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Advanced In-Vessel Retention (IVR) Strategy by External Reactor Vessel Cooling (ERVC) with Liquid Metal

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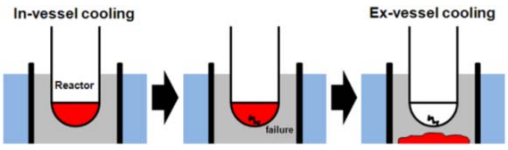
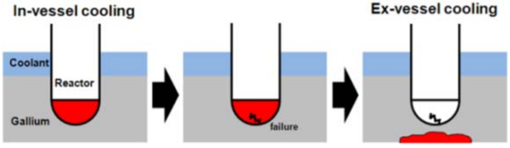
1. Introduction

In-vessel retention strategy by the external reactor vessel cooling is mitigation method under severe accidents in nuclear power plant. ERVC strategy has some advantages such as preventing the escape of radioactive materials and simplifying the accident scenario. Successful strategy of external reactor vessel cooling could lead to retain the molten fuel in the reactor vessel. IVR-ERVC strategy could remove the concerns about the ex-vessel progression of a severe accident like the direct containment heating (DCH), ex-vessel fuel-coolant interaction (FCI) and molten core concrete interaction (MCCI) which are complicated and still uncertain. This concept has been adopted in some advanced light water reactors such as AP600, AP1000 and APR1400 power plant. IVR-ERVC is limited when the CHF occurs on the reactor vessel. There are enough thermal margins in small reactor like AP600 and AP1000. However, uncertainty is still present in high power reactor like APR1400 due to the corresponding high decay heat. The distribution of heat flux is different according to the elevation of relocated corium in the reactor vessel. Light metal component is located on top of corium. This metallic layer could generate high heat flux on the corresponding vessel outer wall. This generated heat flux could be compared with removable heat flux on the vessel outer wall. Many researches have been studied to ensure the thermal margin in IVR-ERVC strategy [1]. Recently, flooding the liquid metal was studied to eliminate the issues related to CHF [2]. The heated vessel contacts with gallium liquid metal. The decay heat could be removed through convection with a single-phase. One of the unique characteristics for this system is available potential of the ex-vessel cooling when IVR strategy is failed as shown in Fig. 1.



(a) Side cooling concept



(b) Upper cooling concept

Fig. 1. Combination of In/Ex-vessel cooling

There is some consideration to install this gallium IVR-ERVC system in the nuclear power plant. The reactor vessel is located in the limited room. The gallium catcher structure should be installed to resolve this issue as shown in Fig. 2. The computational fluid dynamic (CFD) analysis was conducted to confirm the coolability by using the commercial code (CFX).

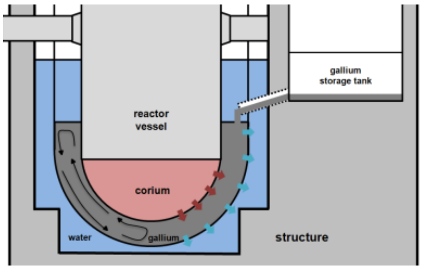


Fig. 2. Schematic diagram for gallium IVR-ERVC

2. Characteristics of gallium IVR-ERVC system

When the gallium liquid metal is flooded in the cavity to remove the decay heat, the following characteristics are shown in comparison with present IVR-ERVC strategy which is using the coolant.

2.1 Single phase heat transfer

The most remarkable difference in gallium IVR-ERVC system is to accomplish the heat transfer in a single phase on the reactor vessel. This type of heat transfer makes the CHF phenomenon removed in IVR-ERVC strategy. The integrity of the reactor vessel could be maintained under severe accidents in the nuclear power plant. Liquid metal has low Prandtl number. It means that thermal diffusivity dominates compared with momentum diffusivity. The effective heat transfer area related to focusing effect is enlarged due to the thermal diffusion of the gallium itself. The magnitude of heat flux between the coolant and gallium could be reduced to proper heat flux level which allows the nucleate boiling.

2.2 Ablation effect

It is difficult to avoid the ablation in the reactor vessel. The melting point of uranium dioxide is about 3120K. The maintainable thickness of reactor vessel is determined by the temperature of the outer surface on the reactor vessel. The temperature of the outer surface is increased when the gallium liquid metal was flooded in the surrounding reactor vessel. The tensile strength of the reactor vessel material is enough high to support the relocated molten fuel and inner pressure with the thin thickness. It is not serious negative effect to apply the liquid metal flooding in IVR-ERVC.

2.3 Heat transfer area

It is expected that the effective heat transfer area is enlarged due to the flooding the liquid metal. It can be divided 3 parts. Firstly, it appears that the vessel with diameter bigger than the reactor vessel is used to retain the corium due to the catcher structure. Secondly, the additional heat transfer area is generated on the top surface of flooded gallium liquid metal. This area is majorly dependent on the gap between the reactor vessel and the catcher structure. When the liquid metal is flooded above the hemispherical vessel, the huge heat transfer area is added to remove the decay heat on the side of the reactor vessel. Ultimately, the enlarged heat transfer area reduces the heat flux between the coolant and the gallium. It makes to have the thermal margin to CHF on the surface of catcher structure.

3. CFD analysis

3.1 Geometry and boundary condition

Figure 3 shows the geometry of IVR-ERVC system for CFD analysis. It is comprised of the reactor vessel, flooded gallium, the catcher structure. The dimension of the geometry is referred with APR-1400 reactor. The gallium liquid metal is designed to flood the space about 1m above the hemispherical vessel. The gap parameter study is conducted by varying the dimension (50mm, 100mm, 150mm and 200mm).

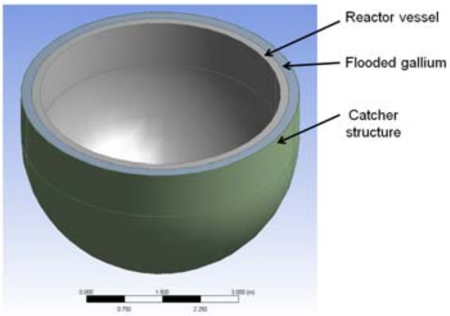


Fig. 3. Geometry of IVR-ERVC system

The boundary condition is described in Fig. 4. The heat source is decay heat generated in the corium. The distribution of heat flux according to the position is referred in report [3].The heat flux profile used as input data follows a consequence of 9.6" LOCA accident as shown in Fig. 5. The maximum heat flux is 3300 kW/m^2 in the high vessel inclination angle. The boundary conditions of the cooling surfaces are set as a static temperature equal to 110 ºC. The heat removal through boiling of water occurs on the surface in contact with the water.

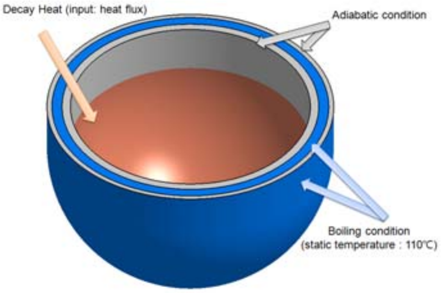


Fig. 4. Boundary condition

3.2 Heat flux distribution

The distribution of the heat flux according to the position on vessel is changed due to the flooded liquid metal as shown in Fig. 5. When the liquid metal is flooded, the heat flux is reduced below the value of CHF. There is enough gap between the analyzed heat flux and the CHF.

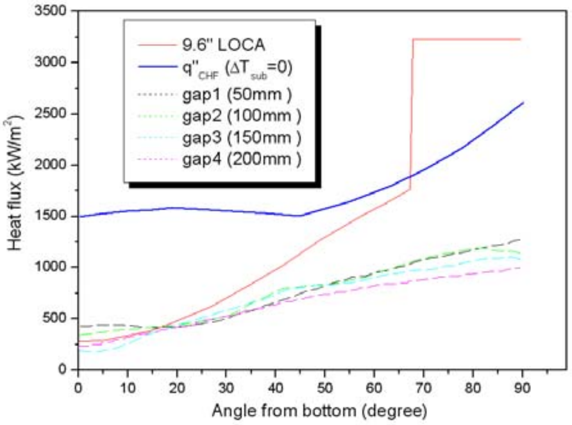


Fig. 5. Heat flux distribution according to the position

4. Further work

To ensure the safety margin for IVR-ERVC strategy, the application of the gallium liquid metal was suggested to avoid the CHF phenomenon on the reactor vessel. The CFD analysis was performed to confirm the feasibility of gallium flooding system. There are enough thermal margins for gallium IVR-ERVC due to the enlarged heat transfer area. The temperature of flooded gallium should be reduced to guarantee the success of IVR-ERVC. Additionally, the experimental tests should be conducted in order to determine the application.

REFERENCES

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