Transactions of the Korean Nuclear Society Virtual spring Meeting

May 13-14, 2021

Analysis of IVR-ERVC Evaluation Characteristics for Small Reactor

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1. Introduction

An IVR-ERVC (In-Vessel corium Retention through External Reactor Vessel Cooling) to prevent the reactor vessel failure during a severe accident is known to be an effective means in nuclear power plants [1]. This measure has been adopted in low power reactors of the AP600 and Loviisa nuclear power plant, in the medium-power reactors of the AP1000 and CAP1000 as a design feature for severe accident mitigation, and in the high power reactors of the APR (Advanced Power Reactor) 1400 and APR+ as an accident management strategy in the SAMG (Severe Accident Management Guideline). It is also adopted in a small power integral reactor of the SMART (System-integrated Modular Advanced ReacTor). Since SMART is an integral reactor, the steam generators, pressurizer, and RCP (Reactor Coolant Pump) s are installed inside the reactor vessel. The thermal output of SMART is 365 MW_{th} which is only around 1/10 of Optimized Power Reactor (OPR) 1000 and APR1400. However, the size of the SMART reactor vessel is larger than those of these power plants. Specifically, the internal diameter of the SMART reactor vessel is 5.3 m, which is larger than the 4.7 m of APR1400, and the thickness 0.2 m is larger than APR1400 0.165 m. As such, the heat flux to the outer wall of the reactor vessel is smaller than OPR1000 or APR1400 when the core corium is relocated in the lower plenum of the reactor vessel.

In general, the evaluation of IVR-ERVC in large scale and small scale reactor is different in many aspects, such as heat transfer in corium pool, natural convection outside RPV wall, CHF correlation and so on. This paper is focused on the analysis of the IVR-ERVC evaluation characteristics of small reactor, such as SMART to compare with a high power reactor, such as APR1400.

2. Evaluation Method of IVR-ERVC

A success criterion of the IVR-ERVC during severe accidents may be evaluated to determine the thermal margin for the prevention of a reactor vessel failure. A thermal load analysis from the corium pool to the outer reactor vessel in the lower plenum of the reactor vessel may be performed to determine the heat flux distribution. The Critical Heat Flux (CHF) on the outer reactor vessel wall may be determined to fix the maximum heat removal rate by the external coolant between the outer reactor vessel wall and the insulation of the reactor vessel. The thermal margin for success of IVR-ERVC during severe accidents may be evaluated through a comparison of the thermal load with the maximum heat removal rate of CHF on the outer reactor vessel wall.

For example, the following methods may be used in order to satisfy the achievement of the IVR-ERVC.

- When the molten core material is relocated in the lower hemisphere plenum of the reactor vessel during severe accidents, the heat flux distribution from the corium to the external reactor vessel wall may be estimated using a numerical model.

- The natural circulation mass flow rate, which is formed in the annular gap between the external reactor vessel wall and insulator, may be estimated using a thermal hydraulic analysis computer code.

- CHF, which corresponds to the maximum heat removal from the external reactor vessel wall depending on the estimated natural circulation mass flow rate, may be determined using SULTAN [2] and KAIST [3] experimental results.

3. Analysis of Heat Transfer in Corium Pool

Two corium layers in the lower plenum of the reactor vessel may be formed during severe accidents, because the metal corium layer with lower density is formed at the top while the oxidized corium layer with higher density is formed at the bottom. In general, the lower plenum numerical model on IVR-ERVC analysis includes core melt relocation into the lower plenum, water boiling, molten pool formation and separation, metallic pool heat transfer, oxide pool heat transfer with crust formation, heat conduction in the lower head vessel wall, and lower head vessel melting and failure. Simulation targets of the lower head model are metallic pool, oxide pool with crust, water level in the lower plenum, heat transfer among water, metallic and oxide pools, and mass and energy balance in the water, metallic and oxide pools. It may be assumed that the thermal energy generated in the bottom oxidized corium layer is transferred to the metal corium layer at the top and the reactor vessel on the side.

Figs. 1&2 show the two corium layers formed in reactor vessel lower plenum of the APR1400 and SMART, respectively. As shown in two Figs, the corium layer depths are different, which depends on initial core material mass (thermal power) and lower reactor vessel size.

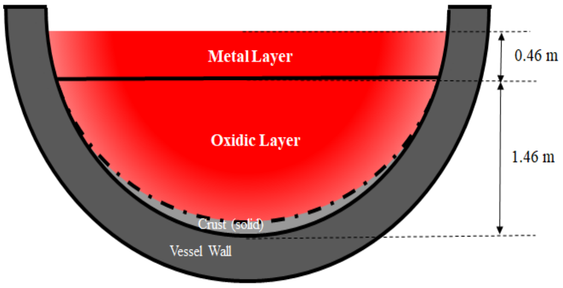

Fig. 1. Two corium layers formed in reactor vessel lower plenum of the APR1400

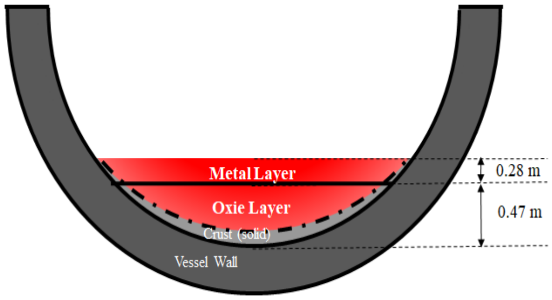

Fig. 2. Two corium layers formed in reactor vessel lower plenum of the SMART

Although, in the real accident, corium pool shows temperature gradient at different locations, the corium pool is modeled by one representative temperature and mass in the lower head model of the used computer code. To define heat flux in the upper part of oxide molten pool, the following Rayleigh number was defined.

$$Ra_{op}=\frac{g\beta q'''_{dh}d_{op}^{5}}{\alpha_{op}\nu_{op}k_{op}} \qquad (1)$$

Here, g is gravitational acceleration, β is thermal expansion coefficient of oxide pool, q'''_{dh} is volumetric decay heat, d_{op} is depth of oxide molten pool, α_{op} is thermal diffusivity of oxide pool, ν_{op} is kinematic viscosity of oxide pool, and k_{op} is thermal conductivity of oxide pool, respectively. Using Rayleigh number defined, Nusselt number for the upward heat transfer is calculated by ACOPO correlation [4]. The thermal load of heat transfer coefficients from the corium pool to the reactor vessel wall is determined using the Nusselt number.

$$\overline{Nu_{op,up}}=1.95\,Ra_{op}^{0.18} \qquad (2)$$

In above correlation, the application rang of the Rayleigh number is $10^{12}<Ra_{op}<10^{16}$.
Similarity, Nusselt number for the lateral heat transfer is calculated by ACOPO correlation.

$$\overline{Nu_{op,w}}=0.3\,Ra_{op}^{0.22} \qquad (3)$$

$$\frac{Nu_{op,w}(\theta)}{\overline{Nu_{op,w}}}=0.1+1.08\frac{\theta}{\theta_p}-4.5\left(\frac{\theta}{\theta_p}\right)^2+8.6\left(\frac{\theta}{\theta_p}\right)^3\cdots\cdots for\ 0.1\le\frac{\theta}{\theta_p}\le0.6$$

$$0.41+0.35\frac{\theta}{\theta_p}+\left(\frac{\theta}{\theta_p}\right)^2\cdots\cdots for\ 0.6<\frac{\theta}{\theta_p}\le1.0 \qquad (4)$$

Here, θ is angular location in the oxide molten pool and θ_p is top location of the oxidic molten pool. With increasing θ (at the top location of the oxide pool), the Nusselt number increases. This equation is made by measured heat flux data from the ACOPO experiment.
Therefore, heat transfer coefficients from the oxide corium pool to the vessel wall depends on non-dimensional number of the Rayleigh number. Thin layer results in the low value of non-dimensional number. ACOPO correlation was used for the oxide pool, whose the application rang of the Rayleigh number is $10^{12}<Ra_{op}<10^{16}$. In SMART case, the Rayleigh number was approximately 10^{13}, but it is approximately 10^{17} in APR1400 case. For this reason, the ACOPO correlation may be used in SMART and APR1400 IVR-ERVC evaluations.
The heat transfer formed in the top metal corium layer is distributed based on the heat transfer from the bottom oxidized corium layer. Therefore, the heat flux in the top metal corium layer is directly affected by the heat transfer q_{op}^{up} transfer from the oxidized corium layer to the metal corium layer. Similar to the oxidic molten pool, for the mass and energy conservation of the metallic molten pool. To determine the heat transfer rate in the upper and the lowest part of the metallic layer, it is necessary to specify Rayleigh number of metallic molten pool, which can be written as

$$Ra_{mp}=\frac{g\beta\left(T_{mp}-T_{mp}^{melt}\right)d_{mp}^{3}}{\alpha_{mp}\nu_{mp}} \qquad (8)$$

Here, T_{mp} is temperature of the metallic pool, d_{mp} is depth of metallic molten pool, respectively. Using Rayleigh number defined, Nusselt number for the top and bottom surface heat transfer is calculated by Globe-Dropkin correlation [5].

$$Nu_{mp,up}=0.15\,Ra_{mp}^{1/3} \tag{9}$$

In above correlation, the application rang of the Rayleigh number is $10^5<Ra_{mp}<10^9$.
Similarity, Nusselt number for the lateral heat transfer is calculated by Churchill-Chu correlation [6].

$$Nu_{mp,w}=0.076\,Ra_{mp}^{1/3} \tag{10}$$

In above correlation, the application rang of the Rayleigh number is $0.1<Ra_{mp}<10^{12}$.
Therefore, heat transfer coefficients from the oxide corium pool to the vessel wall depends on non-dimensional number of the Rayleigh number. Globe-Dropkin and Churchill-Chu correlations were used for the metallic pool, whose the application rang of the Rayleigh number are $10^5<Ra_{mp}<10^9$ and $0.1<Ra_{mp}<10^{12}$, respectively. In SMART case, the Rayleigh number is approximately 10^8, but it is approximately 10^{10} in APR1400 case. For this reason, Globe-Dropkin and Churchill-Chu correlations may be used in SMART and APR1400 IVR-ERVC evaluations.
There is no difference between a high and small power reactors in IVR-ERVC evaluation method on thermal load evaluation. Main difference for IVR-ERVC evaluation is in scale, which affects heat transfer in molten pool. It is concluded that the difference between the high and small power reactors is that Rayleigh numbers, namely, a large value in the high power reactor of the APR1400 and a small value in the small power reactor of the SMART.

4. Analysis of Maximum Heat Removal Rate

When the melted core material relocates to the lower plenum of the reactor vessel, the heated lower spherical reactor vessel wall induces a two-phase natural circulation flow in the annular gap between the outer reactor vessel wall and the insulation material.
According to the result of SULTAN test conducted by CEA in France, as shown in the following Fig. 3 and the result of the KAIST test, as shown in Fig. 4, the maximum heat removal rate of CHF (Critical Heat Flux) in outer reactor vessel wall increases when the natural circulation flow between the outer wall of the reactor vessel and insulator increases. In general, an increase in the mass flow rate of the coolant leads to an increase in the CHF at the lower outer reactor vessel wall. This results in an increase of the wall heat removal rate caused by the convective coolant circulation flow. This circulation mass flow rate is dependent on the configuration of the reactor vessel insulation material, such as the water inlet area and position, the coolant (water and steam) outlet area and position, and the gap geometry between the outer reactor vessel and the insulation material. For this reason, a detailed analysis on the coolant mass flow in the reactor cavity during severe accidents is necessary to evaluate the IVR-ERVC evaluation using a thermal hydraulic analysis computer code. This analysis determines the coolant circulation mass flow rate formed between the outer wall of the reactor vessel and insulator when the heat flux inside the reactor vessel inner wall is given while there is no initial coolant circulation flow.

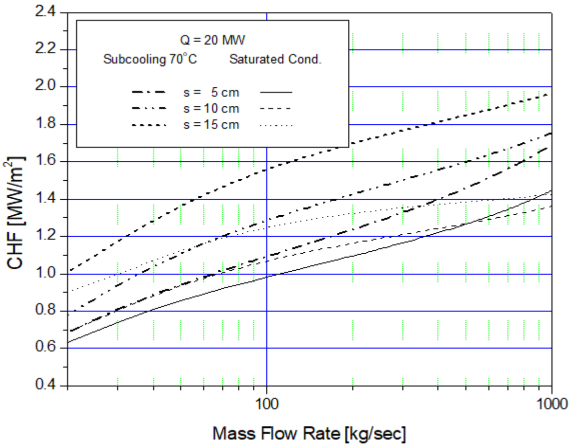

Fig. 3. SULTAN test result of CHF on outer vessel wall

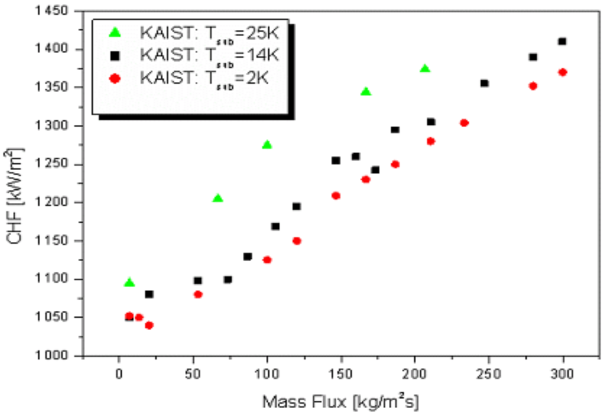

Fig. 4. KAIST test result of CHF on outer vessel wall

In natural convection outside RPV wall, the difference between the high and small power reactors is value of the natural coolant circulation mass flow rate, which depends on the geometry scale and heat flux from the corium pool to the coolant in the outer reactor vessel wall. The difference between two reactors of the SMART and the APR1400 is a large value in high power reactor and a small value in small power reactor. This affects the CHF (Critical Heat Flux) on the outer reactor vessel wall. The large value in this flow rate leads to large value of the CHF, but a small value leads to a small value.

5. Conclusion

This paper is focused on the analysis of the IVR−ERVC evaluation characteristics of small power reactor, such as SMART to compare with high power reactor, such as APR1400. There is no difference between the high and small power reactors in IVR-ERVC evaluation method in general. However, main difference for IVR-ERVC evaluation is in scale, which affects heat transfer in molten pool and natural convection outside reactor vessel wall. In heat transfer evaluation for molten pool, non-dimensional Rayleigh number for used correlations are used. For this reason, the difference between the high and small power reactors is that these values, namely, a large value in the APR1400 and a small value in the SMART, which affects the used correlation value. In natural convection outside reactor vessel wall, the difference between the high and small power reactors is value of the natural coolant circulation mass flow rate, which depends on the geometry scale and heat flux from the corium pool to the coolant in the outer reactor vessel wall. The difference between two reactors of SMART and APR1400 is a large value in high power reactor and a small value in small power reactor. This affects the CHF on the outer reactor vessel wall. If experimental data on the CHF, such as SULTAN and KAIST experiment are used, the maximum heat removal depends on the coolant circulation mass flow rate. The large value in this mass flow rate leads to large value of the CHF, but a small value leads to a small value. For this reason, it is concluded that there is no difference on the IVR-ERVC evaluation method between the SMART and APR1400, because non dimensional Rayleigh number and experimental data are used, which depends on the reactor scale.

ACKNOWLEDGEMENT

This study was supported by the National Research Foundation (NRF) grant funded by the Korea government (MSIP) (2020M2D7A1079182)

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