Preliminary Requirement of Hot Pool Free Surface Level from PGSFR Reactor Head

Gyeong-Hoi Koo [a*], Hyeong-Kook Joo [a]
[a]*Korea Atomic Energy Research Institute, 111, Daedeok-Daero, 989 Beon-Gil, Yuseong-Gu, Daejeon, Korea*
[*]*Corresponding author: ghkoo@kaeri.re.kr*

1. Introduction

The sensitivity study on structural integrity evaluations are carried out to make a decision of a hot pool free surface location from the reactor head for a preliminary designed reactor enclosure system. To do this, the thermal stress evaluations for a reactor vessel are carried out for a steady state normal operating condition with detailed heat transfer analyses through the reactor enclosure system. From these results, the preliminary design requirement of a hot pool free surface location from the reactor head is established to be 2.0m.

2. Sensitivity Studies

2.1 Heat Transfer Analysis

As first step to calculate the thermal stresses, the heat transfer analysis is performed to obtain the temperature distributions for the reactor vessel in steady-state condition.

2.1.1 Analysis Model

Radial and axial thermal gradients of the reactor vessel is calculated from the finite element analyses using an axisymmetric analysis model including the redan structure, reactor vessel, stagnant cold sodium, and guard vessel. Fig.1 presents the heat transfer mechanism and the thermal boundary conditions used in this analysis. As shown in figure, overall heat transfer mechanism, which includes the conduction, convection, and heat radiation, from hot pool to guard vessel outside air through the reactor enclosure structures is so complicated. The hot pool coolant heat is modeled to be transferred to the redan inner surface by the convection. The region between the redan and the reactor vessel is modeled using various heat transfer mechanism including the conduction through the stagnant cold sodium, the convection at the inner surface of the reactor with flowing cold sodium, and the heat radiation between the redan outer surface and the reactor vessel inner surface at a cover gas region. Above the sodium free surfaces of the hot and cold pool, heat transfer across this region is by radiation only, as convection is assumed to be negligible. In this region, the radiation mechanism is assumed as the open system with the assumed cover gas temperature 450°C. The reactor vessel is thermally coupled to the guard vessel only by radiation heat transfer. The radiation between the reactor vessel and the guard vessel is treated as the closed system.

For the heat transfer analysis, the ANSYS 14.0 computer code is used with STIFF 55 two-dimensional iso-parametric thermal conduction and convection elements representing the structures and sodium, and with LINK32 element providing the 3-dimensional radiation links across structural gaps where no sodium is present. The element size is generated enough to produce accurate results for radiation, which is so sensitive to element size.

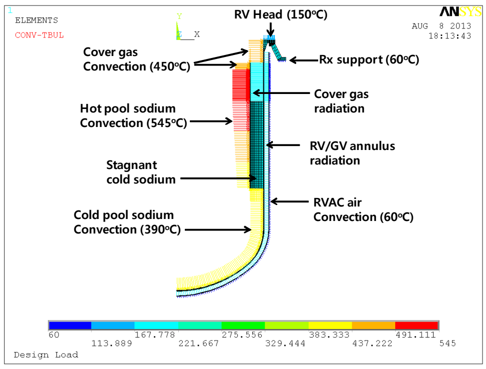

Fig. 1 Axisymmetric Model and Thermal Boundary Conditions

2.1.2 Thermal Boundary Conditions

The summary descriptions for thermal boundary conditions[1] used in the thermal analysis are as follows:

a. The applied maximum hot sodium bulk temperature inside of the redan structure is 545°C for upper hot pool region and linearly changed to the inlet cold pool sodium temperature of 390°C with assumed larger film coefficient of $1x10^4$ kg/hr.m^2.°C.
b. The cold pool sodium bulk temperature is 390°C, which is applied to the inner surface of the reactor vessel below the elevation of the IHX outlet nozzles with an assumed larger film coefficient of 600 kg/hr.m^2.°C.
c. The bulk temperature of the air flowing through the annulus between the guard vessel and the collector cylinder is assumed as 60°C with a film coefficient of 2.278 W/m^2.°C.
d. The inner surfaces exposed to the cover gas are modeled with convection heat transfer boundary condition with a bulk temperature of 450°C and a film coefficient of 2.278 W/m^2.°C.
e. The temperatures of the reactor vessel top flange and the bottom of the Rx support are assumed to

be 150 °C and 60 °C respectively.

f. The inner and outer surfaces of the Rx support are assumed to be insulated.
g. The used radiation emissivity for RV and GV annulus region is 0.67.

2.1.3 Results of Temperature Distribution

Fig. 2 presents the temperature distributions of the reactor vessel in case that the distance of a hot pool free surface from the reactor head is 1.36m. As shown in figure, the maximum temperature is 526°C in hot pool region. We can see very severe axial temperature gradient at the upper end region from the hot pool free surface elevation to the reactor vessel top flange. Fig. 3 shows a vector contour of a heat flux in the reactor vessel. We can see a large heat flux through a reactor vessel cylinder to top flange by conduction due to lower boundary temperature of a reactor vessel flange, which is maintained by the requirement of a reactor head cooling requirement of 150°C and an assumed Rx support anchor concrete temperature of 60 °C.

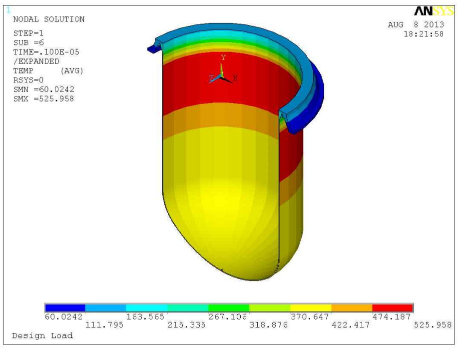

Fig.2 Temperature Distributions of RV

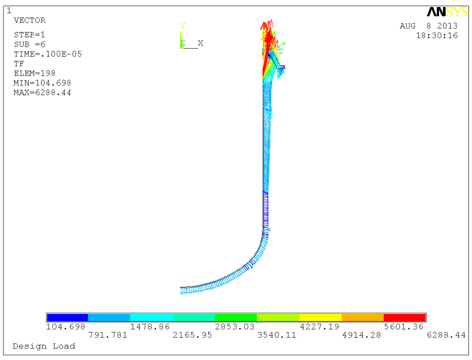

Fig.3 Vector Plot of Heat Flux Distributions

2.2 Results of Thermal Stress Analyses

Fig.4 presents a thermal stress contour for a design in case that the distance of a hot pool free surface from the reactor head is 1.36m. From the thermal deflection shape in figure, we can see that a severe radial thermal expansion difference between hot metal region and cold metal region invokes a large bending stress in vessel. The maximum thermal stress is 509MPa at upper region of a reactor vessel. When we just consider this secondary stress value, this design does not satisfy the ASME allowable stress of 369MPa at 274 °C.

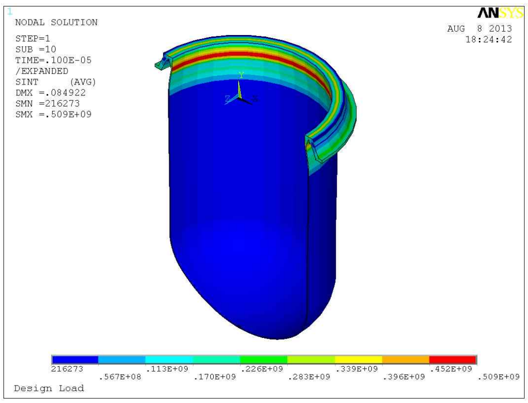

Fig. 4 Thermal Stress Distributions of RV

To mitigate the thermal gradient above hot pool free surface region, the case study for a design distance of a hot pool free surface from the reactor head increase was carried out. Table 1 presents the summary results for this study.

Table 1. Summary of Sensitivity Studies

Design distance (m)	Thermal stress (MPa)	Allowable stress (MPa)	Metal temp. (°C)	Criteria Satisfaction
1.36	509	369	274	No
2.36	334	390	227	Yes
3.36	297	393	218	Yes

As shown in Table 1, the maximum thermal stresses significantly decrease as increasing the design distance between reactor head and hot pool free surface and the allowable stresses also increase due to the metal temperatures decrease. From this evaluation, it is found that we need to keep the hot pool free surface far away from the reactor head enough to satisfy the ASME allowable stress criteria. Actually, these evaluations are not performed for the optimized reactor vessel upper flange shape and its transition region connected with reactor vessel cylinder, which invokes the maximum thermal stresses during the steady state condition. Therefore, we need to precede more detailed flange and its connection structural design in order to evaluate an appropriate location of a hot pool free surface. And we need to consider the load combinations with mechanical design loads such as dead weight, seismic loads, vibration loads, and so on for more detailed evaluations.

3. Thermal Stresses of PGSFR Reactor Vessel

From the sensitivity studies above, the distance between the hot pool free surface and the reactor head is preliminarily designed to be 2.0m. For this design dimension, the thermal structural analyses are performed by using the axisymmetric assumption for both IHX region and primary pump region.

For the IHX region, Fig. 5 shows the axisymmetric finite element model with thermal boundary conditions. Fig. 6 presents contour of thermal stress distributions in the reactor vessel and Fig. 7 shows the thermal stress distributions along the reactor vessel inner surface from top location. As shown in results, the maximum thermal stress intensity(Q) is 397MPa at a transition region between flange and cylinder. This value slightly exceeds the allowable stress limit, 3Sm (382MPa at 242°C).

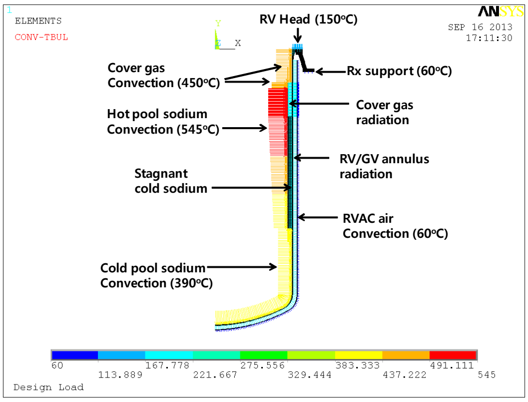

Fig. 5 PGSFR FE Analysis Model and Thermal Boundary Conditions (IHX Region)

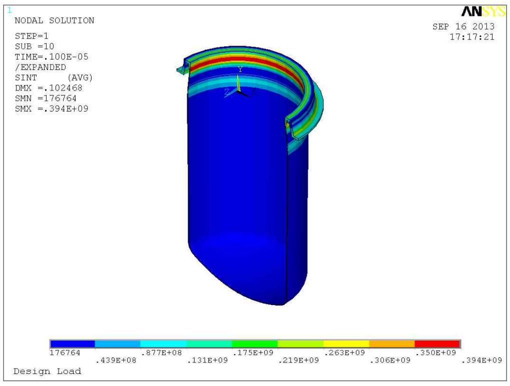

Fig. 6 PGSFR RV Thermal Stress Contour

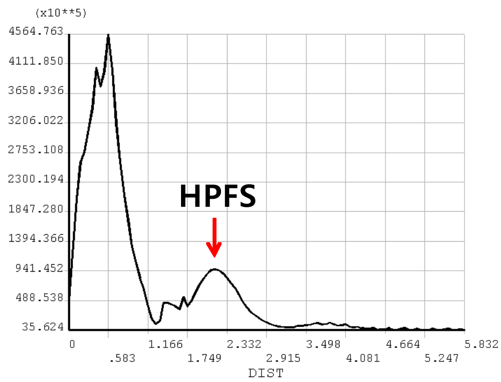

Fig. 7 Thermal Stress along the RV inner surface

For the primary pump region, Fig. 8 shows the axisymmetric finite element model with thermal boundary conditions. As shown in model, the stagnant sodium in a cold pool region is so large in comparison with IHX region. Fig. 9 presents contour of thermal stress distributions in the reactor vessel and Fig. 10 shows the thermal stress distributions along the reactor vessel inner surface from top location. As shown in results, the maximum thermal stress intensity(Q) is 378MPa at a transition region between flange and cylinder. This value slightly satisfies the allowable stress limit, 3Sm (384MPa at 237°C).

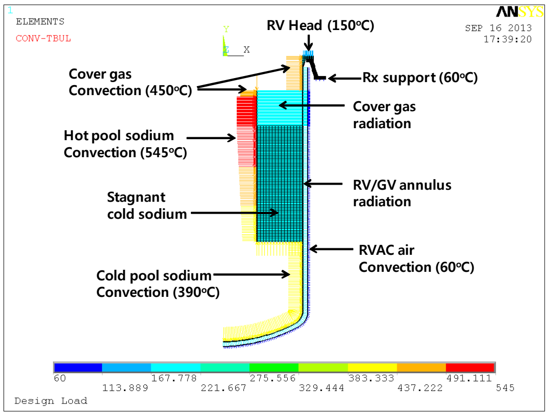

Fig. 8 PGSFR FE Analysis Model and Thermal Boundary Conditions (Pump Region)

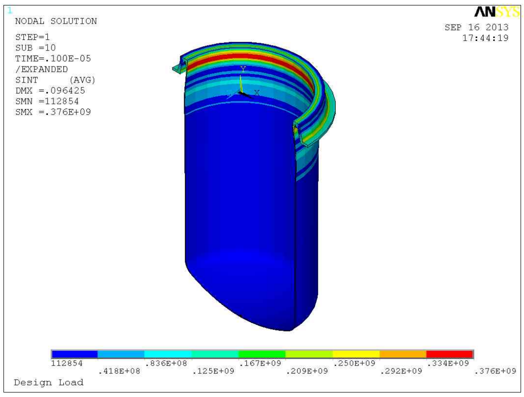

Fig. 9 PGSFR RV Thermal Stress Contour

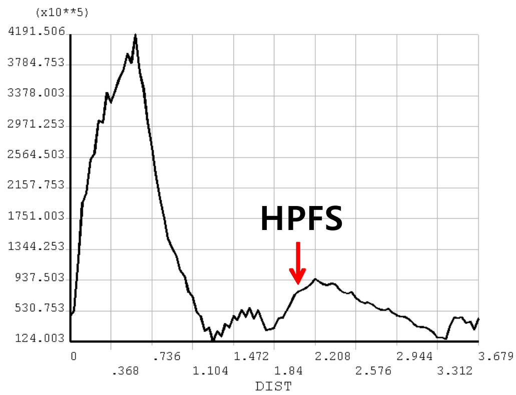

Fig. 10 Thermal Stress along the RV inner surface

4. Conclusions

From the sensitivity studies on the structural integrity evaluations for a steady state condition, the preliminary distance from the hot pool free surface to the reactor head is determined to be 2.0m same as a conceptual design. More detailed structural analyses for a reactor enclosure system will be carried out as a PGSFR structural design goes forward in detail.

REFERENCES

[1] G.H. Koo and J.H. Lee, "Design of Reactor Structures of LMR in the Vicinity of Hot Pool Free Surface Regions Subjected to Moving Elevated Temperature Cycles," *International Journal of Pressure Vessels and Piping*, Vol.79, No. 3, pp.167-179, 2002.