Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 10-11, 2007

Analysis of Heat Transfer Characteristic in Upper Part of KALIMER-600 Reactor Vessel

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1. Introduction

In order to maintain the integrity of sealing material and to prevent a creep fatigue in the reactor head, the reactor head should be cooled during the reactor operation. Especially, the proper function of sealing material requires the temperature in the reactor head to be less than 150 °C. In KALIMER-600, the insulation plates are installed to reduce the heat transfer from the hot pool surface which is maintained at 545 °C during normal power operation, and the containment dome cooling system performs the cooling of reactor head. In a previous study [1], the heat transfer characteristic was analyzed for the simplified 1/4 geometry of reactor vessel upper part in which the Upper Internal Structure (UIS) was excluded by using a CFX-4.4 [2]. The present study extends the analysis domain to the UIS and the 1/2 geometry from a symmetric consideration, and analyzed the steady state, 3-dimensional heat transfer by using a CFD method to evaluate the cooling requirement for the reactor head.

2. Analysis

The analysis domain is presented in Fig. 1 with the applied boundary conditions. The domain is vertically from hot pool surface to reactor head, and is radially from vessel center line to containment vessel. The boundary conditions were determined based on the data at a 100 % full power operation [1, 3]. Among the conditions shown in Fig. 1, the heat transfer coefficient on the top surface of reactor head was estimated as follows [1].

$$\begin{aligned} h_{head\ top} &= \frac{0.666Q^{0.8}}{t} \equiv htc1 \qquad for\ r \le r_{plug} + 1\,[m] \\ &= htc1\left(\frac{1}{r}\right)^{0.8} \qquad for\ r > r_{plug} + 1\,[m] \end{aligned} \tag{1}$$

In Eq. (1), Q, t, r and r_{plug} are the volumetric flow rate of air entering the cooling channel, the size of channel, the radial distance from reactor center line and the radius of rotating plug, respectively. By varying the $htc1$, the capacity of reactor head cooling system to meet the temperature requirement was evaluated.

Using a commercial code CFX-10.0 [4], the natural convection of Helium gas with the conjugate heat transfer considering the radiation was solved. Discrete Transfer Model was applied for the radiative heat transfer, and Shear Stress Transport Model was used for the turbulent natural convection analysis. These models were selected based on the result from the benchmark test for the natural convection with radiative heat transfer in the closed square space. Hexahedral mesh was adopted. From the examination of the results for the different mesh sizes, about 1.45 million meshes were used to obtain the result which is nearly independent of mesh size.

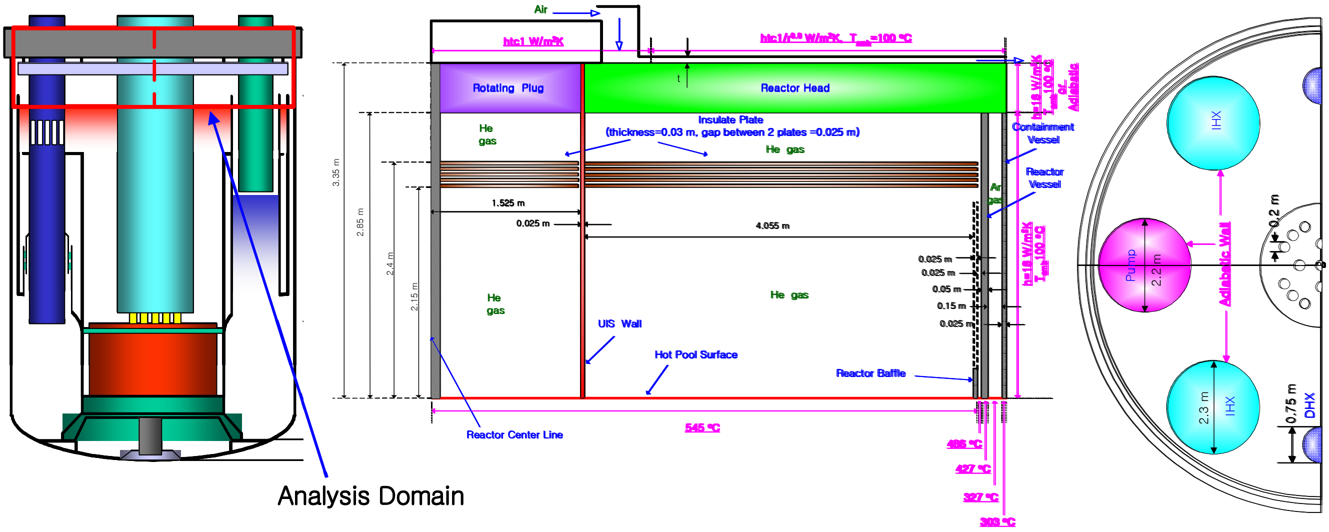

Fig. 1 Analysis domain and applied boundary conditions

3. Results

Fig. 2 and Fig. 3 show the calculated temperature distributions and the typical radial temperature profiles on the bottom surface of reactor head, respectively. In those figures, *htc*1 is the heat transfer coefficient on the top surface of reactor head (see Eq. (1)), and *h* means the heat transfer coefficient on side surface. In case where the side surface of head is insulated, the low temperature region grows with the increase of *htc*1 . However, near the reactor vessel around the pump, the local high temperature region is formed due to the reduction of *htc*1 with the radial distance. Thus, the cooling of side surface is necessary to improve the cooling performance. As shown in the figures, the region around the reactor vessel is cooled down with the relatively small heat transfer coefficient, *h* when compared with *htc*1 . To meet the temperature requirement for the sealing material in reactor head, it was found that *htc*1 and *h* should be larger than 90 W/m^2-K and 18 W/m^2-K, respectively. The *htc*1 of 90 W/m^2-K corresponds to the air flow of 32.5 m^3/s through the flow channel inlet. On the other hand, the reason for the high temperature region around reactor vessel is related to the flow of Helium gas in the gap between the insulation plate and the reactor vessel inner wall. The convection energy of Helium gas which ascends through the gap contributes to the temperature rise near reactor vessel. Thus, instead of increasing the capacity of reactor head cooling system, the restriction of ascending flow by reducing the gap size is another design option.

The ratio of radiative to convective heat transfer was estimated to be 5.27~5.66 at hot pool surface and 1.28~1.47 at the most upper surface of insulation plate depending on the applied boundary conditions. This indicates that the radiative heat transfer is the main heat transfer mode from the hot pool to the insulation plate, and the five insulation plates sufficiently block the heat transfer to reactor head.

4. Conclusion

From the steady state three-dimensional heat transfer analysis, the cooling requirement for the reactor head was determined, and the performance of the insulation plate was evaluated. Also, the reduction of the gap between the insulation plate and the reactor vessel wall was suggested to reduce the load of the cooling system.

ACKNOWLEDGEMENT

This work has been performed as a part of the Nuclear R&D program supported by the Ministry of Science and Technology (MOST) of Korea

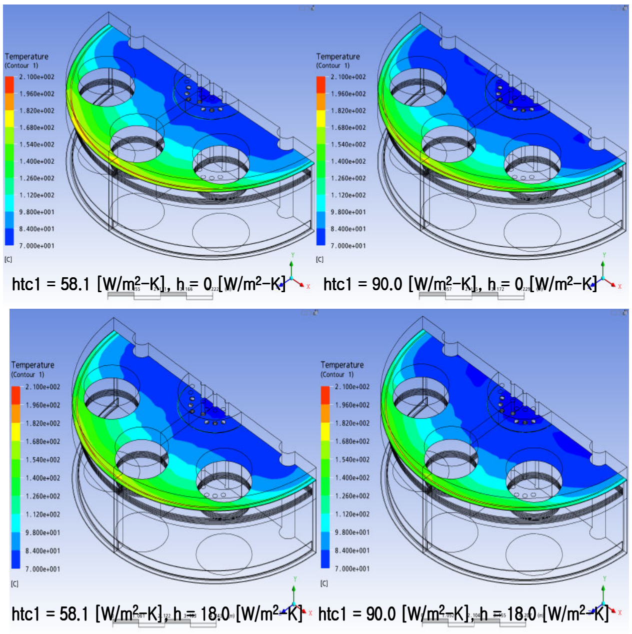

Fig. 2. Temperature distributions on bottom of reactor head

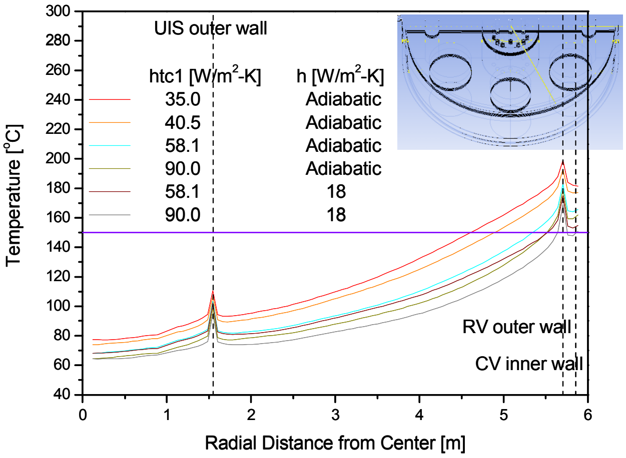

Fig. 3. Radial temperature profiles on bottom of reactor head

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