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Treatment of the analysis for the heat transfer in the reactor cavity of HTGR

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1. Introduction

The reactor cavity cooling system (RCCS) of a high temperature gas-cooled reactor (HTGR) is a system for the removal of the decay and residual heat and its heat removal capacity is one of the major parameters limiting a plant's capacity. To develop an improved RCCS with an increased capacity, a reliable and effective analysis method for the RCCS performance is required. In establishing the required analysis method, the modeling of the RCCS cavity heat transfer is one of the major areas that determine the complexity of the analysis system, and an analysis method with a simple structure and a fast running capability is required for the RCCS cavity heat transfer.

To meet these needs, the heat transfer characteristics of the cavity were studied and a simplified and reliable analysis method for the heat transfer in the cavity is proposed based on the heat transfer characteristics study.

2. Development of the analysis methodology for a heat transfer in the cavity

A reference calculation method was first set up and a simplified analysis method was devised by using the calculation results from the reference system

2.1 Setting up the reference calculation method

The geometry and the thermal conditions of the reference calculation method were set up by considering the GT-MHR design [1]. The upper and lower walls of the cavity were considered as insulated and the temperatures of the reactor vessel and the cavity outer wall were set as uniform. The CFX with the Monte Carlo method[2] for the radiation heat transfer was used as the calculation tool.

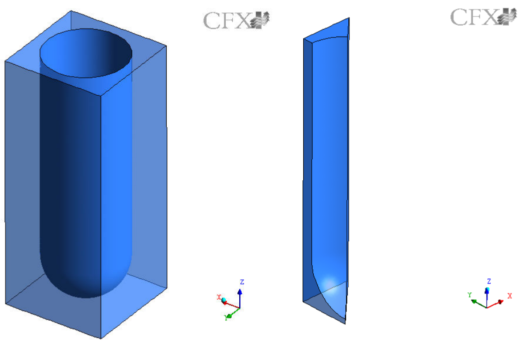

Figure 1. Calculational domain

Regarding the modeling parameters for the radiation treatment in the CFX, the sensitivity of the photon history steps was checked by varying its value from $2x10^5$ to $16x10^5$. The dependency of the calculation result on the factor turned out to be only 0.03~0.1% in the total heat transfer from the reactor vessel for the selected parameter range and $4x10^5$ was used as the reference calculation method value.

To check the basic accuracy of the reference system, a calculation was made for two different domain models for the same boundary conditions in this physics. One was with the whole domain and the other was with a 1/8 domain of the RCCS cavity, i.e. a 45° domain as shown in Fig.1.

The error in the energy balance was 0.3 and 0.4% in the calculations. The difference in the transferred total heat between the two cases was 0.3 %. Also the temperature contours in the transverse section show a good agreement as shown in Fig. 2.

The reliability of the reference system was also checked by comparing its calculation results with the work of Takada et al [3]. They performed experimental and numerical studies on the RCCS of a HTGR. A calculation with the Takada's experimental condition was carried out by the reference calculation method. The portion of the radiation heat transfer in the total heat transfer from the reactor vessel (RV) was 74.6% by the reference method while that in Takada' at al's work was 74.4%, and they are in a good agreement with each other. From these, the reference calculation method was evaluated to be sufficiently reliable for the purpose of this study.

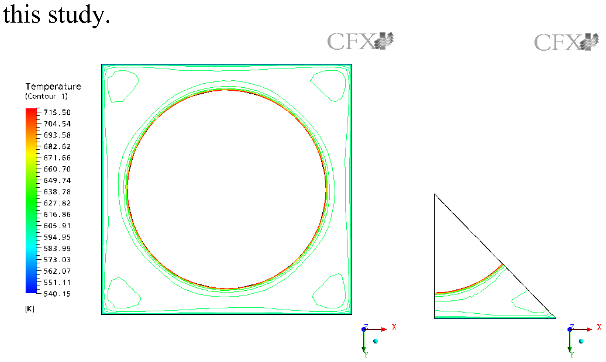

Figure. 2 Temperature contours

2.2 Simplified analysis method

2.2.1 Heat transfer characteristics in the cavity

To evaluate the importance or the required level of modeling accuracy of each heat transfer mode, a calculation was made for the heat transfer from the reactor vessel to the cooling panels for a possible design and the operation parameter ranges. The variation in the parameter was made for the cavity shape and size, the reactor vessel temperature, and the surface emissivity. The results are summarized in Table 1. From the table, one can see a difference in the radiation portion between the values in Table 1 and that of Takada's which was previously mentioned. The difference mainly comes from the differences in the temperatures of the boundary walls, i.e., the cooling panel wall and the reactor vessel. The temperature in Takada's condition was 210°C for the reactor vessel and 23°C for the panel wall. The temperatures are obviously not in an actual RCCS operation range.

Table 1 shows that most of the heat transfer is made by a radiation and its portion is as much as 95%~98%. Accordingly the portion of the convection is only 2~5%. It means there will be a substantial level of flexibility in modeling of the convection heat transfer. One could even consider ignoring a convection without loosing a physical validity

Table 1. Portion of each heat transfer mode

[%]		Radiation	Convection
Cavity shape	rectangular	95.7	4.3
	circular	95.8	4.2
Cavity size	±10 %	95.6~95.9	4.1~4.4
RV temperature	350~750 °C	95.4~97.9	4.6~2.1
Emissivity	0.4~0.8	92.0~96.4	8.0~3.6

2.2.2 Simplified analysis method

The rectangular cavity geometry is simplified to a circular geometry with the same outer wall area. This simplification does not yield a significant difference as one can infer from Table 1.

A correlation for a natural convection heat transfer proposed by Thomas and de Vahl Davis[4] is adopted for an annular cavity.

$$Nu_R = 0.286 Ra_R^{0.258} Pr^{0.006} H^{-0.236} K^{0.442}$$

$$Ra_R = Gr_R Pr = R^3 g\beta Pr \Delta T / \nu^2 \quad (1)$$

The applicable range of the correlation is limited by the Rayleigh number and the geometric factor. However, the correlation can be extrapolated as done in Takada's work. The heat transferred by a radiation between the annular surfaces can be expressed as follows.

$$Q_R = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon}{A_1\varepsilon} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon}{A_2\varepsilon}} \quad (2)$$

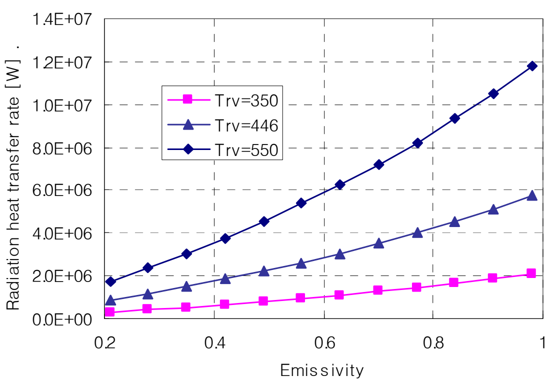

Figure 3. Characteristics of radiation heat transfer

When the view factor is approximated to a unity from Eq. (2), the equation is rearranged as follows.

$$Q_R = \frac{A_1 \varepsilon\sigma\left(T_1^4 - T_2^4\right)}{1 + \frac{A_2}{A_1}(1-\varepsilon)} \quad (3)$$

Figure 3 is the results by the simplified analysis method and it shows how sensitively the radiation heat transfer changes upon a change in the emissivity and vessel temperature. A comparison of the simplified analysis method with the reference calculation method is summarized in Table 2 by the differences between them. The difference Δ is for the heat transfer rate of each heat transfer mode and it was normalized with the result from the reference method.

Table 2. Difference between the simplified and the reference methods in the heat transfer rates

[%]	Cavity size	RV temperature	Emissivity
	+-10%	350~750 °C	0.4~0.8
Δ_{total}	2.5	2.8~3.3	0.5~3.2
Δ_{rad}	2.8~3.5	3.1~3.7	1.7~3.9
Δ_{conv}	-6.3~ 19.6	-15.7~ 12.4	-15.6~ -13.1

The difference in the convection heat transfer is relatively large but that in the total heat transfer is small since the portion of the convection heat transfer is pretty small. From the comparison results, it can be said that the simplified analysis method can be applied to the RCCS cavity heat transfer calculation for a RCCS design improvement.

3. Conclusion

The characteristics of a heat transfer in the reactor cavity were investigated and the radiation heat transfer was found to be a highly dominant heat transfer mode in the RCCS cavity. Based on the study results on the heat transfer characteristics, a simplified analysis method has been proposed for use in a RCCS design improvement analysis.

Acknowledgment

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