Study on Structural Improvement to Reduce Thermal Stress of Reactor Enclosure System of Sodium-cooled Fast Reactor

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1. Introduction

The Small, Advanced, Long-cycled and Ultimate Safe SFR (SALUS) which is being developed by Korea Atomic Energy Research Institute (KAERI) is a sodium cooled fast reactor(SFR) which is based on prototype generation IV sodium-cooled fast reactor (PGSFR). The reactor enclosure system(RES) of SALUS is composed of reactor vessel (RV), reactor head (RH), reactor support structure (RSS) and containment vessel (CV)[1].

The reactor vessel of SALUS contains hot pool sodium(510 ℃) and cold pool sodium(360 ℃) which are used as coolant like PGSFR, so it is exposed to high temperature conditions. On the other hand, reactor head and reactor support structure are in low temperature condition due to cooling system. These temperature conditions can cause the temperature gradient in reactor enclosure system. Therefore, the thermal stress which is caused by temperature gradient in reactor enclosure system is one of the main interest in structural design.

In this study, the structural design to decrease the thermal stress of reactor enclosure system of SALUS is discussed and suggested.

2. Design analysis and modification

2.1 Structural analysis

The SALUS was designed on the base of PGSFR, so the structural concept and shape are similar to PGSFR. At first, the reactor enclosure system of SALUS was suggested that reactor vessel is supported by reactor support structure and reactor head is supported by reactor vessel as shown in Fig. 1[2]. There is a containment vessel outside of reactor vessel, and the space enclosed with reactor vessel, containment vessel and reactor support structure is filled with nitrogen gas.

To analyze the thermal stress of reactor enclosure system of SALUS, finite element analysis model was built by using ANSYS S/W as shown in Fig. 2[3]. The analysis model was simplified as axisymmetric model considering the shape of reactor enclosure system of SALUS, and thermal boundary conditions were assumed like Fig. 3 refer to the thermal boundary conditions of PGSFR[2].

Liquid sodium coolant and reactor vessel are in contact with each other in cold pool area of reactor vessel, so heat transfer between liquid and metal is occurred. In the cover gas area of reactor vessel, heat transfer between gas and metal is occurred. In the upper part of reactor enclosure system of SALUS, the heat transfer from inside to outside of reactor enclosure system is occurred in reactor head. In case of side, the heat of reactor vessel is transferred to reactor support structure and containment vessel through nitrogen gas area by thermal radiation.

The thermal stress analysis was conducted on the finite element analysis model of Fig. 2 by using the thermal boundary conditions of Fig.3, and the analysis results are given in Fig. 4. As shown in Fig. 4, high thermal stress was generated in upper part and middle part of reactor vessel.

2.2 Design modification

To reduce the thermal stress of upper part of reactor vessel, the structures of reactor enclosure system should be modified to allow the thermal deformation caused by temperature gradient of reactor enclosure system. For this, the design of reactor enclosure system was modified so that reactor vessel was connected directly to reactor head, and reactor head was supported by structure support structure as shown in Fig. 5.

The thermal stress analysis was conducted on modified design, and the analysis results showed that the thermal stress was decreased from 178 MPa to 140 MPa in upper part of reactor vessel as shown in Fig. 6.

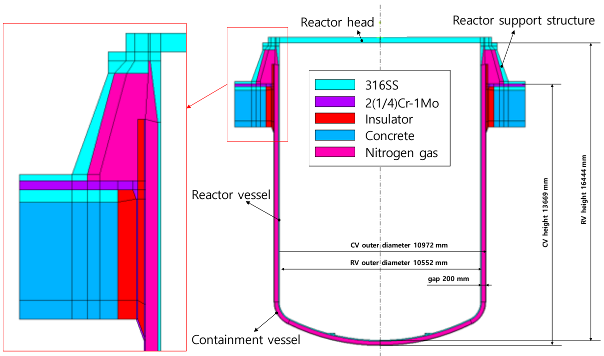

Fig. 1. Geometry of reactor enclosure system of SALUS(front view).

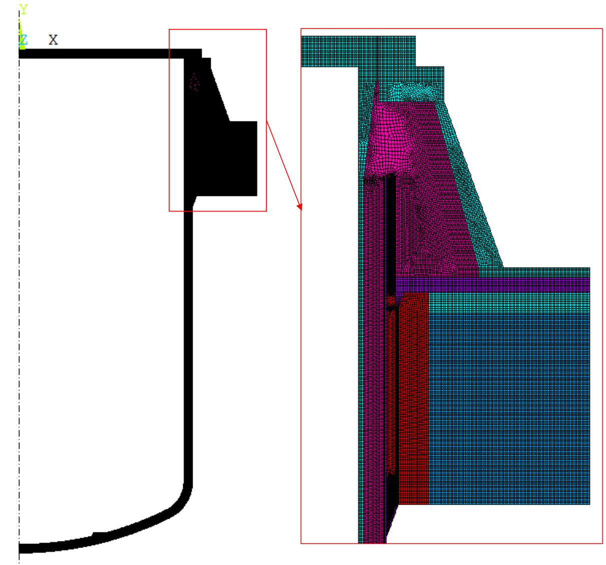

Fig. 2. Finite element analysis model of reactor enclosure system of SALUS.

<table>
<tr><th>RV Height (m)</th><th>RV inner Bulk Temp. (℃)</th><th>Film coefficient (W/m^2℃)</th></tr>
<tr><td>-0.3</td><td>250</td><td rowspan="2">5</td></tr>
<tr><td rowspan="2">-1.3</td><td rowspan="2">300</td></tr>
<tr><td rowspan="2">5</td></tr>
<tr><td rowspan="2">-4.0</td><td rowspan="2">440</td></tr>
<tr><td rowspan="2">20</td></tr>
<tr><td rowspan="2">-5.183</td><td rowspan="2">360</td></tr>
<tr><td rowspan="2">10000</td></tr>
<tr><td>-15.344</td><td>360</td></tr>
</table>

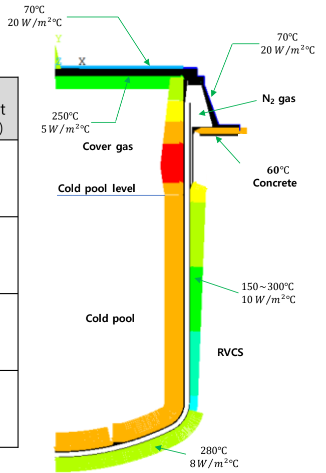

Fig. 3. Thermal boundary conditions of SALUS.

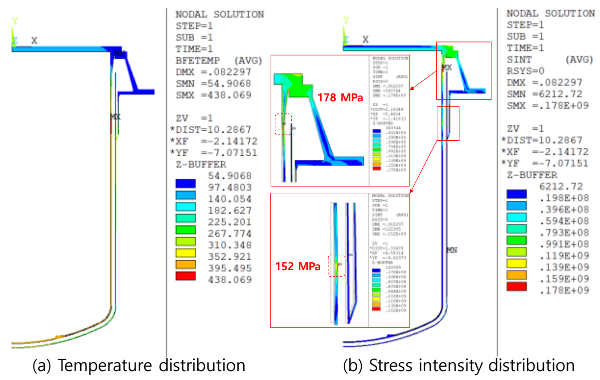

Fig. 4. Thermal stress analysis results of SALUS.

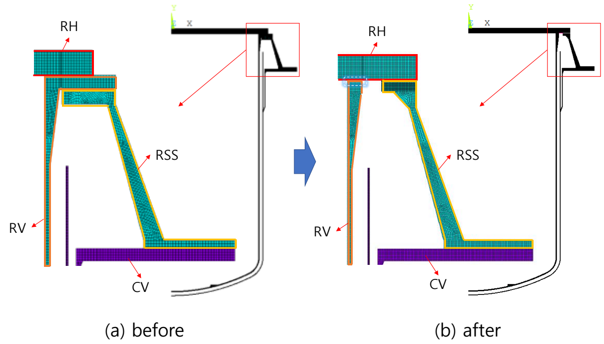

Fig. 5. Modification of reactor enclosure system of SALUS (before and after)

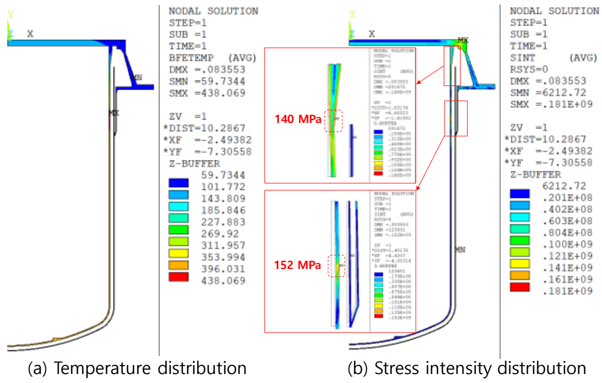

Fig. 6. Thermal stress analysis results of SALUS (modified model).

2.3 Sensitivity analysis

The sensitivity analysis about thermal stress was conducted on modified design by changing the main design variables of reactor vessel. For this, the thickness t and length L of upper connecting part of reactor vessel were selected as design variables as shown in Fig. 7.

(a) Case 1

First, the change of thermal stress in upper and middle part of reactor vessel was investigated by increasing thickness t from 60 mm to 173 mm. The analysis results showed that the thermal stress in upper part of reactor vessel was increased according to increasing t as shown in Fig. 8. On the other hand, the thermal stress in middle part of reactor vessel was maintained constantly.

(b) Case 2

Secondly, the change of thermal stress in upper and middle part of reactor vessel was investigated by increasing length L from 800 mm to 1400 mm. The analysis results showed that the thermal stress in upper part of reactor vessel was decreased according to increasing L as shown in Fig. 9. On the other hand, the thermal stress in middle part of reactor vessel was increased slightly when L increased over 1300 mm.

As the sensitivity analysis suggests, reducing thermal stress of reactor vessel requires a design that decreasing thickness t and increases length L of upper connecting part of reactor vessel.

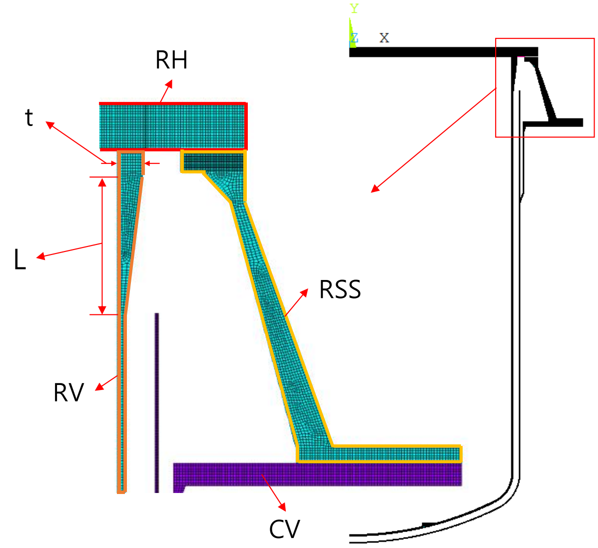

Fig. 7. Main design variables of reactor vessel of SALUS.

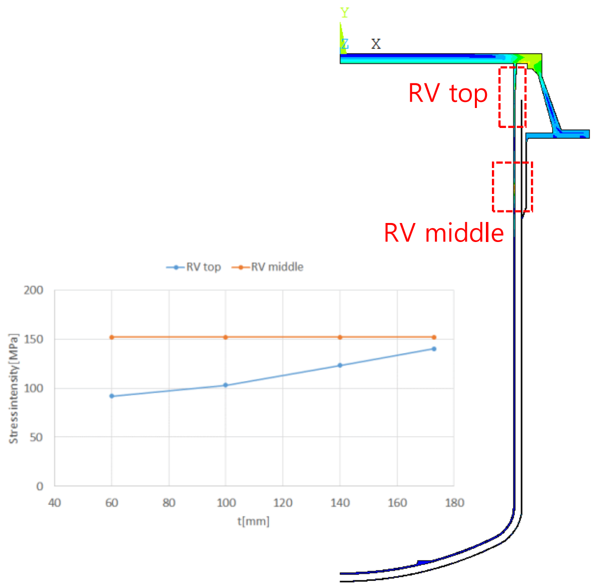

Fig. 8. Thermal stresses according to changing thickness t of upper part of reactor vessel.

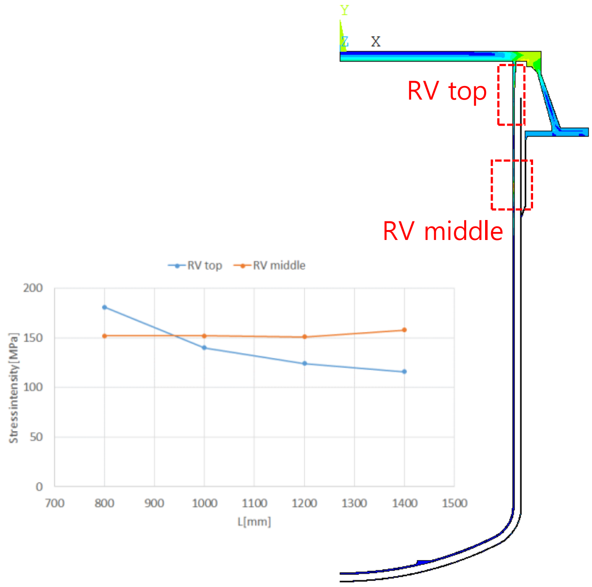

Fig. 9. Thermal stresses according to changing length L of upper part of reactor vessel.

3. Conclusions

In this study, the designs to decrease thermal stress of reactor enclosure system of SALUS were discussed.

First, the reactor enclosure system was modified like that the reactor vessel was connected directly to reactor head and reactor head was supported by reactor support structure to decrease the high thermal stress in upper part of reactor vessel. The thermal stress in upper part of reactor vessel was decreased more than 20 % through these design modifications.

To investigate the effect of design variables which can affect thermal stress of reactor enclosure system, the sensitivity analysis was conducted by changing thickness t and length L of upper connecting part of reactor vessel. The sensitivity analysis showed that the smaller thickness t and the longer L results in decreasing thermal stress of upper part of reactor vessel. On the other hand, it was shown that the thermal stress in middle part of reactor vessel was hardly affected according to changing given design variables.

ACKNOLEDGEMENT

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