Thermal-Hydraulic Analysis of Reactor Hot Pool of Sodium-cooled Fast Reactor

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1. Introduction

The thermal-hydraulics of the reactor hot pool is important in the sodium-cooled fast reactor (SFR) design. Many activities [1] are concentrated in this region, and one of them is the natural convection situation during decay heat removal operation [2]. In a SFR which is currently being developed in KAERI [3], the passive decay heat removal circuit (PDRC) is adopted as one of the safety grade systems, which cools the reactor by using the natural convections inside reactor vessel and PDRC loop. In the PDRC loop, the sodium flow is circulated through the piping which connects the decay heat exchanger (DHX) inside reactor vessel and the sodium-to--air heat exchanger (AHX). Inside the reactor vessel, a part of the hot pool sodium is cooled by the DHX but a part of it goes directly to the intermediate heat exchanger (IHX) without cooling by DHX, as shown in Fig. 1. The amount of sodium flow to DHX is very important for ensuring the passive decay heat removal performance, and the flow division between DHX and IHX has the multi-dimensional characteristics which depend on the heat removal capacity of DHX, the hot pool geometry, the flow rate at core exit and so on.

The multi-dimensional characteristics in the reactor hot pool are being analyzed by using a commercial CFD package [4] to assess the flow through the DHX for various boundary conditions. In this study, a steady-state result is presented as the first step to assess the PDRC design condition at normal (100 %) operating condition.

2. Analysis

The analysis domain is presented in Fig. 1 with the locations of the applied boundary conditions. The domain mainly includes 2 IHXs, 2 DHXs, a primary pump barrel and an upper internal structure. The inlet of the domain is the core exit (①), the outlet is the IHX exit (⑨) and the heat sink is applied to the DHX tube (②). In this analysis, the boundary conditions at the specified locations in Fig. 1 correspond to the normal operating condition. The temperature and flow rate at ① are 510 ^{o}C and 4183 kg/s, respectively and the heat removal capacity at each DHX (at ②) is 1.18 MW. The adiabatic conditions are applied at ③, ④, ⑤ and ⑥, and the temperature at ⑦ and ⑧ is 365 ^{o}C.

The DHX with 250 heat transfer tubes is modeled as a real geometry, and the IHX is represented as the porous media to satisfy the pressure loss requirements for the shell-side flow because the thermal-hydraulic behaviors there have little influence on the local flow distributions in the reactor hot pool. The SST model is used for the turbulent flow analysis. The conjugate heat transfer through the reactor vessel internal structure is also accounted for. From the examination of the results for the different mesh sizes, about 12.5 million meshes of tetra and wedge types are used to obtain the result which is nearly independent of mesh size as shown in Fig. 2.

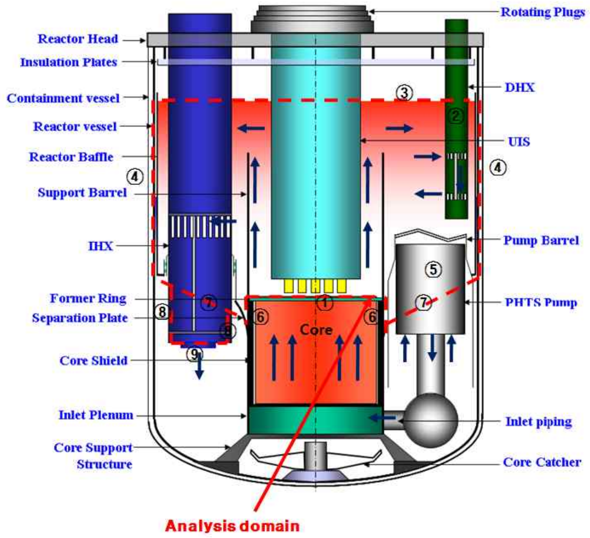

Fig. 1. The flow path inside reactor vessel and the analysis domain with the locations of boundary conditions

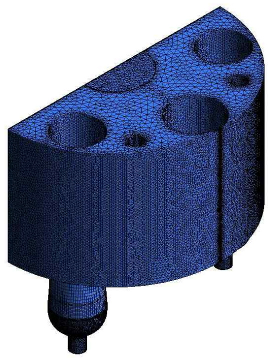

Fig.2. Meshes for CFD analysis

3. Results

For the normal operating condition, the heat loss through PDRC is required to be 0.075 % (1.18 MW) of the rated core thermal power for each loop. This heat loss is used to drive the appropriate natural circulation flow in a PDRC loop during the normal operating condition for ensuring the initial startup of natural circulation flow when PDRC operation is necessary in the accident conditions. In this case, the flow rate through DHX should be considered in the design because the cooled sodium by DHX can cause the undesirable temperature and flow distributions in the reactor hot pool which may induce the thermal stress on the reactor vessel internal structures.

The flow rate through DHX is calculated to be 46.2 kg/s, and the average temperatures at the inlet and outlet of DHX are calculated to be 509.6 ^{o}C and 491.4 ^{o}C, respectively. Also, the average temperature at the IHX inlet is estimated to be 505.9 ^{o}C. The decrease of average core exit temperature by DHX cooling is 4 ^{o}C at IHX inlet, which should be considered the temperature control of the primary heat transport system during power operation.

Fig. 3 and Fig. 4 show the typical temperature and velocity distributions at the planes crossing a DHX and the region without any component, respectively. As shown in the figures, the temperature distribution around the region without any component is rather thermally stratified compared with that around DHX. This is because the flow through DHX enhances the mixing around DHX. Also, the flow and temperature distributions in the reactor hot pool are asymmetrical and the recirculation region is found. These would cause the thermal stress on the vessel structure, and should be considered in the structural design. On the other hand, for the low flow rate conditions during decay heat removal operation, the thermal stratification is expected to be more significant, and these conditions will be analyzed for the different boundary conditions.

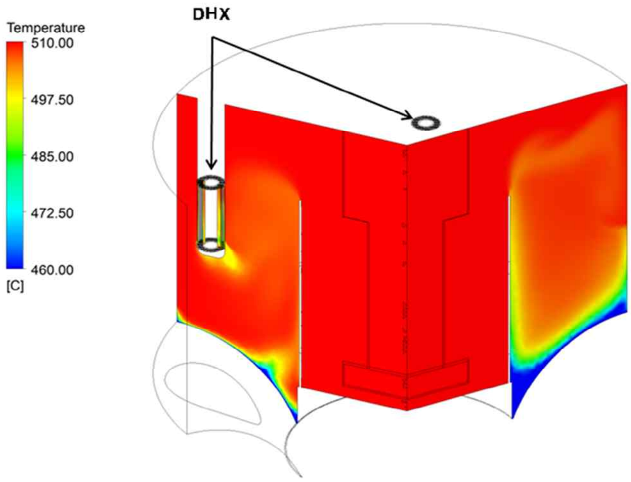

Fig. 3. Calculated typical temperature distributions

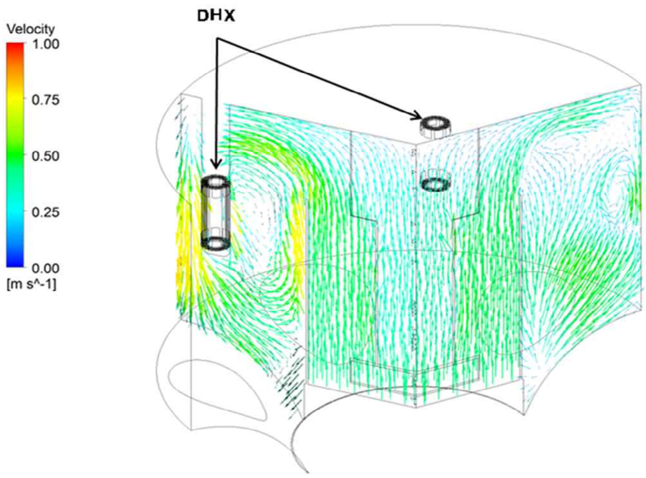

Fig. 4. Calculated typical velocity distributions

4. Conclusion

The thermal-hydraulic analysis of the reactor hot pool was performed to assess the influence of the PDRC design condition on the normal operating condition. The flow rate through DHX and the decrease of average core exit temperature by DHX was estimated to be 46.2 kg/s and 4 ^{o}C, respectively. The calculated flow and temperature distributions will be used in the structural analysis

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