Technical Report

Experimental Analysis on Mitigation of Thermal Stratification in the Suppression Pool of a Water Wall Type Passive Containment Cooling System

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A water wall type passive containment cooling system with an outer pool surrounding the suppression pool is one passive containment cooling system. In the system, a baffle plate in the suppression pool mitigates thermal stratification formed at the vent tube outlet level and enlarges the heat transfer area. The effectiveness of the baffle plate in mitigating thermal stratification was experimentally confirmed; the heat transferred to the outer pool increased about 50% due to a larger high temperature region and a longer effective heat transfer length. The experimental analysis was performed using a three-dimensional thermal-hydraulic analysis program. In the analysis, a laminar flow model and slip conditions on structural walls were used, and the calculated temperature profiles and natural circulation flow rates along the baffle plate agreed with measurements. The model was then judged as a valid and practical tool to evaluate global natural circulation and temperature distributions in a large pool. And it was analytically confirmed that the thermal resistance of the PCV wall and the heat flux to the outer pool affected the performance of the baffle plate.

KEYWORDS: BWR type reactors, heat removal, thermal hydraulics, loss of coolant, natural convection, heat transfer, temperature distribution, containment vessel, thermal stratification, three-dimensional analysis

1. INTRODUCTION

New concept light water reactors as next generation power reactors have been investigated in the USA, Europe and Japan(1)~(4). Differing from conventional safety system concepts, passive safety systems, which do not use active components, are adopted in those reactors. Introduction of passive safety systems simplifies the overall reactor safety system in structure and operation.

A water wall type passive containment cooling system(4)(6), which has an outer pool surrounding the suppression pool, is one of passive containment cooling systems (PCCSs) for containment cooling during loss-of-coolant accidents (LOCAs). The system utilizes only natural phenomena such as condensation, natural convection and heat conduction, to provide long term containment cooling in accident situations.

Thermal hydraulic behavior of this system has been experimentally investigated(6)(7), in which the thermal stratification just below the vent tube outlet in the suppression pool was clarified. Its formation corresponded to stagnant conditions in the lower portion of the
suppression pool. It might restrict the heat transfer capability due to limitation of the high temperature region in the pool. The lower part stays at a relatively low temperature for a long time. These thermal stratification phenomena affect the effective volume of heat sink and net heat transfer area to the outer pool. Thermal stratification phenomena in the suppression pool and effect of the baffle plate, which is a countermeasure to mitigate thermal stratification, have been experimentally evaluated using several differently scaled apparatuses. In this paper, details of the experimental results are presented and thermal stratification phenomena in the suppression pool are analyzed by using the three dimensional thermal-hydraulic computational program THERVIS. The calculated results are compared with the experimental ones, and the effects of a thermal resistance of the primary containment vessel wall on the baffle plate performance are discussed based on the calculated results.

II. SYSTEM DESCRIPTION

The concept of decay heat removal by the water wall type (PCCS) is shown in Fig. 1. The primary containment vessel (PCV) is furnished with a suppression pool, and an outer pool located outside the steel PCV wall. The detail features of this system during LOCA are described in the reference.

The pressure rise in the PCV can be suppressed due to the water wall type passive containment cooling system. This system is very simple and reliable because it utilizes only the PCV wall as the heat transfer area and do not need any pumps, piping or valves.

The increase of temperature in the suppression pool is determined by the amount of the accumulated heat and the pool volume. When thermal stratification occurs in the suppression pool, the lower part of the pool is kept cool. Typical experimental results are shown in Fig. 2. The water temperature above the vent tube outlet increased with time. The temperature distribution above the vent tube was almost uniform and the maximum temperature difference was within 0.5°C. Natural convection made the temperature distribution in this region almost uniform. On the other hand, the temperature in the lower part stayed at about its initial value. The temperature profiles in the outer pool were similar to those in the suppression pool. This indicated that heat transfer to the outer pool occurred only from the high temperature region above the vent tube outlet. Natural convection was observed in each pool above the vent tube outlet, but flow was almost stagnant below it. According to the flow pattern, the thermal stratification appeared just below the vent tube outlet elevation.

The baffle plate can increase the effective heat capacity in the pool and effective heat transfer area. The effect of the baffle plate has been experimentally and analytically investigated.
III. EXPERIMENTAL APPARATUS

The experimental apparatus is shown in Fig. 3. It is a 15° sector model, 5.3 m in height and 1.25 m in radial width. It consists of a suppression pool and an outer pool open to atmosphere. The 15° sector simulates an area containing one of the 24 vent tubes in the basic containment arrangement. The PCV wall (heat transfer wall) is made of 22 mm thick stainless steel, and its thermal resistance is about twice as large as that of the prototype PCV wall. Steam, which simulates evaporation due to decay heat, is supplied from a boiler into the vent tube which is located on the opposite side of the PCV wall in the suppression pool.

In the experiments, the suppression pool was heated by steam injected through the vent tube and cooled by heat transfer to the outer pool. The experiments were performed with and without a baffle plate installed in the suppression pool in order to evaluate its effectiveness for mitigation of thermal stratification. Pressure in the wet well, water levels in the suppression pool and outer pool, injected steam flow rate, and temperature distributions in the pools were measured. Radial and vertical temperature profiles in both pools were measured with CA thermocouples of 1 mm outer diameter. The temperatures of the inner and outer surfaces of the stainless steel heat transfer wall were also measured. Locations of the thermocouples are shown in Fig. 4.

IV. ANALYTICAL MODEL

For the design of the actual plant, the plant scale experiment was not realistic. For

Table 1 lists the experimental conditions. Two experiments were conducted with and without the baffle plate to evaluate its effectiveness. The baffle plate geometry was set from the static head balance inside and outside the baffle plate as $l_1 > l_2$, where $l_1$ and $l_2$ were the vertical lengths of the top and bottom of the baffle plate from the vent tube outlet, respectively. Their actual values were: $l_1 = 1.8$ m and $l_2 = 1.3$ m. Also the radial distance between the baffle plate and the PCV wall was determined to be 0.15 m so that flow resistance is not so large in the region between the baffle plate and PCV wall. This geometry induces natural circulation flow along the baffle plate. In the experiments, the vent tube submergence from the pool surface to the vent outlet was 2.1 m.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Experimental conditions</th>
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<tbody>
<tr>
<td>Suppression Pool Level</td>
<td>Vent Submergence</td>
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<tr>
<td>3.9 m</td>
<td>2.1 m</td>
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<tr>
<td>3.9 m</td>
<td>2.1 m</td>
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Other conditions:
- Outer Pool Level: 4.2–5.0 m
- Initial Pool Temperature: 30°C
- Initial Wet Well Pressure: 0.19 MPa
- Steam Flow Rate: 30 kg/h
this reason, the three-dimensional thermal-hydraulic analysis was needed as the design tool. If the heat transfer rate to the outer pool, which could be calculated using a system performance analysis program\(^{(6)-(7)}\), was given, the three-dimensional thermal-hydraulic analysis was useful as the tool to calculate the pool surface temperature. Moreover, in the experiments, a thermal resistance of the PCV wall was about twice as large as that of the supposed PCV wall, and its effects on the baffle plate performance were not experimentally examined. Therefore, the effects were analytically evaluated using a three-dimensional thermal-hydraulic computational program.

The three-dimensional thermal-hydraulic computational program THERVIS\(^{(10)}\) was used for analysis of thermal-hydraulic characteristics in the suppression pool. The analytical mesh division is shown in Fig. 5. The inner radius was 0.54 m, outer radius was 1.54 m, and the analytical region was the 1/24 sector. The pool water level was 3.9 m, the distance of the baffle plate from the PCV wall was 0.15 m, and the baffle plate length was 3.1 m. Elevation of the vent outlet was 1.8 m and its distance from the inner wall was 0.15 m. The total number of meshes was 2,340: 12 meshes in the radial direction, 5 in the circumference direction (Figure 5 shows 10 meshes using symmetry), and 39 in the vertical direction. The average mesh size was 0.1 m, but the neighborhood of the baffle plate and the PCV wall were divided into smaller meshes. The total number of meshes was changed from 2,340 to 1,500, and 2,262, and it was confirmed that the calculated circulation flow rate was not effected by the number of meshes, because the numerical viscosity was very small in these conditions.

THERVIS includes a k-ε turbulence model, which requires a very fine spatial mesh division. The authors performed several preliminary analyses using different models and found that the results with the turbulence model strongly depended on the mesh size. The results have also been obtained by Huggenberger et al.\(^{(11)}\) Then, the use of the turbulence model is not practical to calculate natural circulation in a large pool. On the other hand, the laminar flow model is not sensitive to the mesh size. However, if no-slip conditions were applied on the structural walls, the laminar model predicted a very thick boundary layer near the walls. Therefore, slip conditions were used. The numerical equations and assumption in the present study were the same as reference\(^{(10)}\).

In this analysis, the laminar flow model and slip conditions on the structural walls were used because the liquid velocity in the pool was lower than 0.01 m/s, the pressure loss at the inlet and outlet of the baffle plate was dominant, and the friction on the walls was small in the natural convection of this system. The pressure loss coefficient of 20 was used at the inlet and outlet of the baffle plate. The friction coefficient on the PCV wall was estimated to be 2 for the measured liquid velocity of 0.001 m/s. The pressure losses at the inlet and outlet of the baffle plate were automatically calculated in the computational program. However, the calculated circulation flow rate at the pressure loss coefficient of 2 increased rapidly after 1.5 h. To suppress the rapid
increase in the calculated circulation flow rate, the pressure loss coefficient of 20 was used. The local velocity in the boundary layer along the PCV wall was 0.1 m/s\(^4\). On the other hand, the average velocity obtained by the circulation flow rate was 0.001 m/s. The difference between these values was caused by the stagnant or the reverse flow except the boundary layer in the gap. These results meant that many small circulations may have existed in the gap between the PCV wall and the baffle plate, and the large pressure loss occurred in the gap. In this paper, 20 was used as an empirical constant for the total pressure loss. The future subjects are to clear the detailed structure of the flow in the gap and to replace the experience constant 20 with the pressure loss coefficient.

The initial temperature of the pool water was 30°C in the experiments, and it was used as an initial condition in the calculation. The total heat input rate due to steam condensation \(Q_{\text{in}}\) equals the summation of the heat accumulation rate in the suppression pool \(Q_{\text{sp}}\), the heat transfer rate to the outer pool \(Q_{\text{op}}\), and the heat loss rate from the side walls \(Q_{\text{loss}}\).

\[
Q_{\text{in}} = Q_{\text{sp}} + Q_{\text{op}} + Q_{\text{loss}}. \tag{1}
\]

The heat accumulation rate in the suppression pool \(Q_{\text{sp}}\) and the heat transfer rate to the outer pool \(Q_{\text{op}}\) were evaluated based on the measured temperature profiles in the pool and the temperature gradient in the PCV wall, respectively. Heat loss rate from the side wall \(Q_{\text{loss}}\) was calculated using the heat transfer area, the calculated temperature difference between the inside and outside of the apparatus and the measured overall heat transfer coefficient\(^6\). The measured heat accumulation rate in the suppression pool and heat transfer rate to the outer pool are shown in Fig. 6. In the initial period of the transient, most of the heat input was accumulated in the suppression pool. As the temperature in the suppression pool increased, the heat transfer rate to the outer pool increased, but heat accumulation rate in the suppression pool became smaller. In the calculation, the heat accumulation rate \(Q_{\text{sp}}\) and heat transfer rate \(Q_{\text{op}}\) were given every 2 h, and were fitted by a linear function for each 2-h interval. During the initial period, however, the calculated results were very sensitive to the input data, such as the heat transfer rate to the outer pool and the pressure loss coefficient. Therefore in the calculation the heat accumulation and transfer rates were given every one hour during the initial four hours. The heat transfer to the outer pool and heat loss from the side wall were given in terms of heat fluxes on the PCV and side walls, respectively.

The heat input \(Q_{\text{in}}\) was given in terms of volumetric heat source in the mesh points at the vent tube outlet. Modeling of heat loss from the side walls do not almost affect temperature profiles in the pool.

\[
\text{Fig. 6 Accumulated heat and transferred heat}
\]

V. RESULTS AND DISCUSSION

Experimental results of the suppression pool temperature and wet well pressure obtained with and without the baffle plate are compared in Fig. 7. The temperature difference between regions above and below the vent tube outlet was smaller with the baffle plate than without it. As a result, pool surface temperature and wet well pressure with the baffle plate became lower than those without it.

Experimental and analytical results of the temperature distributions in the suppression pool with the baffle plate are compared in Fig. 8. The temperature was high and uniform in the region inside the baffle plate and above the heat source because of heat input.
Fig. 7 Comparison of measured suppression pool temperature and wet well pressure.

Fig. 8 Comparison of pool temperature distributions with baffle plate.

and natural circulation there. In the region outside the baffle plate, the temperature was high at the top of the pool, and decreased almost linearly along the baffle plate due to the heat release to the outer pool. The temperature in the region inside the baffle plate and below the vent tube outlet (i.e., heat source) increased with time due to circulation flow around the baffle plate. The temperature in the region below the bottom of the baffle plate stayed low because there was no heat source and the liquid was stagnant. The results showed the effectiveness of the baffle plate. At 4 h after steam injection, analytical results agreed with the experimental data within 2%. In the experiment, temperatures inside and outside the baffle plate were the same near the pool surface. In the calculation, however, temperature outside the baffle plate was a little lower than that inside because of local natural circulation above the top of the baffle plate and heat release to the outer pool. At 12 h, the difference between the analytical and experimental results increased to 4%. Moreover, the calculated temperature profile outside the baffle plate was not linear, and the calculated temperature was higher than the measured in the region below the bottom of the baffle plate due to local natural circulations outside and below the baffle plate. There were some differences between the analytical and experimental results, but the calculated results satisfactorily reproduced the trends of the temperature profiles in the suppression pool.

Figure 9 compares the experimental and calculated results of circulation flow rate around the baffle plate. Experimental circulation flow rate \( W_c \) was derived from the energy balance of the fluid between the baffle plate and the containment wall:

\[
W_c = \frac{Q_{op}}{C_p d T_{bp}}, \tag{2}
\]

where \( Q_{op} \) is the heat transfer rate to the outer pool, \( C_p \) the specific heat capacity of water and \( d T_{bp} \) the fluid temperature difference between the top and bottom of the baffle plate. In the initial period, most of the heat input was stored in the suppression pool.
especially inside the baffle plate and above the vent tube outlet, and then the heat release to the outer pool increased rapidly as shown in Fig. 6. Therefore, the average temperature was higher and the average density was lower inside the baffle plate than outside. During this time, the measurement error due to assumption of the steady state would be large. The difference between the calculated and experimental values was rather large in the initial period. After 2 h, however, the calculated circulation flow rate agreed with the experimental data almost within the measurement error. In order to simulate the temperature distributions in the pool, it was important to estimate the circulation flow rate in the long range.

The maximum difference in temperature above and below the vent tube outlet (i.e., heat source) was about 50°C in this experiment but about 30°C in the experiment by Kataoka et al. (9) The PCV wall was made of stainless steel 304 of 22 mm in thickness and had a thermal resistance about twice as large as that of the prototypical PCV wall, and the over-all heat transfer coefficient between the pools was 244 W/m²·K in this experiment. On the other hand the PCV wall thickness was 12 mm and the over-all heat transfer coefficient between the pools was 283 W/m²·K in the experiment by Kataoka et al. The over-all heat transfer coefficient in the apparatus by Kataoka et al., which simulated the prototypical PCV, was 16% larger than the present study. Moreover there was heat loss from the side walls and the over-all heat transfer coefficient was 2 W/m²·K in this experiment. Therefore the effects of the heat transferred to the outer pool \( Q_{op} \) and the heat loss from the side walls \( Q_{loss} \) on heat transfer characteristic were analytically investigated. In the analyses, the condition without heat loss from the side walls \( Q_{loss}=0 \) and the condition of the heat transferred to the outer pool \( 1.16Q_{op} \) to simulate low thermal resistance of the PCV wall were used.

**Figure 10** compares the calculated temperatures inside the baffle plate. As shown in Fig. 10, the effect of \( Q_{loss} \) was small, but the effect of \( Q_{op} \) was large. As the heat transferred to the outer pool became large, the circulation flow rate around the baffle plate became large due to the static head balance and the temperature below the vent tube outlet became high. In the case of \( 1.16Q_{op} \), the circ-
The calculation flow rate was about 20% larger and the difference in temperature between above and below the vent tube outlet was 40% smaller than in the case of $Q_{op}$. So the difference in the present test results with those by Kataoka et al. resulted mainly from the differences of the PCV wall thickness and heat transferred to the outer pool.

The effects of the baffle plate on heat transfer characteristic were investigated by comparing the results with and without the baffle plate. Comparison for the amount of the accumulated heat in the suppression pool is made in Fig. 11.

![Fig. 11 Comparison of accumulated heat in suppression pool](image1)

Comparison for the transferred heat is shown in Fig. 12.

![Fig. 12 Comparison of transferred heat to outer pool](image2)

As the evaluation method of the performance, the pool surface temperature, which affected the temperature and the steam partial pressure in the PCV, was used, because the present objective was to find maximum heat removal at the given temperature and pressure conditions. The accumulated heat in the suppression pool, which was evaluated from the temperature rise, increased in proportion to the pool surface temperature rise. For a given pool surface temperature rise, the accumulated heat with the baffle plate was 20% larger than that without the baffle plate due to enlargement of the high temperature region below the vent tube outlet. The lower abscissa in Fig. 11 shows the steam partial pressure at the pool surface, which was evaluated from the saturated pressure corresponding to the pool surface temperature. Therefore, the baffle plate effectively decreased the PCV pressure due to the better heat transfer characteristics. For improvement of the heat transfer capability by the baffle plate, the amount of heat transferred to the outer pool was larger than that without the baffle plate, and the increase was about 50% as shown in Fig. 12. The effectiveness of the baffle plate to mitigate thermal stratification in the suppression pool and to enlarge the heat transfer area was clarified by these results.

The differences between measured and calculated values in Figs. 11 and 12 depended on the measurement errors and calculation error of the pool surface temperature. According to the temperature profiles shown in Fig. 8, the calculated accumulated heat was a little larger than the measured which indicated that the input values might be a little larger for the accumulated heat or be a little smaller for the transferred heat. However, the differences were not significant. In the supposed PCV, thermal resistance of the PCV wall is smaller and it is expected that heat flux to the outer pool would be 1.16 times larger than the heat flux in this experiment. For the large heat transferred to the outer pool of $1.16Q_{op}$, the accumulated heat at a given pool surface temperature did not increase in the case without the baffle plate because of the same temperature distribution, but it increased about 20% with it as shown in Fig. 11 because the difference in temperature above and below the vent tube outlet became small as shown in
Fig. 7. The heat transfer rate to the outer pool increased in both cases with and without the baffle plate, and increased rate was larger for the former.

The feasibility of the water wall type passive containment cooling system as the decay heat removal system was shown in previous studies(5)(6). The baffle plate has a capability to enlarge the effective heat capacity of the suppression pool, the heat transfer area between pools and the heat transferred to the outer pool for the water wall type passive containment cooling system. Theses effects of the baffle plate were confirmed experimentally and analytically in this study. A thermal resistance of the PCV wall was larger and the heat transferred to the outer pool was smaller in the experiment than in the supposed system. It was analytically shown that the baffle plate performance was increased in the system with a small thermal resistance of the PCV wall. Therefore, when adopting the baffle plate as a measure to improve the heat transfer capability, the applicable reactor power is expected to be increased due to the above effects.

In the experimental analyses, a laminar flow model and slip conditions on the structural walls were used and the calculated results were in rather good agreement with the measured ones. This means that the laminar flow model and slip conditions are valid and practical to evaluate a global natural circulation and temperature distribution in the pool. In the calculation, the pressure loss coefficient of 20 was given to suppress the rapid increase in the calculated circulation flow rate after 1.5 h. However, the pressure loss coefficient was not sensitive to the calculated circulation flow rate before 1.5 h. Therefore, as a practical method, it should be determined to suppress the rapid increase in the circulation flow rate. It seems that many small circulations existed in the gap between the PCV wall and the baffle plate, and the large pressure loss occurred in the gap. The future subjects are to clear the detailed structure of the flow in the gap and to replace the experience constant of 20 for the pressure loss coefficient with theoretical one. Furthermore, experimental data were used for boundary conditions such as the transferred heat to the outer pool. In the design calculations of the water wall type passive containment and the baffle plate, however, the boundary conditions can be given by a system performance analysis program(6)(7).

VI. CONCLUSION

The effectiveness of a baffle plate as a countermeasure for mitigation of thermal stratification, which occurs in the suppression pool, was experimentally confirmed. The baffle plate configuration increased the heat transferred to the outer pool by about 50% due to enlargement of the effective heat transfer area.

Analyses of thermal stratification behavior and natural convection in the suppression pool of the external water wall type containment vessel have been performed, using the three-dimensional thermal-hydraulic program THERVIS. A laminar flow model and slip conditions on the structural walls were used. However, the shear stress in the fluid was underestimated. Therefore the total pressure loss was compensated with large pressure loss coefficient. The calculated temperature profiles agreed with the measured data within 4%, except in the bottom region below the lower edge of the baffle plate. The results indicated that the laminar flow model was valid and practical to evaluate global natural circulation and temperature distribution in a large pool.

In the experiments, thermal resistance of the PCV wall was larger and the heat flux between the suppression and outer pools might be smaller than in the supposed PCV. The analytical results indicated that the effectiveness of the baffle plate increased on increasing the heat flux between the pools. The accumulated heat in the suppression pool and transferred heat to the outer pool increased as the heat flux to the outer pool became larger.

REFERENCES

(1) TAYLOR, J. J., STALHKOFF, K. E.: The U.S. advanced light water reactor program; A case for simple, passive safety systems, Proc. Int. Topical Mtg. on Safety of Next Generation

(2) Duncan, J.D., McCandless, R.J.: ASBWR; An advanced simplified boiling water reactor, *ibid.*


