Structural evaluation of FHX for PGSFR at steady state condition

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1. Introduction

The FHX (Forced-draft sodium-to-air Heat Exchanger) employed in the ADHRS (active decay heat removal system) is a shell-and-tube type counter-current flow heat exchanger with serpentine finned-tube arrangement. Liquid sodium flows inside the heat transfer tubes and atmospheric air flows over the finned tubes. The configuration and overall shape of the unit are shown in Figure 1. The unit is placed in the upper region of the reactor building and has function of dumping the system heat load into the final heat sink, i.e., the atmosphere. Heat is transmitted from the primary cold sodium pool into the ADHRS sodium loop via DHX (Decay Heat Exchanger), and a direct heat exchange occurs between the tube-side sodium and the shell-side air through the FHX tube wall.

Cold atmospheric air is introduced into the air inlet duct at the lower part of the unit by using an electrically operated air blower or by the natural circulation force. Air flows across the finned tube bank rising upward direction to make uniform air flow with perfect mixing across the tubes. The finned tube bundle is placed inside a well-insulated casing. The air heated at the tube bank region is collected at the top of the unit and then is discharged through the air stack above the unit. Although a blower supplies atmospheric cooling air into the FHX unit, a tall air stack of 30 m in height is also provided to secure natural draft head of natural circulation air flow against a loss of power supply. The stack also has rain protecting structures to prevent inflow of rain drops or undesired harmful objects. Each FHX unit is designed to have the heat removal capability of 2.5 MWt corresponding to the design capacity of the ADHRS.

In this study, design loads for design condition and normal operating steady state condition were classified and the structural analyses for each design loads were carried out. And, structural integrities under each service level were evaluated according to ASME design code [1].

2. Structural analysis

2.1 Finite Element Model

The finite element model for FHX is made by using ANSYS [2] program as shown in Fig. 2. The element types for structural and thermal analyses are SOLID185 and SOLID70 elements, respectively and PIPE288 is used for the tubes. The general assumptions for the structural analyses are as follows.

- The weight of sodium is considered by imparting an equivalent density to the structure.
- Sodium temperature within hot and cold chamber are assumed to be 379.6 ºC and 352.2 ºC, respectively.
- Inlet and outlet air temperature are assumed to be 20 ºC and 376.47 ºC, respectively.
- Design and normal operation pressure for chamber and tubes are assumed to be 0.5 MPa and 0.22 MPa, respectively.

Table 1 Loading conditions for service levels

Service Level	Event Name	Service Time	# of Cycles	Max Temp (ºC)	
				Hot chamber	Cold chamber
Design	• Dead weight • Design pressure	60 y	-	470	470
A	• Dead weight • Design pressure • SS full power	60 y	180	380	352

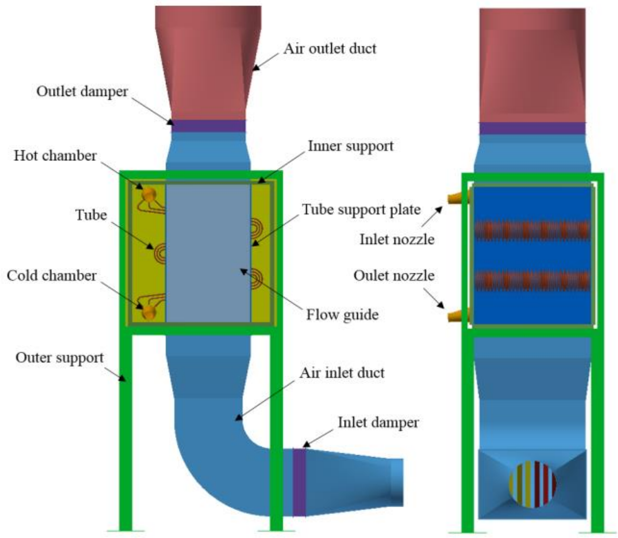
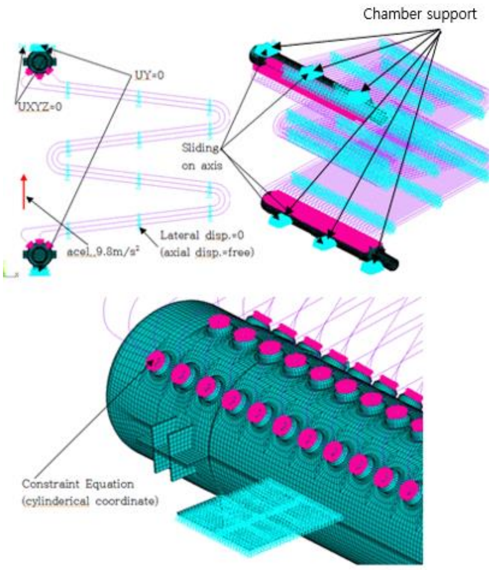
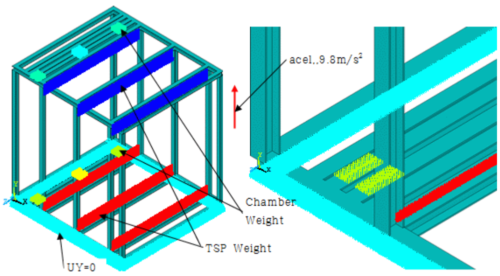


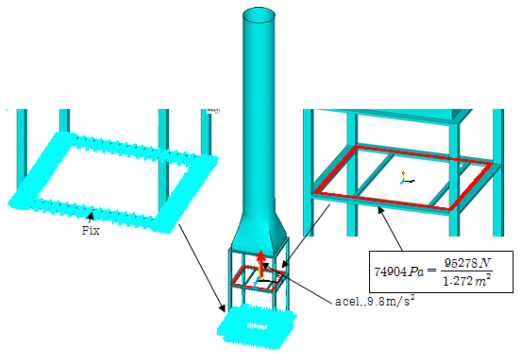
Fig. 1. FHX configuration



(a) Chamber and tubes



(b) Support structure



(C) Housing

Fig. 2. FE mesh and boundary condition for (a) chamber, (b) support structure and (c) housing

2.2 Loading and Boundary Conditions

Table 1 shows the loading conditions in each service level. The loading and boundary condition for deadweight are shown in Fig. 2.

2.3 Structural analysis

The structural analysis by using ANSYS program are carried out for each loading condition independently.

Table 2 Evaluation results of structural integrity under design condition

Sections	Node	Stress (MPa)	Calculated	Allowable	Margin	Temp. (°C)	C&S
DW	inner 401313	Pm	6.66E+00	1.56E+02	22.44	470	ASME Sec. III Div.5-HBB
		PL+Pb	7.06E+00	2.34E+02	32.19		
	outer 401462	Pm	6.66E+00	1.56E+02	22.44	470	
		PL+Pb	8.46E+00	2.34E+02	26.69		
PR	inner 888803	Pm	6.23E+01	1.56E+02	1.51	470	
		PL+Pb	1.03E+02	2.34E+02	1.28		
	outer 888534	Pm	6.23E+01	1.56E+02	1.51	470	
		PL+Pb	4.34E+01	2.34E+02	4.40		
TE	inner 884099	Pm	5.84E+00	1.56E+02	25.75	470	
		PL+Pb	4.02E+00	2.34E+02	57.22		
	outer 884228	Pm	5.84E+00	1.56E+02	25.75	470	
		PL+Pb	8.47E+00	2.34E+02	26.66		

Table 3 Evaluation results of structural integrity under normal operating steady state condition

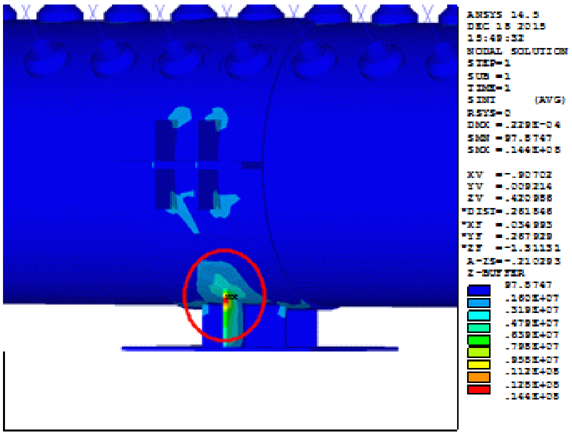
Sections	Node	Stress (MPa)	Calculated	Allowable	Margin	Temp. (°C)	C&S
PR	inner 888803	Pm	2.67E+01	1.82E+02	5.83	380	ASME Sec. III Div.5-HBB
		PL+Pb	4.40E+01	2.73E+02	5.21		
		PL+Pb/kt	4.06E+01	3.12E+02	6.68		
		UFS(t/tm)	2.69E-02	1.00E+00	37.14		
		UFS(t/tb)	2.83E-02	1.00E+00	35.38		
	outer 888534	Pm	2.67E+01	1.82E+02	5.83	380	
		PL+Pb	1.86E+01	2.73E+02	13.70		
		PL+Pb/kt	1.83E+01	3.12E+02	16.01		
		UFS(t/tm)	2.69E-02	1.00E+00	37.14		
		UFS(t/tb)	2.62E-02	1.00E+00	38.20		
TE	inner 884099	Pm	2.40E+00	1.83E+02	75.10	378.1	
		PL+Pb	9.87E-01	2.74E+02	276.59		
		PL+Pb/kt	1.27E+00	3.17E+02	248.57		
		UFS(t/tm)	1.53E-02	1.00E+00	65.30		
		UFS(t/tb)	1.53E-02	1.00E+00	65.53		
	outer 884228	Pm	2.40E+00	1.82E+02	74.95	379.9	
		PL+Pb	3.82E+00	2.74E+02	70.63		
		PL+Pb/kt	3.53E+00	3.12E+02	87.24		
		UFS(t/tm)	2.44E-02	1.00E+00	41.06		
		UFS(t/tb)	2.44E-02	1.00E+00	40.91		

Figure 3 shows the stress intensity distributions of chamber for each loading condition. The maximum stress is 342 MPa at chamber support structure by thermal load. The stresses at critical sections are linearized independently and then they are summarized in each stress component. The margin is calculated by following equation:

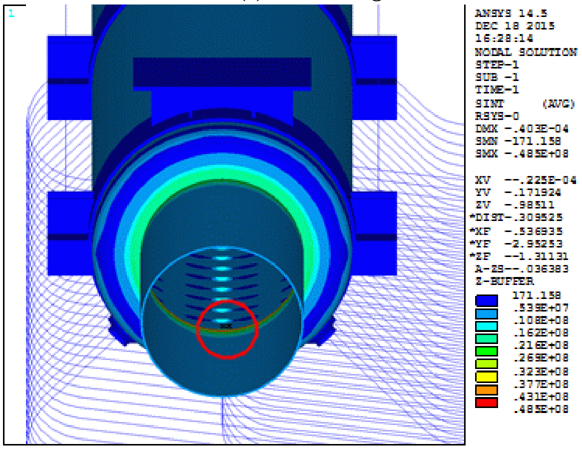
$$\text{Margin}=\text{Caculated}/\text{Allowable}-1$$

2.4 Structural Integrity Evaluation

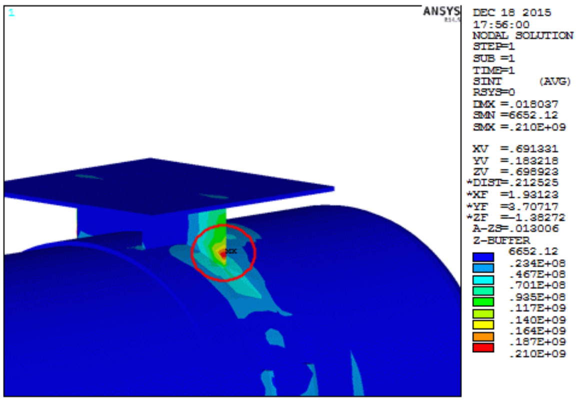
From the stress analyses, evaluation sections are selected for the structural integrity evaluation. The stress results are classified and summarized each component of stress under each service level. The design criteria for design condition are membrane stress (P_m, P_L) and bending stress (P_b) for primary loading. Table 2 shows the results of structural integrity for the design condition. The most critical section is section-PR, but all sections including section-PR satisfies the design criteria with design margin over 1.28.



(a) Dead weight



(a) Pressure



(c) Thermal

Fig. 3. Stress intensity distributions for (a) dead weight, (b) pressure and (c) thermal analysis

Additional structural integrity is evaluated for the normal operating steady state condition. The design criteria for service Level A is primary stresses, secondary stress (Q), thermal ratcheting, and use-fracture sums(USF_m, USF_b) with P_m and P_L+P_b. Table 3 shows the results of the structural integrity evaluation at the full power condition. The results show that all sections satisfy the design criteria

3. Conclusions

The structural analysis of a FHX are carried out and its structural integrity under the given service levels is evaluated per ASME Code rule. The design loads according to design condition and normal operating steady condition are classified and stresses calculated from stress analyses are linearized and summarized in their stress components. As a result, the FHX satisfies with design criteria for design condition and service level A.

Acknowledgement

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REFERENCES

[1] ASME B&PV Code, Section III Division 5 High Temperature Reactors, ASME, 2013.
[2] ANSYS User's manual, Release 15.0, ANSYS Inc.