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Thermal Hydraulic Analysis on the Reactor Head Cooling of PGSFR

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1. Introduction

Since the sodium-cooled fast reactor operates at a higher temperature than the light water reactor, it is important to design the high-temperature structure and to secure the structural integrity at the high temperature condition. In particular, the reactor head should be cooled below the proper temperature during normal operation to ensure a sufficient design life of the rotating plug seal of the elastomer material. In order to protect the components and structures of the Head Access Area (HAA) from the heat of reactor head, the heat from the reactor should be limited as much as possible, and the means to remove heat inside the HAA is required.

The purpose of this study is to propose the design concept of reactor head cooling system and to evaluate the performance considering the PGSFR design features. The thermal-hydraulic characteristics of reactor head cooling was analyzed through the three-dimensional steady-state thermal hydraulic analysis from the sodium surface in the reactor to the HAA. The suitable concept of reactor head cooling of PGSFR was derived by evaluating the analysis results against design requirements.

2. Methods and Results

2.1 Design Requirements

Fig. 1 shows the arrangement diagram of the reactor of the PGSFR. The reactor head is heated by the radiation and convection from the hot and cold pool surfaces. Upper shielding structure is composed of 20 pieces of anti-radiation plate made of stainless steel in order to block radiant heat from the hot and cold pool surfaces.

The reactor head cooling system is intended to maintain the integrity of the reactor head and the rotating plug seal and to maintain the proper temperature of the HAA. In this regard, the design requirements of the reactor head cooling system are as follows.

- Rotating plug seal temperature: < 150℃(normal operation) [1]
- Temperature difference between upper and lower surface of reactor head: < 30℃ [2]
- Reactor head bottom temperature: > 97℃ (sodium solidification temperature)
- HAA temperature(normal operation): 10 – 50℃ [3]

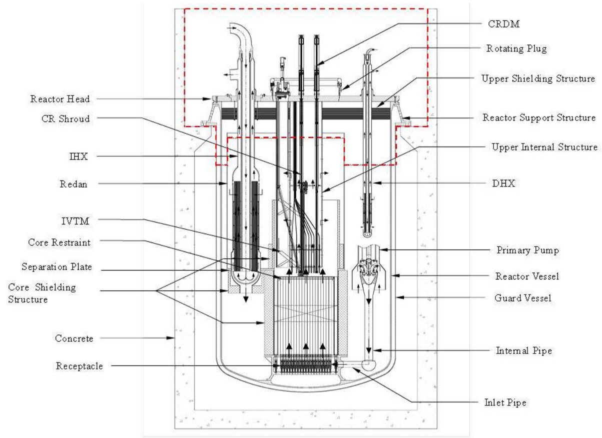

Fig. 1. The arrangement diagram of the reactor of the PGSFR.

- Mean surface temperature of concrete surface in HAA: < 65℃ (normal operation), < 175℃ (accidents)[4]

2.2 Thermal Insulation Requirements

The requirement for the upper and lower temperature difference of the reactor head is to consider the structural integrity of the reactor head and the arrangement of the components by the reactor head bending. As the temperature difference between the upper and lower surfaces of the reactor head becomes larger, the deflection of the reactor head due to the difference in thermal expansion becomes larger. Since the heat transfer inside the reactor head is only conduction, the maximum temperature difference between the upper and lower surfaces of the reactor head determines the maximum heat transfer rate through the reactor head. The internal heat source of reactor must be limited under the maximum heat transfer rate, which can determine the reactor internal insulation requirements. Since the side area of the reactor head is much smaller than the top and bottom area, the conduction heat transfer through the reactor head can be assumed by a simple 1-D Fourier equation as follows.

$$Q_{RH,\max} = kA\frac{dT_{\max}}{dx} \tag{1}$$

Where k, A, dT_{max}, and dx are the thermal conductivity of SUS316, the cross section area, the maximum temperature difference between top and bottom surfaces, and the thickness of the reactor head, respectively. The maximum heat transfer through the

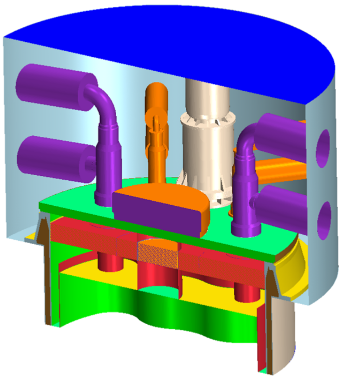

Fig. 2. 3-D model for reactor head cooling analysis.

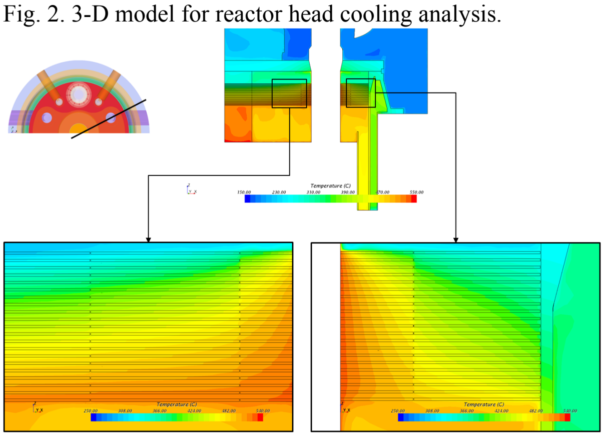

Fig. 3. The temperature distribution in the reactor when the IHX and DHX surface was not insulated.

reactor head was 108 kW by the above equation, therefore, the inside of the reactor should be properly insulated so that the internal heat source is less than this maximum heat transfer rate.

2.3 CFD Analysis

CFD analysis was carried out to analyze the reactor head cooling concepts. The analysis region, which is marked by a red dotted line on the Fig. 1, is from the hot and cold pool surfaces to the HAA. Analysis was performed using the 1/2 model as shown in Fig. 2 to reduce the calculation time considering that the reactor head is symmetrical.

The grid was constructed with a polyhedral mesh, and configured in great detail to simulate all thin gaps between the upper shield structures inside the reactor. The emissivity of Type316SS and sodium was set to 0.9 and 0.04 by reference [5]. The main heat sources of the reactor head are the heat from the hot and cold pool surfaces and the IHX and DHX outer surfaces. The average hot pool surface temperature applied 545℃. The average cold pool surface temperature assumed 521℃ which was derived from CFD analysis [6]. The surface temperatures of IHX and DHX were assumed 528℃ and 379.6℃ which were the nominal conditions. The setting used for modeling, such as grid, turbulence

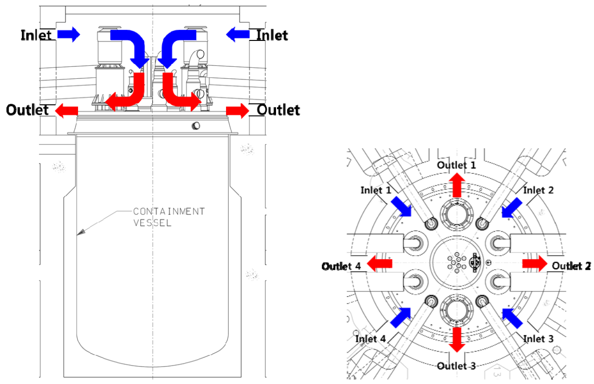

Fig. 4. The conceptual diagram of the reactor head cooling during normal operation.

model, properties and boundary conditions, is described in detail in reference [6].

In order to set the insulation requirements when the reactor head surface temperature satisfies the cooling requirement of 150℃, the CFD was performed under fixing the temperature of reactor head upper surface of 150℃. Fig. 3 shows the temperature distribution in the reactor when the IHX and DHX surface was not insulated. In this case, the upper and lower temperature difference of the reactor head was about 41℃, and the heat transfer rate through reactor head was about 161 kW, which did not satisfy the temperature difference requirement of 30℃ and the heat transfer rate calculated from equation (1). Fig. 3 shows that the upper shielding structure generally blocked the radiant heat, and the temperature is rapidly decreased in the upward direction. However, it can be seen that the heat near the IHX is not blocked but rather acts as extended surface, transferring heat to the surrounding area. On the other hand, when the IHX and DHX surfaces were insulated, the heat transfer rate through the reactor head was about 101 kW and the temperature difference was about 21℃. Therefore, in order to meet the design requirements, IHX and DHX surfaces must be insulated to reduce the heat source.

In order to establish the reactor head cooling concept, 16 cases of CFD analyses was carried out according to cooling concepts and design parameters [6]. The cooling concept with the best performance among the analysis cases is shown in Fig. 4. The cooling air flows through four ducts from the top of the HAA, and the cooling air gathered at the center of the reactor head is directed downwards to cool the reactor head from the rotating plug, and the heated air is discharged through the four ducts at the bottom of the HAA.

Fig. 5 shows the air flow distribution inside the HAA. The cooling air introduced from the top of the HAA converges at the center of the reactor head to form a downward flow, and the rotating plug is cooled intensively by the downward flow.

Fig. 6 shows the temperature distribution of the symmetry plane including IHX insulation.

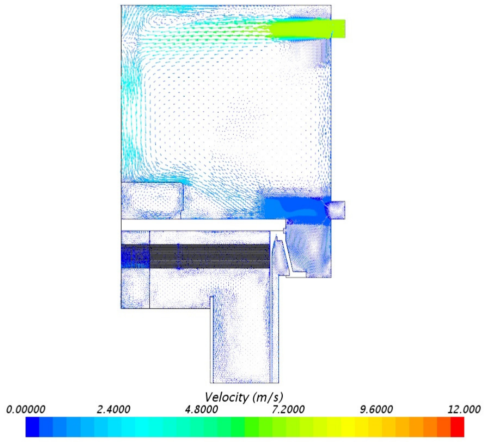

Fig. 5. The air flow distribution inside the HAA

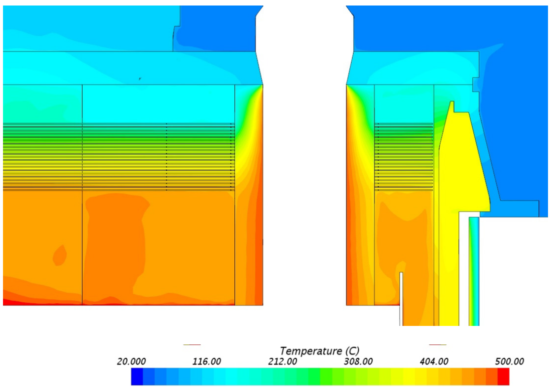

Fig. 6. The temperature distribution of the symmetry plane including IHX insulation.

The temperature distribution of the reactor head is formed uniformly in the circumferential direction. The thermal insulation performance of the outer surface of the IHX can be confirmed from the identical temperature between insulation surface and surrounding upper shielding structure. The maximum temperature around the rotating plug is 105℃ satisfying the seal temperature requirement. The minimum temperature at the reactor heat bottom surface is 109℃ and the temperature difference between the top and bottom surface of reactor head is 16℃, which satisfies all of the design requirements of a reactor head cooling system.

3. Conclusions

In this study, the design concept of reactor head cooling system was proposed and the performance was evaluated considering the PGSFR design features.

The thermal hydraulic analysis of the reactor indicated that the thermal insulation of IHX and DHX surface was required. It was confirmed that the final conceptual design of the reactor head cooling met all the design requirements through the 3-D steady state thermal hydraulic analysis.

ACKNOWLEDGEMENT

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