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Original Article

Optimal design of passive containment cooling system for innovative PWR

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ABSTRACT

Using the Generation of Thermal-Hydraulic Information for Containments (GOTHIC) code, thermal-hydraulic phenomena that occur inside the containment have been investigated, along with the preliminary design of the passive containment cooling system (PCCS) of an innovative pressurized water reactor (PWR). A GOTHIC containment model was constructed with reference to the design data of the Advanced Power Reactor 1400, and report related PCCS. The effects of the design parameters were evaluated for passive containment cooling tank (PCCT) geometry, PCCS heat exchanger (PCCX) location, and surface area. The analyzed results, obtained using the single PCCT, showed that repressurization and reheating phenomena had occurred. To resolve these problems, a coupled PCCT concept was suggested and was found to continually decrease the containment pressure and temperature without repressurization and reheating. If the installation level of the PCCX is higher than that of the PCCT, it may affect the PCCS performance. Additionally, it was confirmed that various means of increasing the external surface area of the PCCX, such as fins, could help improve the energy removal performance of the PCCS. To improve the PCCS design and investigate its performance, further studies are needed.

1. Introduction

One of the key features of advanced light water reactors such as AP1000, ESBWR, HPR1000, VVER1200, and CAP1400, is the passive containment cooling system (PCCS), which uses natural forces to provide long-term decay heat removal from the containment. Also, the Korea Hydro and Nuclear Power is currently developing the innovative PWR (iPower), which will be equipped with various passive safety features, including a PCCS [1]. The PCCS can transfer decay heat inside the containment to the environment without an external power supply. Thus, the PCCS can be the ultimate heat sink under an extended loss of AC power (ELAP) such as was the case during the Fukushima accident.

PCCSs can be classified into four types, as follows: (1) a passive containment spray and natural draft air (adopted in AP1000); (2) an external heat exchanger (adopted in ESBWR); (3) a steam condensation on internal steam condenser (HPR1000, VVER1200); and (4) an external circulation loop [2]. Fig. 1 provides a schematic diagram of the iPower. As can be seen in the figure, the iPower adopts the type of PCCS of removing discharged energy using steam condensation on the internal heat exchanger.

With respect to this type of PCCS, heat transfer phenomena that occur on the surface of the PCCS heat exchanger (PCCX) have been studied experimentally at dedicated facilities [3–6] and numerically by using a commercial computational fluid dynamics package [7]. According to previous studies, the heat transfer rate at the heat exchanger surface is affected by various parameters such as the steam velocity, noncondensable contents, heat exchange length and diameter, and so on. Due to these variations, specific experimental data and models are required for each PCCS. For example, experimental [8] and numerical analysis [9,10] to determine the thermal-hydraulic phenomena that occur inside the containment under PCCS operating conditions were carried out to develop the PCCS that is applied to the VVER1200.

For the PCCS of iPower, a design specific heat transfer rate and model will be developed. The objective of this paper is to provide performance assessment data and optimized designs that will be needed to perform PCCS of iPower before design specific experiments. The containment thermal-hydraulic analysis software package Generation of Thermal-Hydraulic Information for Containments (GOTHIC) is utilized for the performance assessment. Because the design specifications of iPower are not currently available, the GOTHIC containment model had to be constructed with reference to the design of the Advanced Power Reactor 1400 (APR1400) [11]. The PCCS model was constructed based on the

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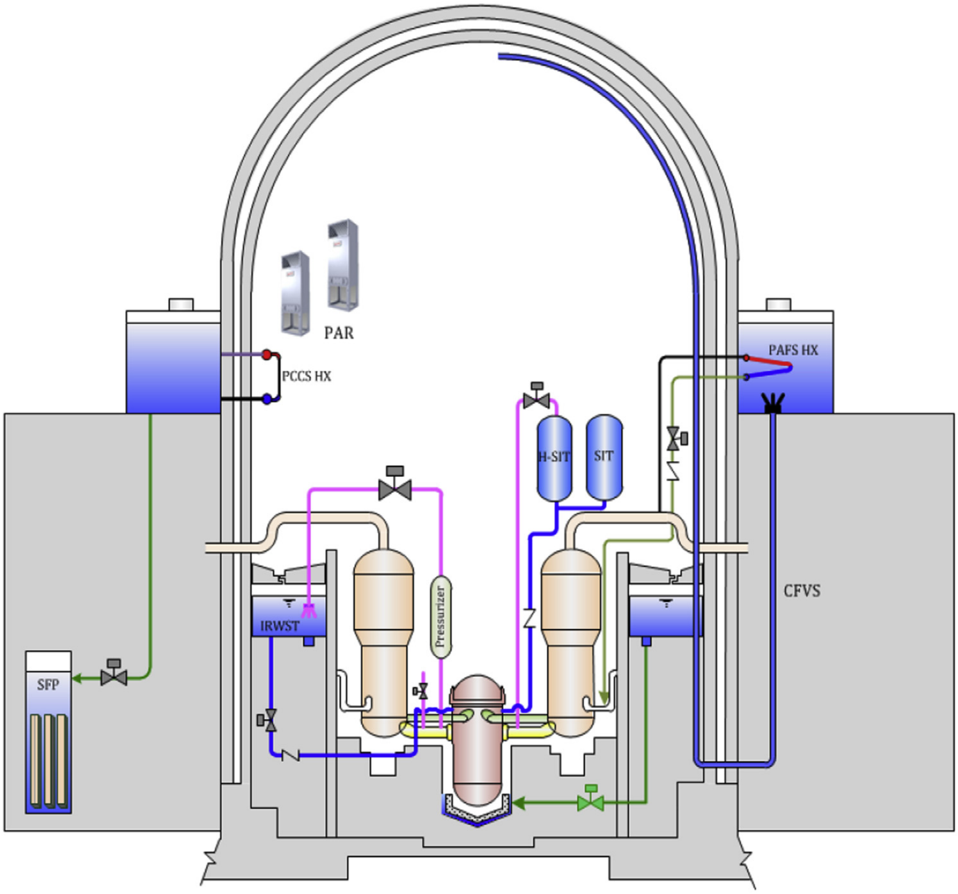

Fig. 1. Schematic diagram of innovative PWR (iPower). CFVS, containment filtered venting system; H-SIT, hybrid-safety injection tank; HX, heat exchanger; IRWST, in-containment refueling water storage tank; PAFS, passive auxiliary feedwater system; PAR, passive autocatalytic recombiner; PCCS, passive containment cooling system; PWR, pressurized water reactor; SFP, spent fuel pool; SIT, safety injection tank.

design information of the PCCS contained in the report on the iPower concept design project [12], performed in the past. The effects of the design parameters were evaluated for passive containment cooling tank (PCCT) geometry, PCCS heat exchanger (PCCXs) locations and external surface area, with detailed discussion of the pressure, temperature, and energy removal rate of the thermal conductors.

2. Materials and methods

2.1. PCCS design description

Fig. 2 shows the schematic diagram of the PCCS of iPower. The PCCS consists of a heat exchanger located at a high elevation in the containment, coolant storage tank on the auxiliary building, and coolant circulation pipe. In loss of coolant accidents (LOCAs), high-pressure steam is released from breaks into the containment. Released steam is condensed on the surface of heat exchanger tubes installed vertically. With this system, the pressure and the temperature of the containment decrease. The falling condensate is collected and reused to cool the reactor core. Cooling water inside the heat exchanger tubes flows naturally by buoyant force. The main features of the PCCS are as follows.

- Design basis event for the PCCS is double-ended large break LOCA.
- The heat transfer rate is assumed to be 22.5 kw/m^2 for heat exchanger sizing [8].
- There are no active components in the PCCS, including valves. Therefore, we do not apply a single failure assumption.
- The PCCS is installed in the upper part of the containment.
- The PCCS is composed of four trains.

Fig. 3 provides a schematic diagram of the single train of the PCCS. The train consists of eight PCCXs. The PCCX consists of an upper head, a lower head, and a tube bundle, shown in Fig. 4; the design parameters are shown in Table 1.

2.2. Analysis method

The analysis method for containment thermal-hydraulic phenomena is as follows. The thermal-hydraulic response of the reactor coolant system (RCS) has been analyzed using the computer code Reactor Excursion and Leak Analysis Program 5 - Mass & Energy (RELAP5-ME) [13]. The coolant discharge rate and enthalpy obtained from RELAP5-ME are used as boundary condition data for the containment thermal-hydraulic response analysis by the GOTHIC code.

2.2.1. Computer code

The containment thermal-hydraulic phenomena have been calculated using the GOTHIC version 8.0 computer code. GOTHIC is a general-purpose thermal-hydraulic computer code often used in

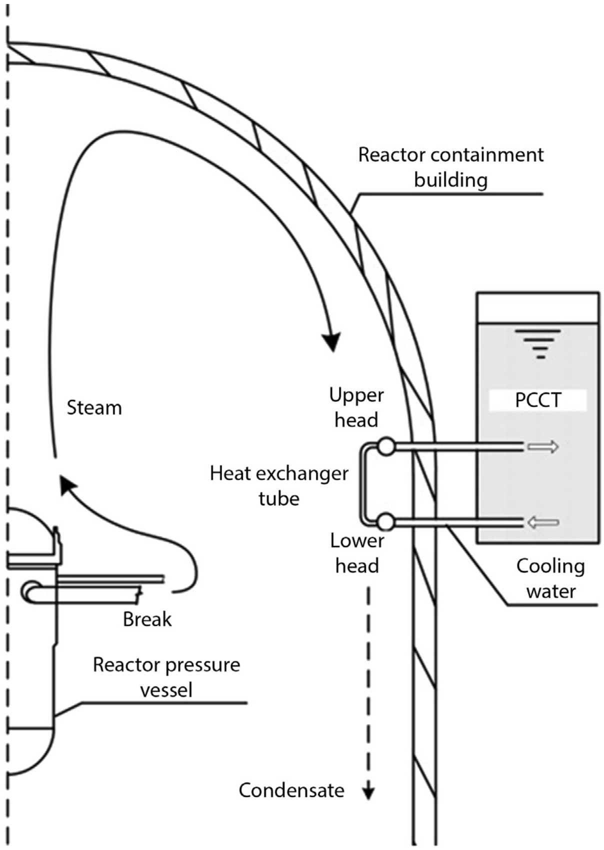

Fig. 2. Schematic diagram of the passive containment cooling system (PCCS) of innovative PWR (iPower). PCCT, passive containment cooling tank; PWR, pressurized water reactor.

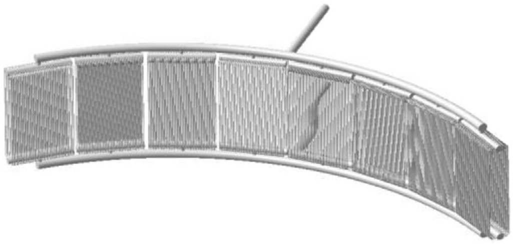

Fig. 3. Schematic diagram of a single train of the passive containment cooling system (PCCS).

Fig. 4. Schematic diagram of a passive containment cooling system (PCCS) heat exchanger (PCCX).

Table 1
Design parameters of a passive containment cooling system heat exchanger (PCCX).

Parameter	Upper/lower head	Heat exchanger tube
Outer diameter (m)	0.4/0.4	0.04
Thickness (cm)	0.3/0.3	0.3
Length (m)	3.44/3.44	5 (effective length)
Number	1/1	251
Arrangement	–	6 × 42

the design, licensing, safety, and analysis of nuclear power plant containments. GOTHIC performs containment thermal-hydraulic analysis by solving mass, energy, and momentum conservation equations for multicomponent, multiphase flow. The GOTHIC code provides detailed thermal-hydraulic information for various containment areas.

2.2.2. *Initial conditions*

Initial conditions are summarized below:

Containment
- Temperature: 326.45 K
- Pressure: 116.52 kPa
- Relative humidity: 5%

In-containment Refueling Water Storage Tank
- Temperature: 322.05 K
- Pressure: 116.52 kPa
- Relative humidity: 100%

PCCT
- Temperature: 322.05 K
- Pressure: 97.7677 kPa
- Coolant capacity: 5950 m^3
- Elevation: 55 m
- Water level: 8.5 m

2.2.3. *Containment analysis model*

The GOTHIC nodalization of the containment is shown in Fig. 5. In the GOTHIC model, the containment and the PCCS have been modeled via a lumped-parameter model. The lumped-parameter modeling approach is acceptable for containment LOCA response because this large break is expected to result in a well-mixed containment. Comparisons of the lumped-parameter model and a three-dimensional model for the Carolinas-Virginia Tube Reactor [14,15] showed that the lumped-parameter model results in conservatively high peak pressures. In the case of the PCCS model, the lumped-parameter model for the Debhi MIT tests [3,14] showed good agreement between the GOTHIC calculations and the experimental data. The containment model was primarily composed of five control volumes, three boundary conditions, 19 thermal conductors, and three components. For the wall heat transfer coefficients, GOTHIC Direct/UCHIDA and DLM-FM have been chosen for the condensation model on the external surface of the passive heat sinks and the PCCX, respectively. In addition, the film model

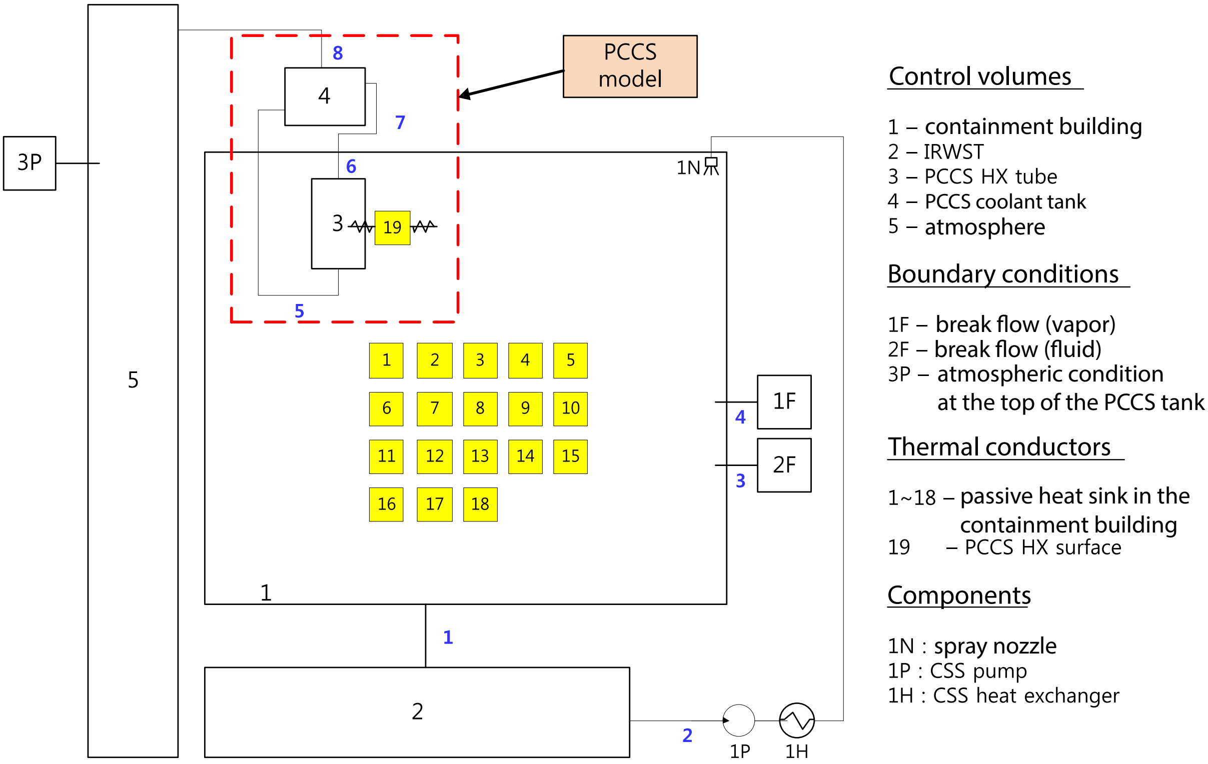

Fig. 5. Generation of Thermal-Hydraulic Information for Containments (GOTHIC) nodalization scheme for containment. CSS, containment spray system; HX, heat exchanger; IRWST, in-containment refueling water storage tank; PCCS, passive containment cooling system.

has been used on the internal surface of PCCX to account for boiling heat transfer.

2.2.4. Break discharge model

The phase separation of the LOCA break flow is treated according to the transient's discharge period, i.e., the blowdown and post-blowdown phases. During blowdown, the break's liquid discharge is superheated relative to the containment pressure. The liquid jet breaks into small drops due to flashing and the drops quickly reach thermal equilibrium with the containment atmosphere as they fall to the containment floor. To consider the flashing condition, the drop breakup model option in GOTHIC flow path modelling has been used and the drop diameter has been set a 0.01 cm based on the guidance provided in the GOTHIC user manual [16]. The effect of the drop breakup model used is automatically stopped when the fluid temperature becomes subcooled.

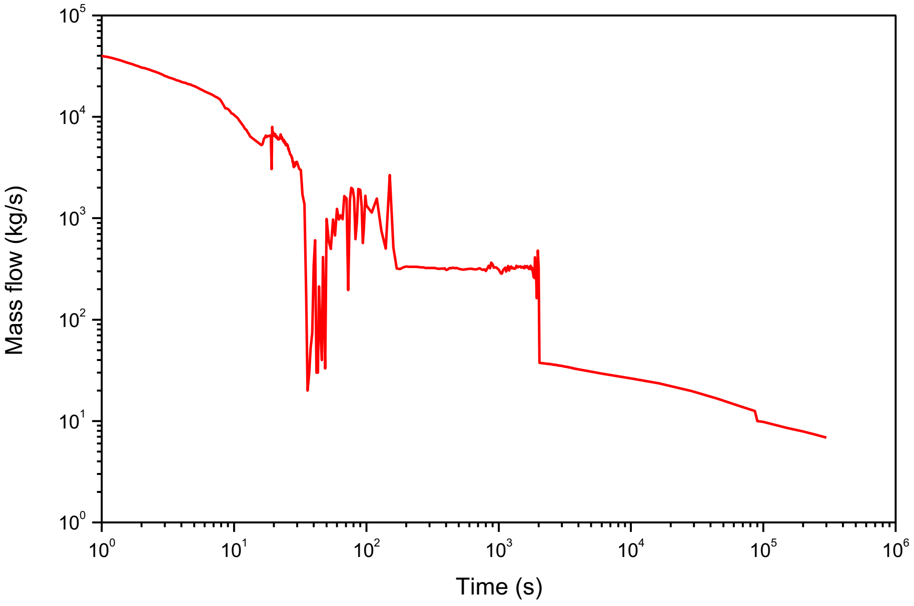

Fig. 6. Mass discharge rate (kg/s) for LBLOCA.

3. Results and discussion

Among the various types of accidents that can occur in nuclear power plants, this analysis was performed by assuming LOCA with maximum safety injection. Under these conditions, analyses have been carried out for the following purposes: (1) to understand the effect of the condensation model on the external surface of the PCCX tube; (2) to understand the effect of the design on the performance of the PCCS and gain insight for the designing of the PCCT; and (3) to understand the effect of the installation position and the surface area of the PCCX. Tests related to the PCCT design have been carried on two different types of coolant tank: the first, single coolant tank; the second, two coolant tanks connected by a flow path. The analysis has been carried out for the same period, because the PCCS must be operated without operator intervention for 72 hours after accident initiation. The mass and energy discharge rates are shown in Figs. 6 and 7.

3.1. Base case analysis result

In the reference case, analysis was conducted for a condition in which the containment building cooling systems were not working at all. In Figs. 8 and 9, the results are compared with those obtained using the containment spray system (CSS) and the PCCS operating case. In the CSS actuation case, the containment pressure increased rapidly following the break and reached the containment isolation signal for pressure at 5 seconds; the first peak pressure occurred at 26 seconds. CSS actuation started at 114 seconds after accident

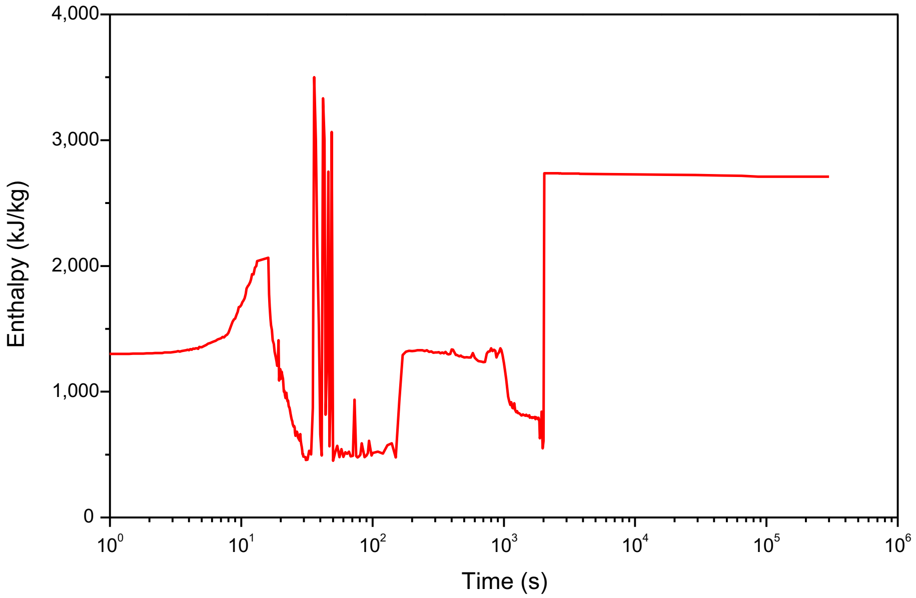

Fig. 7. Enthalpy discharge (kJ/kg) for LBLOCA.

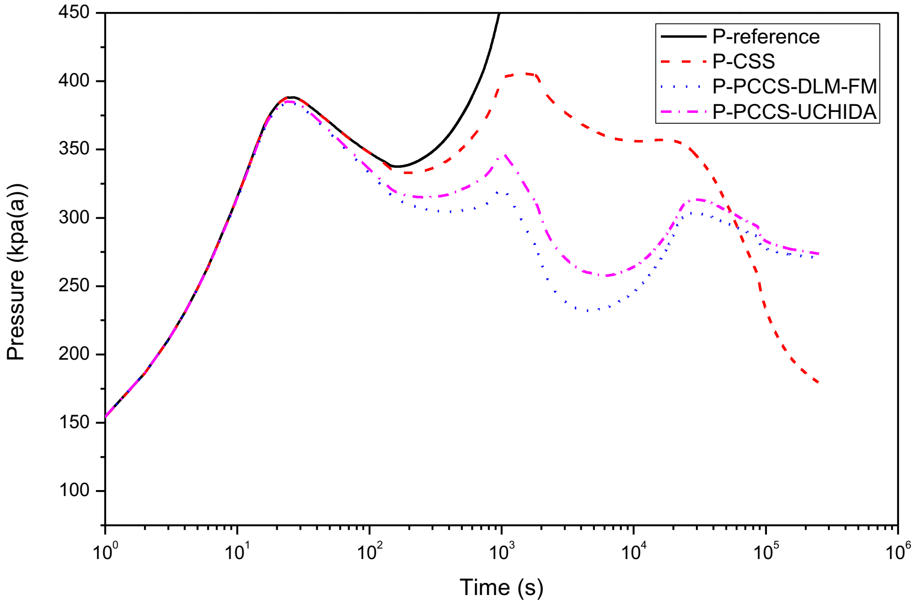

Fig. 8. Comparison of containment pressure transient response (CSS actuation vs. reference). CSS, containment spray system; PCCS, passive containment cooling system; DLM-FM, diffusion layer model with film roughening and mist generation; UCHIDA, uchida heat transfer correlation.

initiation. According to the mass and energy discharge rate variation, containment pressure decreased and increased again following the first peak pressure. Containment pressure reached maximum peak pressure at approximately 1,700 seconds. Thereafter, the containment pressure decreased gradually due to the effect of the CSS. As described above, CSS properly controlled the pressure and temperature. However, without any means of cooling, it can be seen that the opposite would happen.

The PCCS operating case was calculated using the GOTHIC containment model with one coolant tank (volume 4) connected to the PCCX, as shown in Fig. 5. The tank coolant capacity is 5,930 m^3. Because the PCCS does not require operator operation for initiation, PCCS actuation automatically starts following accident initiation. After the first peak pressure, the containment pressure decreases due to the effect of the PCCS and the passive heat sinks until the 4,000 second mark, except for the small second pressure peak. Thereafter, the containment pressure gradually increases to 300 kPa and decreases again. The trend of the containment temperature response is similar. Compared with the CSS operating case, energy removal performance is higher until 16.67 hours and a reversal subsequently occurs. This is considered to be due to the passive safety system characteristics; this system is without means to continuously cool the coolant. With the increasing of the operating time of the PCCS, the temperature of the coolant increases and

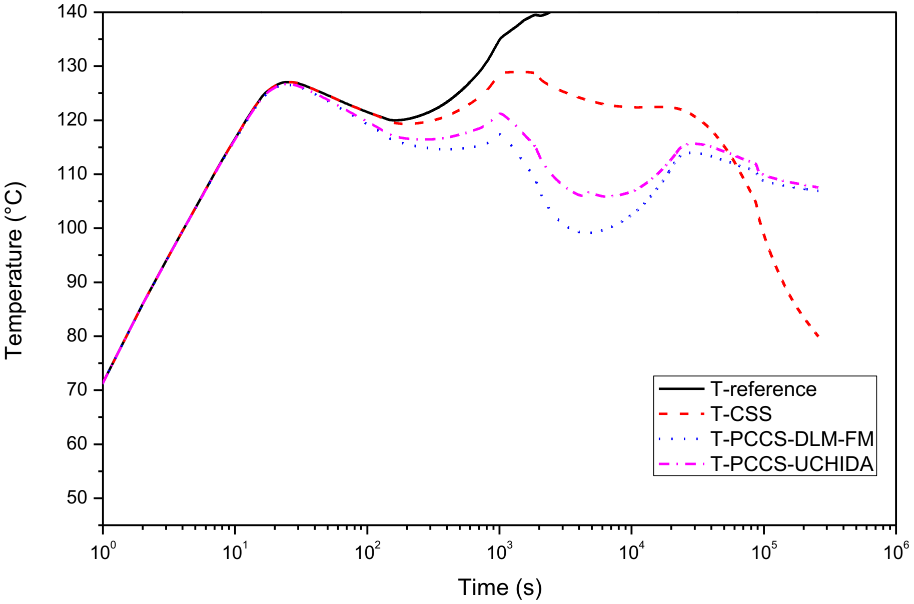

Fig. 9. Comparison of containment temperature transient response (CSS actuation vs. reference). CSS, containment spray system; PCCS, passive containment cooling system; DLM-FM, diffusion layer model with film roughening and mist generation; UCHIDA, uchida heat transfer correlation.

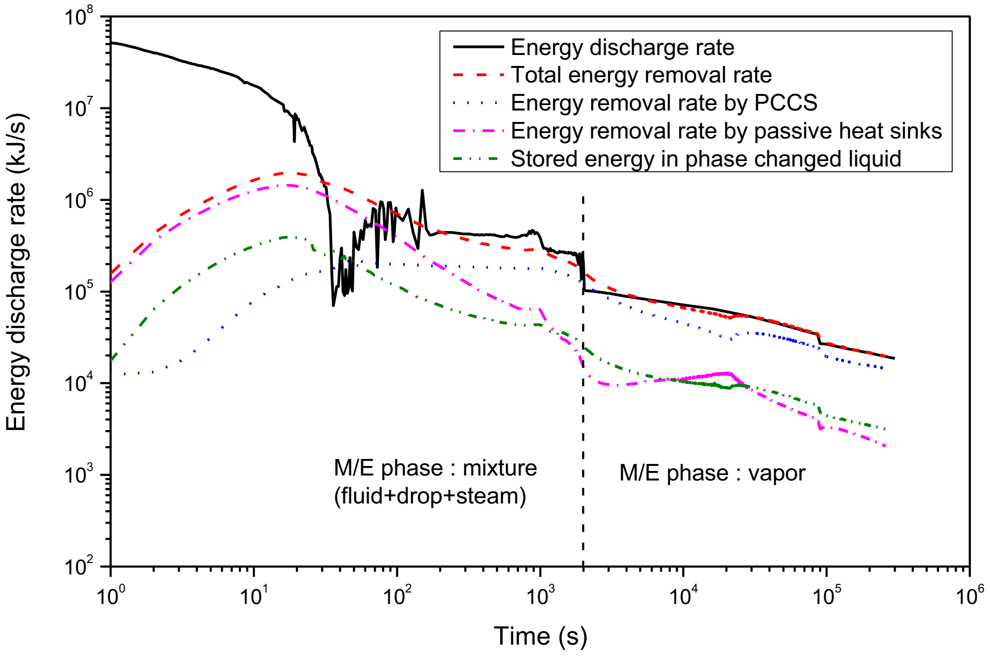

Fig. 10. Comparison of energy discharge rate and energy removal rate [single passive containment cooling tank (PCCT) case]. PCCS, passive containment cooling system.

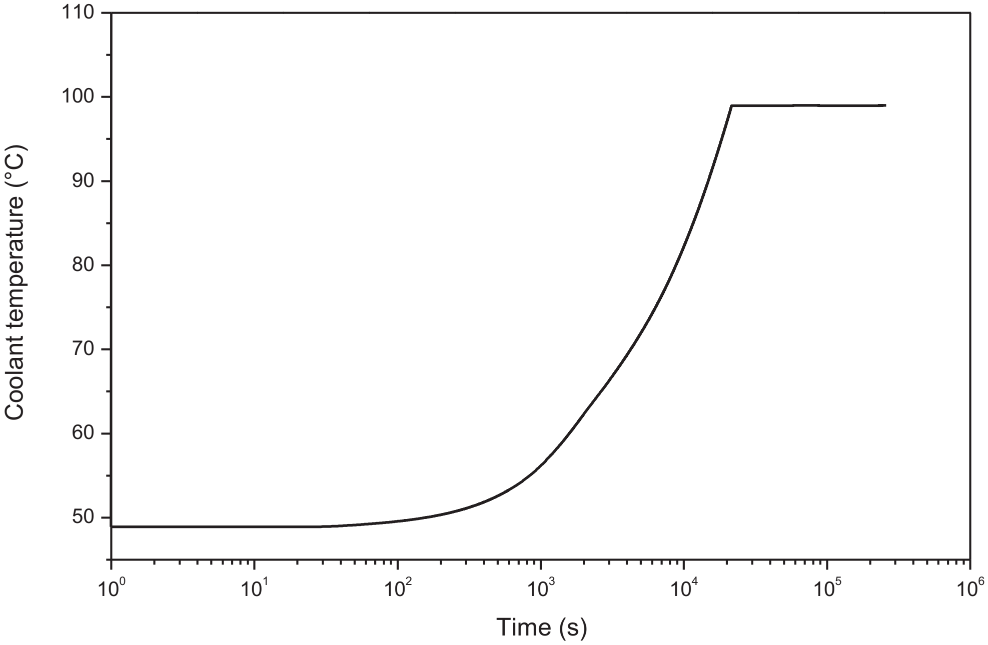

Fig. 11. Coolant temperature of passive containment cooling tank (PCCT) transient response (single PCCT case).

subsequently performance gradually decreases.

For the condensation model on the external surface of the PCCX, analysis using the DLM-FM and UCHIDA condensation model has been performed; results are shown in Figs. 8 and 9. Energy removal performance of the case of using the DLM-FM model is higher than in the case of using the UCHIDA model. This is because the UCHIDA model simply determines the heat transfer coefficient using only the noncondensable gas fraction; however, the DLM-FM model performs calculations realistically by using heat/mass transfer analogies that reflect the various calculation conditions [14,17]. Differences in the results are determined to be due to this discrepancy. Further analyses have been conducted in order to obtain more realistic results using the DLM-FM model.

In the analysis results of the PCCS operating case (with the DLM-FM model), it can be seen that containment pressure and temperature rebound occurred between 4,000 seconds and 21,000 seconds. The cause for this can be found in Figs. 10 and 11. Fig. 10 provides a comparison of the break's energy discharge rate and the energy removal rate by main energy removal means (PCCS and passive heat sinks) in the containment. After 200 seconds, most of the break's discharge energy is removed by the PCCS due to the energy removal performance degradation of the passive heat sinks. However, energy removal rate by passive heat sinks increased after about 3,000 seconds, as can be seen in Fig. 10. In this regard, some passive heat sinks, such as concrete, with large heat transfer area, or a dome in contact with the outside atmosphere at a constant temperature, continuously remove energy throughout the calculations. Except for these, most of the passive heat sinks absorb excess energy early in the accident and release energy. The amount of released energy is found to continuously decrease. Although there is some fluctuation, the energy removed by some passive heat

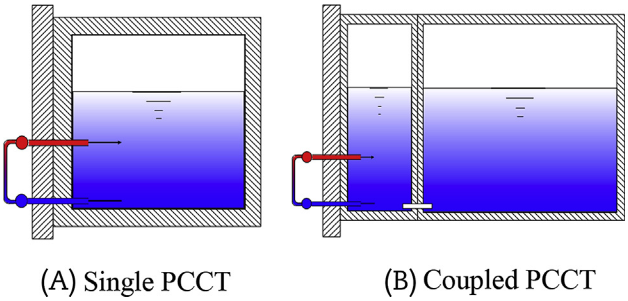

Fig. 12. Comparison of schematic diagram for passive containment cooling tank (PCCT).

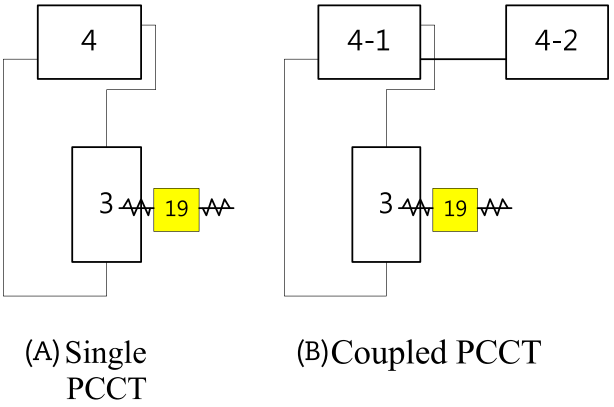

Fig. 13. Comparison of nodalization scheme for passive containment cooling tank (PCCT).

Table 2
Calculation case for coupled passive containment cooling tank (PCCT).

Case no.	Coolant capacity ratio (Tank 1:Tank 2)	Coolant capacity (m^3)	
		Tank 1	Tank 2
1	1:9	595	5,355
2	2:8	1,190	4,760
3	3:7	1,785	4,165
4	4:6	2,380	3,570
5	5:5	2,975	2,975

sinks (concrete, dome, etc.) from about 3,000 seconds remains at a constant level for a considerably long period. Regardless of this, the amount of energy released back to containment atmosphere by the remaining passive heat sinks continuously decreases, so that the total energy removal rate by passive heat sinks increases again. The energy removal rate rise due to the passive heat sinks is relatively insignificant and does not affect the total energy removal rate change. Therefore, the total energy removal rate is consistent with the behavior of the energy removal rate of the PCCS. From about 1,000 seconds, the energy removal rate of the PCCS decreases. In this regard, the performance of the PCCS is greatly influenced by the temperature difference between the coolant and the containment atmosphere. As shown in Fig. 11, the coolant temperature rises sharply from the same time. Therefore, this decrease in energy removal rate can be attributed to the rise in the coolant temperature. This phenomenon continues until the coolant temperature reaches the saturation temperature. Similarly, the sum of the energy removal rate also continuously decreases after 1,000 seconds and falls below the energy discharge rate at 4,000 seconds. After that, it rises again at the time of energy removal rate of PCCS increase. This seems consistent with the behavior of the containment pressure during the same period. Based on the information described above, the degradation of the PCCS performance occurring in the period of PCCS coolant temperature increases is determined to be the main cause of the pressure and temperature rebound.

These pressure and temperature rebound phenomena that occur during PCCS operation may cause the operator to question

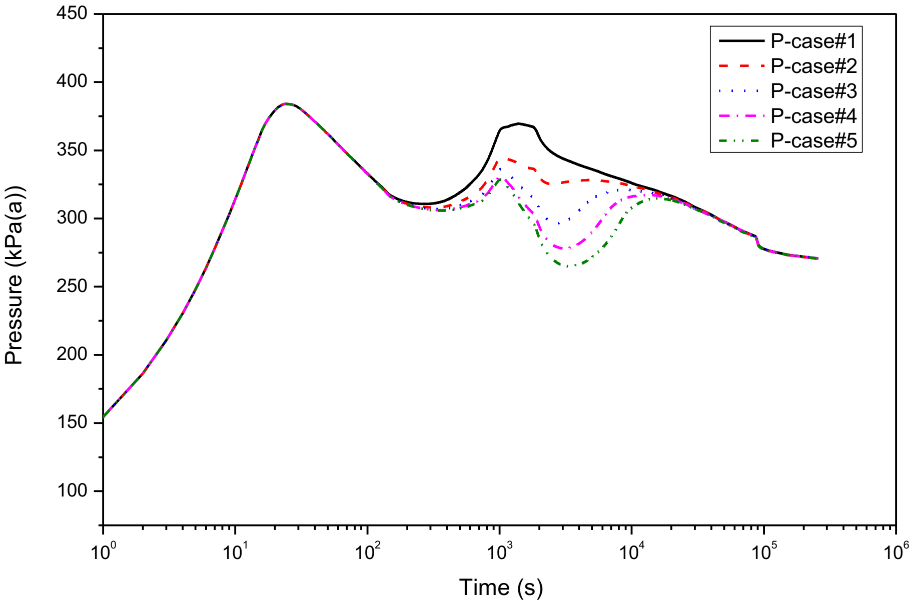

Fig. 14. Containment pressure transient response [coupled passive containment cooling tank (PCCT) case].

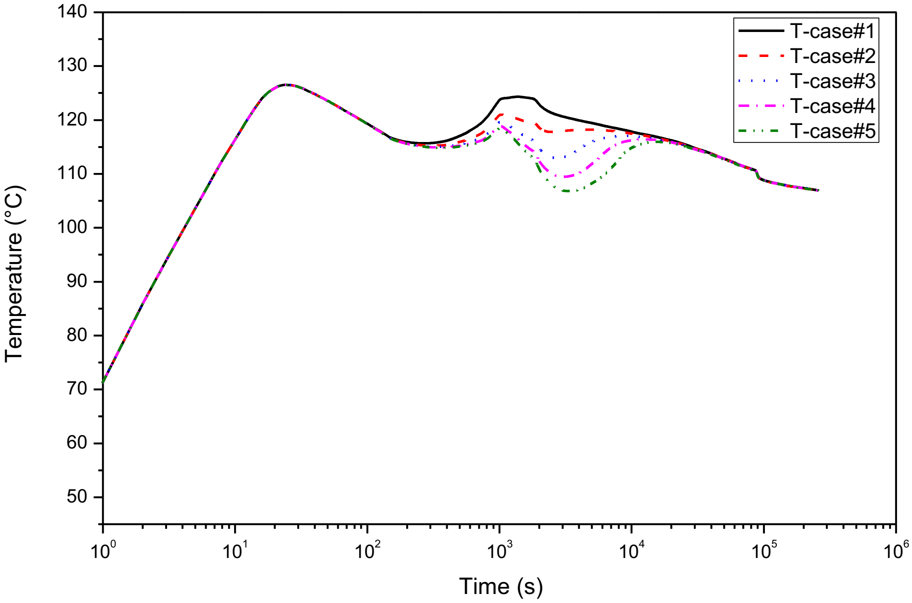

Fig. 15. Containment temperature transient response [coupled passive containment cooling tank (PCCT) case].

whether or not the normal operation of PCCS is adequate and results in the problem of applying a repetitive physical stress to the containment building. In addition, we have set one of the safety requirements that iPower should have a minimum 3 days for operator action time [1]. Based on this, we have determined that it is not advisable for the operator to watch the repressurization over several hours, even when the safety system has been activated in the event of an accident. Thus, we try to find a solution to resolve this problem. As a part of this, we focus on the variation of the energy removal rate of the PCCS, as shown in Fig. 10. In the vicinity of 21,000 seconds, it can be seen that there is an increase in the energy removal rate of the PCCS. As shown in Fig. 11, this happens at the same time that the temperature of the coolant reaches the saturation temperature. In the GOTHIC code, the flow and heat transfer regime change according to the liquid volume fraction and the liquid/wall temperature. Therefore, the energy removal rate increase is determined to be due to changes in the flow and heat transfer regime, which depends on the coolant temperature rise. If the regime changes in this way, the heat transfer coefficient formula changes from the following single phase liquid correlation:

$$H_{spl} = Max\begin{bmatrix} \dfrac{2k_l}{\delta} \\ \dfrac{k_l}{D_h}0.023Re_l^{0.8}Pr_l^{0.4} \\ \dfrac{k_l}{D_h}Max\left(0.13[Gr_lPr_l]^{1/3}, 0.59[Gr_lPr_l]^{0.25}\right) \end{bmatrix}$$

to the following boiling phase correlation:

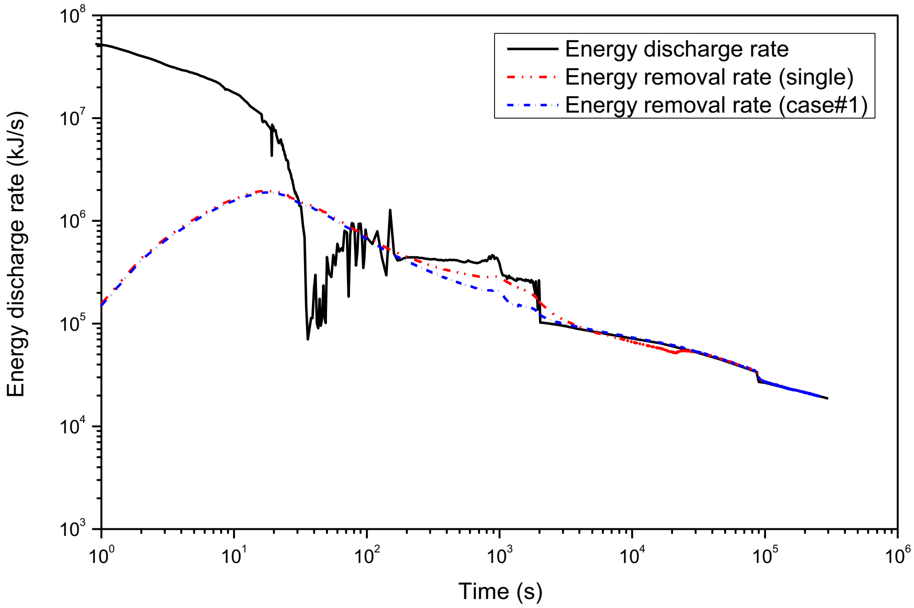

Fig. 16. Comparison of energy discharge rate and energy removal rate [single and coupled passive containment cooling tank (PCCT) case].

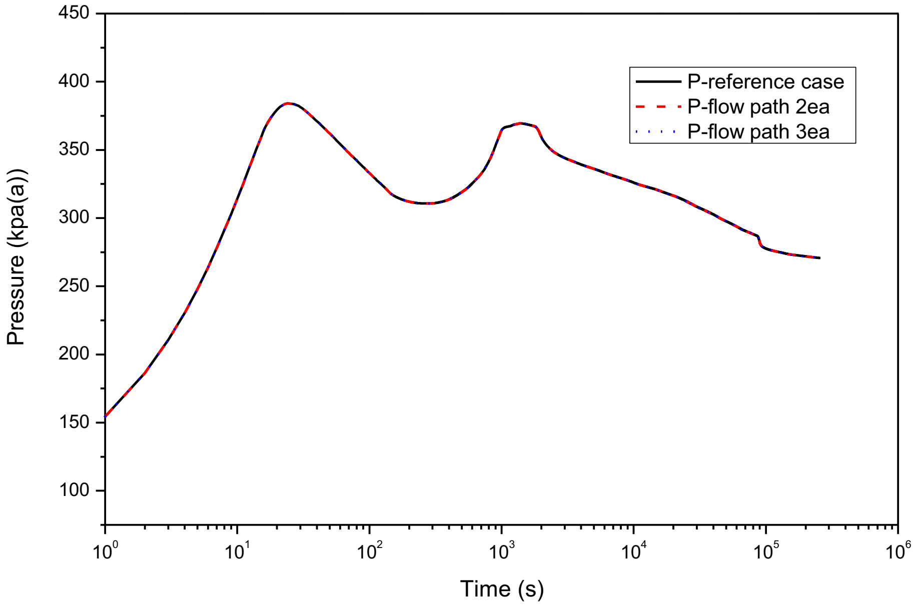

Fig. 17. Comparison of containment pressure transient response due to change in the number of flow paths.

$$H_{nb} = 0.00122\lambda_v\lambda_S\frac{k_l^{0.79}c_{p_f}^{0.45}\rho_f^{0.49}}{\sigma_f^{0.5}\mu_f^{0.29}h_{f_g}^{0.24}\rho_g^{0.24}}\left(T_w - T_f\right)^{0.24}(P_w - P_{sat})^{0.75}$$

or a combination formula of the two correlations according to the heat transfer selection logic inside the GOTHIC code [17].

3.2. PCCT design effects

3.2.1. Coupled PCCT case

In the previous section, we found that the energy removal rate decreases during the transient period when the coolant temperature of the PCCS rises, and that the energy removal rate increases when the saturation temperature is reached. Based on these facts, it is determined that as the coolant capacity of the PCCT connected to the PCCX decreases, the time for the coolant temperature to reach the saturation temperature will reduce. However, if the capacity of coolant is reduced, the operation time of the PCCS will also reduce. We changed the PCCT design as shown in Fig. 12 to satisfy both of these requirements at the same time.

As shown in Fig. 13, the PCCT of the GOTHIC model is divided in two (Tank 1 and Tank 2) to solve the temperature and pressure rebound problem of the PCCS with single PCCT, which are connected with a single flow path. The diameter of the flow path is 0.1 m. Tank 1 is connected with the PCCX and has a smaller capacity than that of Tank 2. The coolant quantity of each tank is shown in Table 2; the sum of both is always constant at 5,950 m^3. The previously described GOTHIC containment model has two purposes, as follows: the first purpose is to stabilize the energy removal performance of the PCCS within the early moments of accident when

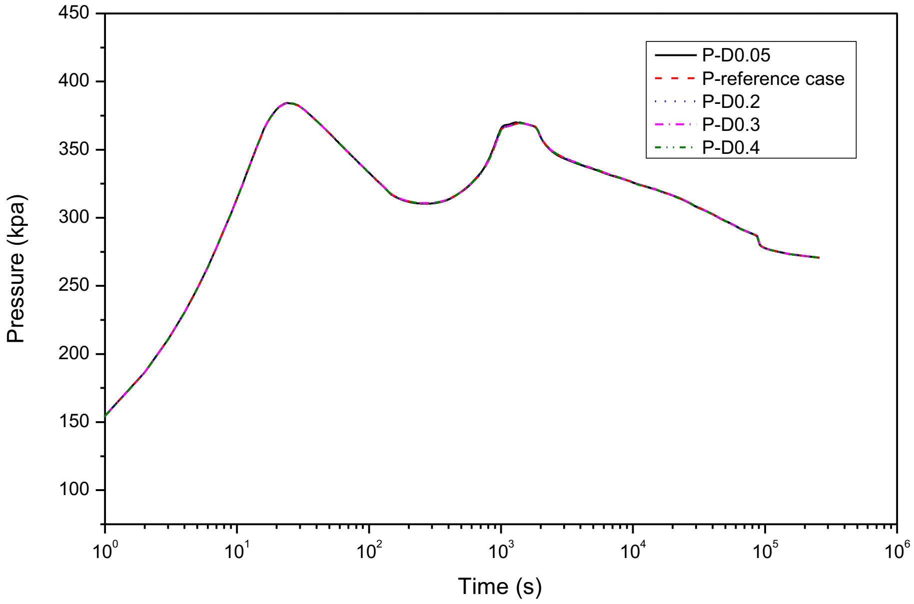

Fig. 18. Comparison of containment pressure transient response due to change in the diameter of flow path.

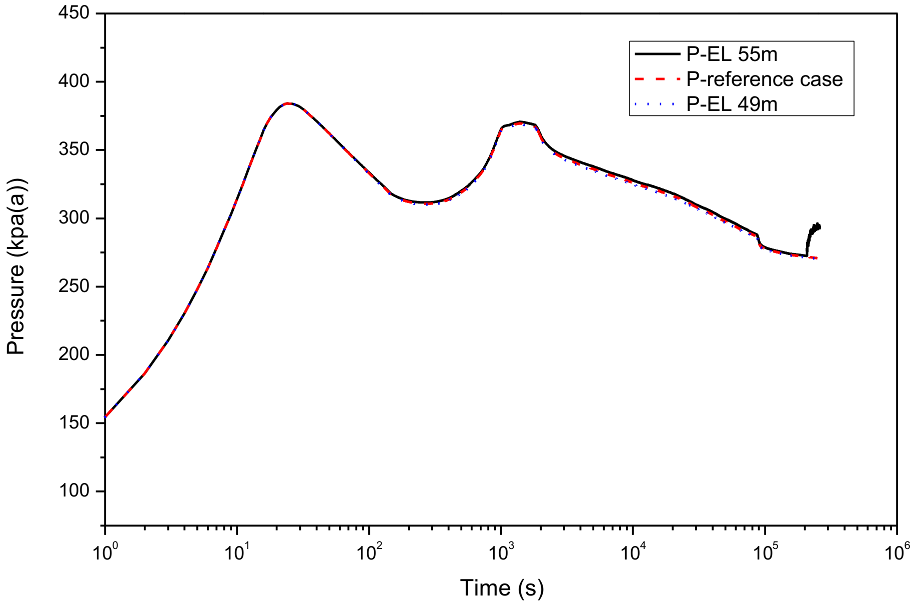

Fig. 19. Comparison of containment pressure transient response due to change in the installation location of the passive containment cooling system heat exchanger (PCCX).

coolant temperature of Tank 1 reaches saturation temperature quickly; the second purpose is to receive a continuous supply of cold coolant of an amount equal to that which evaporates in Tank 1 from Tank 2. Fig. 14 shows the containment pressure transient responses when using the coupled PCCT with a different coolant ratio. Because the capacity to remove the discharged energy decreases due to the reduced coolant level of Tank 1, the containment pressure of Case #1 is highest after 200 seconds; it can be seen that the pressure rebound period has disappeared. Fig. 15 shows the containment temperature transient response. Fig. 16 shows a comparison of the energy discharge rate and the energy removal rate of the PCCS with single and coupled PCCT (Case #1). For the coupled PCCT case, the fluctuation of the energy removal rate is smaller than that of the single PCCT case after 1,000 seconds. The energy removal rate, coupled with the energy discharge rate, gradually decreases.

3.2.2. Flow path design of coupled PCCT

If there is no proper supply of water from Tank 2 to Tank 1, the PCCS will fail. Therefore, the number and cross-sectional area of the flow paths are also important input parameters for coupled PCCT calculations. In Figs. 17 and 18, the reference case is Case #1 of Table 2. The results show that the number and cross-sectional area of the flow paths do not influence the containment thermal-hydraulic response for the selected cases.

3.3. PCCX location effects

In determining the design of the PCCS, the installation location of the PCCX is one of the most important parameters. Due to the

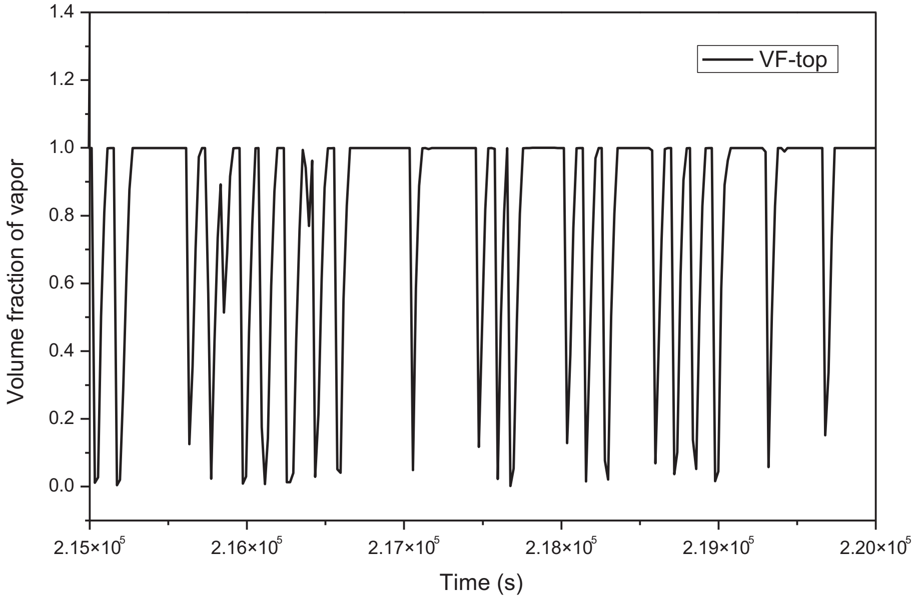

Fig. 20. Vapor volume fraction of the passive containment cooling system heat exchanger (PCCX) tube transient response.

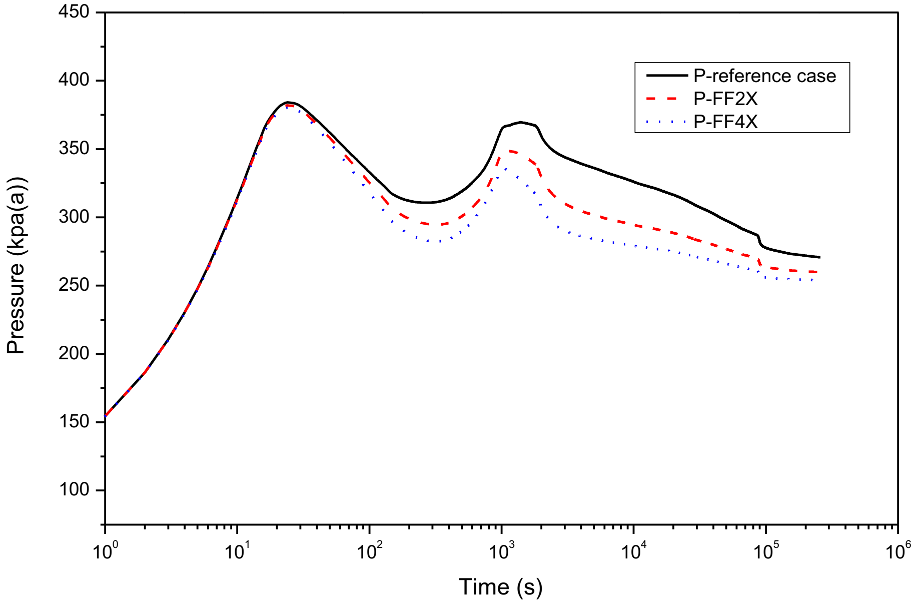

Fig. 21. Comparison of containment pressure transient response due to change in the multiplier FF.

limitations of the current lumped-parameter containment model, the level of the PCCT is fixed and examined to determine its effect on the installation location of the PCCX. In Fig. 19, the reference case is Case #1 from Table 2 and the installation level of the PCCX is at 52 m. Results from the calculations suggest that if the installation location is lower than the reference case, the difference between the results will be negligible. However, the pressure rebounds after 55 hours if the PCCX is installed on the same level as the PCCT. In this case, the differential head between the PCCX and the PCCT is about 2.5 m. Because the water level of the PCCT drops under PCCS operating conditions, the saturation temperature inside the PCCX decreases. Therefore, boiling occurs at the top of the PCCX tube at the time that the saturation temperature is equal to the coolant temperature, as shown in Fig. 20. This is considered to cause the heat removal rate of the PCCS to decrease and the pressure to rebound.

3.4. *PCCX external surface area effects*

'Multiplier FF' is one of the thermal conductor surface options of the GOTHIC code. It provides a simple multiplier for the condensation heat transfer coefficient calculated by GOTHIC [16]. With this, the same effect can be added to increase the heat transfer means, such as using heat exchanger fins. Fig. 21 shows the pressure transient response due to the change in the multiplier (2 and 4). As the multiplier increases, pressure and temperature decrease. However, this increase in the energy removal capacity is limited by the maximum amount of energy that can be removed from the internal surface of the PCCX tube.

4. Conclusion

The containment thermal-hydraulic response was analyzed by the GOTHIC containment model to provide performance assessment data and optimized designs of the PCCS for the iPower. The effects of the design parameters were evaluated for PCCT geometry, PCCX location, and external surface area. The analyzed results showed that the coupled PCCT more rapidly stabilized the performance of the PCCS and that, if the installation level of the PCCX is higher than that of the PCCT, it may negatively affect the performance of the PCCS. Additionally, it was confirmed that the increase of the surface area of the PCCX, by means of devices such as fins, could help improve the energy removal performance of the PCCS. These insights are important for developing the PCCS of the iPower.

To improve the PCCS design and investigate its performance, the following studies are needed:

- Develop and evaluate a new condensation heat transfer model for the PCCS of the iPower
- Develop a new GOTHIC containment model for identification of detailed thermal-hydraulic phenomena inside the containment building and PCCS
- Evaluate and verify the GOTHIC built-in condensation heat transfer model and PCCS modeling methodology based on the results of experiments related to PCCS

Conflicts of interest

All authors have no conflicts of interest to declare.

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