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Performance Assessment of Passive Containment Cooling System Using MAAP5 Code in Pressurized Light Water Reactor

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1. Introduction

The containment building is the final barrier to release of radioactive materials in accidental conditions. Therefore containment cooling system to prevent the failure of containment is very important for the safety of nuclear power plants. In the second generation PWR designs, the removal of decay power is achieved through the use of active systems such as containment sprays and fan coolers, which rely on the availability of electrical power. However, a proposed passive containment cooling system (PCCS), which relies on natural driving forces, removes decay power and depressurizes the containment. It provides long-term cooling capability without external power supply and human intervention. The heat resulting from accidents is transferred to the passive containment cooling tank (PCCT) located outside of containment via heat exchanger placed inside of containment.

In this paper, we carried out a thermal-hydraulic performance assessment of PCCS applied to Zion-like 4-loop nuclear power plant, a representative pressurized light water reactor (PWR) by using MAAP5.05 beta version code.

2. Methods

2.1 PCCS design

The proposed PCCS consists of heat exchangers, a PCCT serving as cooling water source and natural circulation loop connecting the heat exchangers and PCCT. A schematic diagram of the PCCS is shown in Fig. 1. During accidents, internal heat is removed by interaction between heat exchangers and containment atmosphere. As the cooling water in the tube side of the heat exchanger is heated, it induces natural circulation in the connecting loop due to density differences. The hot water and steam from the heat exchanger is discharged into the ultimate heat sink, PCCT. The cold cooling water of PCCT returns to heat exchangers of PCCS by natural circulation. Long-term cooling can be achieved until cooling water inventory is depleted [1].

The PCCS for APR+, which is the next generation nuclear power plant, has been under developing as one of severe accident mitigation features. In the present study, the PCCS for Zion-like plant was determined by reference to PCCS in APR+. For example, the number of heat exchangers was scaled down based on the thermal power of Zion-like plant and APR+. And bundle-type heat exchangers are assumed to be employed in PCCS for Zion-like plant as like that of APR+. The size of heat exchangers and PCCT for Zion-like plant was determined based on the decay heat generated after five minutes from reactor shutdown [2].

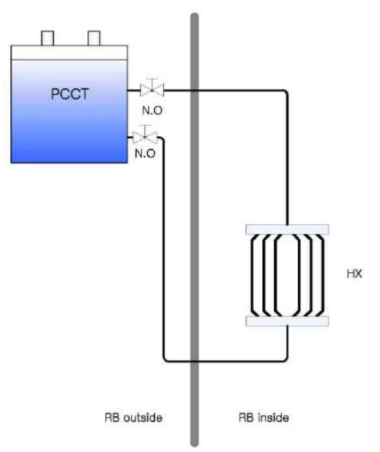

Fig. 1. Schematic diagram of the passive containment cooling system (PCCS) [3]

2.2 MAAP5 Code

A new PCCS model has been being developed for the MAAP5 code version, The new MAAP5 PCCS model can evaluate the natural circulation flow inside the loop and containment gas side heat transfer.

As shown in Fig. 2 for the nodalization scheme of PCCS natural circulation loop, the nodes and junctions of this model consist of the hot leg pipe, the cold leg pipe, and the heat exchanger tubes. Mass and energy transport between the tube and containment side are considered along the axial direction of these nodes. The PCCT design is modeled as a MAAP5 auxiliary building compartment and the natural circulation loop model interfaces with the water tank through the inlet and outlet.

Using this PCCS model, MAAP5 can evaluate the following properties:

- Natural circulation rate along the loop
- Temperature, steam quality, pressure and other property profiles along the loop
- Heat removal and condensation rates from the containment and water depletion rate in the water tank.

Also the PCCS model can estimate containment gas side heat flux to the PCCS heat exchanger tubes. Containment gas side heat transfer is affected by various conditions such as composition of steam and non-condensable gas in containment building, and the containment temperature and pressure. Considering these conditions, the PCCS model provides external heat transfer coefficients for PCCS heat exchanger tube bundles. To calculate the heat transfer in bundles, this model derives firstly condensation heat transfer on a single (isolation) tube. Then it is modified in consideration of tube bundle geometry effects on heat transfer to individual tubes in the bundle. In this process, the effects of water fog formation occurring between steam and gas boundary layers surrounding the heat exchanger tubes are considered. The bundle effect of model was compared against experimental data [4].

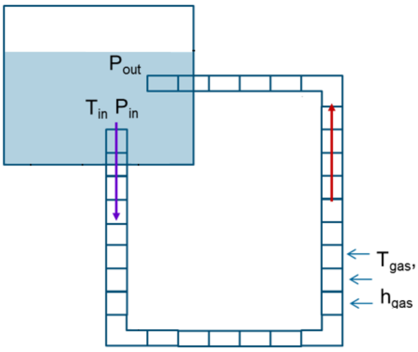

Fig. 2. Nodalization Scheme of PCCS Natural Circulation Loop [4]

3. Analysis Case

In this paper, the integral performance of the PCCS system for Zion-like 4 loop PWR was assessed for a Large Break of Loss Of Coolant Accident (LBLOCA) sequence, which simulated a double ended cold leg break. Under this condition, containment response is studied for 72 hours from the initiating event. Two cases are calculated in this study; with PCCS operation and without PCCS per original design of Zion-like plant (referred to reference case).

4. Results

4.1 Pressure

In reference case, because Zion-like plant has no containment spray heat exchangers, the heat of recirculating water with higher temperature cannot be effectively removed during the recirculation period after the refueling water storage tank (RWST) with lower temperature is depleted at 0.74 hours [5]. Finally the containment loses heat removal capability due to the inefficient containment spray effect and the pressure increases sharply until containment fails at 22.7 hours (Fig. 3).

For the PCCS operation case, the decay heat is removed by PCCS heat exchangers continuously, which results in depressurization effect. A large amount of energy released through the breaks causes the rapid pressurization in the early phase, but energy release is reduced as time goes on. Therefore the pressure shows a gradual increment for an early phase of accident, and the pressure decreases in the later phase. However, the temperature of the PCCT water increases continuously and the PCCT water reaches the saturation temperature in the later phase. The water level decreases and the heat removal capability of the PCCS is reduced. Therefore the effect of depressurization on PCCS is not significant in the late phase.

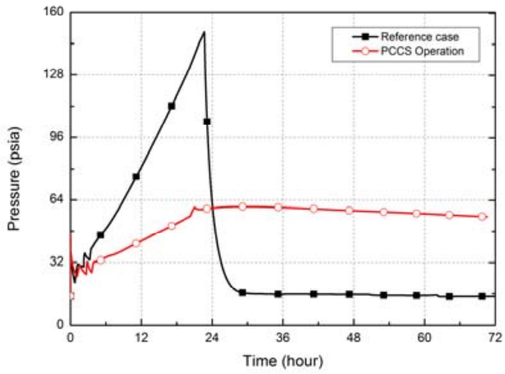

Fig. 3. Comparison of containment pressure with reference case and PCCS operation

4.2 Temperature

In reference case, as mentioned in section 4.1, the containment loses heat removal capability at 0.74 hours and the temperature increases sharply until containment fails at 22.7 hours (Fig. 4). In this particular case, the temperature rises again at 64 hours, because water in the reactor cavity is depleted because of steaming by the decay heat of corium and molten core-concrete interaction begins to influence on the containment atmospheric conditions by non-condensable hot gases and the radiation heat from the uncovered corium.

When the PCCS is applied to Zion-like plant, the decay heat is removed by PCCS and the hot steam in the containment is condensed on the surface of the PCCS heat exchanger tubes, which leads to temperature drop. It prevents the sharp temperature build-up in the containment. In the late phase of accident, the decay heat is reduced as time goes on. Therefore the temperature shows a gradual decrement. However, the temperature of the PCCT water increases continuously and the PCCT water reaches the saturation temperature in the later phase. The water level decreases and the heat removal capability of the PCCS is reduced. Therefore, the effect of temperature reduction on PCCS is not significant in late phase.

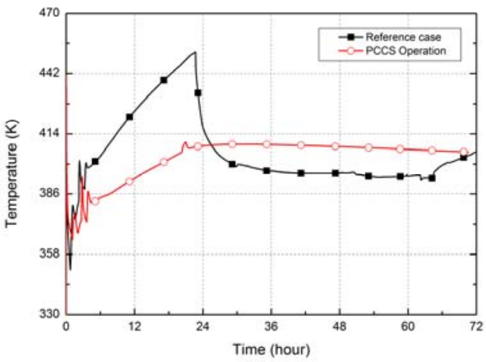

Fig. 4. Comparison of containment temperature with reference case and PCCS operation

5. Conclusion

A new PCCS model has been being developed for MAAP5 code. The new model consists of containment gas side heat transfer model including condensation effect and natural circulation of two-phase flow in the tube-side of a heat exchanger. In the present study, the PCCS model is tested for Zion-like 4 loop PWR. MAAP5 calculation tells the containment pressure buildup following the LBLOCA can be limited under PCCS operation. This is because the sufficient amount of steam is able to be condensed by heat exchangers in the PCCS system. The results show that the PCCS can remove the decay heat in the containment and prevent the containment failure. However, the decay heat in the containment building is not reduced significantly in the late phase of accident in case of without long-term management of the PCCT water tank. Therefore the detailed assessment of the long term heat removal capability of the PCCS should be performed is expected.

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