Study on the Dimension of Ex-Vessel Passive Molten Core Cooling System for iPOWER

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1. Introduction

Since the Fukushima accident in 2011, more people have been concerned about the safety of nuclear power plants all around the world and especially have paid more attention to the plants nearby. In addition, the latest earthquakes in Korea make it difficult to ensure that Korea is safe from earthquakes as well as other external hazards.

Therefore, nowadays people are requesting a higher level of safety on a nuclear power plant rather than before, to ensure that each plant has enough capability to prevent and mitigate a severe accident even though it is unlikely to occur. Generally speaking, the severe accident is defined as a situation that fuel melts in a reactor core relocates into a lower part of reactor vessel, and finally the melted core penetrates the reactor vessel.

So far, two types of severe accident mitigation strategy and related system for molten core have been adopted in many nuclear power plants. One is In-Vessel Retention (IVR) strategy through External Reactor Vessel Cooling (ERVC), and the other is Ex-Vessel corium cooling strategy using a so-called core catcher with a corium cooling system.

In Korea, an innovatively safe nuclear power plant, which is called iPOWER, is being developed to significantly enhance the safety for public acceptance of nuclear power as well as the international competitiveness for potential exports. And as a part of the safety enhancement, Passive Molten Core Cooling System (PMCCS) which will be installed in iPOWER, is being developed to mitigate a severe accident, reach a safe state, and finally maintain the containment integrity.

The purposes of PMCCS development are summarized as follows:

- To be operated in a passive manner without operators' action
- To have sufficient cooling performance with minimum required cooling time duration (72h) and 100 % thermal margin

2. Heat Load Estimation for Ex-Vessel PMCCS in iPOWER

2.1 Methodology

First of all, to determine the dimension of PMCCS, development requirements should be set up in detail based on the purposes of PMCCS development.

According to European Utility Requirements (EUR) [1], a passive system is defined as a self-contained or self-supported system that relies on natural forces, such as gravity or natural circulation. According to IAEA-TECDOC 626, "Safety related terms for advanced nuclear plants", four degrees of passivity are presented. The PMCCS, however, excludes the possibility of using stored energy such as batteries to initiate the operation even though the use of the stored energy is also considered within the concept of passivity.

EU-APR [2], modified and improved from its original design of APR1400 which is being constructed in Korea and UAE, has been developed for European market. As a severe accident mitigation system, the EU-APR adopted Passive Ex-vessel corium retaining and Cooling System (PECS) to which cooling water is provided via battery-powered valves by high temperature signal.

The amount of heat to be removed by PMCCS relies on reactor core heat flux which exponentially decays over time as shown in Figure 1. For conservative design, the earliest time of reactor vessel failure is typically applied. From the result of Large Break Loss of Coolant Accident (LBLOCA) analyses for APR1400 using MAAP4 code as a reference (Table 1), the earliest time of reactor vessel failure is identified about 6,300 seconds after the occurrence of accident.

According to ANSI/ANS 5.1-1979 Decay Heat Curve as shown in Fig. 1, the decay power fraction at the earliest reactor vessel failure time is identified as 0.009752 (0.9752%). As the total thermal power of iPOWER is 3,600 MW at the moment, the quantity of heat to be removed by PMCCS is calculated as follows:

3,600 MW x 0.009752 = 35.106 MW

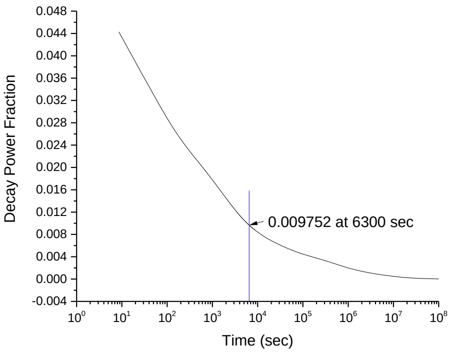

Fig. 1. ANSI/ANS 5.1-1979 Decay Heat Curve

Table 1 Reactor Vessel Failure Time for LBLOCA cases in APR1400

Analysis	Core uncover (sec)	Hot-leg creep rupture (sec)	Corium relocation (sec)	Reactor vessel failure (sec)
LB00000	197	3,119	3,006	6,631
000S0	197	-	2,900	6,396
0000P	197	3,119	3,007	6,631
000SP	197	-	2,900	6,396
0H00P	197	3,119	3,007	6,631
0H0SP	197	-	2,900	6,396
0HF0P	197	3,115	3,001	6,600
0HFSP	197	-	2,893	6,365
AH00P	197	-	4,679	9,039
AS0SP	197	-	4,406	8,464
AHF0P	197	-	4,700	9,021
AHFSP	197	-	4,395	8,441

For a conservative estimate, 36 MW is adopted as the goal of heat removal for PMCCS and the value corresponds to 1% of iPOWER thermal power.

As a next step, it should be determined the dimension of reactor cavity where the PMCCS is installed. The overall geometrical size of the reactor cavity is calculated based on available previous experimental and analytical results or otherwise reasonable assumption.

2.2 Required Heat Removal Capacity for PMCCS

Prior to the design of Passive Molten Core Cooling System (PMCCS), the dimension of reactor cavity in which the PMCCS is installed should be determined. As the PMCCS is assumed to be hemispherical-shaped container, the overall geometrical size of the reactor cavity is calculated based on available previous experimental and analytical results or otherwise reasonable assumptions.

It is known that a typical commercial Pressurized Water Reactor (PWR) of 1,300 MWe, has about 200 ton of molten core including oxides and metal [3]. Therefore, the properties of molten core for iPOWER of which the electric power is expected to be less than 1,200 MWe, are assumed as follows:

- Total volume : 180 ton
- Corium density : 8,000 kg/m^3
- Total volume : 22.5 m^3 (calculated from total volume and corium density)

As the PMCCS has a function to cool the corium from downwards with cooling water, the downward heat flux ratio of corium is a key parameter for the design of PMCCS. From the result of studies [4] for upward and downward heat flux ratio as shown in Fig.2, the downward heat flux ratio was estimated between 43% and 53%. Therefore, the maximum downward heat flux ratio is expected to be less than 60%. The downward heat flux ratio for the PMCCS, however, is set to be 70% for conservative design.

As the total amount of corium heat to be removed was set as 36 MW in the methodology section, the total heat to be removed by PMCCS is calculated to be 25.2 MW (= 36 MW X 70%) and as a target of the design of PMCCS it becomes twice as 50.4 MW in case that the safety margin of 100% is considered.

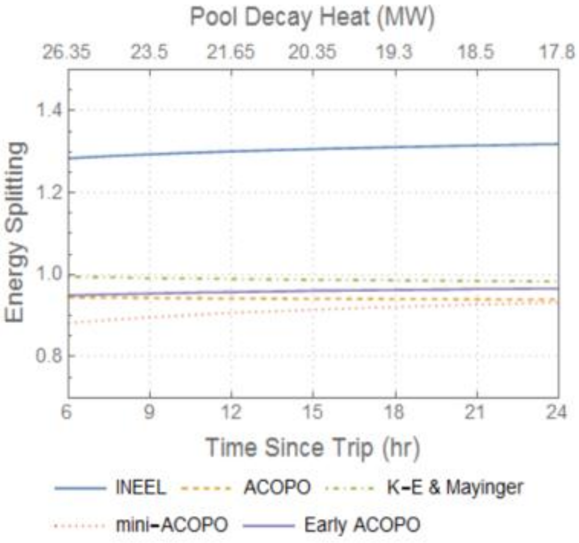

Fig.2. Upward/downward thermal flux ratio

Fig. 3 shows the result of Critical Heat Flux (CHF) experiment for the lower head of reactor vessel that was performed in Idaho National Engineering and Environmental Laboratory (INEEL), indicating the CHF values in the condition of pool boiling [5]. In this study, the type 1, representing a plain vessel without surface coating or thermal insulation, is selected to evaluate the thermal margin of PMCCS for more conservative design while the type 2, representing coated vessel without thermal insulation, is used as a reference.

To derive the volume of PMCCS to accommodate and cool the corium, it is assumed that the hemispherical-shaped core catcher in PMCCS should have 90 m^3, four times the total corium volume (22.5 m^3) to take into account the installation space of sacrificial material and the volume expansion of bubbles created by the reaction between sacrificial material and corium.

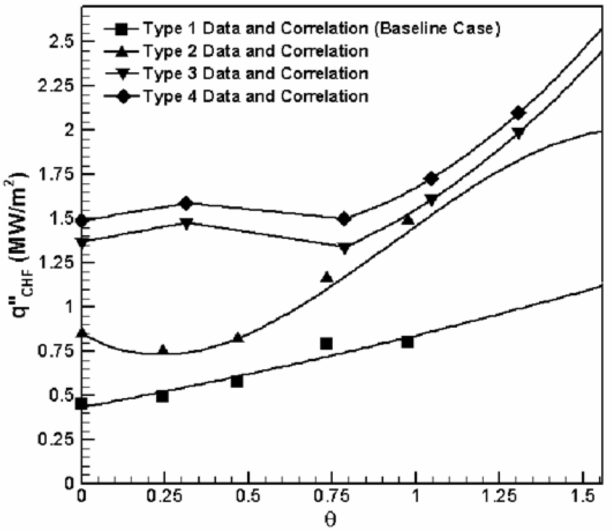

Fig. 3. Spatial variation of the local CHF and correlation curves

To derive optimal dimension for PMCCS, a definite integral of CHF from 0 to 90 degree is calculated for several radius such as 2.8 m, 3.0 m, and 3.5 m as 0 degree indicates the bottom of lower hemisphere at center and 90 degree indicates the circumference of the hemisphere. As mentioned above, the integrated value of CHF should satisfy 50.4 MW to remove the heat of corium with 100% safety margin.

3. Estimation on the Dimension of PMCCS

Based on the results of integrated critical heat (Y-axis), which mean the removable heat from PMCCS filled with corium by specific degree of angle, calculated by the definite integral of specific CHF curve above from 0 degree to the specific degree (X-axis) presented in Fig. 4 and Fig. 5, it is shown that the hemispheres with 2.8 m and 3.0 m cannot accommodate the required heat removal amount (50.4 MW) as the black curves do not reach 50.4 MW (Y-axis) at the 90 degree of angle (X-axis). Therefore, they need additional part of container over the hemisphere container to meet the target value. On the other hand, it is shown in Fig.6 that in case of 3.5 m radius, the hemisphere container alone can accommodate the target value at 80 degree as the volume occupies 296.2% of the corium.

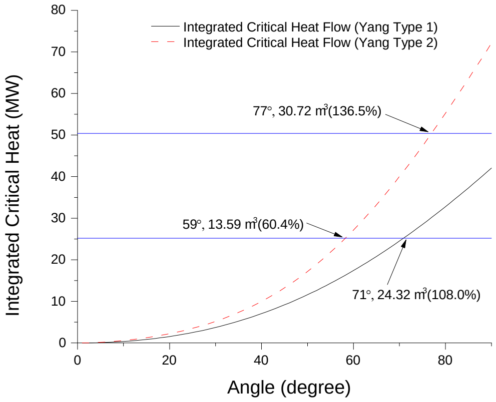

Fig.4. Integrated Critical Heat from 0 to 90 degree (R=2.8 m)

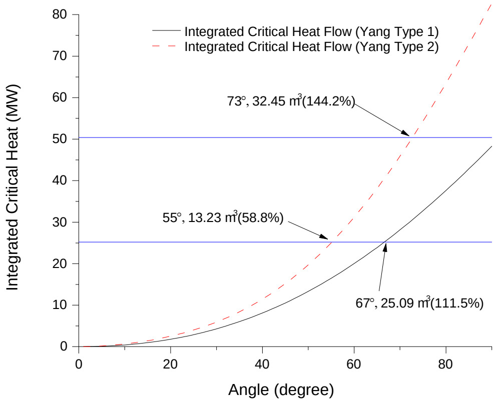

Fig.5. Integrated Critical Heat from 0 to 90 degree (R=3.0 m)

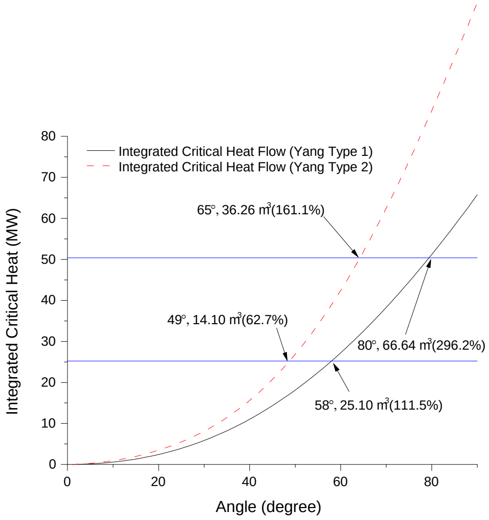

Fig.6. Integrated Critical Heat from 0 to 90 degree (R=3.5 m)

In consideration of the results above, the optimal dimension of PMCCS is presented in Fig. 7. The minimum height between the bottom of reactor and the cavity floor is 3.35 m at which PMCCS is filled with corium from 0 to 80 degree of angle while the radius of reactor and reactor cavity is 2.54 m and 3.66 m respectively. For the cavity width, extra size of 50 cm in radial direction from the center of hemisphere is considered in the region outside the hemispheric-shaped PMCCS body where cooling water passes. The cavity extension for PMCCS installation should be determined to the extent that it would not impair the structural integrity of cavity wall.

4. Conclusions

In this paper, the dimension of ex-vessel PMCCS for iPOWER was derived based on available previous experimental and analytical results or otherwise reasonable assumption in consideration of 100% safety margin.

In the future, the performance of PMCCS will be evaluated through safety analyses as the conceptual design advances toward a basic design. In addition, the cooling strategy for corium will be determined through technical discussions.

Acknowledgement

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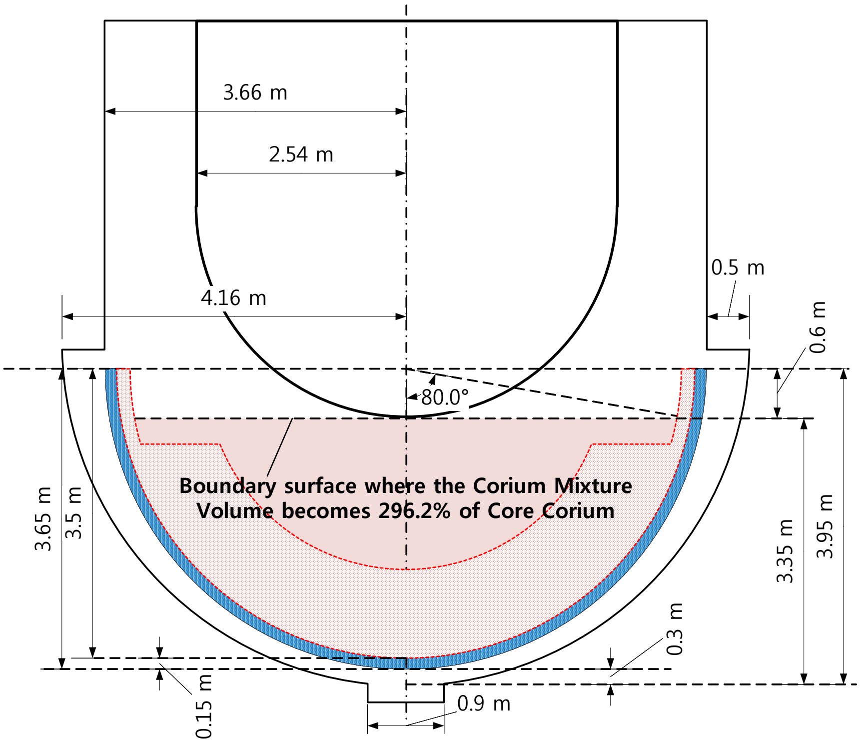

Fig.7. Estimated dimension of hemispherical-shaped PMCCS (R=3.5 m)