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# Thermal Stress Investigation of Reactor Coolant System of VVER-1000 Reactor for Normal Operation Condition

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## 1. Introduction

Mechanical behavior of materials which are subjected to thermal effects is an important issue in mechanics design. When a structure is heated or cooled, it deforms by expanding or contracting. Thermal stresses are induced from non-uniform deformations which are attributed to varying thermal expansion coefficients of different materials, or restriction in deformation due to displacement constraints or opposing pressures.

In this study, thermal stresses of internally heated reactor coolant system (RCS) of the VVER-1000 type nuclear power plant (NPP) during normal operation are analyzed. The analysis focuses on the hot and cold leg piping of the RCS, which represent thick-walled piping structures in a NPP. Non-uniform deformations and thermal stresses typically develop on thick-walled pipes of cylindrical body shape when exposed to temperature gradients caused by the internal heat flow of liquid or gaseous materials. Evaluation of these phenomena is vital in RCS design considerations. The thermal stress analysis is performed using ANSYS 14.5 as a design and simulation tool.

## 2. Thermal stress analysis with FEM

The thermal stress analysis is based on heat balance equation derived from the principle of conservation of energy. Nodal temperatures are calculated using finite element method, and the solutions are subsequently used to obtain other thermal parameter values.

### *2.1 Modeling*

The VVER-1000 RCS contains four loops which are symmetrical about the vertical axis through the center of the reactor vessel. For the scope of this study, only one loop is modeled for thermal stress investigation. The Loop 1 model consists of a quarter of the reactor vessel, one steam generator (SG) vessel, one reactor coolant pump (RCP), one hot and cold leg pipe, and the support structures for each component. The casings of the RCP and SG vessel are modeled based on the exact weight of these components. The load weights of these components are used as boundary conditions.

### *2.2 Meshing*

Higher mesh quality will result in increased accuracy of the simulation results. The mesh size is controlled by limiting the minimum element size to 50 mm. In addition, all elements are quadrilateral mesh with a relevance value set to 30 and the relevance center set to medium. Fig. 1 shows the results of the primary loop mesh with approximately 3.58 million elements and 891,000 nodes.

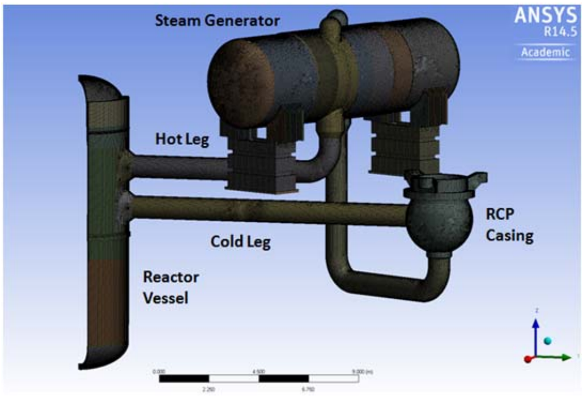


Fig. 1. The primary Loop 1 meshing

### *2.3 Boundary conditions*

Table I shows the loading conditions of operating temperature and self-weight applied to the model. Fig. 2 shows the setup of boundary conditions for the Loop 1 model.

| Parameters | Values |
|---|---|
| Hot leg operating temperature, $T_H$ ($^oC$) | 318.9 |
| Cold leg operating temperature, $T_C$ ($^oC$) | 287.0 |
| Secondary side SG operating temperature, $T_{SG}$ ($^oC$) | 278.5 |
| Environment temperature, $T_E$ ($^oC$) | 20.0 |
| Weight of RCP motor (kg) | 45,500 |
| Total weight of SG components (kg) | 244,140 |

Table I: Loop 1 loading conditions

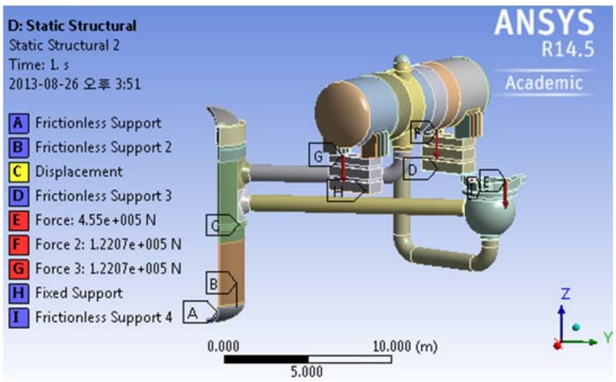


Fig. 2. Loop 1 boundary conditions

## 3. Results and discussion

Steady-state thermal analysis is used to determine the temperature distributions and thermal stresses of the model. Fig. 3 shows the effective thermal stress distributions induced by differential temperatures in Loop 1. Large thermal stresses are concentrated in regions where different components are connected, i.e. between the reactor vessel, RCP, and SG nozzles and the hot and cold leg piping. Out of these, the highest thermal stress occurred at the reactor vessel outlet nozzle. This is caused by the differences in thermal expansion coefficients between two different structure materials of the reactor vessel outlet nozzle and hot leg pipe, which consequently cause uneven elasticity. Another contributing factor is due to higher temperatures at this region compared to other locations.

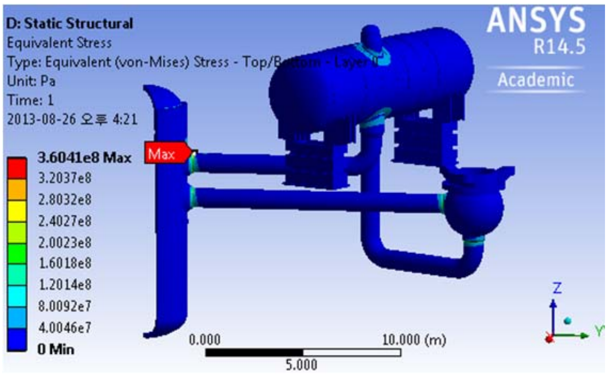


Fig. 3. Loop 1 stress distributions

Figs. 4 and 5 show the thermal stresses in 3-dimensional axis directions at the reactor vessel outlet nozzle and the RCS hot leg pipe. The X, Y, and Z directions represent the hoop stress, axial stress, and radial stress, respectively. The stress distribution, $\sigma_e$, of the model is calculated according to the von-Mises theory:

$$\sigma_e = \sqrt{\frac{1}{2}[(\sigma_t - \sigma_r)^2 + (\sigma_r - \sigma_z)^2 + (\sigma_z - \sigma_t)^2]} \qquad (1)$$

Simulation results are acceptable when the effective thermal stress is smaller than or equal to allowable stresses, $[\sigma]$, that occur in the pipes. The allowable stress is based on material yield stresses, denoted as $\sigma_t$, $\sigma_r$, $\sigma_z$, which are the hoop stress, radial stress, and axial stress, respectively.

| Component | Von-Mises stress ($\sigma_e$) MPa | $[\sigma]$ MPa | $\leq [\sigma]$ |
|---|---|---|---|
| Outlet nozzle | 161.47 | 441 | Yes |
| Inlet nozzle | 128.23 | 441 | Yes |
| Hot leg | 51.25 | 295 | Yes |
| Cold leg | 69.73 | 295 | Yes |

Table II: Von-Mises stress distribution of components

Table II summarizes the results for von-Mises stresses of the components, which are calculated using Eq. (1). It is evident that all the values are well below the allowable stress, hence validating the elastic solution investigation.

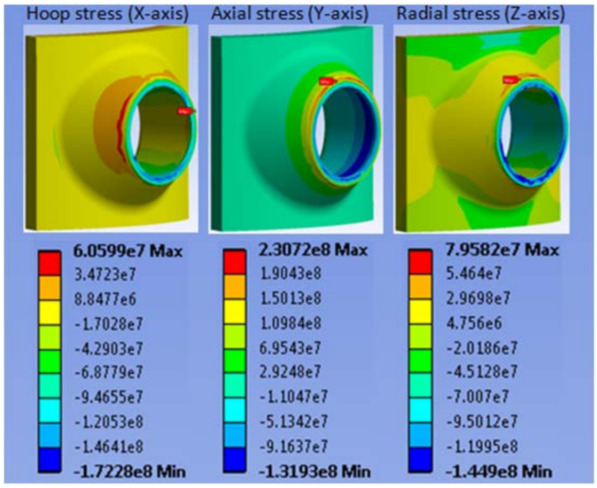


Fig. 4. Reactor vessel outlet nozzle stress distributions

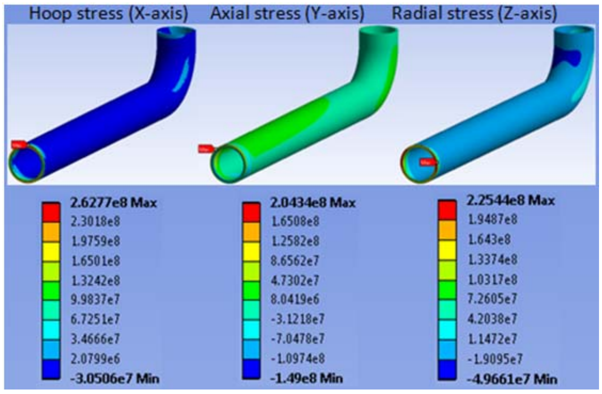


Fig. 5. Hot leg pipe stress distributions

## 4. Conclusions

The analyses revealed that the maximum effective thermal stress always occurs at the external surface of the nozzles or piping. Consequently, the regions surrounding the nozzles and hot leg piping ends are more easily damaged. From this result, it can be concluded that to minimize thermal stress in structures and components, it is essential to choose its materials such that the thermal expansion coefficients are similar or as close as possible. With increasingly sophisticated computer technologies, it has become more practical to apply numerical techniques to perform investigations on thermal stresses and temperature distributions of complex systems such as the VVER-1000 RCS.

## REFERENCES

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