Effect of new drywell cooler application for venting start time during severe accidents

Naoyuki ISHIDA*, Yasunori NAGATA**, Ryusuke KIMURA** and Koji ANDO**

*Hitachi, Ltd.

1-1, Omika-cho 7-chome, Hitachi-shi, Ibaraki-ken 319-1292, Japan

E-mail: naoyuki.ishida.sx@hitachi.com

**Hitachi GE Nuclear Energy, Ltd.

1-1, Saiwai-cho 3-chome, Hitachi-shi, Ibaraki-ken 317-0073, Japan

Received: 30 October 2019; Revised: 19 January 2020; Accepted: 9 March 2020

Abstract

Nuclear power plants are equipped with a hardened containment venting system and a filtered containment venting system to avoid a primary containment vessel (PCV) break by over-pressurization. Considering the gas release from these venting systems, it is desirable to delay venting start time or to avoid operation of the systems by ensuring sufficient PCV cooling in view of the time needed to evacuate residents and the half-life of the radioactive materials. We have been developing a new drywell cooler specialized for severe accidents (DWC_SA) as one additional PCV cooling method. The DWC_SA can cool the PCV by continuous steam condensation using downward flow induced by natural force without any electrical devices in the PCV. We have already conducted element tests using a small tube bundle to confirm the occurrence of continuous downward flow with the DWC_SA configuration and to measure heat transfer rate of condensation with non-condensable gas (NCG). The heat transfer model was validated using the element test data. Here, to estimate plant performance of a representative advanced boiling water reactor (ABWR) applying the DWC_SA, we carried out a severe accident analysis using the MAAP code. We originally installed the heat transfer rate map of the DWC_SA as a function of pressure and NCG ratio in the code. The velocities using in the heat transfer model were estimated from CFD analysis. According to the severe accident analysis results, the DWC_SA can extend venting start time sufficiently to allow evacuation of residents in the accident scenario (LOCA with large pipe failure + ECCS failure + SBO) with the external water injection into the PCV and it can avoid operation of the containment venting systems in the case of internal water circulation in the PCV.

Keywords : Severe accident, Drywell cooler, Condensation, Non-condensable gas, Downward flow, External water injection, Internal water circulation

1. Introduction

During the Fukushima Daiichi Nuclear Power Plant accident, the hardened containment venting systems were cautiously operated to prevent breaking of the primary containment vessel (PCV) due to over-pressurization (Investigation Committee, 2012). During these venting operations, radioactive materials were released into the environment. Learning from the lessons of the accident, utilities of nuclear power plants equipped with a hardened containment venting system have added a filtered containment venting system to remove more radioactive materials from the vented gas. It is also desirable to delay venting start time or to avoid operation of the systems by ensuring sufficient PCV cooling in view of the time needed to evacuate residents. The local governments have assumed that one or more days are needed to secure evacuation of residents from the Urgent Protective action planning Zone (UPZ) which is the area from about 5 km to 30 km around a nuclear power plant site.

It has been recommended that existing drywell coolers (DWC), which are regular equipment to be conditioning gas temperature in the drywell (D/W) during a normal operation, be used for steam condensation as additional PCV cooling methods for an accident management during a severe accident. The condensation heat transfer rates with non-condensable gases (NCG) of the existing DWC (Yokobori et al., 2003) and the DWC with the duct (Kapulla, et al., 2012) were measured. If the DWC worked during a severe accident with steam generation, the DWC would contribute to mitigation of PCV pressure increase. However, since regular equipment are not assumed to be worked during a severe accident, we

are developing a new drywell cooler specialized for severe accidents (DWC_SA) as an additional component to enhance PCV cooling and to increase the variety of available PCV cooling methods (Ishida et al., 2017). The DWC_SA will be additionally placed as equipment for a severe accident at the upper side of the D/W in the PCV and it will condense steam generated by decay heat from the core. The DWC_SA with sufficient heat removal capacity will mitigate the pressure increase and keep the PCV pressure below the ultimate pressure of the PCV. Depending on the accident scenario, steam with nitrogen initially filling the PCV will be condensed by the DWC_SA. It is generally known that the steam condensation rate decreases with an increase in the non-condensable gas (NCG) ratio. Therefore, the DWC_SA is designed to remove all decay heat even under high nitrogen ratio conditions. Some active equipment such as a circulation pump is needed to supply cooling water to the DWC_SA, but Kurita et al. suggested a completely passive system using a DWC with supplying cooling water from an upper side pool by gravity (Kurita et al., 2007).

During a severe accident, it is conservatively assumed that active components in a PCV would fail to start up due to the severe conditions present in the PCV. Therefore, a mixed gas of steam and nitrogen has to flow into the DWC_SA by natural force. Nitrogen has a density about 50% larger than steam density. Since the mixed gas density increases in the DWC_SA with steam condensation, the density difference inside and outside the DWC_SA would induce natural force bringing the mixed gas into the DWC_SA.

To investigate the heat removal rate under high nitrogen ratio conditions and the occurrence of downward flow in the DWC_SA induced by natural force, we conducted element tests using a small version of the DWC_SA with five levels each consisting of a row of three tubes under severe accident conditions (Ishida et al., 2017). We obtained heat transfer data from the element tests and confirmed that heat transfer performance could be evaluated by the heat transfer model that considers steam condensation, gas convection and thermal conductivity in condensate. Furthermore, the measured gas temperature distribution in the tube bundle indicated the occurrence of downward flow in the DWC_SA.

Nagasaka et al. conducted the system integral tests simulating BWR pressure vessel failure using the test facility with volumetric scaling ratio of 1/600 (Nagasaka et al., 2003). They also carried out severe accident analysis using MELCOR code with their original heat transfer correlations for the existing DWC that was validated by the system integral test data. Analysis results showed the DWC mitigated increase of PCV pressure and reduced PCV spray flow rate.

The objective of this study is to evaluate the effect of the DWC_SA in delaying the venting system operation time during a severe accident. We conducted a severe accident analysis using the MAAP code with the heat transfer map of the DWC_SA that we originally installed. We evaluated the effectivity of the DWC_SA from the severe accident analysis results.

2. Heat transfer model of the DWC_SA

2.1 Outline of the DWC_SA

Figure 1(a) shows gas flow direction in the existing DWC at a normal operation. The DWC consists of heat transfer tube bundle, an electric fan, a casing housing them and ducts. Nitrogen filled in the PCV is warmed by released heat from a reactor pressure vessel etc. To be conditioned nitrogen temperature and moisture, nitrogen is sucked into the DWC by the fan operation and cooled on the heat transfer tubes. Cooled nitrogen is delivered to the whole PCV through the ducts. Figure 1(b) shows gas flow direction at a severe accident with steam releasing in the PCV. Since the electric fan may stop in the situation, gas flows only by natural force. The steam and nitrogen mixture flows through the upper part of the tube bundle in horizontal direction. Steam is condensed on the tube bundle and gas density is increased with steam condensation. Higher density gas flows downward in the casing and is discharged through the lower part of the tube bundle. According to the reference (Yokobori et al., 2003), nitrogen accumulated at the bottom of the casing and reduced heat transfer rate at the lower part of the tube bundle.

Figure 2 shows a schematic drawing of the DWC_SA. The DWC_SA consists of several rows and levels of horizontal heat transfer tubes and a casing surrounding the tubes. The casing has dimensions of 1.6m width, 1.6m depth and 1.6m height and it has openings at the top and bottom. The steam and nitrogen mixture flows into the DWC_SA from the top opening and only steam is condensed on the heat transfer tubes. The nitrogen ratio of the mixture in the DWC_SA increases steadily with steam condensation at each tube level. Since the density of the mixture inside the DWC_SA is larger than that outside, the mixture inside moves downward and then out from the bottom opening with the condensate. As just described, downward flow is formed in the DWC_SA with only natural force and the straight flow induces less pressure loss. Additionally, a chimney region without any tubes is located in the lower region of the casing to enhance

natural force by the chimney effect. Since this configuration of the DWC_SA gives more mixture flow rate into the DWC_SA with low pressure loss and large natural force, the DWC_SA effectively removes heat with more amount of steam condensation. Such downward flow in the DWC_SA was indicated from gas temperature distributions surrounding the tubes in the element test (Ishida et al., 2017).

Figure 3 shows the concept of the new PCV cooling system. The system mainly consists of six units of the DWC_SA, a pressurizer, a mobile heat exchanger and pumps and is independent of other systems. The mobile heat exchanger and pumps are put in vehicles (inside the res chain line in Fig.3) and delivered from safe waiting places to connecting points of the system when necessary. The system is connected a mobile heat exchanger using connectors, and the PCV cooling system is pressurized using the pressurizer to avoid coolant boiling at the DWC_SA. Electricity is supplied from power generation vehicles and the circulation pump and water pump are started by this electricity. Removal heat at the DWC_SA is transferred to sea water, for example, at the mobile heat exchanger and finally released to a heat sink. The system is independent from other systems as special equipment for a severe accident.

Fig.1 Gas flow direction in the existing DWC.

Fig.2 Schematic drawing of the DWC_SA.

Fig.3 Concept of the new PCV cooling system.

2.2 Heat transfer model

For pure steam condensation on a horizontal tube, Nusselt theoretically established a condensation heat transfer model (Nusselt, 1916). In the case of steam condensation with NCG, as shown in Fig. 4, steam has to reach the condensate film surface by passing through the thin boundary layer formed on the condensate film; this layer is rich in NCG. Three heat transfer phenomena for condensation heat transfer with NCG are considered in the heat transfer model and calculated using Eqs. (1) to (7). The heat transfer rate from the tube inner surface to the coolant is calculated with the forced convection heat transfer coefficient derived from Eq. (8). Therefore, the total heat transfer rate from the mixed gas to the coolant can be calculated using Eqs. (1) to (8).

Fig.4 Condensation heat transfer mode with NCG on a tube wall.

1) Heat transfer rate by mixed gas convection

$$Q_{conv} = h_g A_o (T_g - T_s) \quad (1)$$

$$h_g = \frac{k_g}{d_o} \cdot C_1 \text{Re}^{C_2} \text{Pr}^{1/3} \quad (2)$$

Q_{conv} : Heat transfer rate by mixed gas convection [W], A_o : Heat transfer area [m^2], h_g : Convection heat transfer coefficient [$\text{W}/\text{m}^2/\text{K}$], T_g : Mixed gas bulk temperature [$^\circ\text{C}$], T_s : Condensate surface temperature [$^\circ\text{C}$], k_g : Mixed gas thermal conductivity [$\text{W}/\text{m}/\text{K}$], d_o : Outer diameter of heat transfer tube [m], Re : Reynolds number [-], Pr : Prandtl number [-], C_1 , C_2 : Empirical constants [-]

2) Heat transfer rate by steam diffusion through NCG layer

$$Q_{cond} = A_o \frac{K_g \rho_g}{P_{am}} [P_{steam} - P_{sat}(T_s)] H_{fg} \quad (3)$$

$$K_g = \left(\frac{h_g}{\rho_g c_{pg}} \right) \left(\frac{\text{Pr}}{Sc} \right)^{2/3} \quad (4)$$

$$P_{am} = \frac{P_{steam} - P_{sat}(T_s)}{\ln \frac{P_{tot} - P_{sat}(T_s)}{P_{tot} - P_{steam}}} \quad (5)$$

Q_{cond} : Heat transfer rate by steam diffusion [W], K_g : Mass transfer coefficient [m/s], ρ_g : Mixed gas density [kg/m^3], c_{pg} : Mixed gas specific heat [$\text{J}/\text{kg}/\text{K}$], Sc : Schmidt number [-], P_{am} : Logarithmic average pressure [Pa], P_{steam} : Steam partial pressure [Pa], $P_{sat}(T_s)$: Saturated pressure at T_s [Pa], P_{tot} : Total pressure [Pa]

3) Heat transfer rate through condensate film

$$Q_{film} = h_{cond} A_o (T_s - T_w) \quad (6)$$

$$h_{cond} = 0.725 \left[\frac{k_\ell^3 \rho_\ell^2 g H_{fg}}{n \mu_\ell (T_s - T_w) d_o} \right]^{0.25} \quad (7)$$

Q_{film} : Heat transfer rate through condensate [W], h_{cond} : Condensation heat transfer coefficient [W/m²/K],
 k_ℓ : Condensate thermal conductivity [W/m/K], ρ_ℓ : Condensate density [kg/m³], g : Gravity acceleration [m/s²],
 H_{fg} : Latent heat [J/kg], n : Level of tube from the top [-], μ_ℓ : Condensate viscosity [Pa-s], T_w : Temperature of the tube outer surface [°C]

4) Forced convection heat transfer inside the tubes

Dittus-Boelter's equation (Eq. (8)) is used for calculating forced convection heat transfer on the tube inner surface.

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (8)$$

Nu : Nusselt number [-]

2.3 Heat transfer map for the DWC_SA

We evaluated heat transfer of the actual DWC_SA using the heat transfer model mentioned in section 2.2 that was validated using heat transfer data obtained in the element tests (Ishida et al., 2017). Downward flow velocity is needed to calculate Re number in Eq.(2). The velocity was obtained with parameters of pressure and nitrogen volume ratio from CFD analysis using the STAR-CCM+ code. Figure 5 shows an example of velocity distribution calculated from CFD analysis. The analysis indicates the occurrence of downward flow in the DWC_SA. The magnitude of the velocity shows by color. In this case, gas velocity just above the tube bundle is about 0.6m/s. Heat transfer rate for the top level tube was calculated by the heat transfer model using the velocity. The velocity and nitrogen ratio of the mixture was updated considering with the amount of steam condensation for the calculation of the next tube level. Heat transfer rate for the second or later level tube from the top was calculated using the velocity and nitrogen ratio updated by the upper level tube. The heat transfer rate of the DWC_SA was calculated by summation of heat transfer rate of all level tube and then a heat transfer rate map was obtained.

Figure 6 shows a heat transfer map of the actual DWC_SA, which was normalized with the value at a pressure of 0.72MPa (absolute) and nitrogen ratio of 30vol%. The heat transfer rate is increased with higher pressure because mixture temperature is increased with higher saturated steam temperature. The heat transfer rate is also increased with lower nitrogen ratio because of less inhibitory effect of NCG for steam condensation. Hitachi originally installed the map in the MAAP code. Heat transfer rates of the DWC_SA were calculated using the heat transfer map for each pressure and nitrogen ratio in the code. For the given pressure and nitrogen ratio, heat transfer rates were calculated by linear interpolation from three lines in the map. The map will be validated by heat transfer data obtained using an actual DWC_SA in the future.

Fig.5 Example of velocity distribution calculated by CFD.

Fig.6 Heat transfer map of the DWC_SA.

3. Severe accident analysis conditions

3.1 Nodalization

Figure 7 shows a schematic of a representative ABWR, including some of the PCV cooling systems and showing the pipe break point in the assumed severe accident scenario, and nodalization of the ABWR for severe accident analysis using the MAAP code. The PCV of the ABWR was divided into four compartments. These compartments were connected by junctions. The MAAP code can simulate water injection into the reactor pressure vessel (RPV) using a reactor core isolation cooling system (RCIC) or an alternative water injection system from the outside.

The heat transfer map was used to calculate condensed steam mass rate in the D/W compartment. Condensed water and injected water by a D/W spray flows to the suppression chamber (S/C) via the downcomer compartment. The junction between the pedestal and the S/C is a vacuum breaker which opens when pressure in the S/C becomes larger than that in the D/W. The junction between the S/C and the environment compartment is the line of the venting system which opens when pressure is over 0.72MPa or water level in the S/C is over the limit (about 13m) to avoid covering the inlet of the venting system line by water.

Fig.7 Nodalization of a representative ABWR for the MAAP code.

3.2 Severe accident scenario

We chose the severe accident scenario as the effective scenario in a representative ABWR for PCV over-pressurization mitigation by the DWC_SA which was a loss of coolant accident (LOCA) with large pipe break + an emergency core cooling system (ECCS) failure + station blackout (SBO) + water injection to the RPV and the D/W spray from the external water injection lines. We also estimated an additional condition which was a LOCA with large pipe break + an ECCS failure + SBO + water injection to the RPV by internal water circulation (IWC). In this study, large pipe break occurred at a piping of a residual heat removal system. Analysis conditions are summarized in Table 1; the check marks indicate what equipment (DWC_SA) or action (D/W spray or IWC) was considered in the analysis. The number in parentheses means DWC_SA unit number in the D/W.

Severe accident analysis was conducted in the three cases with the external water injection condition (case E-1 to E-3) as shown in Fig.8. In case E-1, only water was injected into the RPV from the outer water source. In case E-2, water was injected into the RPV from the outer water source, and the D/W spray, to which water was supplied from the outer water source with the flow rate of 160m³/h and temperature of 35°C, worked at the PCV pressure of 0.55MPa and stopped at the PCV pressure of 0.5 MPa. The D/W spray has the heat removal capacity of about 22MW using spray water sensitive heat. In case E-3, operation of the DWC_SA was started 12 hours after the accident began considering the time needed

to set it up. The six units of the DWC_SA have enough capacity to remove the decay heat at 24 hours after the accident begins under the D/W pressure of 0.72MPa and nitrogen ratio of 30vol%.

Severe accident analysis was conducted in three cases with the internal water circulation condition (cases I-1 to I-3) as shown in Fig.9. In case I-1, only water was injected into the RPV from the S/C. In case I-2, the DWC_SA was operated in the same manner as case E-3. In case I-3, three units of the DWC_SA were operated on the assumption that start-up failed for half of the six units.

Table 1 Severe accident analysis conditions.

Case	D/W spray	IWC	DWC_SA	Remarks
E-1				3 cases for external water injection
E-2	✓			
E-3	✓		✓ (6)	
I-1		✓		3 cases for internal water circulation
I-2		✓	✓ (6)	
I-3		✓	✓ (3)	

Note: The check marks indicate what equipment (DWC_SA) or action (D/W spray or IWC) was considered in the analysis. The numbers in parentheses show the DWC_SA unit number in the D/W.

Fig.8 Analysis conditions of external water injection case.

Fig.9 Analysis conditions of internal water circulation case.

4. Analysis results

4.1 External water injection cases

Figure 10 shows water and steam flows in the PCV and the transient pressure in the D/W and the water level in the S/C in case E-1. Water was injected into the RPV from the outside and it was vaporized by decay heat in the RPV. Steam generated in the RPV were released to the D/W through the pipe break location. The released steam did not condense in the D/W. The steam flowed into the S/C through the downcomer and was condensed in the water. Water level in the S/C increased with the amount of condensed steam. The D/W was pressurized because no PCV cooling system worked in the D/W. The pressure monotonically increased and reached the ultimate PCV pressure at about 16 hours after the accident began. At 16 hours, the venting system was operated to avoid the PCV break and the pressure was rapidly decreased. The water level in the S/C showed an upward trend until venting by water injection into the RPV from the outside.

Figure 11 shows water and steam flows in the PCV and the transient pressure in the D/W and the water level in the S/C in case E-2. Here, released steam from the RPV was condensed by the D/W spray which consisted of water supplied from the outside. The condensate with the spray water flowed into the S/C through the downcomer. Water level in the S/C increased with the amount of the condensed steam and the spray water. The pressure monotonically increased by 0.55MPa. The spray worked when the D/W pressure reached 0.55MPa and decreased the pressure immediately. The spray stopped when the pressure was below 0.50MPa. After the spray stopped, the pressure increased again with higher pace of increase before that of spray operation and the spray worked again; this spray cycle was repeated. Before spray started, steam condensation in the S/C pool contributed to mitigation of pressure increase because water temperature of the S/C pool was less than saturated temperature going up according to pressure increase. After spray started, the pressure was kept in the range of 0.50 to 0.55MPa and water temperature of the S/C pool was kept in saturated temperature, so the water of the S/C pool could not contribute to PCV cooling. That was reason of the pressure increase with higher pace after spray started. The water level in the S/C became increasingly higher because of the larger amount of water injection from the outside and reached the limit level at about 29 hours. The spray was stopped to avoid covering the inlet of the venting system line by water even though the D/W pressure was above 0.55MPa. And then the pressure rapidly reached the ultimate PCV pressure and the venting system was operated.

Figure 12 shows water and steam flows in the PCV and the transient pressure in the D/W and the water level in the S/C in case E-3. Here, released steam from the RPV was condensed in the DWC_SA. The condensate at the DWC_SA dropped onto the D/W floor and flowed into the S/C through the downcomer. When operation of the DWC_SA started 12 hours after the accident began, the pressure was kept below the D/W spray working pressure of 0.55MPa, so the spray did not work. The pressure was decreased to about 0.4MPa by the DWC_SA immediately due to its higher heat transfer rate under the condition of high pressure and low nitrogen ratio. When the pressure was decreased, nitrogen flowed into the D/W from the S/C through a vacuum breaker and then the heat transfer rate of the DWC_SA was

decreased and balanced with the decay heat. The pressure was slightly increased because of reduction of gas volume in the PCV due to ongoing of the water injection to RPV from the outer water source. Since the spray did not work, the water level in the S/C was increased only by the water injected into the RPV. The water level reached the limit level at about 105 hours. The venting system was operated at this time before the inlet of the venting system line was covered by the water.

In the external water injection cases, the venting system should be operated within about 105 hours to avoid the PCV break even though the DWC_SA has enough cooling capacity because operation of the venting system depends on the water level in the S/C. And the DWC_SA can extend the venting start time sufficiently to allow evacuation of residents.

Fig.10 Water and steam flows (left) and D/W pressure and S/C water level (right) in case E-1.

Fig.11 Water and steam flows (left) and D/W pressure and S/C water level (right) in case E-2.

Fig.12 Water and steam flows (left) and D/W pressure and S/C water level (right) in case E-3.

4.2 Internal water circulation cases

Figure 13 shows water and steam flows in the PCV and the transient pressure in the D/W and the water level in the S/C in case I-1. Water was injected into the RPV from the S/C using the circulation pump and it was vaporized by decay heat in the RPV. The released steam behaved in the same way as in case E-1. The pressure monotonically increased and reached the ultimate PCV pressure at 14 hours after the accident began. At this time, the venting system was operated to avoid the PCV break and the pressure was rapidly decreased. In case I-1, venting start time was shortened by 2 hours compared with the time in case E-1. In case E-1, sensible heat and latent heat of the water injected from the outside were additionally used to cool the core with the water in the S/C. Therefore, venting start time in case I-1 was sooner because of the lower amount of water to remove the decay heat. The water level in the S/C slightly increased until venting started because of the increase of water volume by the higher temperature, and after that the water level monotonically decreased because steam vaporized from the water in the S/C was released to the environment through the venting system.

Figure 14 shows water and steam flows in the PCV and the transient pressure in the D/W and the water level in the S/C in case I-2. Here, released steam from the RPV was condensed in the DWC_SA. The condensate at the DWC_SA dropped onto the D/W floor and flowed into the S/C through the downcomer. The condensate was sent again to the RPV from the S/C using the circulation pump. When operation of the DWC_SA was started at 12 hours after the accident began, the pressure was decreased to about 0.46MPa by the DWC_SA immediately due to its higher heat transfer rate under the condition of high pressure and low nitrogen ratio. When the pressure was decreased, nitrogen flowed into the D/W from the S/C through a vacuum breaker and then the heat transfer rate of the DWC_SA was decreased and balanced with the decay heat. After that, the pressure was gradually decreased with reduction of the decay heat. The water level in the S/C slightly increased until the DWC_SA started because of the increase of water volume by the higher temperature. After the DWC_SA operation, the water level in the S/C was kept constant because no water was injected from outside and none was released to the environment, and all decay heat was removed by the DWC_SA. Therefore, the water level did not reach the limit level and the venting system did not operate due to the water level limit. Since the DWC_SA removed all decay heat from the PCV by steam condensation, the D/W pressure did not increase. In case I-2, the venting system operation could be avoided because both the D/W pressure and the water level in the S/C did not reach the limits for the venting system operation.

Figure 15 shows water and steam flows in the PCV and the transient pressure in the D/W and the water level in the S/C in case I-3. Water and steam flows were the same as those in case I-2. Although operation of the three units of the DWC_SA was started at 12 hours after the accident began, the pressure continued to increase because the decay heat was larger than the heat removal capacity of the three units of the DWC_SA at the moment. After three units of the DWC_SA had removed all the decreasing decay heat at about 20 hours, D/W pressure turned downward. The pressure went down with decreasing decay heat, and the pressure was higher than that in case I-2. Since the decay heat was the same among all six cases, the three units of the DWC_SA had the same heat removal capacity as the six units of the DWC_SA. Since the total amount of nitrogen was kept until the venting system operation started, the high pressure meant that the nitrogen

ratio was relatively low with a large amount of steam. As shown in Fig.6, the heat removal rate became larger with the higher pressure and lower nitrogen ratio. The DWC_SA could keep the D/W pressure at less than the limit by increasing the heat removal rate per unit even with only half of the units of the DWC_SA in operation. In case I-3, the water level in the S/C was kept constant because no water was injected from outside and none was released to the environment, and the venting system operation could be avoided because both the D/W pressure and the water level in the S/C did not reach the limits for its operation.

Fig.13 Water and steam flows (left) and D/W pressure and S/C water level (right) in case I-1.

Fig.14 Water and steam flows (left) and D/W pressure and S/C water level (right) in case I-2.

Fig.15 Water and steam flows (left) and D/W pressure and S/C water level (right) in case I-3.

4.3 Summary of the analysis results

Table 2 shows summary of the analysis results. In the external water injection cases, the venting start times were about 16 hours after the accident began without any cooling method in the D/W due to the PCV pressure limit (E-1) and about 29 hours with the D/W spray injected from the outside due to the pressure limit (E-2). The DWC_SA could extend the venting start time to about 105 hours which is more than 76 hours from the start time with the D/W spray (E-3). As long as the water is injected to the RPV and the D/W from the outside water source, the water level in the S/C certainly reaches the limit and the vent operation is started even if the DWC_SA has sufficient heat removal capacity.

In the internal water circulation cases, the venting start time was about 14 hours without any cooling method in the D/W due to the PCV pressure limit (I-1). The DWC_SA could avoid the venting system operation because the DWC_SA removed all the decay heat and the water level in the S/C was kept constant by the internal water circulation (I-2). Furthermore, it was shown that the DWC_SA could avoid the venting system operation even with only half of the units of the DWC_SA in operation (I-3).

It is essential requirements for no vent operation to establish the internal water circulation before the water level in the S/C reaches the water level limit and to start up the DWC_SA before the D/W pressure reaches the pressure limit.

Table 2 Summary of the analysis results.

Case	D/W spray	IWC	DWC_SA	Venting start time
E-1				16 hours
E-2	✓			29 hours
E-3	(✓)		✓ (6)	105 hours
I-1		✓		14 hours
I-2		✓	✓ (6)	No vent
I-3		✓	✓ (3)	No vent

Note: The check mark in parentheses in case E-3 indicates the D/W spray stood by but did not operate since the D/W pressure did not reach the spray operating pressure.

5. Conclusion

We have been developing a new drywell cooler for severe accidents (DWC_SA) as one of the additional PCV cooling methods. To estimate plant performance of a representative advanced boiling water reactor (ABWR) that applies the DWC_SA, we carried out a severe accident analysis using the MAAP code in which we originally installed the DWC_SA heat transfer map developed using the heat transfer model and CFD analysis.

We assumed six cases for the severe accident scenario, three external water injection cases and three internal water

circulation cases. The basic scenario was a loss of coolant accident with large pipe break + an emergency core cooling system failure + station blackout + RPV water injection.

The analysis results are summarized in section 4.3. In the external water injection case, the DWC_SA could extend the venting start time to about 105 hours but the vent operation was needed because the water level in the S/C certainly reaches the limit as long as water is injected from the outer water sources. For no vent operation, it is essential requirements to establish the internal water circulation before the water level in the S/C reaches the water level limit and to start up the DWC_SA before the D/W pressure reaches the pressure limit.

We expect the DWC_SA will contribute to assuring the necessary time for evacuation of residents is available and to enhancing nuclear power plant safety.

References

- Ishida, N., Watahiki, N., Hosoi, H., Nagata, Y., Kushima, Y. and Ando, K., Development of new PCV cooling system for severe accidents, Proceedings of 2017 International Congress on Advances in Nuclear Power Plants (ICAPP 2017) (2017), Paper number 17127.
- Kapulla, R., Mignotet, G. and Paladino D., Large-Scale Containment Cooler Performance Experiments under Accident Conditions, Science and Technology of Nuclear Installations, Volume 2012, Article ID 943197 (2012).
- Kurita, T., Tobimatsu, T., Kojima, Y. and Yokobori, S., Development of drywell-cooler for severe accident, Japanese Journal of Multiphase Flow, Vol.21, No.3 (2007), pp. 281-287 (in Japanese).
- Nagasaka, H., Tobimatsu, T., Tahara, M., Yokobori, S. and Akinaga, M., System integral test by BWR drywell cooler applied as accident management, Transactions of the Japan Atomic Energy Society, Vol.2, No.3 (2003), pp. 240-250 (in Japanese).
- Nuclear Information and Resource Service, Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, Final Report. Available at: <https://www.nirs.org/wp-content/uploads/fukushima/SaishyuRecommendation.pdf> (2012) (accessed on October 9, 2019)
- Nusselt, W., Surface condensation of water vapor, Journal of the Association of German Engineers, Vol.60, No.27 (1916), pp.541-546 (in German).
- Yokobori, S., Tobimatsu, T., Akinaga, M., Fukasawa, M. and Nagasaka, H., Steady heat removal test by BWR drywell cooler under severe accident conditions, Transactions of the Japan Atomic Energy Society, Vol.2, No.3 (2003), pp. 230-239 (in Japanese).