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CHF enhancement through Pressurized Intermediate Layer in IVR-ERVC Strategy

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1. Introduction

A number of nuclear power plants have been operated to generate the electricity. The difference between the nuclear power plant and other type of power plant is that the radioactive material is produced. It is important to prevent the leakage of this hazard material from nuclear power plant. Depends on depth concept is applied to protect and mitigate the accidents in nuclear power plant. When these safety systems are not properly working to remove decay heat, the core could be damaged and melted which is severe accident. The molten fuel is sequentially relocated to bottom of reactor vessel. In-vessel retention through the external reactor vessel cooling (IVR-ERVC) strategy has been adapted to some reactors at this situation in order to prevent the progression of an accident.

The limitation of IVR-ERVC strategy is CHF phenomenon on the outer wall of reactor vessel. The boiling is main heat transfer mode to remove decay heat between the reactor vessel and the coolant surrounding the reactor vessel. The vapor film could be generated and covered on the reactor vessel when the local heat flux level is beyond the removal capacity. As a result of CHF occurrence, the temperature of heater surface is increased immediately. Consequently, heated molten radioactive material is leaked. The fuel coolant interaction (FCI) phenomenon could cause the steam explosion in a state of fully flooding condition. Therefore, the CHF should be enhanced in order to be a successful IVR-ERVC strategy. Related studies were performed to confirm the CHF limit with UPLU, SBLB, KAIST and UNIST test facilities [1, 2, 3, 4] The recommendations to increase CHF include coating some materials on the vessel outer surface, increasing the reactor cavity flood level and streamlining the gap between the vessel and the vessel insulation. Recently, flooding the liquid metal is proposed to prevent the boiling itself [5].

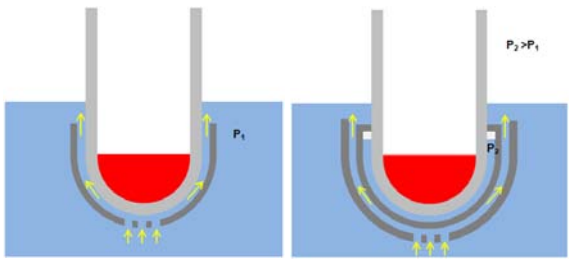
In this work, the effects of pressurized liquid layer inserted between the reactor vessel and flooded coolant was studied. Suitable reactor geometry was also presented to apple this concept. Generally, CHF is increased as high pressure was applied until about 1/3 of critical pressure. The limit of IVR-ERVC strategy could overcome by using pressurized intermediate layer.

2. Characteristics of pressured IVR-ERVC

There are some questions to determine to adopt this IVR-ERVC with pressurized intermediate layer. 1) Geometry of overall shape including the reactor vessel. 2) Required pressure condition. It is required to describe the expected effects with this IVR-ERVC system.

2.1 Geometry of reactor vessel

Figure 1 shows the geometry and fluid flow in IVR-ERVC condition with pressured intermediate layer. Two-phase flow was formed between the reactor vessel and surrounding thermal insulator. The generation region for high heat flux is formed from the metallic layer which is located upper position in molten fuel pool due to the relative density difference. The high temperature of this layer is maintained to keep the heat balance. There is a potential to generate the un-expected heat flux due to the thin metallic layer. Although the reactor vessel could be damaged in (a) type, the molten fuel could be retained due to the enhanced CHF in (b) type. As shown in Fig. 1(b), specific structure is surrounding both a hemisphere and a part of cylindrical of a reactor vessel to form the independent space. This space is close system with its own pressure condition.



(a) Present design (b) Modified design

Fig. 1. Geometry of reactor for IVR-ERVC

2.2 flood elevation in intermediate layer

Water is selected to fill the intermediate space. Flooding level is important parameter to determine the heat removal capability. When flooding water in the space including a part of cylindrical, the heat transfer area could be enlarged. The high heat flux from the metallic layer is reduced because of the convective heat transfer in the intermediate layer. The flooding height is limited due to both the complex pipe line connected to the reactor and the saturation effect. There will be a saturation point or height because the position of heat source is fixed.

The pressurized condition could be formed by injecting nitrogen or air into the intermediate layer. Injected nitrogen or air is naturally located at top position of this space. The volume of fluid is changed according the temperature condition. The nitrogen or air will perform to reduce the effects caused by the volume change.

2.3 Degree of pressurization

Many studies have been carried out at pressurized pool boiling condition. Related traditional correlations are shown in Eq. (1) – (4). The physical properties of the fluid vary according to pressure condition. CHF is increased at high pressure condition. Eq. (1) is widely used to predict the CHF value. However, it is known that this equation underestimates the CHF at high pressure condition. Equation (1) is used in this work as conservative approach to IVR-ERVC system with pressurized intermediate layer. Table I shows the predicted CHF according to the pressure condition. The highest possible CHF value is 3300 kW/m^2 at 9.6" loss of coolant accident (LOCA) [6]. This value is similar to the CHF prediction value at 3 MPa. The boundary of pressurized layer should be maintained above a minimum of 3 MPa.

The temperature of core inlet is 290^{o}C at normal operation condition of APR-1400. The boiling could be negative influence on the integrity of reactor structure from the intermediate layer. This layer should be maintained to prevent the boiling at 8 MPa which boiling point is higher than the core inlet temperature. The CHF prediction at this pressure condition is about 4076 kW/m^2. Pressurized IVR-ERVC system has a sufficient CHF margin.

Table I: CHF Prediction with Eq. (1)

Pressure (MPa)	Boiling point (^{o}C)	Predicted CHF (kW/m^2)
0.1	100	1119.8
2	212	2663.0
3	233	3292.8
4	250	3648.1
5	263	3865.3
6	275	3994.3
7	285	4060.1
8	294	4076.8
9	303	4053.4
10	310	3996.1
11	318	3908.5

$$q''_{CHF,Zuber} = 0.1331 \rho_v h_{fg} \left[\frac{\sigma(\rho_l - \rho_v) g}{\rho_v^2} \right]^{0.25} \left(1 + \frac{\rho_v}{\rho_l} \right)^{0.25} \quad (1)\ [7]$$

$$\frac{q''_{CHF,Lienhard}}{q''_{CHF,Zuber}} = 1.14 \quad (2)\ [8]$$

$$\frac{q''_{CHF,Bailey}}{q''_{CHF,Zuber}} = 1.3 \quad (3)\ [9]$$

$$\frac{q''_{CHF,Sakashita}}{q''_{CHF,Zuber}} = 4.98 \left[\frac{\rho_l^3 (\rho_l - \rho_v) g v_l^4}{\rho_v \sigma^3} \right]^{1/22} \quad (4)\ [10]$$

where q is the density, σ is the surface tension, g is the gravitational acceleration, h_{fg} is the latent heat of vaporization, and the subscripts l and v refer to the liquid and vapor, respectively.

3. CFD analysis

3.1 Geometry and boundary condition

Commercial CFD code (CFX) was used to confirm the heat transfer characteristics in pressurized intermediate layer. Figure 2 shows the geometry simulating the water layer with 2-D plate shape. Dimension of APR-1400 was referred to determine the size. Base flood elevation is selected as 2 m. The about 60% of heat transfer area is enlarged. The properties of water are set to a physical property under 8 MPa condition. Parameter study about the amount of flooding water was conducted by changing the thickness of intermediate layer like 100, 200 and 300 respectively.

Figure 3 show the boundary condition to simulate the decay heat and boiling. The

The boundary condition is described in Fig. 3. The heat source is decay heat generated in the corium. The distribution of heat flux according to the position is referred in report [6].The heat flux profile used as input data follows a consequence of 9.6" LOCA accident as shown in Fig. 4. 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 constant temperature (130 ºC) and heat transfer coefficient (20,000 W/m^{2}K). The heat removal through boiling of water occurs on the surface in contact with the water. The boiling temperature set high because of a hydro-static head. The heat transfer coefficient set conservatively low in comparison with the value calculated with Rohsenow correlation.

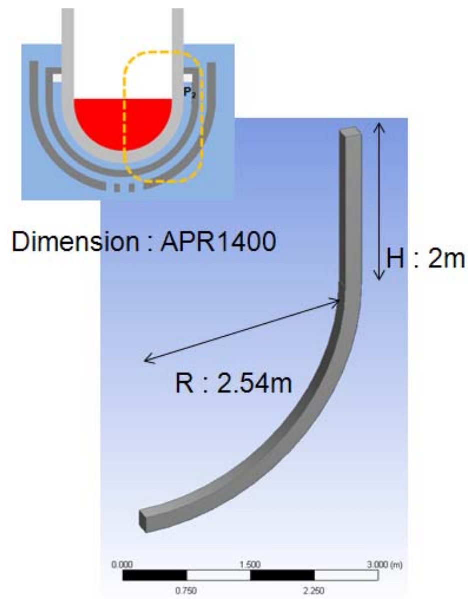


Fig. 2. Geometry of pressurized IVR-ERVC

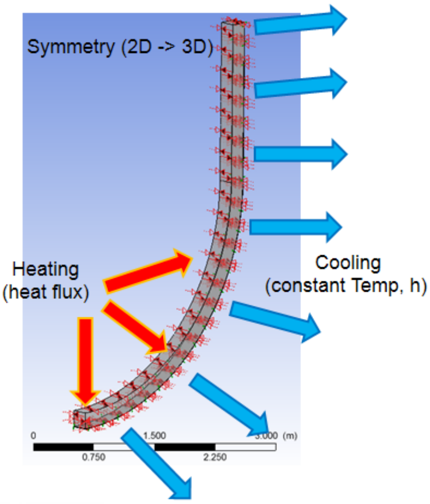
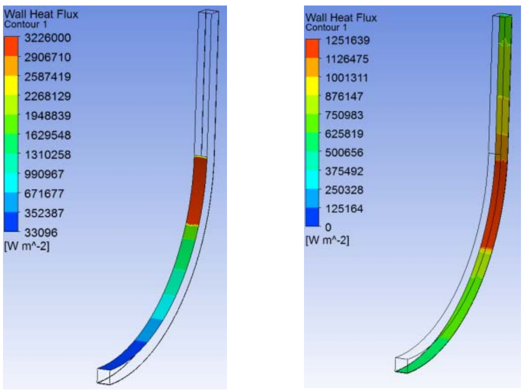


Fig. 3. Boundary condition

3.2 heat flux distribution on the wall

The distribution of the heat flux according to the position on vessel is changed due to the intermediate layer as shown in Fig. 4 and 5. Highly concentrated heat flux is reduced after going through the pressurized layer. Especially, heat flux reduction is larger in the wide gap condition. The small thermal margin is ensured at the case 1 (gap: 100mm). Other cases show the enough margins to CHF.



(a) vessel-pressurized layer (b) pressurize layer-water
Fig. 4. Heat flux distribution on the walls (gap: 200mm)

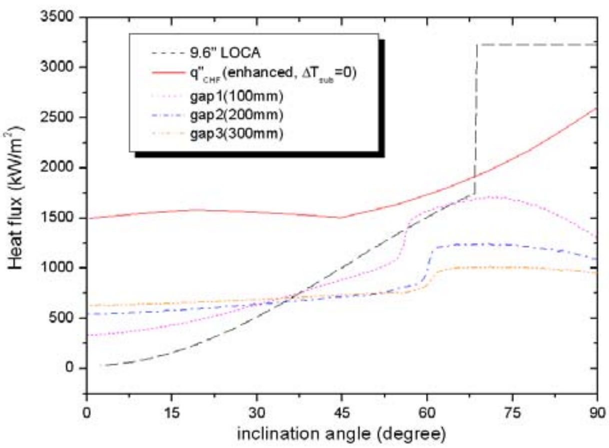
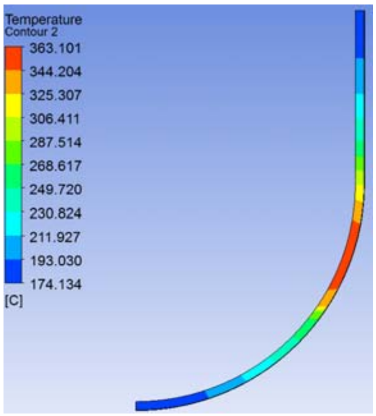


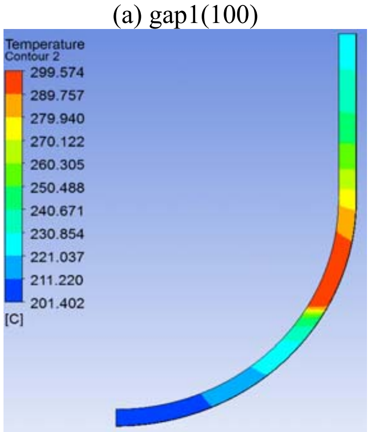
Fig. 5. Heat flux distribution according to the position

3.3 Temperature distribution in longitudinal section

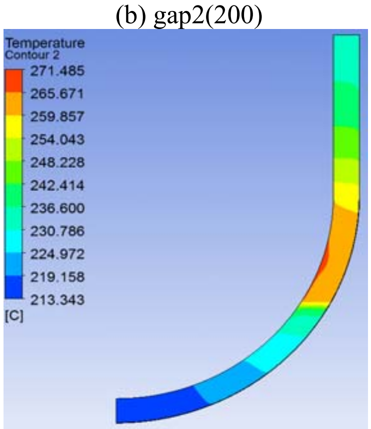
Figure 6 shows the temperature distribution in longitudinal section. There is a region with above 294°C temperature. It means that the vapor is present in this region. This zone is narrowed when the gap is large. Flow channel is larger than a case with a small gap. Ultimately, the relative low temperature region was formed due to enhanced convection heat transfer.



(a) gap1(100)



(b) gap2(200)



(c) gap3(300)
Fig. 6. Temperature distribution in pressurized fluid

4. Subcooling effects on CHF

The intermediate layer does not reach a saturation state as shown in Fig. 6. It means that the intermediate layer is maintained at sub-cooling condition. The average temperature for each case is 246°C (gap:

100mm,), 241°C (gap: 200mm,), 236°C (gap: 300mm,) respectively. These values are significantly lower than the boiling point under 8 MPa. Sub-cooling condition is influence on determining the CHF. Equation (5) predicts the CHF at the same time taking into account the operating pressure and sub-cooling condition [11]. As a result of the calculation, CHF is enhanced about 3 times compared with the value at saturation condition. A huge margin could guarantee the prevention of CHF in pressurized intermediate layer.

$$q"_{CHF,sub} = q"_{CHF,sat}\left[1+0.70\left(\rho_v/\rho_l\right)^{1/4} Ja/Pe^{1/4}\right] \quad (5)$$

$$\text{Ja(Jakob number)} = \left(\rho_l/\rho_v\right)\left(c_p\Delta T_{sub}/h_{fg}\right)$$

$$\text{Pe}\left(\text{Peclet number}\right) = \sigma^{3/4}/\left[\alpha\rho_v^{1/2}\left\{g\left(\rho_l-\rho_v\right)\right\}^{1/4}\right]$$

where α is thermal diffusivity.

5. Conclusions

New approach was proposed for success of IVR-ERVC strategy. CHF is enhanced by setting the pressurized boundary area. The reactor could be maintained at high thermal load condition with a pressurized intermediate layer. The CFD analysis was performed to confirm the feasibility of pressurized IVR-ERVC system. There are enough thermal margins for due to the enlarged heat transfer area and the convection heat transfer.

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