INVESTIGATION OF OPERATIONAL CHARACTERISTICS OF PASSIVE CONTAINMENT COOLING SYSTEM FOR AN ADVANCED PWR

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ABSTRACT

The passive safety system is of great importance to improve the safety, reliability and economics of the nuclear power plant, especially after the Fukushima accident. To maintain the containment's integrity in a loss of coolant accident (LOCA) without the spray system, a new type of passive containment cooling system (PCS) using the natural circulation loop (NCL) is designed for an advanced pressurized water reactor. By using the RELAP5 code, the steady-state operational characteristics of the PCS were studied, and the heat removal capacity as a function of boundary temperatures was derived. The containment is simulated by the MELCOR, with the PCS modeled as a heat sink. The transient responses of both the containment and the PCS during accidents were obtained. Moreover, the efficiency of the PCS in long-term period can be further enhanced by feeding and bleeding the cooling tank, which is evaluated by an analytic model. The results show that the heat in the containment can be effectively removed by the PCS in a certain period after the accident occurs. The shorter actuation time and lower initial tank temperature can facilitate the mitigation of accident in the early stage, but the effect is not evident in the long-term period. For the feed-and-bleed operation, the larger the feeding flow rate, the lower the stable temperature of the cooling tank and the shorter time it takes to achieve stable state. For both single-phase flow and two-phase flow, changing loop height has little effect on the heat transfer capacity of the PCS, which provides more flexibility for the layout in the containment.

KEYWORDS
Containment thermal-hydraulics; Passive cooling system; Natural circulation; RELAP5; MELCOR

1. INTRODUCTION

In the loss of coolant accident (LOCA) or main steam line break accident (MSLB) of a pressurized water reactor (PWR), when a break occurs in the pipeline, large amount of high-energy fluid discharge into the containment, causing the dramatic increase in containment pressure and temperature. If the spray system is not available due to the loss of power or failure, the containment integrity is likely to be threatened, leading to the large release of radioactive material into the environment.

In order to maintain the containment integrity in the above postulated accident scenarios, various types of passive containment cooling system (PCCS) have been employed in the advanced NPPs [1]. For AP1000, the heat inside the containment is transferred to the steel wall by steam condensation, and the steel containment is cooled by the water drained from the above storage tank and air flow in the channel outside the containment. For ESBWR, the passive containment cooling system condenser, which is immersed in the pool on the top of the containment, receives steam-gas mixture directly from the dry well. The steam is condensed when passing through the condenser and return to the reactor vessel via the gravity-driven cooling system (GDCS) pool, while the noncondensable gas is vented into the wet well driven by the pressure difference.

For a third-generation advanced PWR, a new design of passive containment cooling system (named PCS instead) is utilized, which uses a natural circulation loop (NCL) to extract heat from the containment. To increase the redundancy, it is composed of 3 independent trains. As illustrated in Fig. 1, each train of the PCS mainly consists of 4 parallel heat exchangers (HX), a condenser, an expansion tank, a cooling tank, isolation valves, and pipes. The heat exchangers situate inside the upper space of containment. The cooling tank, which lies outside the containment, is opened onto the atmosphere. The expansion tank connecting with the loop is used to compensate the fluid volume change due to the density fluctuation, keeping the loop pressure relatively stable. When accident occurs and the PCS comes into operation, the heat is transferred from containment's atmosphere to the heat exchangers by means of condensation, convection, and radiation. Thus the fluid inside the heat exchangers is heated up. Driven by the buoyancy force due to the density difference, the flow is maintained and natural circulation is established. Then the hot fluid in the heat exchangers is cooled by the cooling tank when passing through the condenser submerged in the tank. As the result, the energy extracted from the containment is conveyed to the cooling tank, and eventually, to the ultimate heat sink (environment atmosphere). When the heat flux received by the heat exchangers is relatively high, the working fluid inside the loop is likely to evaporate or flash. Then the circulation becomes two-phase flow.

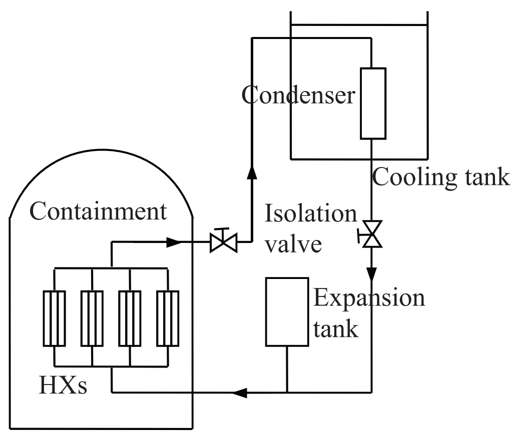


Figure 1. Schematic diagram of PCS.

Plenty of numerical and experimental investigations regarding the natural circulation loop have been carried out. N.M. Rao (2006) studied the steady-state behaviors of rectangular NCL with uniform heat flux as boundary conditions by using the homogeneous equilibrium model and the thermal equilibrium drift flux model [2]. Jin Ho Song (2012) derived the analytic solution for mass flow rate of NCL as a function of geometric parameters, frictional loss coefficient, and pressure based on the pressure balance [3]. A generalized correlation to estimate the steady-state flow in two-phase NCL was developed by M.R. Gartia, et al. (2006) based on governing equations, and validated by the comparison with the experimental data from five test facilities [4]. The instability of supercritical flow in NCL was investigated by numerically solving one-dimension governing equations by Prashant K. Jain and Abhilash K.Tilak etc.[5-6]. C.S. Byun et al. proposed a conceptual design of an internal evaporator-only (IEO), and analyzed its performance using the GOTHIC code, with IEO modeled as a conductor whose inner temperature was roughly specified [7]. The thermal hydraulic evaluation of the performance of the PCCS of the Korea improved APR+ were carried out by Byong Guk Jeon et al. using a system code MARS [8].

However, most of the above works are mainly concerned with the steady-state or instable behaviors of the natural circulation loop under some simple boundary conditions (constant, ramp, sinusoidal, etc.), without further study of the transient response of the containment as well as the passive containment cooling system during the accident. In the present work, both steady-state and transient characteristics were investigated. The transient response of the containment and the PCS are simulated simultaneously. Moreover, the efficiency of the PCS in long-term period can be further enhanced by feeding and bleeding the tank, which is evaluated by an analytic model. The influence of various parameters, such as the natural circulation loop pressure and height, were also studied.

2. THE MODEL

2.1. Steady-State Calculation Model

For the PCS, the main physical phenomenon is natural circulation which couples both hydrodynamics and heat transfer process. RELAP5 is a highly generic thermal-hydraulic code that can be used for simulation of a wide variety of hydraulic and thermal transients in nonnuclear systems involving mixtures of steam and water. Therefore, RELAP5 MOD3.4 is selected to simulate the natural circulation loop of the PCS.

The nodalization of the PCS model is depicted in Fig. 2. The natural circulation loop is mainly divided into 4 sections, i.e. heat exchangers, riser, condenser, and downcomer. Each section is modeled using pipe component which is further subdivided into 20 control volumes. These pipes are numbered from 121 to 124 and connected by junctions. The volume 901 representing the containment is simply modeled as a time-dependent volume, whose temperature is set to be a specific constant value for each run. The cooling tank 601 is modeled by a control volume connected to the environment 700 (time-dependent volume). 131 is the expansion tank ideally modeled as time-dependent volume. The heat transferred from the containment to the heat exchangers and from condenser to cooling tank is modeled by heat structures. The riser and downcomer are considered to be adiabatic, without any heat structure associated with them. The geometric parameters of the PCS loop are given in Table I.

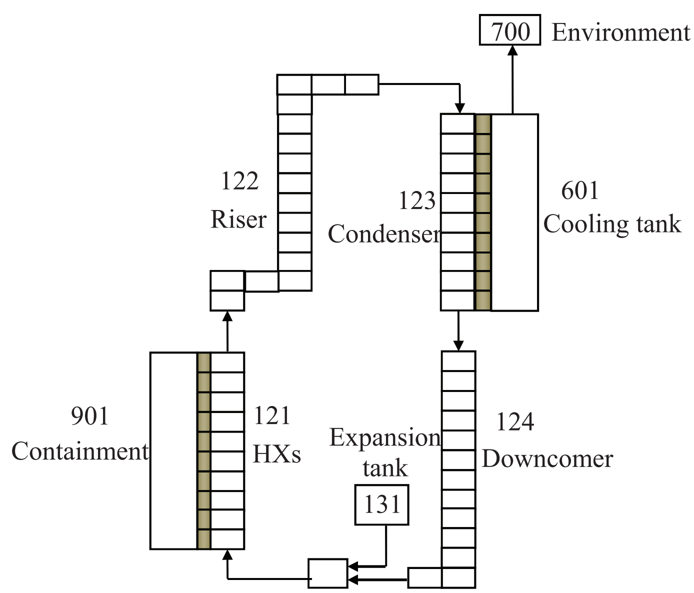


Figure 2. Nodalization of the PCS model

Table I. Geometric parameters of PCS loop

Section	Parameter	Value
Riser	Diameter (m)	0.40
	Length (m)	10.0
Downcomer	Diameter (m)	0.30
	Length (m)	10.0
HX/condenser	Diameter of tube (m)	0.034
	Total heat transfer area (m^2)	300.8
	Tube material	Stainless steel
Cooling tank	Depth (m)	5.0
	Nominal Volume (m^3)	1000.0

The steam condensation heat transfer between containment atmosphere and HXs is of great significance to the performance of PCS. However, the presence of even a small amount of noncondensable gases can cause a large reduction of the heat transfer coefficient, compared with the pure vapor condition [9]. In this work, empirical correlations obtained from the experiment conducted by J.Q. Su (2013) for the steam condensation outside a vertical tube in presence of noncondensable gases are used in the simulation [10].

For steam-air mixture:

$$h_a = (T_b - T_w)^{-0.6}[10189.3 + 90416.4P - (4314.4 + 46537P)Log10(100\omega_{nc})] \quad (1)$$

For steam-air-helium mixture:

$$h = \begin{cases} 0.98(T_b - T_w)^{-0.6}h_a & , \ N_{He}/N_{nc} < 0.10 \\ (1.102 - 1.165\, N_{He}/N_{nc})(T_b - T_w)^{-0.6}h_a, & 0.10 < N_{He}/N_{nc} < 0.35 \end{cases} \quad (2)$$

2.2. Transient Calculation Model

Since the current version of RELAP is not capable of simulating containment phenomena, another containment code is needed. In this study, MELCOR is chosen to calculate the thermal-hydraulic responses of containment. The containment is simply modeled as one control volume with the free volume of 60000 m^3, and the inside heat structures (HS) are considered. By modeling the PCS by using the function of heat removal power obtained from RELAP calculation, the transient behaviors of both PCS (including heat removal power and cooling tank temperature) and containment are able to be calculated simultaneously. As shown in Fig. 3, the transient calculation procedures are:

- Step 1: Calculate the heat removal power of PCCS under different constant boundary heat source and sink temperatures using REALP5.
- Step 2: Obtain the heat removal function with the temperatures of containment and tank as independent variables by means of data fitting.
- Step 3: Use MELCOR to simulate the response of containment during accident, with PCS modeled as a heat sink whose power is calculated by the function derived above. Meanwhile, update the cooling tank temperature according to the balance of energy by Eq. (3), until the water in the tank is saturated.

$$T_{tank}(t + \Delta t) = T_{tank}(t) + W_{PCS}(t) \cdot \Delta t/(c_p m_{tank}) \quad (3)$$

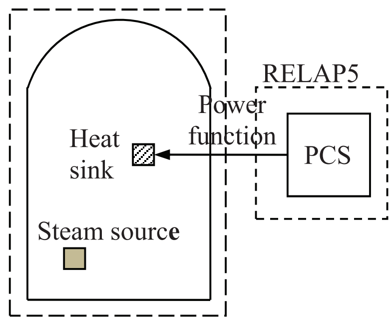


Figure 3. Illustration of transient calculation method

2.3. Cooling Tank feed-and-bleed Model

As the heat is being conveyed into the cooling tank during PCS operation, the tank temperature is gradually growing, leading to a reduction of the heat removal capacity. In order to further increase the PCS efficiency in long-term period, the cooling tank is necessary to be cooled down. Generally it is plausible to assume that the external power source can be recovered after a period of time (typically 72 hours), so that an active mitigation system carrying out the tank feed-and-bleed operation is introduced.

As shown in Fig. 4, the cold water enters the cooling tank through an inlet at the bottom, and the hot tank water is drained from the outlet at the top. Besides, the tank also exchanges mass and energy with the coolant of the NCL. The basic assumptions for the model describing the feed-and-bleed operation are:

- The mass of the drained hot water equals the feeding cold water, i.e. $\dot{m}_{in} = \dot{m}_{out}$, which means that the total mass of the water in the tank doesn't change during the feed-and-bleed process;
- The cold and hot water mix completely and instantaneously the moment the cold water enters.

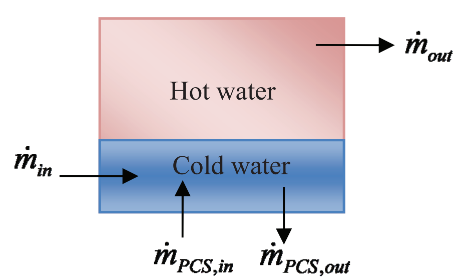


Figure 4. Illustration of cooling tank feed-and bleed model

Consider a short time interval Δt, the mass of the feeding cold water and the hot water left in the tank are:

$$m_{cold} = \dot{m}_{in} \cdot \Delta t \quad (4)$$

$$m_{hot} = m_{tank} - m_{cold} \quad (5)$$

The change of the tank temperature can be considered to be the sum of two parts: 1) related to the cold and hot water mixing process; 2) associated with the natural circulation in the loop. For the first aspect, the energy balance for the mixing process is:

$$c_{p,cold}m_{cold}[T_{mix}(t+\Delta t)-T_{in}] = c_{p,hot}m_{hot}[T_{tank}(t)-T_{mix}(t+\Delta t)] \quad (6)$$

where $T_{mix}(t+\Delta t)$ is the new post-mixing temperature. On the other hand, the temperature increase due to the energy conveyed by the PCS natural circulation loop is:

$$\Delta T_{PCS} = W_{PCS}\cdot \Delta t/\left(c_{p,hot}m_{tank}\right) \quad (7)$$

Thus the new tank temperature is obtained as:

$$T_{tank}(t+\Delta t) = T_{mix}(t+\Delta t) + \Delta T_{PCS} \quad (8)$$

Combine Eq. (4)~(8) , we can derive the differential equation describing the instant tank temperature as:

$$\frac{dT_{tank}(t)}{dt} = -\frac{\dot{m}_{in}}{m_{tank}}T_{tank}(t) + \left[\frac{\dot{m}_{in}}{m_{tank}}T_{in} + \frac{W_{PCS}}{c_{p,hot}m_{tank}}\right] \quad (9)$$

By solving Eq. (9) we have the exponential expression for the tank temperature with respect to time as:

$$T_{tank}(t) = C_1 e^{-\frac{t}{\tau}} + T_{tank}(\infty) \quad (10)$$

in which C_1 is the integral constant which can be determine by the initial condition, $\tau = m_{tank}/\dot{m}_{in}$ is the time constant describing the speed to achieve steady state since the initiation of the feed and bleed, while $T_{tank}(\infty) = T_{in} + \frac{W_{PCS}}{c_{p,hot}\dot{m}_{in}}$ is the long-term steady cooling tank temperature. Actually, for $T_{tank}(\infty)$, if we assume that all the energy transferred by natural circulation loop is used to heat up feeding cold water to the long-term steady temperature, then the same expression can also be derived.

3. RESULTS AND DISCUSSIONS

3.1. Steady-State Analysis

In the calculation, the containment temperature ranges from 120 to 150°C, while the tank temperature varies from 40 to 100°C. The pressure of the expansion tank is set as 0.30MPa. Fig. 5 shows the static quality at the outlet of the riser. It can be seen that PCS can operate either in one-phase mode or two-phase mode at a specific loop pressure, depending on the boundary temperature condition. As shown in Fig. 6, the mass flow rate monotonically grows with the containment temperature. With the increase of the tank temperature, the mass flow rate slightly decreases for the one-phase flow but sharply increases for the two-phase flow. Therefore, the minimum flow rate arrives during the phase transition. It is because for one-phase flow, the density of fluid in the tank decreases as the tank temperature grows, but not too much because the volumetric thermal expansion coefficient for liquid is indiscernible. However, for two phase flow the density of fluid in drops significantly when tank temperature rises due to the evaporation, leading to the increase of driving force. Fig. 7 displays the heat removal power of PCS under different temperature combinations of the containment and the tank. Overall, for each operation mode (excluding the phase transition region), the heat removal power linearly decreases as the heat sink temperature grows (Fig. 7.a), and linearly increases with the temperatures of heat source (Fig. 7.b). Moreover, for given containment and tank temperatures, the power of two-phase flow is always higher than the extrapolated value of line of one-phase power. The main reason is that the natural circulation is enhanced as it turns into two-phase flow (see Fig. 6).

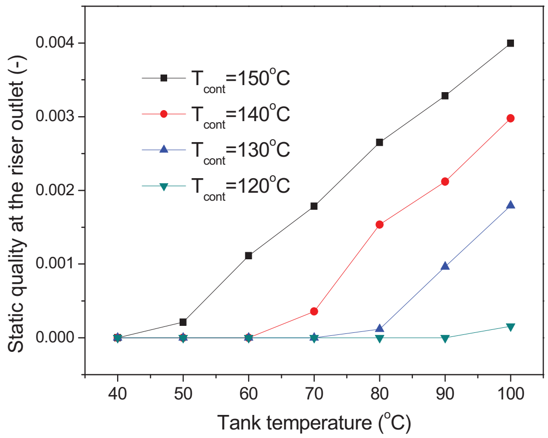


Figure 5. Static quality at the outlet of the riser

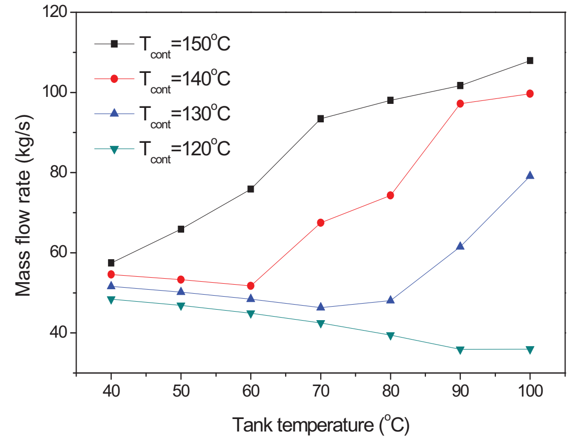
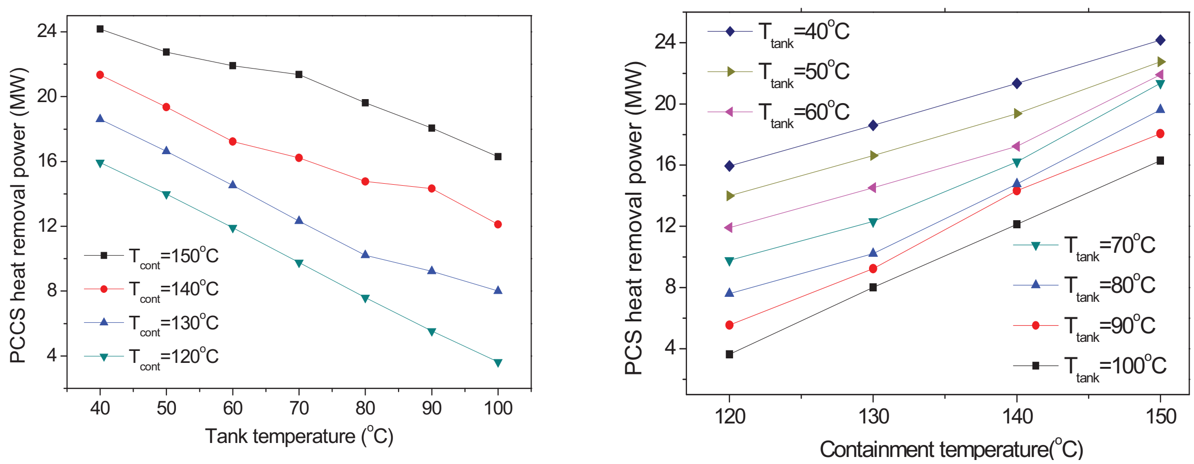


Figure 6. Mass flow rate of natural circulation



(a) With tank temperature as x axis (b) With Containment temperature as x axis

Figure 7. Heat removal power of PCS

For a particular pipe diameter, there is a limitation for the maximum fluid velocity, regarding frictional pressure loss and corrosion of pipe wall. By searching along the loop, it is found that the maximum fluid velocity appears at the outlet for the riser, while at the inlet for the downcomer. The maximum fluid velocities for both riser and downcomer under different boundary temperatures are shown in Fig. 8, from which we can see that the maximum fluid velocity of riser varies much more evidently than that of downcomer, because it is possible to generate vapor in riser when the receiving heat flux is relatively high, but the fluid in downcomer always remains liquid state during operation. For one-phase flow, the maximum velocity of downcomer is larger than that of riser, but smaller for two-phase flow. Moreover, it can be observed that both the maximum fluid velocities for riser and downcomer culminate when heat source and sink temperatures are both highest. The maximum values are 3.33m/s and 1.45m/s respectively, which don't exceed the limit corresponding to the given diameters in present work.

In actual engineering design, the orientation of part of the loop pipe may be horizontal. These horizontal segments not only contribute little to the driving head, but also possibly reduce the stability of natural circulation due to the change of flow pattern or stratification. Therefore, it is necessary to study the location where fluid starts to evaporate or flash. Fig. 9 shows the location of onset of boiling in the riser with the bottom defined as origin. It shows that the lowest location, which occurs when both temperatures of the containment and the tank are highest, is 4.5m above the bottom of the loop. It is suggested that the horizontal pipes be placed below this elevation.

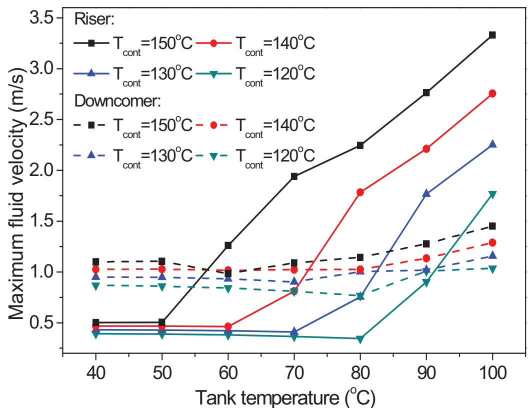


Figure 8. Maximum fluid velocities the loop

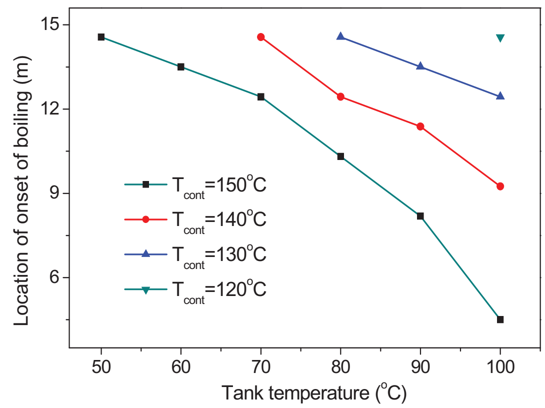


Figure 9. Location of onset of boiling in the riser

3.2. Transient Response

In this section, MELCOR is used to calculate the transient behaviors of both containment and PCS, with PCS modeled as a heat sink whose power is given by control function (CF). To obtain the heat removal function with the temperatures of containment and tank as independent variables, since the linearity is well (Fig. 7), the fitting function for one train of PCS can be simply assumed to be (in MW):

$$W_{PCS}(T_{cont}, T_{tank}) = aT_{cont} + bT_{tank} + c \quad (11)$$

Fit the data of heat removal power calculated by REALP5 using least squared method, the coefficients in Eq. (11) are determined as: $a = 0.36$, $b = -0.16$, $c = -22.39$. The comparison of the data calculated by RELAP5 and predicted by above fitting function is shown in Fig. 10. The relative deviation is roughly within ±10%, which is acceptable for the transient calculation. Regarding the PCS actuation time and the cooling tank initial temperature, three cases are selected (Table II). The double-end break of cold leg accident scenario is chosen for the transient calculation. The initial containment temperature is 40.0℃, and 3 trains of PCS are put into operation during accident.

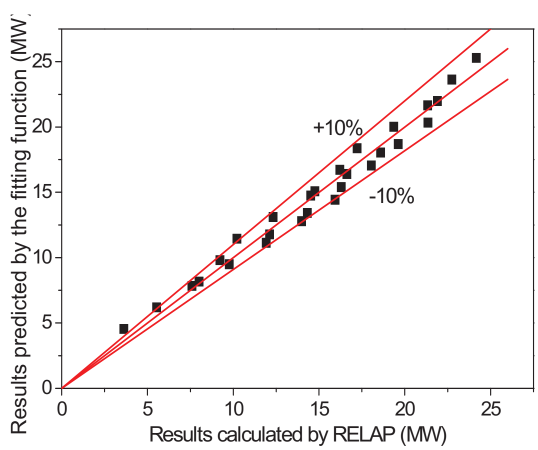


Figure 10. Comparison of results calculated by REALP and fitting function

Table II. Transient calculation case matrix

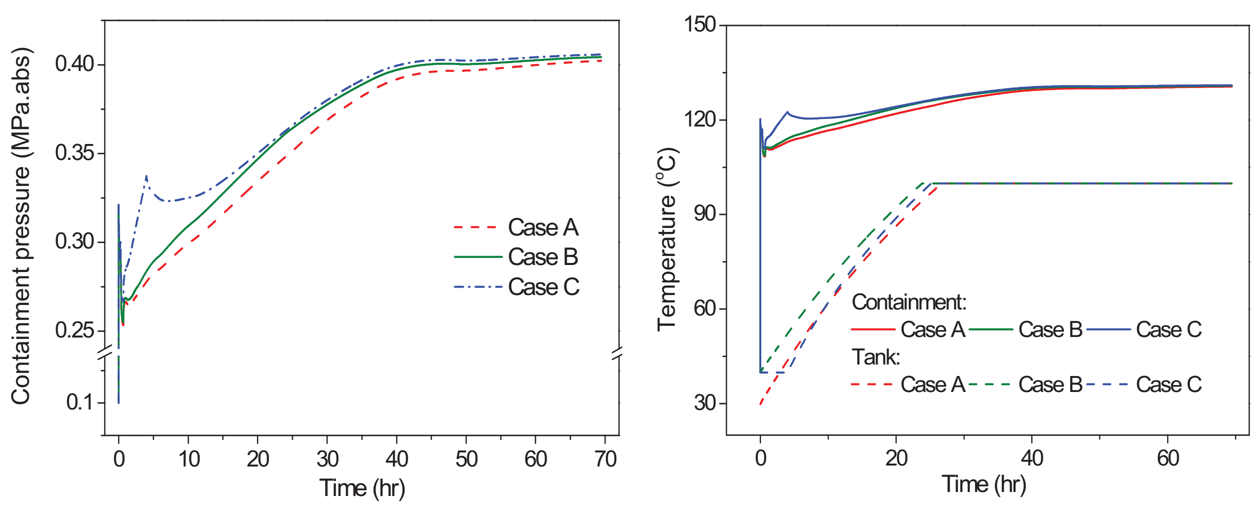
Parameter	Case		
	A	B	C
Tank temperature (℃)	30.0	40.0	40.0
Actuation time (hr)	0	0	4.0

3.2.1. Before the feed-and-bleed operation

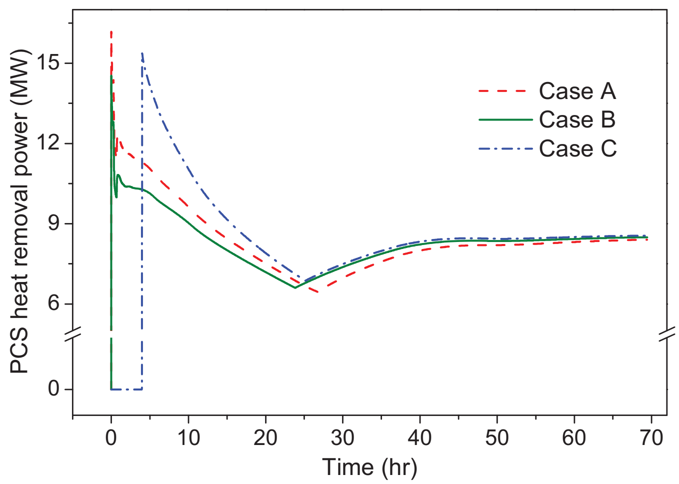
In this section, the calculation time is 72 hours, and the feed-and-bleed system is assumed not to be actuated yet. Fig. 11 shows the transient responses of both the containment and PCS. At the early stage, once the PCS actuates immediately after the accident occurs, the pressure and the temperature of containment drop rapidly. For the case C where the actuation of PCS is delayed 4 hours, due to the lack of efficient method to remove energy, the pressure and the temperature of containment hike up significantly. Once the PCS is put into operation, since the temperature is more higher than case A and case B at that moment, the heat removal power is also larger according to Eq. (11), resulting in faster decrease of pressure and temperature.

For the long-term period, because the energy is conveyed incessantly into the cooling tank, the tank is heated up continuously. Thus the heat removal capability of PCS decreases, and the pressure and temperature of containment build up again. When the tank water is saturated, since the tank temperature doesn't change while the containment temperature still grows a little bit, the PCS removal power starts to slightly increase again according to Eq. (11). Finally, the pressure and temperature of containment level off when the energy balance between containment and PCS is established. However, in order to further decrease containment pressure and temperature for a long-term period, it is necessary to refill the tank to compensate the loss due to evaporation, and lower tank temperature to increase PCS removal power.

The results also show that the earlier PCS is actuated, the more beneficial to reduce the containment pressure and temperature. The lower the tank initial temperature, the later the tank water becomes saturated. Nevertheless, the effects of these two parameters on the containment state in long-term period are not evident.



(a) Containment pressure (b) Temperatures of the containment and the tank

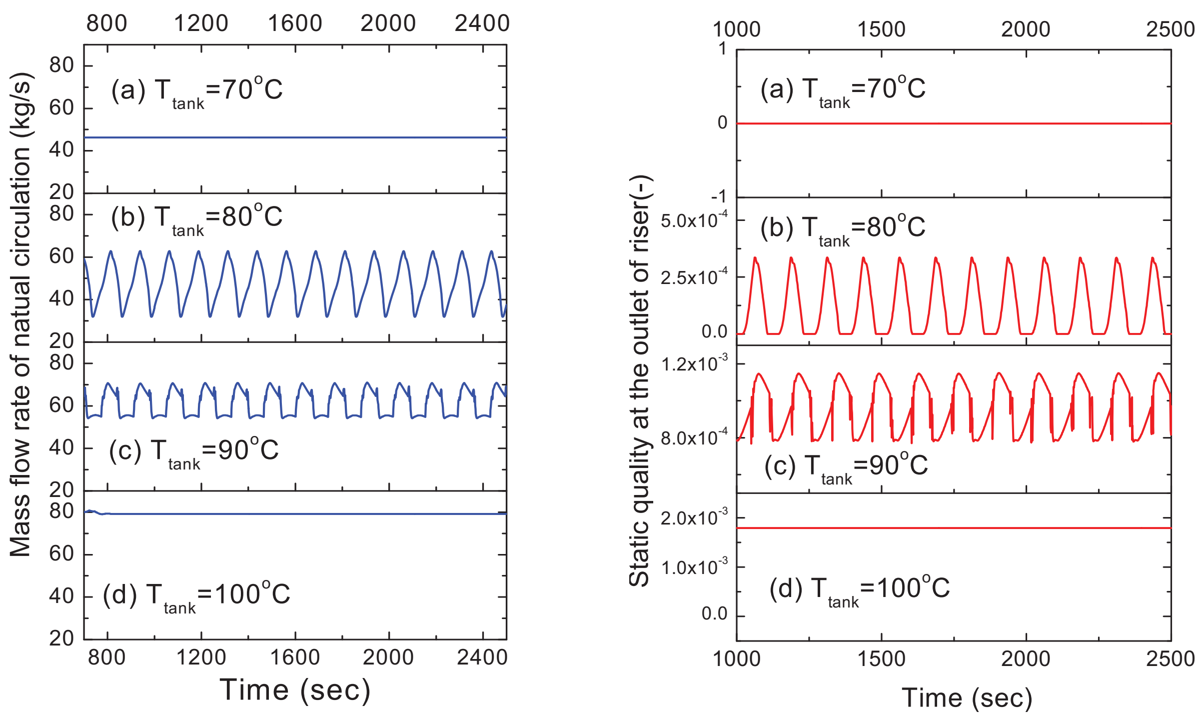


(c) Heat removal power of PCS

Figure 11. Transient responses of the containment and PCS

It is found that in the calculation the natural circulation of the PCS will experience an intermediate unstable region during the transition from stable one-phase flow to stable two-phase flow (Fig. 12), which can be categorized into two types [11]:

- Intermittent natural circulation, in which the static quality is relatively low and the one-phase and two phase natural circulation alternate periodically;
- Unstable two-phase circulation, in which the static quality is relatively high (always larger than zero) and the natural circulation oscillates in the form of the sinusoidal-type flow.

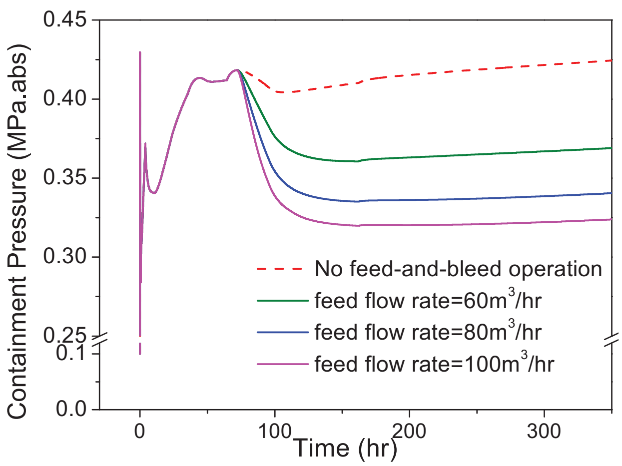


(a) Mass flow rate of natural circulation (b) Static quality at the outlet of the riser

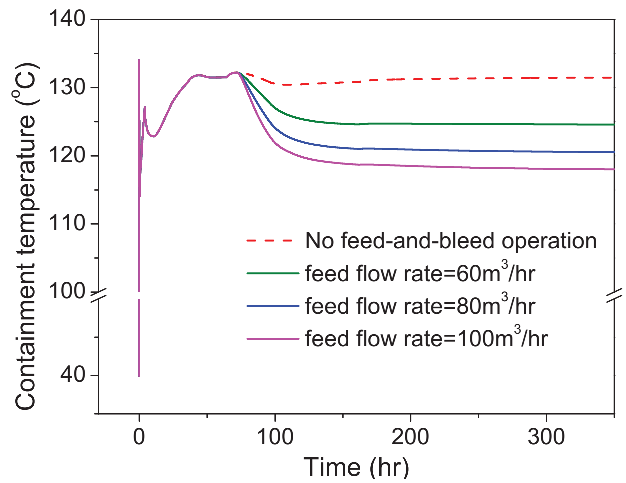
Figure 12. Intermediate unstable region of natural circulation during phase transition (T_{cont}=130℃)

3.2.2. Consider the feed-and-bleed operation

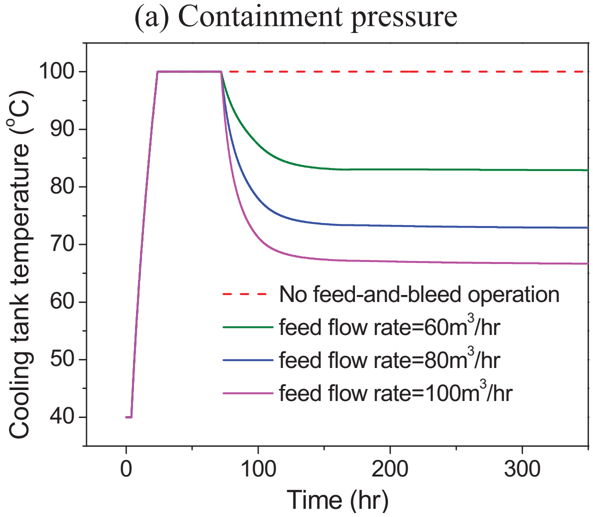
Taking case C analyzed in previous section for instance, the feed-and-bleed operation for the cooling tank is considered to be carried out at 72 hours after the accident occurs considering the recovery of the external power source. The transient responses of containment and the PCS are shown in Fig. 13. It can be seen that the feed-and-bleed operation can effectively enhance the performance of the PCS in long-term period by reduce the tank temperature, and further mitigate the accident consequence compared with the case without this measure (red dash curve in the figure). Moreover, the larger the feeding flow rate, the lower the long-term stable cooling tank temperature, and the shorter time it takes to achieve the stable state, which also coincides with the conclusion that can be gained from Eq. (10).



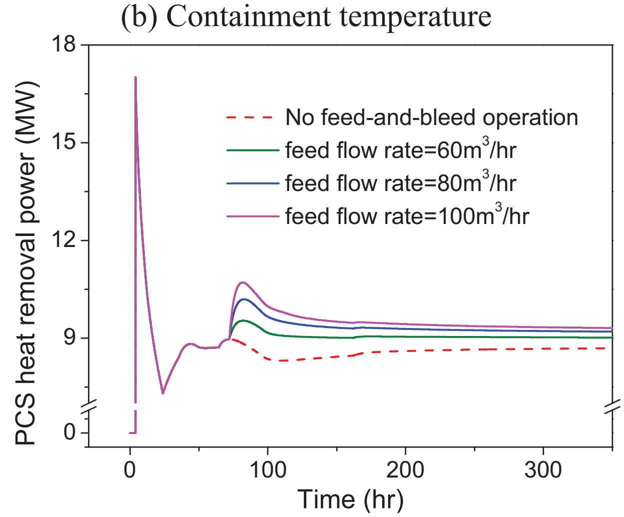
(a) Containment pressure



(b) Containment temperature



(c) Cooling tank temperature



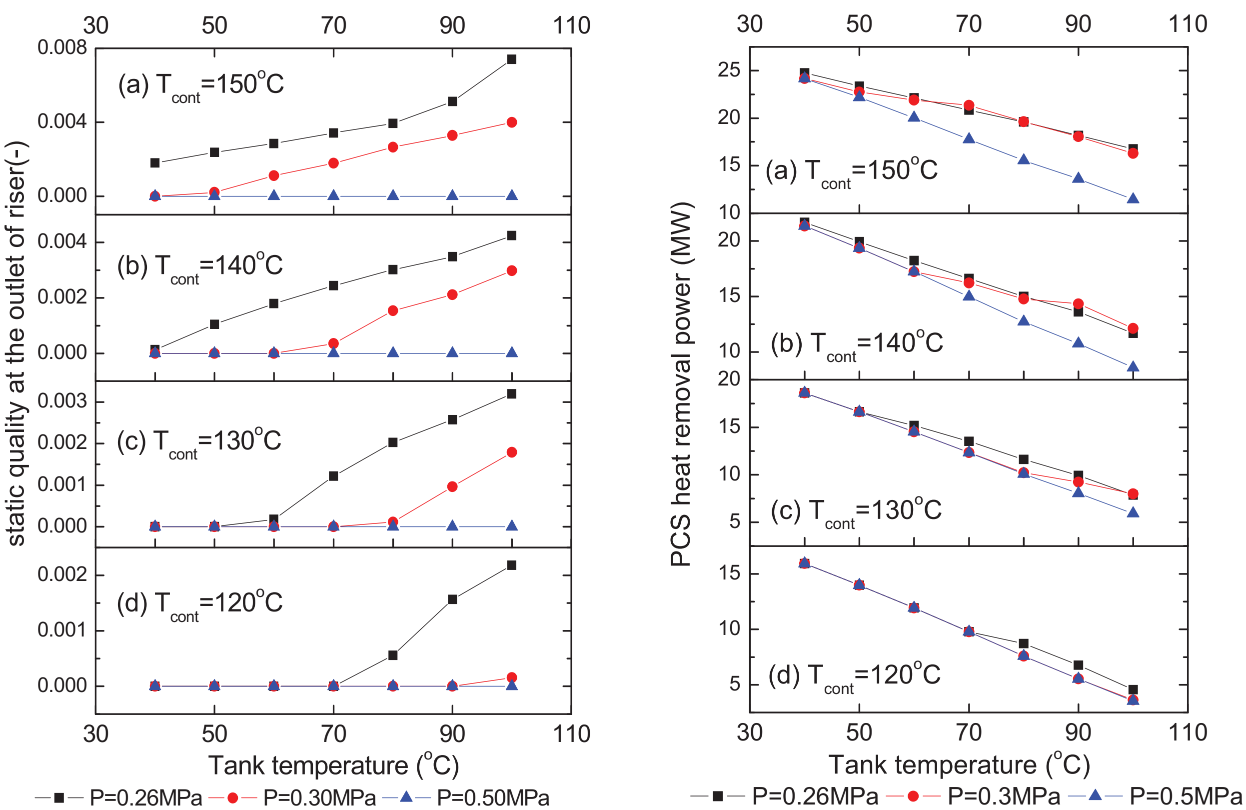
(d) Heat removal power of PCS

Figure 13. Transient response considering feed-and-bleed operation

4. PARAMETRIC STUDIES

4.1. Effect of Natural Circulation Loop Pressure

The temperature, at which the fluid turns into vapor, is determined by the local pressure. To study the pressure influence, three values are selected for evaluation, i.e. 0.26MPa, 0.30MPa and 0.50MPa. Fig. 14 shows that when boundary temperatures are relatively low, the lower the pressure is, the higher the power. But the distinction between different pressures is indiscernible when the temperatures are relatively high, and even in some cases the heat transfer power at higher loop pressure is higher. The main reason is that the static quality increase as the pressure decrease, which can lead to both the increase of driving force and frictional pressure loss as well. When the boundary temperatures are low, the increase of driving force is dominated and flow is enhanced, whereas the increase of frictional pressure loss can be overwhelming when the temperatures and static quality are high, which is disadvantageous for natural circulation.



(a) Static quality at the riser outlet (b) PCS heat removal power

Figure 14. Characteristics of the PCS at different loop pressures

4.2. Influence of Natural Circulation Loop Height

The elevation difference between the heat sink and source may be important for natural circulation which is driven by the gravitational pressure difference. To study the effect of loop height, only the lengths of riser and downcomer are changed. In order to investigate the performances of both one-phase flow and two-phase flow, the loop pressures are set as 0.30MPa and 0.50MPa respectively. As shown in Fig. 15, it is observed that with the increase of the loop height, the heat transfer power is slightly grows for the one-phase flow while slightly decreases for the two-phase flow. Nevertheless, the overall effect is not evident since the relative varying amount is only approximately 6%. Therefore, it can provide more flexibility for the PCS layout in the containment for engineering design. However, decreasing the loop height may increase the risk of the flow instability due to the increase of the void fraction, which may cause the mechanic harm to the equipment.

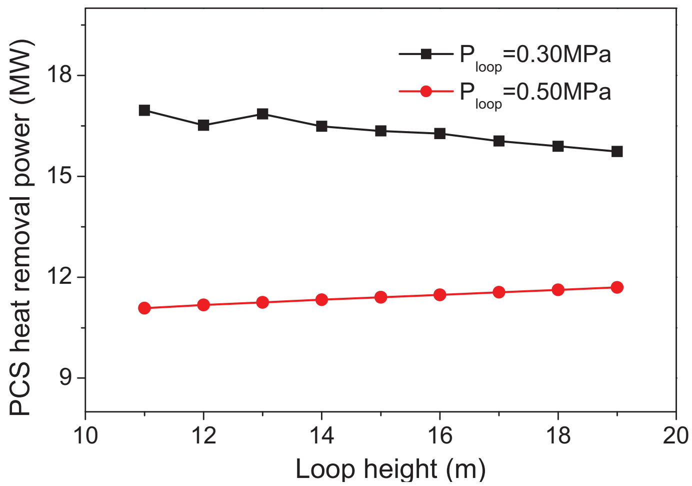


Figure 15. PCS heat removal power versus loop height (P_{loop}=0.30MPa, 0.50MPa)

5. CONCLUSIONS

To maintain the containment's integrity in a loss of coolant accident without spray system, a new type of passive containment cooling system using natural circulation loop is designed for an advanced PWR. Both the steady-state and transient characteristics of the PCS were concerned in this work, and the results can provide reference for engineering design of the PCS.

Using RELAP5 system code, the steady-state characteristics, such as static quality of the riser, mass flow rate, the maximum fluid velocity along the loop, the location of onset of boiling at the riser etc., were investigated. Furthermore, the heat removal power of the PCS as a function of boundary temperatures was obtained from the steady-state calculation results by means of the least-squared fitting method.

The transient responses of both the containment and the PCS during accidents were simulated using the MELCOR code, with the PCS modeled as a heat sink whose power varies according to the function previously obtained. The results show that it is feasible to use the PCS to reduce the temperature and pressure in a certain time. In order to further mitigate the accident consequence in long-term period, a feed-and-bleed operation can be carried out. An analytic model was established to evaluate the performance, showing that this measure can effectively enhance the capacity of the PCS in long-term period by reduce the tank temperature, and the flow rate as well as the temperature of the feeding cold water is an important factor.

The effects of various parameters were also studied. The loop pressure has a great impact on PCS operation mode. The heat removal power of two-phase flow is always higher than that of one-phase flow under the same boundary temperatures. Although decreasing the loop pressure can improve the heat removal capability, it also increases the risk of the flow instability, which should be avoided in engineering design. For both single-phase flow and two-phase flow, the change of loop height has little effect on the heat transfer capacity of the PCS. Therefore, it is more flexible when deciding the layout of the PCS loop pipes in the containment.

NOMENCLATURE

T	temperature (℃)
P	pressure (MPa)
W	heat removal power (MW)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
τ	time constant (s)
h	heat transfer coefficient ($W/(m^2 \cdot$℃$)$)
ω	mass fraction
N	mole fraction

Subscripts

cont	containment
tank	cooling tank
in, out	inlet/outlet of the cooling tank
cold	cold feeding water
hot	hot water in the cooling tank
nc	noncondensable gas
b	bulk
w	tube wall
a	air
He	helium

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