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Design and Performance Analysis of the Passive Cavity Cooling System of KALIMER-600

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1. Introduction

The conceptual design of the sodium cooled fast reactor, KALIMER-600 is currently being developed. The reactor vessel (RV) contains internal structures, equipments, core, and large amount of sodium coolant, and it is surrounded by the containment vessel (CV). All structures are also supported by the reactor support wall made of reinforced concrete. During a normal plant operation, the reactor structures are exposed to high temperature environment even with a high performance insulation layer due to a hot sodium coolant over 500℃ inside RV. For this reason, a proper mean to cool down the reactor structures is necessary to secure their structural integrity. In particular, it was reported that the temperature limit of the reinforced concrete is globally 65℃ and locally 93℃ for normal operation condition [1]. Therefore, the concrete temperature should be maintained as below the limited value during whole plant life time.

In the former SFR designs [2], a non-safety grade active type vessel or concrete cooling systems has been mainly employed. However, an active cooling system has low operational reliability and less economics due to its complicated design and operation mechanism. Accordingly, a completely passive cavity cooling system (CCS) is necessary to safely and reliably cool down the reactor structures during a plant power operation mode. This is the motivation of this work, and thus the passive CCS design concept is provided and its performance analysis was carried out in this study.

2. Methods and Results

2.1 Overview of KALIMER-600 CCS

KALIMER-600 CCS is very similar to the passive reactor vessel cooling system of KALIMER-150[3]. The CCS air cooling process completely depends on a passive mechanism, and this feature makes the CCS very reliable and economical by excluding either any operator's action or any moving parts operated by an external power supply.

2.2 Development of 1-D analysis code

2.2.1 Heat Transfer Path through CCS

During a normal plant operation, a constant heat flux is transferred from the primary sodium pool to the CCS air flow. The heat transfer path shown in Figure 1 consists of a serial and parallel combination of the heat transfer elements, where R denotes the heat transfer resistance of each element process.

Normal plant operation condition

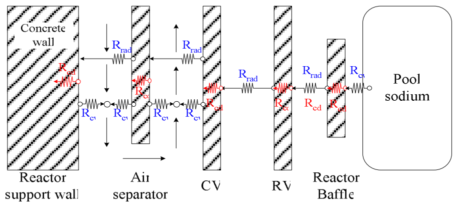

Fig.1 Heat Transfer Path of the KALIMER-600 CCS

In the air region, the heat from the containment wall is transported to the air in two paths. One is the direct convection path and the other is the indirect path where heat is first transported to the air separator by radiation and then transported to the air by convection from the air separator. The process can be identically applied to the cold air downcomer surrounded by the concrete wall.

2.2.2 Mathematical Model

A radial heat transfer process of the CCS can be modeled by employing the thermal resistances of convection, conduction and radiation, and the relations can be written as the following equations;

$$R_{fl}^{conv} = 1/\left(h_{fl,i} \cdot A_s\right) \quad (1)$$

$$R_{st}^{cond} = \ln\left(D_{st,o}/D_{st,i}\right)/\left(2 \cdot \pi \cdot k_{st} \cdot \Delta H\right) \quad (2)$$

$$R_{face}^{Rad} = \frac{1}{\sigma \cdot A_k} \cdot \left[\frac{1}{\varepsilon_k} + \frac{A_k}{A_j} \cdot \left(\frac{1}{\varepsilon_j} - 1\right)\right] \quad (3)$$

where fl stands for heat transfer fluid on the path and st means RV, CV, air separator, insulation and concrete wall. Also ε and σ mean the emissivity and Stefan-Boltzmann constant, respectively. In the KALIMER-600 CCS configuration, since the view factor F_{kj} from surface k to surface j is easily assumed as 1.0, the complex radiation heat transfer process can be simplified by using radiation resistance given in Eq.(3).

In order to simulate the CCS, major three boundary conditions are required and they are cold air inlet temperature(40℃), constant temperature of concrete outer surface(20℃), and uniform heat flux during the plant power operation. The last boundary condition can be obtained by using the vertical fluid temperature distribution inside RV produced in the previous study for a KALIMER pool analysis [4].

2.3 Analysis Results and Discussion

One dimensional analysis for a radial heat transfer process of the CCS was carried out by using the modified one-dimensional PARS code [3]. Figure 2 shows the axial temperature distributions for all structures and air flow situated on the CCS domain.

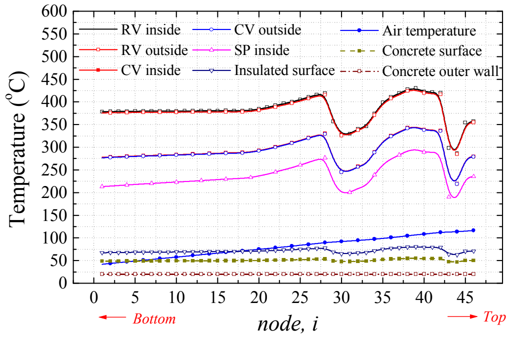

Fig.2 Vertical temp. distributions at each structure

Based on the analysis results, it was easily observed that the average concrete wall temperature is well below the temperature limit of 65℃ during the normal operation condition. This is because i) the air flow effectively removes the radial heat flux which comes from the RV surface and ii) the insulated layer closely contacted with the outer surface of the air separator plays an important role of a thermal barrier in the given environment. Also the heat loss through the CCS is less than 0.05% to the rated core thermal power of 1524.3MW_{th}, which is pretty small so as not to cause a plant thermal efficiency decrease.

In order to evaluate the 1-D heat transfer analysis, multi-dimensional CFD analysis was also performed by using CFX 5.7.1 [5]. Figure 3 shows the temperature distributions of each structure surface compared with the CFX analysis results.

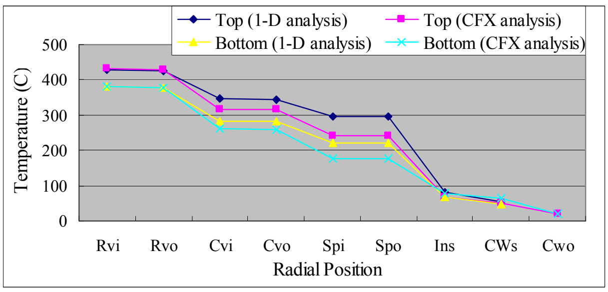

Fig.3 Comparison of Temperature at each structure

As shown in the figure, the overall trend of the radial temperature distributions is very similar to that of the 1-D analysis, but the CV temperature using the CFX analysis is slightly lower than that of the 1-D analysis. This is mainly because the heat transfer correlation of the PARS code [3] developed for the system design is very conservative for predicting actual phenomena reflecting a turbulent mixing effect on the structure surface. Figure 4 also shows the 2-D temperature and velocity fields for all the structures and fluid domains of the CCS. As shown in the figure, it was observed that multi-dimensional effects of the flow characteristics coupling with a thermal radiation can be shown at the bottom part of the CCS air flow path. Since the concrete wall and hot CV surface directly face each other beneath the air separator lower end, the temperature of the concrete wall bottom rises up to more than 100℃ by a direct thermal radiation heat transfer which comes from the hot CV surface.

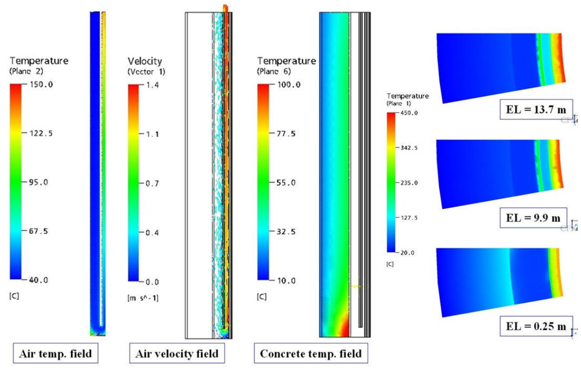

Fig.4 2-D Temperature & velocity field of the CCS

Although the local temperature of the concrete wall exceeds the design limit in this case, most axial temperature distributions show a good agreement with the 1-D analysis results because the phenomenon is very local (3% of the entire CCS heat transfer length) and an axial conduction heat transfer contributes to the mitigation of a local heat up. However, some design improvement to prevent an undesired heating condition is necessary based on the results of the CFD analysis performed in this study.

3. Conclusions

A passive cavity cooling system was designed by using a comprehensive 1-D thermal-hydraulic analysis model. It was confirmed that the 1-D analysis code reasonably predicts the CCS heat transfer phenomena when compared to the CFD analysis results. It was also confirmed that, by employing the passive CCS, the concrete wall temperature was satisfied for its design limit during a normal plant operation. But an undesired hot spot on the bottom part of the concrete wall was also observed from the CFD analysis results performed in this study. Therefore, some design improvement of the CCS is required in a further study.

ACKNOWLEDGEMENT

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