Numerical Prediction of PCCS Heat Removal Performance

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1. Introduction

Passive Containment Cooling System (PCCS) provides a new method for mitigating postulated accidents and replace active engineering safety feature with passive one, for example, spray, fan cooler and etc. With this reason, new nuclear power plant that equips the passive safety system has been widely chosen around the world. KHNP (Korea Hydro & Nuclear Power) is currently developing the conceptual design of new generation power plant, which will be equipped with various passive safety features. In this research, the PCCS performance, which is one of new passive safety features of the nuclear power plant, has been evaluated for APR+ power plant with GOTHIC (8.3Test) code.

2. APR+ Containment Building and PCCS

The containment building of APR+ is similar with the typical large-dry-containment (APR1400) and is made with reinforced concrete, steel lining, and which provides a biological barrier under accident conditions. The containment is built on the common foundation and is enveloped with a cylindrical and hemisphere dome concrete wall. The design pressure is 4.128 kg/cm^2 at 143.3 ^{o}C.

The PCCS consisted of PCCTs and PCCXs and supply and return piping which is connected with the PCCTs and PCCXs. PCCTs are located on the outside containment building and are containing coolant water. PCCXs are module assemblies which is transferring the heat from the containment atmosphere to the circulating coolant of PCCS.

A PCCX consists of eight heat exchanger modules with the upper and lower common distributors. A heat exchanger module consists of the upper and lower headers and a bundle of heat exchanger tubes. The heat exchanger tube has a length of 6 m, an outer diameter of 3.18 cm and a thickness of 0.305 cm. Total number of 336 heat exchanger tubes for one heat exchanger module are connected with a lower and a upper headers.

PCCS Piping system from the PCCTs to the common distributors and vice versa makes a loop of coolant. The supplying pipe (from PCCT to lower distributor) is of a 16 inch (inner diameter of 0.387 m) and the return pipe (from upper distributor to PCCT) of a 20 inch (inner diameter of 0.489 m).

3. Input Model

In this research, the results of analysis for evaluating the cooling performance of PCCS were provided. APR+ has been adopted as target plant. Two approaches have been used for modeling of the containment which is single compartment modeling and multi-dimensional modeling for the containment. Both modeling methods of PCCS are similar and use same mass and energy release data. The main difference of both approaches, however, is the nodalization scheme.

For the single compartment model, only one compartment for a whole containment is used. On the other hand, for the multi-dimensional model, the containment space is divided into two regions by operating floor level. The lower containment space under operating floor is divided with multiple compartments and the upper containment space is distributed by single sub-divided volume. Thus, two spaces are connected with the flow paths and 3D-Connectors of GOTHIC.

Input models of both single compartment model and multi-dimensional model are developed individually. For single compartment model, the control volumes mainly consist of the several volumes representing the space above the floor, IRWST, SIT and the environment. Other elements for the boundary of break flows, the passive heat sinks and the PCCS are considered also. Figure 1 shows the nodal diagram for the single compartment model.

Unlike the single compartment model, the containment space of the multi-dimensional model is divided into two regions by operating floor level. The lower containment space under operating floor is separated into multiple compartments. On the other hand, taking advantage of GOTHIC modeling features that are capable modeling the free space with the distributed grid, the upper containment free space comparatively is distributed by a single sub-divided volume. The nodding diagram of multi-dimensional model is shown in Fig. 2.

For condensation mode on the outer surface of PCCX heat exchanger, the following KAERI single tube correlation is used;

$$Nu_D = 1.078 Gr_L^{0.2024} W_s^{*1.2575} Ja^{-0.6196}$$

GOTHIC can be extended by linking the additional custom code for special applications as Dynamically Linked Libraries (DLLs).[1] To model the PCCX heat exchanger module, the Add-On PCCS component, provided by ZNE, was used for this research.

Fig. 1. Nodding Diagram of Single Compartment Model

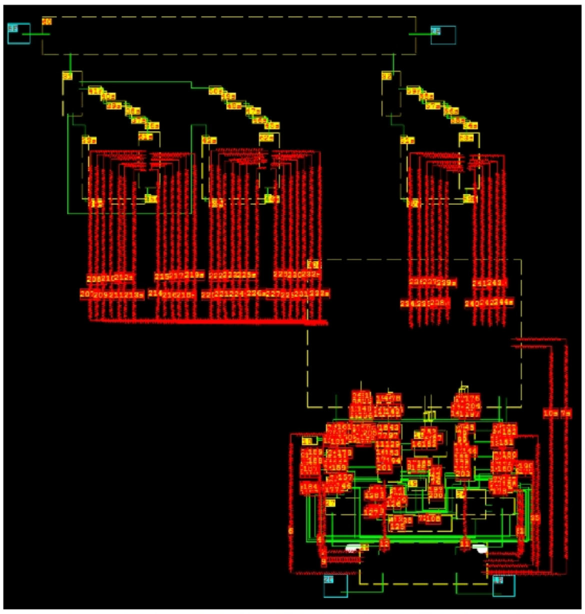

Fig. 2. Nodding Diagram of Multi-dimensional Model

4. Results and Discussion

The long term pressure and temperature responses calculated by the single compartment model are shown in Fig. 3 and Fig. 4. During the accident, the containment pressure and temperature are governed by the break flow rate and the energy from the primary system and heat removal rate by the passive heat sink and PCCS in containment. The containment pressure and temperature during the initial period of accident are only decided by the break flow rate and energy and passive heat sink. Steam injection decreases rapidly at 20 sec and the first peak pressure is detected at about 21 sec. After the first peak, containment is depressurized as the break rate is decreased for a while. As the break rate recovers, containment pressure rises again with decreasing heat removal by the passive heat sink and PCCS, which results in the second peak occurring at 1020 sec. Subsequently, the long term cooling is introduced and the gradual decrease of break rate results in decreasing heat removal rate of PCCS. During this long term cooling, because the heat removal rate of the passive heat sink is continuously decrease and the coolant temperature of PCCT is rising also, the containment reaches the third pressure and temperature peak at about 65,000 sec (18 hr). Just before this third peak, the coolant temperature of PCCT reaches the saturation temperature. After this temperature, the heat removal rate of PCCS is maintained at a certain level where the saturated water can absorb.

PCCT coolant temperature behavior is shown in Fig. 5. After the accident, PCCT coolant absorbs heat from the containment atmosphere through the heat exchanger tube and its temperature continues to rise up to the saturation. According to the single failure assumption, one train connected to PCCT2 is not available so that the coolant temperature of PCCT1 rises faster than that of PCCT2. After saturated at 52,000 sec, the temperature does not rise anymore because of the latent

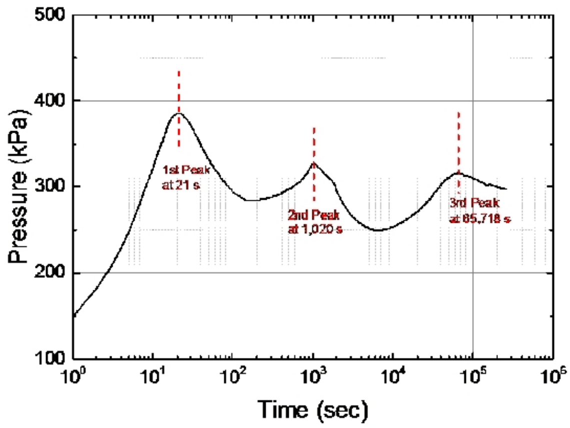

Fig. 3. Pressure Response of Single Compartment Model

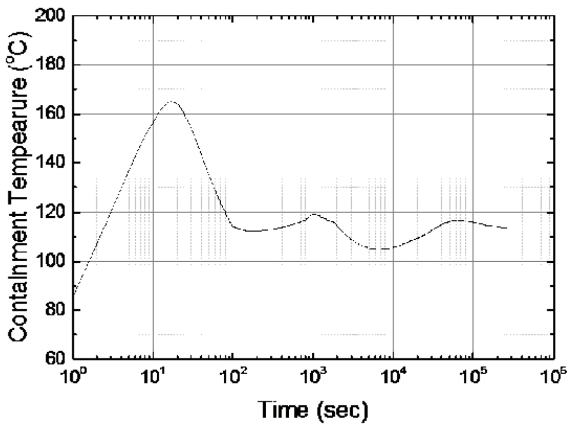

Fig. 4. Temperature Response of Single Compartment Model

heat release on pool surface.

All trends of containment responses in the multi-dimensional model were similar to that of the single compartment model. The multi-dimensional model, however, shows the pressure response lower than the single-compartment model at the beginning of calculation (Fig. 6). This trend can be also found in the document of GOTHIC qualification report [2], in which two approaches, lumped and 3D were compared for the peak pressure of CVTR experiment. According to this report, the peak pressure calculated by 3D model showed the lower value than the lumped analysis and it is because of high steam concentration in the upper containment. Besides, it can be assured from the results of coolant temperature of PCCS in Fig. 7. It shows that the coolant temperature in the multi-dimensional model rises faster than in the single compartment model and it means that heat is more transferred from the containment atmosphere in the multi-dimensional model. As a result, high coolant temperature would leads to a little heat removal through the PCCS after the first peak. Fig. 8 shows the coolant flow rate at the junction of supply pipe and return pipe. Compared with the single compartment model, because of more heat removal at the beginning, the slightly higher circulation is calculated.

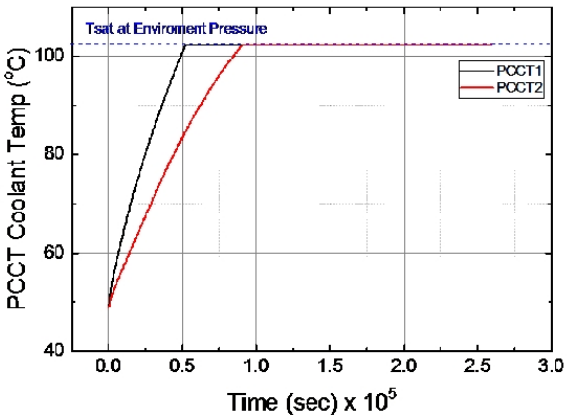

Fig. 5. Coolant Temperature of Single Compartment Model

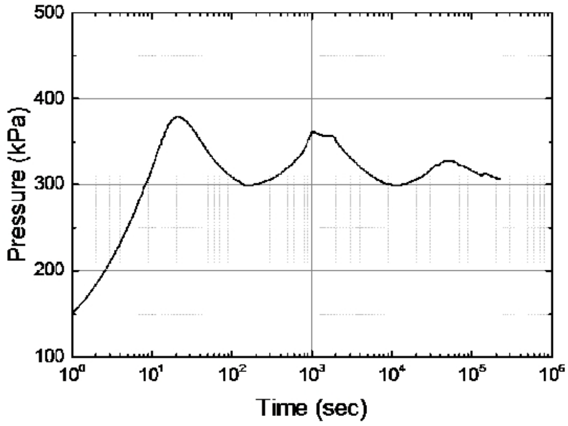

Fig. 6. Pressure Response of Multi-Dimensional Model

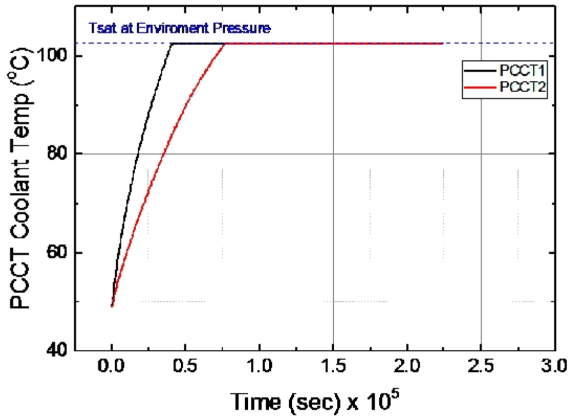

Fig. 7. Coolant Temperature of Multi-Dimensional Model

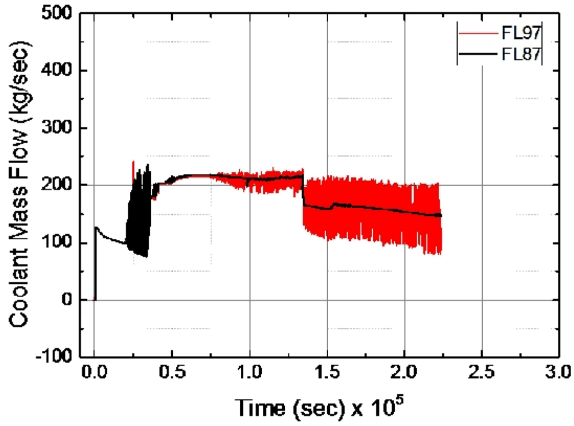

Fig. 8. Liquid Mass Flow Rate of Multi-Dimensional Model at Flow Path 87 and 97

5. Conclusions

In this research, the performance of PCCS equipped in APR+ plant is estimated by GOTHIC 8.2(QA) code. Two modeling approaches of the single compartment and multi-dimensional model were prepared. The calculation results gave the very useful information, from which the removal mechanisms were understood and key parameters governing the performance of PCCS were found.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20161510400120) Additional thanks should also be given to KHNP, the leading company of the project.

REFERENCES

[1] EPRI, GOTHIC Thermal Hydraulics Analysis Package User Manual, Version 8.2(QA), October 2016

[2] EPRI, GOTHIC Thermal Hydraulics Analysis Package Qualification Report, Version 8.2(QA), October 2016