the ones that adhere on the inner wall so there are totally 13 thermocouples on each layer.

(c) There is a thermocouple installed at the nozzle.

(d) The T-type thermocouples are used in the space of the containment and K-type thermocouples are applied for the wall temperature.

The parameters of the steel containment are listed in Table 1.

Table 1 Designed parameters of the steel containment

Parameters		Value
Steel containment	Height in total, m	3.27
	Height of the dome, m	0.57
	Height of the vertical body, m	2.2
	Inner diameter, m	1.98
	Thickness, m	0.01
	Design Pressure, MPa	0.1
	Design Temperature, oC	20-100
Insulating layer	Thickness, cm	1
Working Medium	Air, m3/h	0-30
	Temperature, oC	0-100
Measuring points	Points in the space	91
	Point at the nozzle	1

The experiments are carried out for non-adiabatic and adiabatic condition, in the former condition, the steel containment body was exposed in the air while in the adiabatic condition, the over ground body of the containment was covered with two layers sponged rubber insulation sheet to reduce the heat lost. In each condition, the experiments were carried out for two injection temperatures (T_{in}) at the flow rate (q_v) of 15m^3/h and two flow rates (q_v) at the injection temperatures (T_{in}) of 100^{o}C. Then the comparison can be made by changing one single parameter to get a better understanding of the influence on each parameter. In the beginning of each test, the inlet temperature at the injection nozzle was controlled by setting the power of the air heater. Each individual experiment should process for 6 hours to reach a stable state, and then the data can be collected. Table 2 lists the series of the tests.

Table 2 Experimental conditions

Conditions	Inlet temperature(oC)	Flow rate(m3/h)	Room temperation(oC)	Relative Humidity
Non-adiabatic	50	15	21.8	40%
	100	15	21.6	40%
	100	10	21.1	52%
	100	18	20.7	53%
Adiabatic	50	15	20.1	45%
	100	15	20.8	43%
	100	10	21.3	51%
	100	17.4	20.7	49%

3. Results

3.1 CFD model

CFD simulations were also done to provide comparisons with the experimental results. Fig. 2 shows the geometry of the CFD simulation. All parameters and boundaries in the model are simulated as same as the experiments. The ceiling wall (dome) and over ground cylindrical side wall are considered to be air cooled under a constant room temperature. The underground wall and the floor wall are considered to be constant temperature corresponding to the **experimental conditions**. The turbulence k-ε model and steady method were used in the calculations.

3.2 Comparison

The results are compared in curve charts. The X-axis in the graph is the height in the containment, and Y-axis represents the average temperature of the layer of the cross section in corresponding height. There are 7 layers in the containment so 7 points are used for plotting the experimental data. In CFD simulation, the average temperatures of each layer are taken from the cross sections every 20cm interval from bottom to vertex. The curves of the simulation temperatures can be extended to the vertex while the experimental data only reach the height of 315cm due to the experimental condition. The fluctuation range of flow rate is $0.3m^3/h$ and of the temperature is 2^oC in the experiments.

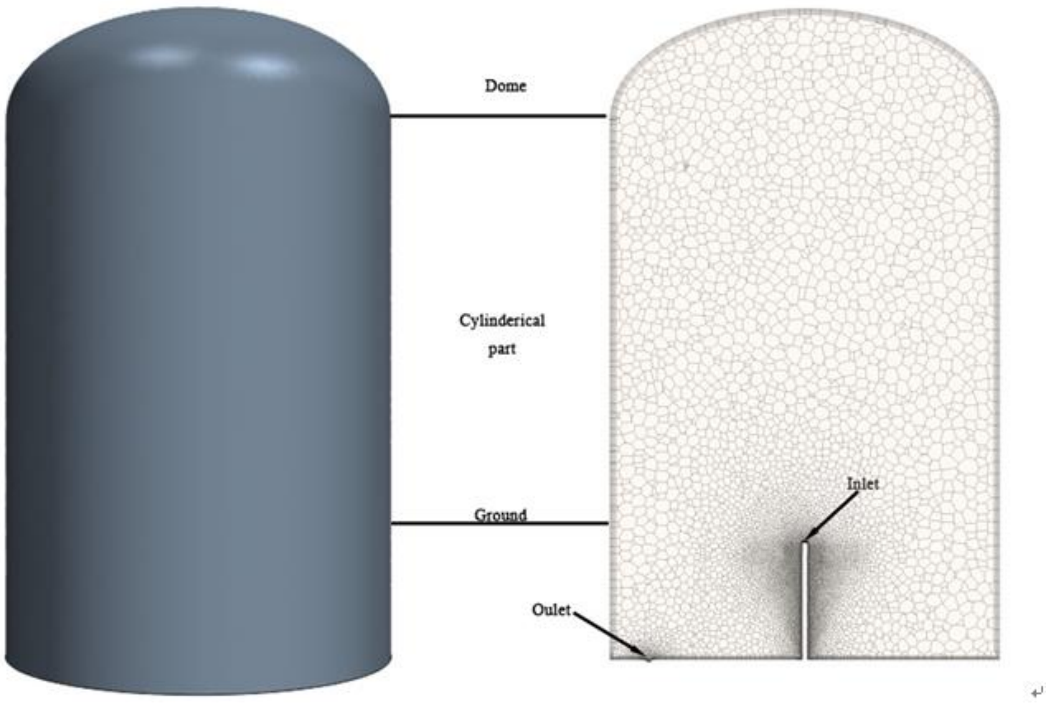

Fig. 2 Geometry and meshes for CFD simulations

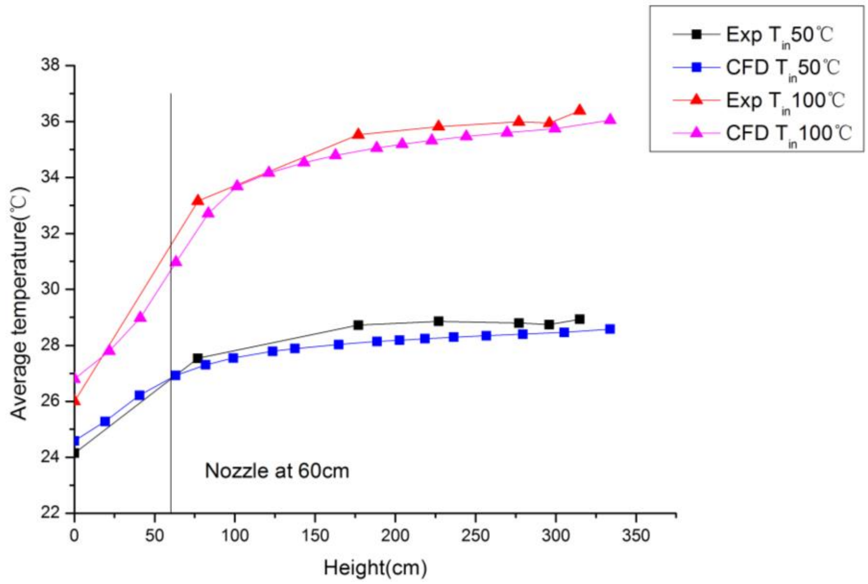

Fig. 3 Non-adiabatic at flow rate of 15m3/h

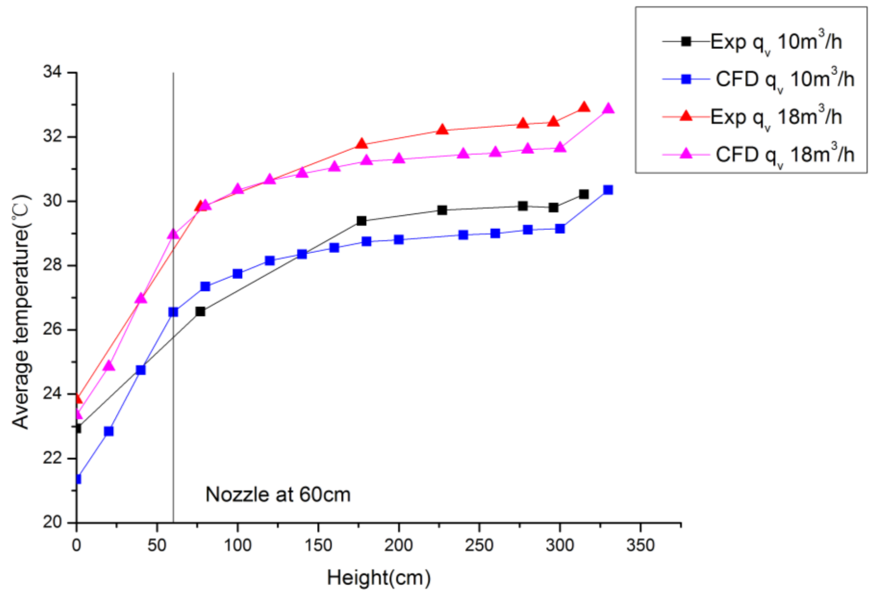

Fig. 4 Non-adiabatic at inlet temperature of 100oC

Fig. 3 and Fig. 4 illustrate the comparisons of temperature distribution in the containment both experimentally and numerically for non-adiabatic condition. In the test condition shown by figure 3, the flow rate is 15m^3/h, and the inlet temperatures of 50^{o}C and 10^{o}C are applied respectively. In figure 4, the inlet temperature is 100^{o}C and the flow rates are 10 m^3/h and 18 m^3/h.

Comparing Fig. 3 and Fig. 4, it can be seen that the thermal stratification is more pronounced with higher inlet temperature or higher flow rate. This can be demonstrated by the CFD simulations which reach a good agreement with the experiments. From these two figures, it can be seen that near the nozzle, the temperatures climb up dramatically along the axial height with a large temperature gradient and hence cause severe thermal stratification. Then the temperature increases slowly from the height of 100cm to 300cm and maintains a relatively high temperature, which implies that most energy is stored in the upper section of the cylindrical part. In the upper part of the containment the temperature increases again due to the shape of the dome in which the heat can be accumulated.

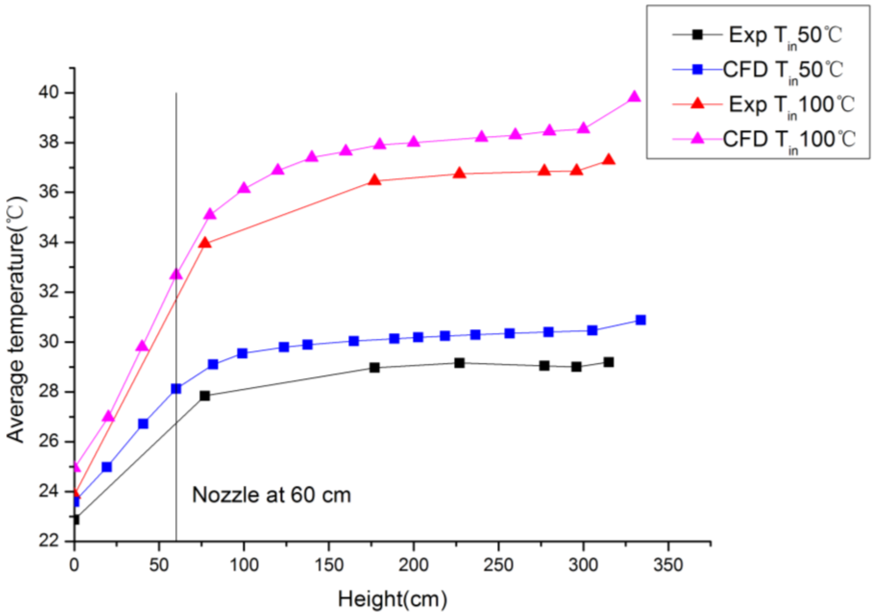

Fig. 5 Adiabatic at flow rate of $15m^3/h$

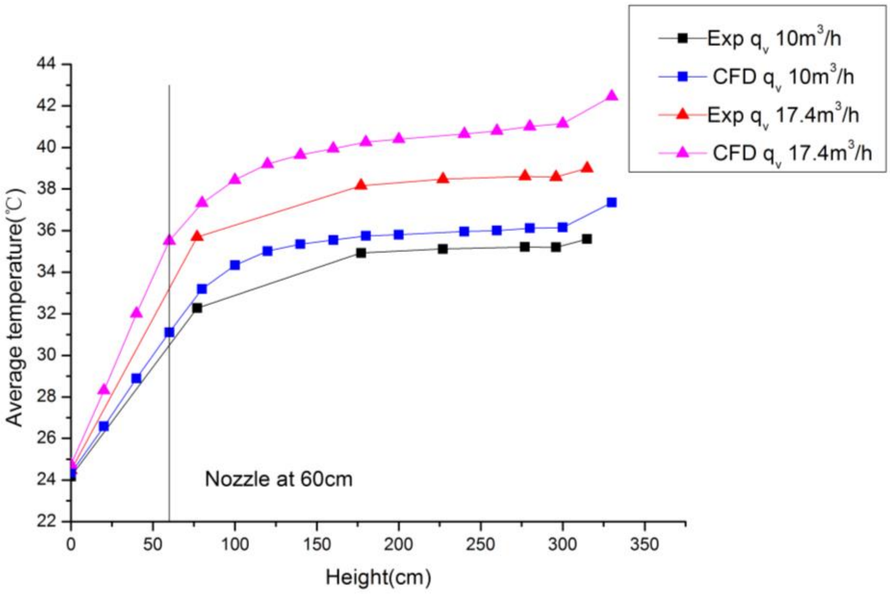

Fig. 6 Adiabatic at inlet temperature of 100°C

Fig. 5 and Fig. 6 indicate that the trend of the results for adiabatic meet a good agreement with the non-adiabatic condition, i.e. the temperatures surge up in the area near nozzle and then slightly ascend from the height of 100cm to 300cm, and continue rising to reach the peak at vertex of the dome. The simulations, however, show a higher temperature than the experiments on a whole. The reason may lie in the insufficient isolation from the sponged rubber sheet wrapping on the containment. The geometry shape changes significantly at the connection part of ceiling wall and cylindrical wall so it impairs the heat isolation of the insulating layer. It can explain that the errors of CFD simulations and experiment reach a maximum in the upper portion.

Compared the same conditions under non-adiabatic and adiabatic respectively, it can conclude that the thermal stratification is more pronounced in adiabatic condition rather than exposed in the air. Meanwhile, it illustrates that the heat dissipation through the containment can weaken the thermal stratification which benefits the nuclear power plant during LOCA.

4. Conclusion

Through the experimental and numerical comparison of the results, the conclusions can be drawn by analyzing the curves in the graphs as follows:

Higher inlet temperature can cause a more severe thermal stratification. It demonstrates that the initial phase of LOCA is the most dangerous period due to the serious stratification phenomenon caused by the high injection temperature of the break. The thermal stratification will reduce the heat transfer efficiency. But with the cooling of the containment, the temperature will drop down and the stratification will be weakened.

Higher inlet flow rate can also enhance the thermal stratification. With the increasing flow rate, the heat is accumulated and the temperature rises in the upper part. Theoretically, the thermal stratification will be weakened by the enhancement of the circular flow due to the increasing flow rate of vertical injection, while such laws cannot be observed in this experiment. It probably can be explained by the insufficient power provided by the air blower, because the flow rate is not large enough to reach the critical value to mix the stratification. The experiment in large flow rate will be carried out in the near future.

The thermal stratification is more pronounced in adiabatic condition rather than non-adiabatic.

In any conditions, both the numerical and experimental results manifest that the temperature gradient of the height under nozzle is larger than that above the nozzle. This implies that the height of the nozzle is another key parameter which can influence the thermal stratification. We will focus on that parameter in the future work.

Acknowledgements

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