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Evaluation of the Performance of the Radiation Heat Transfer Models Applicable for a Simple Geometry

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1. Introduction

In order to obtain a more accurate evaluation of the RCCS(Reactor Cavity Cooling System) performance of the HTGR(High Temperature Gas-cooled Reactor), the calculation accuracy of a radiation heat transfer has to be evaluated very carefully because a radiation heat transfer is dominant in a reactor cavity[1]. Through the numerical simulations using simple hexahedron geometries, we have attempted (i) to evaluate the calculation accuracy and grid sensitivity of each radiation model embedded in FLUENT; and (ii) to select the effective radiation models suitable for an RCCS performance evaluation.

2. Numerical Methods

2.1 Basic assumption

The RCCS cooling panel is a long vertical enclosure where one surface is directly heated by the hot reactor vessel wall, surrounding the outside of the reactor cavity. But in this calculation, to check on the accuracy of a radiation model we assume it as a simple hexahedron enclosure. In order to pay attention to the evaluation of the radiation model only, the flow calculation is neglected. Actually the air in the reactor cavity has a radioactive absorption coefficient of about 0.01, so the effect of air on a radiation heat transfer is negligible. In order to reduce the uncertainty in a radiation model, the absorption and the scattering coefficients assume zero respectively so that the effect of the medium on a radiation heat transfer is completely excluded. All the surfaces are assumed as a gray body so the spectral emissivity and absorptivity do not depend on the wavelength.

2.2 Radiation models

FLUENT provides five radiation models for user's options, but where the medium absorption rate is zero or very small such as the RCCS cavity air, it generally recommends the use of DTM(Discrete Transfer Model) , DOM(Discrete Ordinates Model) or S2S(Surface-to-Surface Model) which are effective for solving optically thin problems[2].

The main assumption of the DTM is that a radiation leaving a surface element in a certain range of solid angles can be approximated by a single ray. The ray paths are calculated and stored prior to a flow calculation. The number of boundary faces(radiating surface) and the number of absorbing cells in the solving domain is set to one, respectively(default value). The number of rays being traced is defined such as a division 24x24 for a base case calculation. DOM solves the radiative transfer equation for a finite number of discrete solid angles. The fineness of the angular discretization can be controlled by defining the polar and azimuthal angles respectively. Theta and phi pixels are used to control the pixelation that accounts for any control volume overhang. S2S can be used for the radiation exchange in an enclosure of gray-diffuse surfaces. The energy exchange between two surfaces depends on a geometric function called a "view factor". FLUENT can compute the view factors for the problem or read the previously computed view factors.

2.3 Method for the accuracy check

The pre-developed analytic RadRec code[3] can provide an accurate reference solution for evaluating the accuracy of the tested radiation models in this paper. RadRec code uses a deterministic approach to ensure its accuracy. This code calculates the radiation heat transfer equation for a non-participant medium, without any simplifications. The view factor is calculated by the equation suggested in reference[4] which is applied for a two finite areas interaction. The model accuracy has been checked by comparing the relative error of the radiation heat transfer rate($\dot{q}$) referred to the RadRec as defined by the following equation (1).

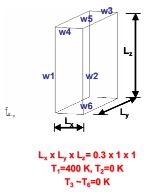
$$(i\text{ - surface})\ \text{relative error}[\%] = \left| \frac{(i\text{ - surface})\dot{q}_{\text{RadRec}} - (i\text{ - surface})\dot{q}_{\text{model}}}{(i\text{ - surface})\dot{q}_{RadRec}} \right| \times 100 \quad (1)$$

Computing time was compared for each model with the stop criterion for an iteration which is based on the relative residuals of energy equation and a value of $1.0\text{x}10^{-13}$ was used.

3. Results and Discussions

The major parameters which affect the calculation accuracy were the number of rays, the number of grids and the aspect ratio of the calculation domain. A non-uniformity of the grids also can be an important factor in the sensitivity study because a real analysis for the RCCS requires fine grids near the wall to capture the convective heat transfer. The sensitivity studies for all the parameters have been done for the radiation models. Table 1 and Fig. 1 show the comparison of the calculation accuracy of the radiation models, the computing time and the radiation heat transfer rate for the geometries of L_x x L_y x L_z = 0.3 x 1 x 1. The calculation accuracy level is S2S, DTM and DOM in sequence. The computing time of the S2S and DOM are nearly the same, but the DTM needs a rather longer time. The resolution of the incident radiation flux at cold wall-2 is similar among the three models.

Table 1 Accuracy, computing time and the radiation heat transfer rate [W] (L_x x L_y x L_z = 0.3 x 1 x 1)



Case	Rel. Error* [%]@ w2	Compu. Time [s]	Hot wall	Cold wall				
			w1	w2	w3	w4	w5	w6
RadRec	-	-	+1451.3	-841.05	-152.55	→	→	→
DTRM (24x24)	0.12	32 (11)	+1451.26	-840.09	-153.70	→	→	→
DOM (3x3)	0.16	3.1 (1.1)	+1451.26	-839.68	-151.66	→	-154.15	→
S2S	0	2.9 (1)	+1451.26	-841.04	-152.55	→	→	→

Ref.: $q_{total} = \varepsilon\sigma(T_h^4 - T_c^4)$*Area = 1451[w]   + : Emissive Radiation
* Relative error [%] = $(HTR_{RadRec} - HTR_{cal})/HTR_{RadRec}$*100   - : Incident Radiation

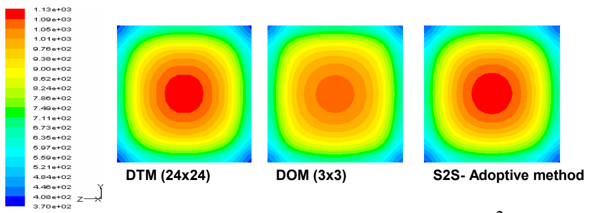
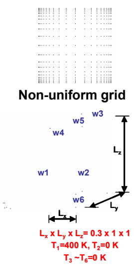


Fig. 1 Contour of incident radiation flux[W/m^2] at cold wall-2(L_x x L_y x L_z = 0.3 x 1 x 1)

Table 2 shows the comparison of the calculation accuracy of the three radiation models for both cases of the uniform/non-uniform grids. The S2S model is relatively stable more than the other models.

Table 2 Accuracy, computing time and the radiation heat transfer rate [W] for non-uniform grids (L_x x L_y x L_z = 0.3 x 1 x 1)

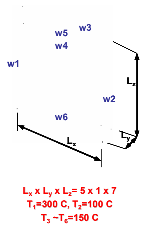


Case	Uni./ Non-uni.	Rel. Error* [%]@ w2	Compu. Time [s]	Hot wall	Cold wall				
				w1	w2	w3	w4	w5	w6
RadRec		-	-	+1451.3	-841.05	-152.55	→	→	→
DTRM (24x24)	U	0.12	32	+1451.26	-840.09	-153.70	→	→	→
	N	0.07	23.1		-840.50	-151.68	→	→	→
DOM (3x3)	U	0.16	3.1		-839.68	-151.66	→	-154.15	→
	N	1.13	8.8		-850.55	-149.14	→	-151.21	→
S2S	U	0.0	2.9		-841.04	-152.55	→	→	→
	N	0	4.5		-841.05	-152.55	→	→	→

Ref.: $q_{total} = \varepsilon\sigma(T_h^4 - T_c^4)$*Area = 1451[w]   + : Emissive Radiation
* Relative error [%] = $(HTR_{RadRec} - HTR_{cal})/HTR_{RadRec}$*100   - : Incident Radiation

Table 3 and Fig. 2 show the comparison of the accuracy of the radiation models for the case of rather real geometries of the RCCS cooling panel(L_x x L_y x L_z = 5 x 1 x 7). Contrary to the previous case, the calculated emissive radiation from the hot wall has a little difference between the three models. The calculation accuracy is DTM, S2S and DOM in sequence. But the calculation accuracy level of the incident radiation for the cold wall is S2S, DTM and DOM in sequence. Considering all the parameters such as the computing time, stability etc. the S2S model seems to be a candidate model even in the case of real geometries. The resolution of the incident radiation flux at the walls shows a little difference among the three models, and the symmetry of the incident radiation flux of S2S and DTM is maintained.

Table 3 Accuracy, computing time and the radiation heat transfer rate [W] (L_x x L_y x L_z = 5 x 1 x 7)



Case	Compu. Time [s]	Hot wall	Cold wall				
		w1	w2	w3	w4	w5	w6
RadRec	-	+20064.0	-4380.5	-6790.0	→	-1051.8	→
DTRM (24x24)	189.9 (29.2)	+20045.6 (0.09)	-4372.4 (0.18)	-6750.3 (0.58)	→	-1030.9 (1.99)	→
DOM (3x3)	17.5 (2.7)	+20018.7 (0.23)	-3702.1 (15.49)	-7173.7 (5.65)	→	-984.6 (6.39)	→
S2S	6.5 (1)	+20042.7 (0.11)	-4375.0 (0.13)	-6782.4 (0.11)	→	-1050.4 (0.13)	→

Ref.: $q_{total} = \varepsilon\sigma(T_h^4 - T_c^4)$*Area = 24571.3[w]   + : Emissive Radiation
* Relative error [%] = $(HTR_{RadRec} - HTR_{cal})/HTR_{RadRec}$*100   - : Incident Radiation

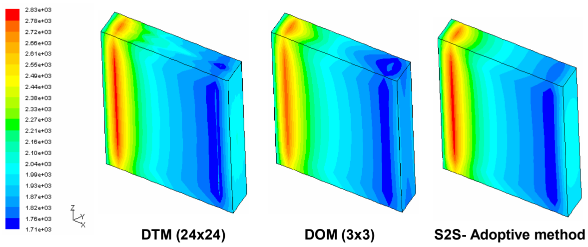


Fig. 2 Contour of incident radiation flux[W/m^2] at walls. (L_x x L_y x L_z = 5 x 1 x 7)

4. Conclusion

In order select an effective radiation model suitable for the RCCS performance evaluation, the calculation accuracy and grid sensitivity of each radiation model embedded in FLUENT has been evaluated. DTM and DOM are somewhat sensitive to the grids. The resolution of the incident radiation flux at walls shows a little difference among the three models. Considering all the parameters such as the grids, computing time, stability etc., the S2S model seems to be an effective model for various geometries.

REFERENCES

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