Analysis Method of the Temperature for the Heavy Reflector

Shi Lin, Fang Jian and Ran Xiaobing

Abstract The metal is much more than the water for the heavy reflector. More heat will generate due to gamma irradiation, and creep failure may occur. Temperature should be calculated. ANSYS can be used for two-dimensional analysis to calculate the temperature distribution of the heavy reflector. The sensitivity of the mesh can be analyzed, and the factors affecting the temperature can be evaluated. The maximum temperature of the heavy reflector is less than 350 °C from analysis results, which can satisfy the material requirements.

Keywords Heavy reflector · ANSYS · Temperature · Reactor

1 Introduction

The heavy reflector is located inside the core barrel, surrounding the core. It rests on the lower plate and extends nearly all the way up to the core cavity, but is not in contact with the upper core plate.

The heavy reflector consists of a stack of twelve austenitic stainless steel-forged slabs without any welds and bolts on core side. The inner contour of the heavy reflector is the same as the outer contour of the core, and the outer contour of the heavy reflector is cylindrical. The upper eleven slabs with vertical hole are similar. The bottom plate is a chamber structure with many holes, arranging lateral hole, drainage slots, and distribution chamber (see Fig. 1).

The heavy reflector has radiation shielding ability, good neutron reflectivity, and strong structural integrity as compared to the widely used baffle and former structure, but the metal is much more than the water for the heavy reflector, and more heat will generate due to gamma irradiation. Creep failure may occur in metal

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H. Jiang (ed.), *Proceedings of The 20th Pacific Basin Nuclear Conference*,
DOI 10.1007/978-981-10-2314-9_4

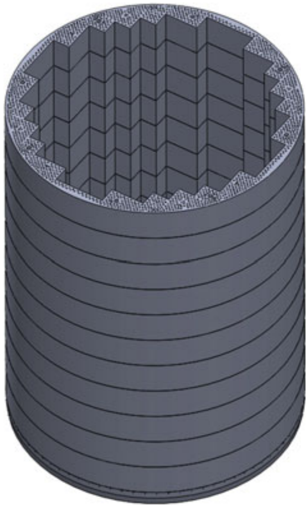


Fig. 1 Heavy reflector

with high temperature, but the creep failure has a very low probability with temperature controlled under 350 °C. Therefore, it is necessary to analysis the thermal filed and to calculate the maximum temperature of the heavy reflector [1].

There is no method for the analysis method of the heavy reflector in domestic. First, temperature field is calculated with ANSYS, and then, the results are evaluated; thereby, the thermal analysis of the heavy reflector is completed.

2 Analysis Method and Calculation Modal

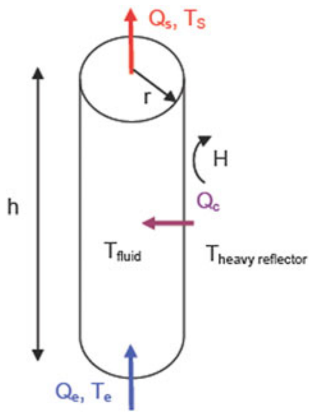
2.1 Analysis Method

Considering the small diameter water holes and the high heavy reflector, 3D model size has large different dimension, and the number of mesh model will be tens of millions. Therefore, 2D model is used for the analysis. Method is described in below.

(1) Because the heavy reflector is composed of 12 slabs which are connected together with tie rods. Therefore the 12 slabs are considered as a whole when calculating. Therefore, we will not consider each of the connecting members, and forging as a whole, not to consider local gap created between the slabs and heat insulation problems caused.
(2) Since the bottom plate of the heavy reflector is located in an area outside the active section, heat generation rate is very small. The structure is so more complex that not easy to simulate. Therefore, the bottom plate is not to be considered in analysis.

The twelfth slab is cooled sufficiently, and the temperature is low by calculation. So the twelfth slab is also not to be considered in analysis. Thereby, the model can be simplified as calculating from the second slab up to the eleventh slab.

(3) The middle cross section is to be selected in 2D analysis.
(4) The second slab inlet temperature is the same as the lower plenum temperature. The heavy reflector temperature will rise due to gamma radiation heat. The coolant temperature will rise through convective heat transfer. Therefore, the heavy reflector and coolant in the heavy reflector outlet temperature distribution will be gained.
(5) The n + 1 slab inlet coolant temperature is the same as the n slab outlet coolant temperature.



Fluid temperature in a slab is described as follows.

For every slab, the quantity of heat evacuated by the fluid (Q_s) is equal to the quantity of heat conveyed by the fluid which enters the slab (Q_e) plus the quantity of heat received from the structure by forced convection (H) with the steel structure (Q_c):

$$Q_c = Q_s - Q_e \tag{1}$$

The quantity of heat evacuated by the fluid can be used to calculate the temperature increase (ΔT) in the water which goes through a slab.

Knowing the temperature of the water at the inlet of the slab (T_e), the quantity of heat received during the crossing (Q_c) is used to determine the temperature in canals at the outlet of the slab (T_s). The ΔT is then calculated as follows:

$$Q_c = Q_s - Q_e = mC_p\Delta T \tag{2}$$

where

m Mass flow
C_p Specific heat

$$Q_c = HS(T_{\text{heavy reflector}} - T_{\text{fluid}}) \tag{3}$$

where

H The heat transfer coefficient between the heavy reflector and the fluid
S The area of contact between the heavy reflector and the fluid
$T_{\text{heavy reflector}}$ The heavy reflector temperature
T_{fluid} The fluid temperature

$$S = 2\pi rh$$

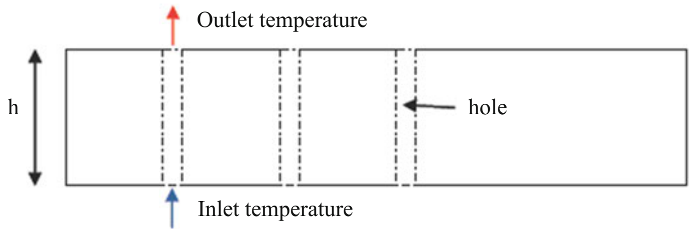
r Radius of the cylinder
h The length of contact

$$\Delta T = \frac{Q_c}{mC_p} = \frac{Q_c}{\rho S' V C_p} = \frac{HS(T_{\text{heavy reflector}} - T_{\text{fluid}})}{\rho S' V C_p} \tag{4}$$

where

ρ Fluid density
V The fluid velocity
S' The cylinder section [2]

$$S' = \pi r^2$$



2.2 Calculation Modal

2.2.1 Mesh Modal

(1) Considering the structure symmetry of the fuel assembly and the heavy reflector, a quarter of the model will be selected to calculate.
(2) There are 40,412 nodes and 36,287 elements in mesh modal with global size 8 mm, local water hole 3 mm, and 2-layer mesh boundary expansion. PLANE55 thermal analysis elements will be used [3]. Mesh modal is shown in Fig. 2.

2.2.2 Mesh Sensitivity Analysis

Evaluating the influence of different mesh schemes depends on calculating results with considering the quality of mesh. Mesh schemes, calculation results, and the quality of mesh are shown in Table 1.

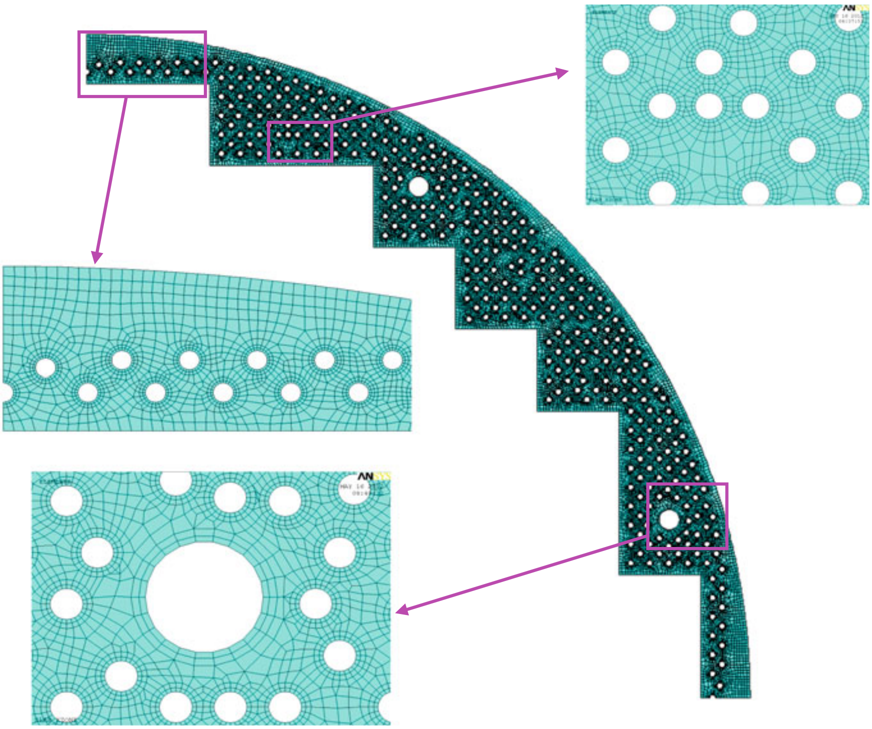


Fig. 2 Mesh model of heavy reflector

Table 1 Mesh schemes

Scheme	Description	Nodes	Elements	Calculating temperature	Deviation (%)	Quality
1	Global size 16 mm	9079	6664	644.587		0.46
2	Global size 10 mm	14,710	11,365	647.918	0.514108267	0.564
3	Global size 8 mm	20,963	16,898	649.377	0.224676883	0.61
4	Global size 8 mm; local water hole 3 mm, 1-layer mesh boundary expansion	34,189	30,071	650.604	0.188593983	0.81
5	Global size 8 mm; local water hole 3 mm, 2-layer mesh boundary expansion	40,412	36,287	651.175	0.087687642	0.82
6	Global size 8 mm; local water hole 3 mm, 3-layer mesh boundary expansion.	48,467	44,354	651.286	0.017043204	0.74

The calculation results change so small when global size reaches to 8 mm from schema 1, 2, 3. Therefore, global mesh size sets to 8 mm. In order to verify mesh sensitivity, some examples are calculated. The suitable mesh modal is gained through comparing calculation results. Moreover, the quality of mesh becomes worse when 3-layer mesh boundary expansion is used. Therefore, 2-layer mesh boundary expansion is used. In summary, scheme 5 with global mesh size 8 mm, local water hole 3 mm, and 2-layer mesh boundary expansion is used.

According mesh sensitivity analysis, the mesh quality is guaranteed when the number of mesh is more than 30,000. Scheme 5 satisfies this requirement. Mesh sensitivity analysis is shown in Fig. 3.

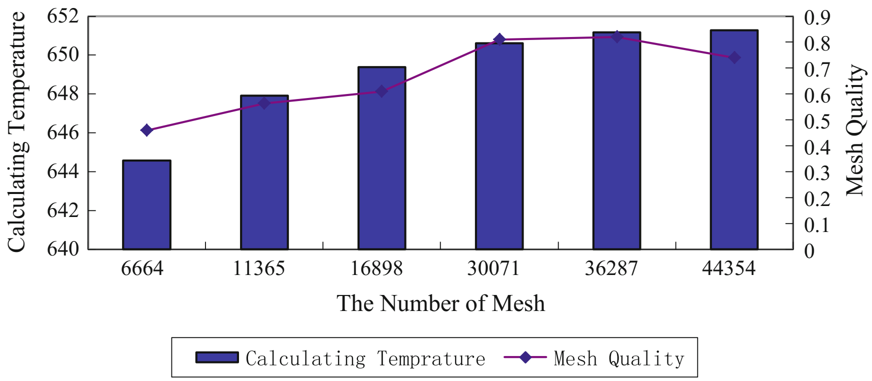


Fig. 3 Sensitivity analysis of mesh model

2.3 Boundary and Load Conditions

2.3.1 Boundary Conditions

According to Dittus-Boelter formula, heat transfer coefficient is calculated under the corresponding temperature.

$$Pr = \frac{\mu C_p}{\lambda} \tag{5}$$

$$Re = \frac{\rho D_h V}{\mu} \tag{6}$$

$$H = 0.023 \frac{\lambda}{D_h} Re^{0.8} Pr^{0.4} \tag{7}$$

where

Pr Prandtl number
μ Viscosity;
C_p Specific heat;
λ Thermal conductivity;
Re Reynolds number;
ρ Fluid density;
D_h Hydraulic diameter;
V Fluid velocity;
H Heat transfer coefficient [4]

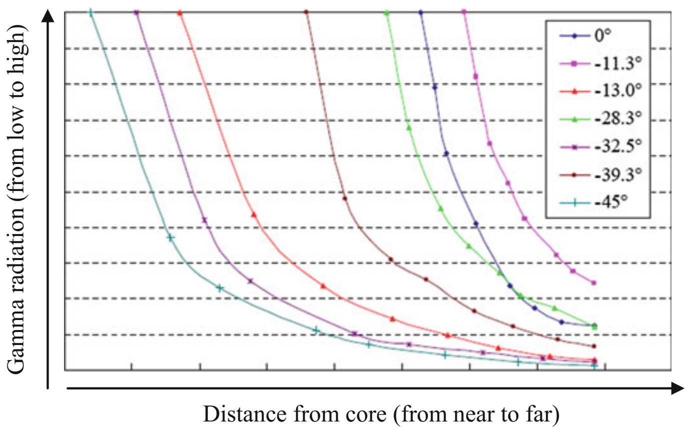


Fig. 4 Radial distribution curve of heavy reflector

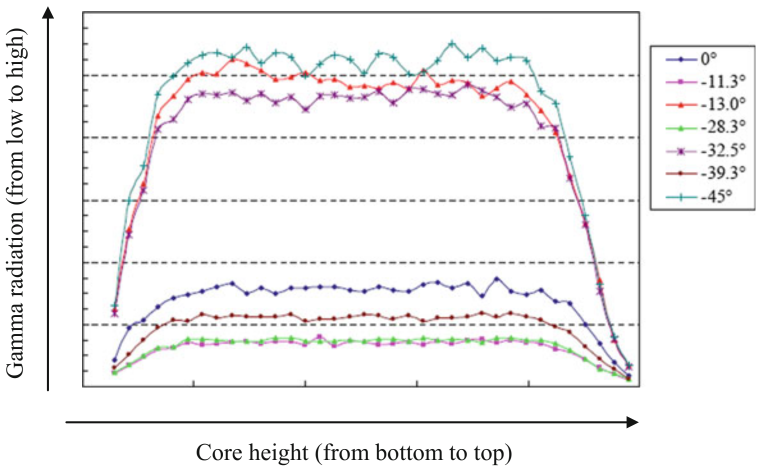


Fig. 5 Axial distribution curve of heavy reflector

2.3.2 Load

Heat generation due to gamma radiation is obtained by combining the radial distribution as shown in Fig. 4 and axial distribution as shown in Fig. 5.

3 Results Analysis and Evaluation

3.1 Calculation Results

The temperature in each slab is shown in Table 2. The temperature distribution is similar from second to eleventh slab. The maximum temperature is 341.5 °C in the tenth slab, and it satisfies material requirements below 350 °C. The temperature contours in tenth slab is shown in Fig. 6.

Table 2 Temperatures of slabs

Slab	Maximum temperature (°C)	Minimal temperature (°C)	Average temperature (°C)
2	313.9	288.8	293.7
3	329.1	289.6	297.0
4	333.4	290.7	299.3
5	333.0	291.9	300.8
6	334.6	293.1	302.8
7	335.4	294.3	304.6
8	339.0	295.6	306.6
9	340.2	296.9	308.5
10	**341.5**	298.2	310.1
11	337.3	299.1	310.9

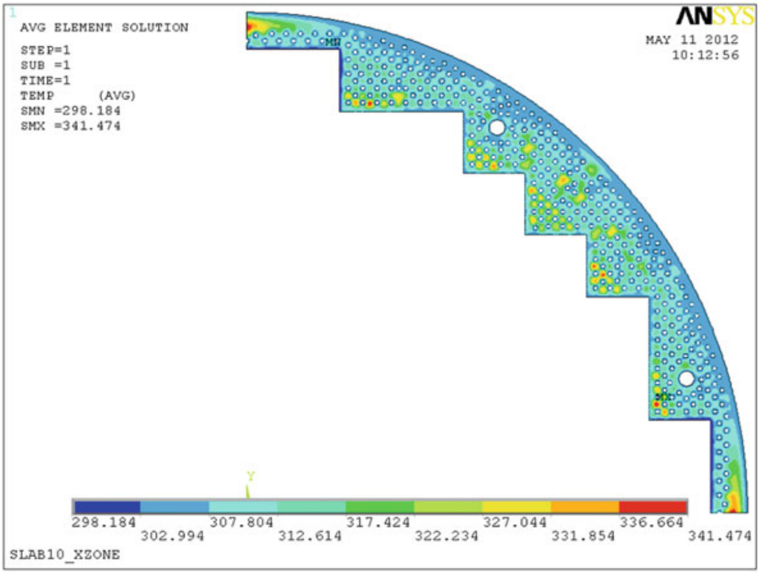
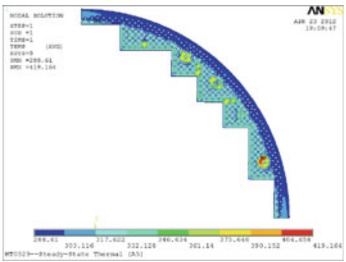
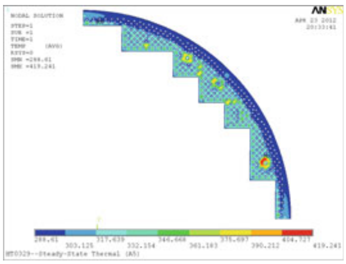


Fig. 6 Temperature contours of tenth slab

3.2 Factors Affecting Temperature Field

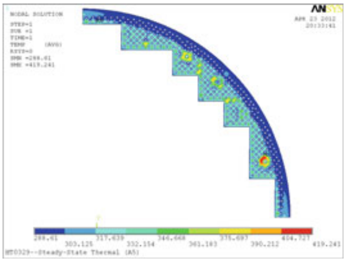
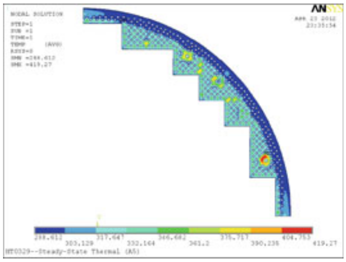
3.2.1 Influence of Loading Method

The influence of the results is verified by two examples when heat generation due to gamma radiation is applied in elements or nodes.

	Example 1	Example 2
Loading method	Heat generation rate is applied in nodes	Heat generation rate is applied in elements
Calculation results	 Maximum temperature 419.164 °C	 Maximum temperature 419.241 °C
Conclusion	There is a similar result: Either heat generation rate is applied in nodes or applied in elements	

3.2.2 Influence of Loading Conditions

The influence of the results is verified by two examples when different load conditions are applied.

	Example 3	Example 4
Loading conditions	Temperature, heat transfer coefficient, heat generation due to gamma radiation	Heat transfer coefficient, heat generation due to gamma radiation
Calculation results	 Maximum temperature 419.241 °C	 Maximum temperature 419.27 °C
Conclusion	There is a similar result: Either temperature is applied or not. Because the temperature is included in the heat transfer coefficient	

3.2.3 Influence of Material Properties

The influence of the results is verified by several examples when two variables are fixed, but the third variable is changed. The thermal conductivity increases with increasing temperature; therefore, the thermal conductivity variable with increasing temperature is used in analysis. Density and specific heat have almost no impact on the results.

3.2.4 Influence of Initial Temperature

Changing the initial slab temperature has almost no impact on the results, because the heat transfer coefficient depends on the coolant temperature but not on the initial temperature of the slab.

4 Conclusions

2D thermal analysis is used for the heavy reflector in this paper. The mesh sensitivity is analyzed, and calculation results are evaluated. Conclusions are described as follows:

(1) The workload is effectively reduced on meshing, and calculation depends on 2D analysis. The number of meshes is small in this calculation method, so the calculation speed is fast. It is suit for repeating calculation when the structure is changed a litte.
(2) The mesh sensitivity and calculation results' sensitivity are analyzed, so accuracy is improved.
(3) The maximum temperature is no more than 350 °C, and the material requirements are fulfilled.

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