

High temperature design and evaluation of forced draft sodium-to-air heat exchanger in PGSFR

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Abstract. In PGSFR (prototype-gen IV sodium-cooled fast reactor), two kinds of DHRSs (decay heat removal systems) are employed for emergency decay heat removal during a loss of normal heat sink accident, which are ADHRS (active decay heat removal system) and PDHRS (the passive decay heat removal system). The ADHRS is safety-grade active system, which is comprised of two independent loops. Each loop has a single sodium-to-sodium decay heat exchanger (DHX) immersed in cold pool region and a single forced-draft sodium-to-air heat exchanger (FHX) located in upper region of the reactor building. The total heat removal capacity of the DHRS is 10 MWt which amounts to about 2.5% of the rated core thermal power. The DHRS is capable of cooling the plant from an initial temperature corresponding to any power operation condition to the safe shutdown condition within 72 hours after reactor shutdown with a single failure. The FHX employed in the ADHRS is a shell-and-tube type counter-current flow heat exchanger with M-shaped finned-tube arrangement. Liquid sodium flows inside the heat transfer tubes and atmospheric air flows over the finned tubes. During normal plant operation, small amount of heat loss through the FHX is permitted to prevent potential flow reversal or stagnation in each decay heat removal sodium loop. After the reactor shutdown, heat removal rate increases by opening dampers located in air flow paths of FHXs, and then the heat transferred to the decay heat removal system is finally dissipated into the atmosphere. In this study, elevated temperature design and creep-fatigue damage evaluation for a FHX were conducted. A creep-fatigue damage evaluation was performed according to the elevated temperature design codes of ASME Code B&PV Section III Division 5 based on a full 3D finite element analysis. The structural integrity of the heat exchangers under creep-fatigue loading was confirmed.

Key Words: PGSFR (prototype-gen IV sodium-cooled fast reactor), FHX (forced-draft sodium-to-air heat exchanger), elevated temperature design

1. Introduction

A Prototype Gen-IV Sodium-Cooled Fast Reactor (PGSFR) has been under development in Korea since 2012 according to a national nuclear R&D program which aims the construction of a prototype sodium-cooled fast reactor by 2028. The purpose of the PGSFR is to achieve an enhanced safety, an efficient utilization of uranium resources, and a reduction of a radioactive waste volume in Korea [1, 2]. The PGSFR is a pool-type SFR with the capacity of 150 MWe and uses metallic fuel.

Fig. 1 shows the overall configuration of the PGSFR [3]. The primary heat transport system (PHTS) is placed in the reactor vessel which is a large sodium pool to make the system transients slower. Two intermediate heat transport systems (IHTSs) are thermally coupled to the PHTS and two steam generators (SGs). The IHTSs transfer the reactor-generated heat from the intermediate heat exchangers (IHXs) of the PHTS to the SGs. The SGs consist of two independent steam-generation loops and convert the subcooled water to a superheated steam. The decay heat removal systems (DHRSs) have a heat removal capacity of 10 MWt which amounts to about 2.5% of the rated core thermal power. The DHRSs are composed of two types based on the design concept of diversity and redundancy [4, 5]. For the diversity of

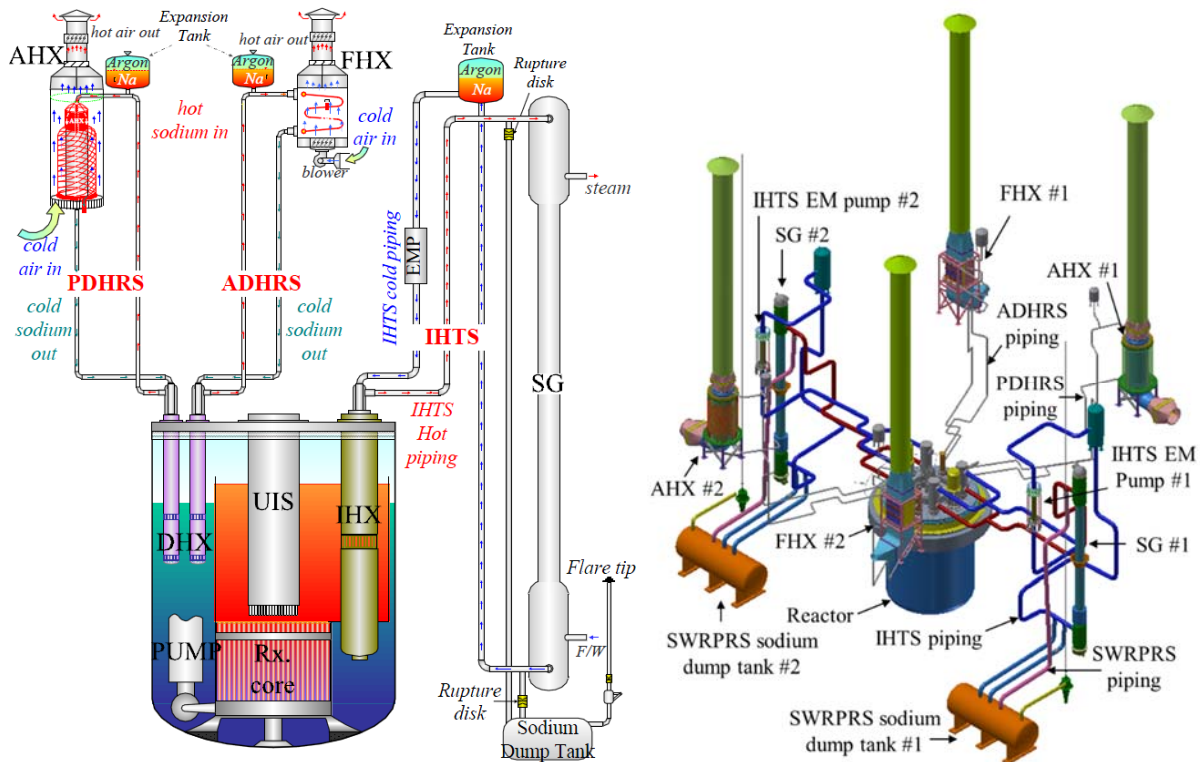


FIG. 1. Schematic diagram and solid modeling for the PGSFR.

the design, one type is an active decay heat removal system (ADHRS) which is operated by active components (e.g. blowers) and the other is a passive decay heat removal system (PDHRS) which operates based on natural convection driving head alone.

Two heat exchangers to be installed in the each ADHRS loop are a forced-draft sodium-to-air heat exchanger (FHX) and a sodium-to-sodium decay heat exchanger (DHX) while two heat exchangers to be installed in the each PDHRS loop are a natural-draft sodium-to-air heat exchanger (AHX) and a DHX. The material of the FHX and AHX is martensitic stainless steel type 9Cr-1Mo-V.

In this paper, a system description for DHRS in PGSFR was provided. And an elevated temperature design and a structural integrity evaluation result of the FHX were described. The finite element analysis was carried out by three-dimensional analysis with ANSYS [6] and structural integrity evaluation was carried out according to the ASME Code B&PV section III Division 5 [7].

2. Description of DHRS and FHX

2.1. The Decay Heat Removal System

The DHRS is used to remove the decay heat from the reactor core or from the spent fuel storage after the reactor shutdown when the normal heat transport path is not available. It is a safety-grade system and is designed to have sufficient cooling capability to bring the plant to safe shutdown condition under post-accident conditions. The total heat removal capacity of the DHRS is 10 MWt which amounts to about 2.5% of the rated core thermal power. The DHRS is capable of cooling the plant from an initial temperature corresponding to any power

operation condition to the safe shutdown condition within 72 hours after reactor shutdown with a single failure. The elevation difference between the DHX and the sodium-to-air heat exchanger (AHX or FHX) in each DHRS sodium loop is sufficiently high to ensure that the natural circulation head in the DHRS sodium loop provides the required sodium flow. Heat is transmitted from the primary cold sodium pool into the DHRS sodium loop via DHX, and a direct heat exchange occurs between the tube-side sodium and the shell-side air through the sodium-to-air heat exchanger tube wall.

The DHRS is composed of four loops, two loops of PDHRSs and two loops of ADHRSs as shown in Fig. 1, considering redundancy and independency requirements. Each ADHRS loop consists of a DHX, a FHX, an expansion tank and a blower. The blower derives the air flow in the shell side of the FHX. The expansion tanks is installed in the highest position of the ADHRS hot piping to accommodate thermal transients in the DHRS sodium. Since the ADHRS can also be operated in a passive mode against a loss of power supply, the heat transferred to an ADHRS can be finally dissipated into the atmosphere through FHXs by a natural convection of sodium and air flow only. The ADHRS has heat removal capacity of at least 50 % of the design value in a passive operation mode.

2.2. The Forced-Draft Sodium-to-Air Heat Exchanger

The FHX employed in the ADHRS is a shell-and-tube type counter-current flow heat exchanger with serpentine (M-shape) 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 2. The key design parameters of the FHX in the PGsFR are summarized in Table I. The material of the FHX is 9Cr-1Mo-V steel. The design pressure and temperature are 0.6 MPa and 470°C, respectively. The outer diameter and thickness of the tube is 34.0 mm and 1.65 mm, respectively. The number of tubes, effective tube length and inclined angle are 96, 8 m and 7.2°, respectively. All of the serpentine (M-

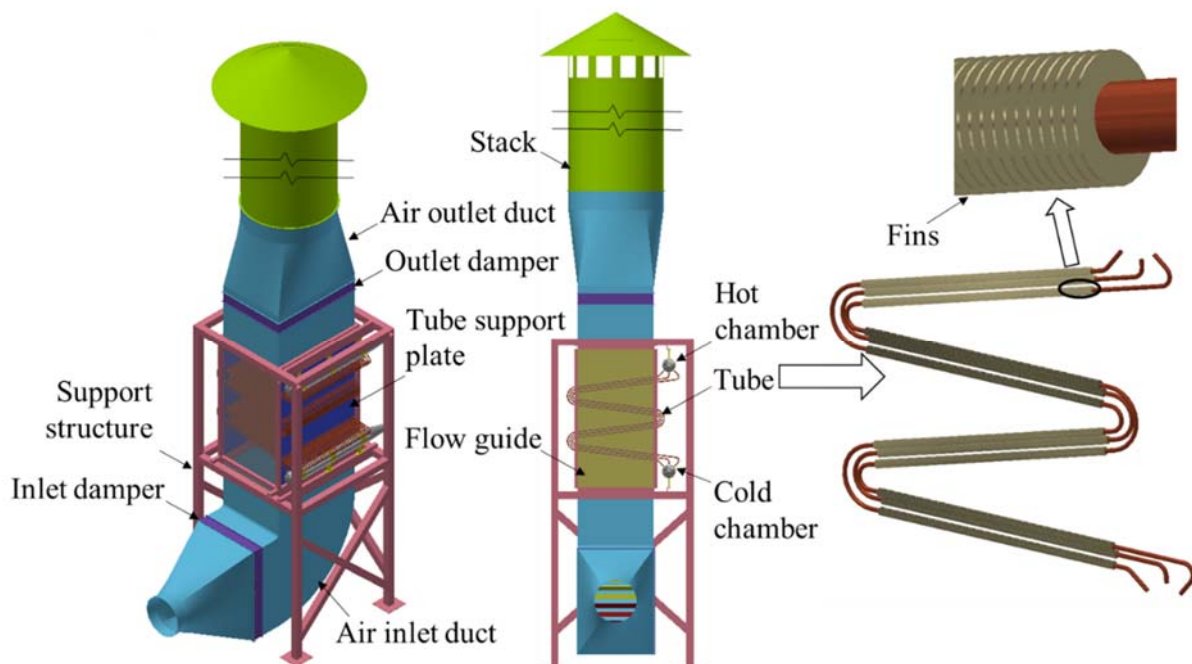


FIG. 2. Configuration of the FHX.

TABLE I: KEY DESIGN PARAMETERS FOR THE FHX.

Thermal duty (MWt)	2.5
Material	9Cr-1Mo-V
Design pressure (MPa) / Temperature (°C)	0.6 / 470
Bare tube OD/ID/Thickness (mm)	34.0 / 30.7 / 1.65
No. of tubes	96
No. of tube rows	32
Effective tube length (m)	8
Tube inclined angle (degree)	7.2
Tube arrangement	4-pass serpentine
No. of fins (per unit length)	152
Fin height/Thickness (mm)	15 / 1.5
Spacing between fins (mm)	5.08

shape) tubes have helical fins over the straight tube parts with a density of 152 fins per meter.

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, 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 FHX 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. This feature leads that the heat transferred from the reactor pool via DHX can be sufficiently and reliably removed to the atmosphere.

3. Finite Element Analysis

The FHX consists of support structure, chamber and tubes, etc. The chamber is under a high temperature condition and pressure boundary. Thus, the chamber is the most interested part of structural integrity. In this paper, the structural analysis was performed only for the chamber with tubes.

3.1. Finite Element Modeling

The hot chamber and the cold chamber were fully modeled in the 3D FE model as shown in Fig. 3. For the convenience of analysis, tubes were modeled as pipe elements. Thus, the fin part of the tube was not modeled. However, the fin effect in the finned tube was taken into account by considering equivalent heat transfer area. The outer surface area of the finned tube is eight times higher than that of bare tube. So the finned-tube part was modeled with bare tube with heat transfer coefficient which is eight times larger than that of the bare tube. The total number of nodes was 738,624 and the total number of elements (3D and pipe element) was 569,956.

As the loading conditions, the transients for the sodium and air was assumed as shown in Fig. 4. The transient time was conservatively assumed to be 30 hours.

As boundary conditions, the bottom surface of the chamber support structure near the nozzle was completely fixed. However, since the other chamber support structures slide axially in order to accommodate axial thermal expansion of the chamber, the other two bottom surfaces

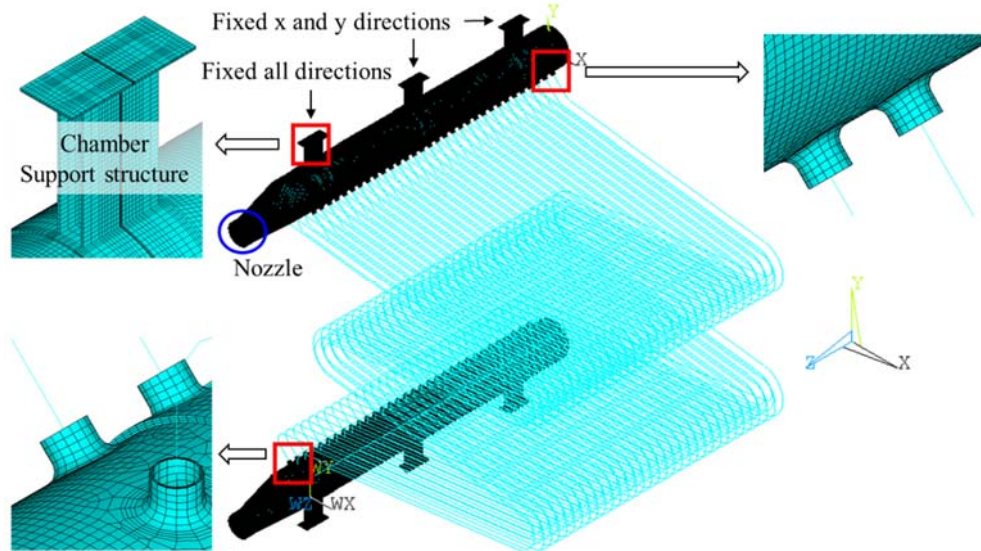


FIG. 3. Finite element model of chamber with tubes in the FHX.

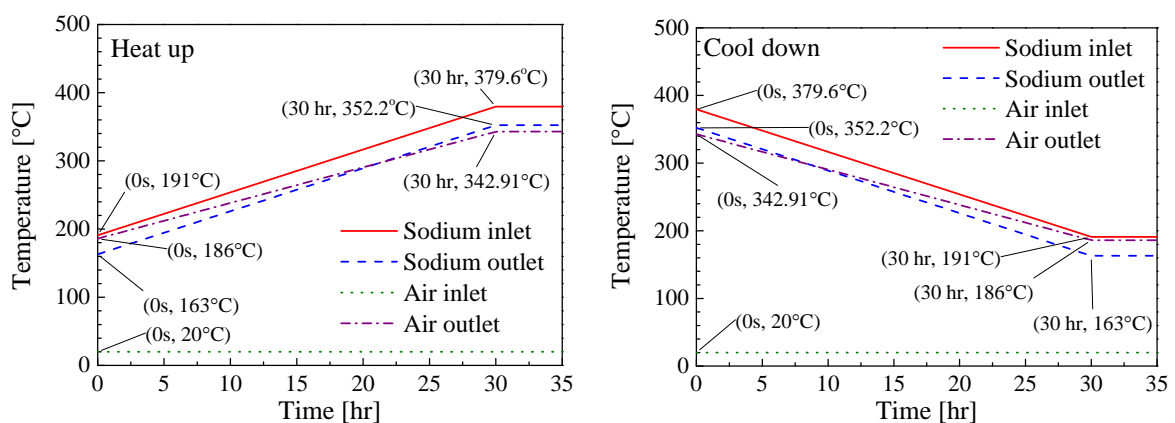


FIG. 4. Transient temperature of the FHX.

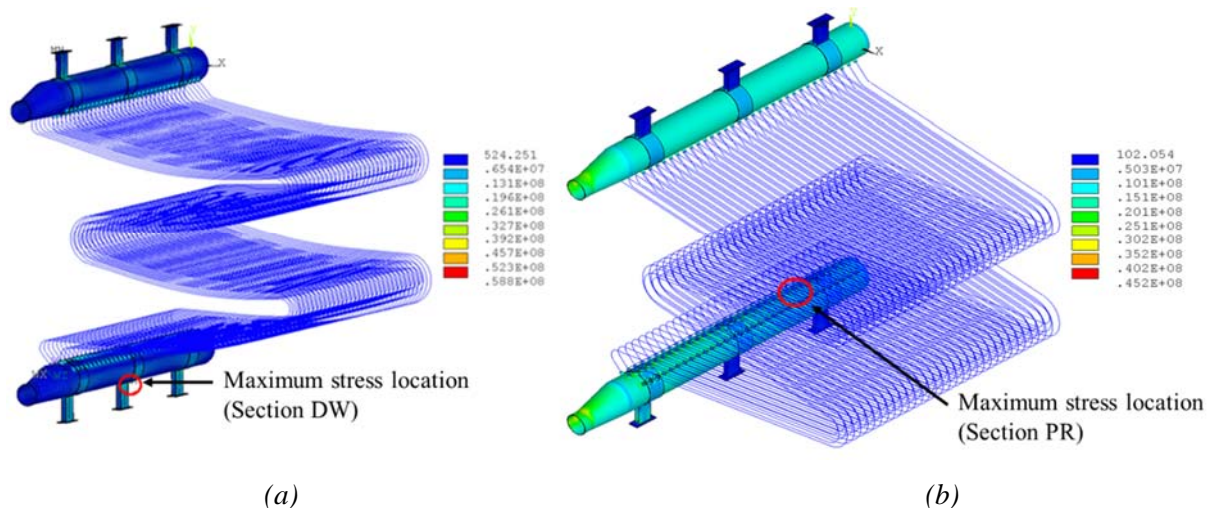


FIG. 5. Stress analysis results of (a) self-weight and (b) pressure loading.

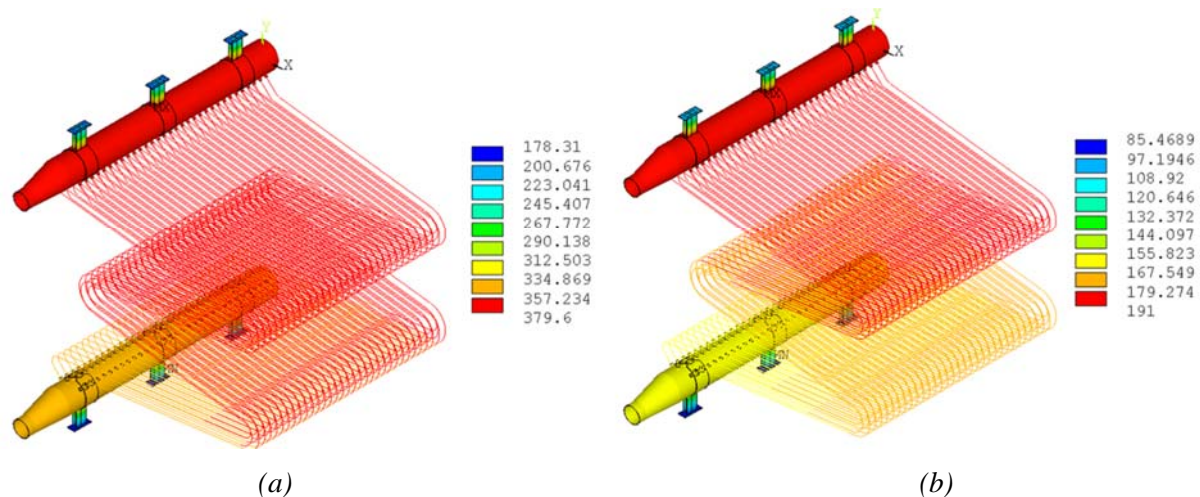


FIG. 6. Heat transfer analysis results at $t=30$ hours of (a) heat up and (b) cool down transient.

were fixed in x and y directions. Using the CERIG option [6], the three-dimensional elements of the chambers were connected to the pipe elements of the tubes. The nodes of the nozzle end were constrained to move only in the radial direction from the nodes of the end of the pipe element.

As heat transfer conditions, the bulk fluid temperatures were assumed to vary linearly from 352.2°C (cold chamber) to 379.6°C (hot chamber) on the sodium side, whereas the air temperatures were assumed to vary linearly from 20°C (cold chamber part) to 342.91°C (hot chamber part) in the shell. The heat transfer coefficient of the finned-tube area was assumed to be uniformly 36.4 W/m²K [8]. The chambers were assumed to be fully insulated.

3.2. Finite Element Analysis Results

Primary and secondary stress analyses were performed. A commercial finite element analysis program, ANSYS [6], was used for the analysis. The self-weight and the pressure loading were considered as primary loads, the transient temperature in Fig. 4 was considered as secondary load. The stress analysis results of self-weight and pressure loading are shown in Fig. 5. As a result of the self-weight loading analysis result, the maximum stress intensity was

58.8 MPa in the middle chamber support structure of the cold chamber as shown in Fig. 5(a). As a result of the pressure loading analysis result, the maximum stress intensity was 45.2 MPa in the nozzle of the cold chamber as shown in Fig. 5(b).

The overall temperature distribution of the chamber at $t=30$ hours of heat up and cool down transients are shown in Fig. 6, which shows a gradual change in the temperature distribution along the axial direction of the tubes. These temperature distribution were used for thermal stress analysis.

A stress analysis taking the temperature distributions into account was conducted for the chamber with tubes. The stress distributions of the chamber at 30 hours after the start of heat up show that the maximum stress intensity at the chamber support structure in Fig. 7(a) was 62 MPa. At 30 hours after the start of cool down, the maximum stress location is same as the heat up transient and the value is 22 MPa. The change in stress intensity at maximum stress location during transient is shown in Fig. 8.

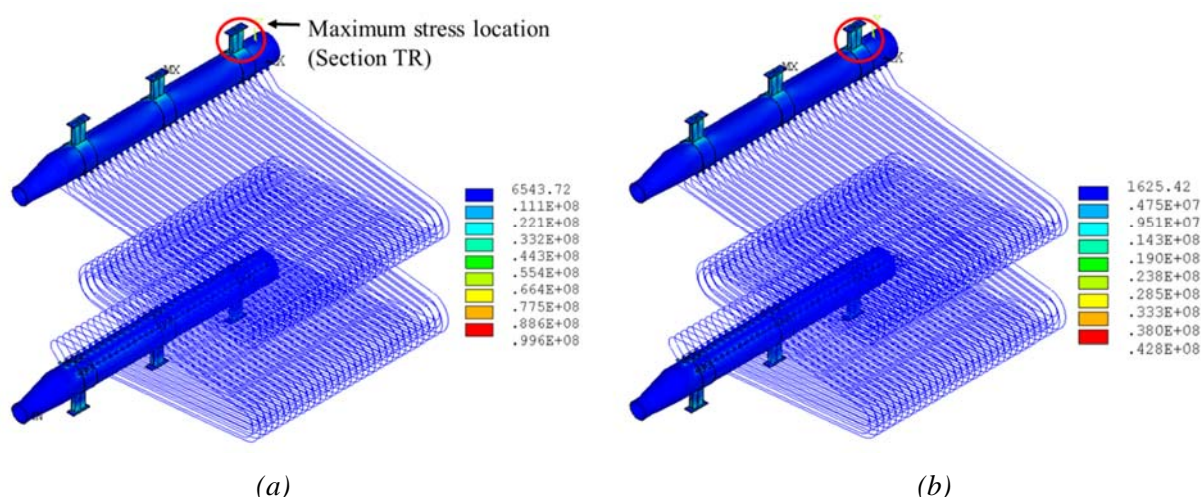


FIG. 7. Thermal stress analysis results at $t=30$ hours of (a) heat up and (b) cool down transient.

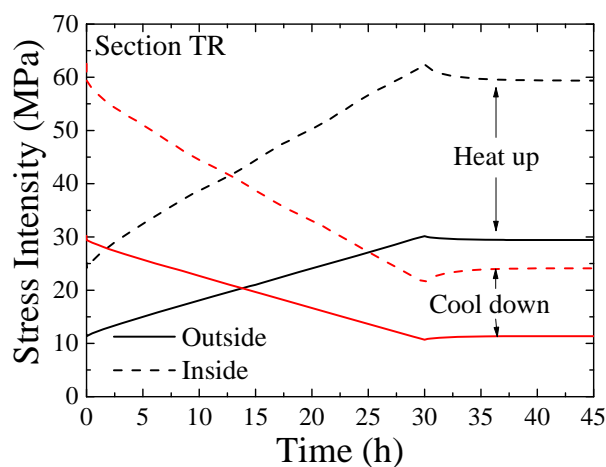


FIG. 8. Stress intensity at maximum stress location during transient

TABLE II: EVALUATION RESULTS OF FHX AT LOW TEMPERATURE CONDITION

Sections	Node	Evaluation items	Calculated (MPa)	Limit (MPa)	Margin	Max. Temp. (°C)	Code
DW	549460	$P_L+P_b+P_e+Q$	12.8	572.6	44	351.6	ASME Sec. III Div.5- HBA
		Thermal Stress Ratchet	9.7	28116.1	2904		
	542812	$P_L+P_b+P_e+Q$	14.5	572.9	39	350.4	
		Thermal Stress Ratchet	23.9	28116.1	1174		
PR	507408	$P_L+P_b+P_e+Q$	20.2	572.5	27	352	
		Thermal Stress Ratchet	4.3	8196.1	1892		
	507375	$P_L+P_b+P_e+Q$	12.5	572.5	45	352	
		Thermal Stress Ratchet	2.5	8196.1	3239		

TABLE III: EVALUATION RESULTS OF FHX AT ELEVATED TEMPERATURE CONDITION

Sections	Node	Evaluation items	Calculated	Limit	Margin	Max. Temp. (°C)	Code
TR	355265	P_m (MPa)	4.9	182.2	36	377.8	ASME Sec. III Div.5- HBB
		P_L+P_b (MPa)	6.8	273.3	39		
		P_L+P_b/k_t (MPa)	6.4	314.6	48		
		$UFS(t_i/t_{im})$	525600	26989000	50		
		$UFS(t_i/t_{ib})$	525600	26862000	50		
		Inelastic strain	0.082	1.0	11		
		Damage	Fatigue	<0.0001	intersection (0.1,0.01)		
	Creep		0.026				
	355327	P_m (MPa)	4.9	182.1	36	377.8	
		P_L+P_b (MPa)	3.5	273.1	76		
		P_L+P_b/k_t (MPa)	3.6	313.2	87		
		$UFS(t_i/t_{im})$	525600	23880000	44		
		$UFS(t_i/t_{ib})$	525600	23985000	45		
		Inelastic strain	0.105	1.0	9		
Damage		Fatigue	<0.0001	intersection (0.1,0.01)	-		
	Creep	0.023					

4. Evaluation Results

According to the ASME Code B&PV Section III Division 5 Subsection HB, subsection A provides rules for design at low temperature condition and subsection B provides rules for design at elevated temperature design. Therefore, the structural evaluation was performed separately for low and elevated temperature. For 9Cr-1Mo-V materials, the criterion for low and elevated temperature is 375°C.

4.1. Low Temperature Condition

In the self-weight and pressure loading analysis, the maximum stress location is the chamber support structure. The maximum temperature where the maximum stress occur is lower than 375°C in transient condition. Therefore, it was evaluated according to ASME Code B&PV Section III Division 5 Subsection HB Subpart A because it is a low temperature condition. The primary and secondary stresses evaluation results are shown in Table II. The section DW and PR in the table are the section of maximum stress location in the self-weight and pressure loading analysis, respectively, as shown in Fig. 5. The calculated stresses in all sections satisfy the criteria of the ASME code.

4.2. Elevated Temperature Condition

As shown in Fig. 6(a), the temperature of the hot chamber is above 375°C during the transient. Therefore, it was evaluated according to ASME Code Section III Division 5 Subsection HB Subpart B because it is an elevated temperature condition. The evaluation results are shown in Table III. The section TR in the table is the section of maximum stress location in the thermal stress analysis as shown in Fig. 7. The calculated values satisfy not only stress limits but also strain limit with sufficient margin. Evaluation results of the creep-fatigue damage for the FHX showed that damage under creep and fatigue loading was negligible and the integrity of the FHX was confirmed.

5. Conclusions

A high temperature design and structural analyses of the FHX were carried out and its structural integrity was evaluated per ASME Code rule. The FHX employed in the ADHRS is a shell-and-tube type counter-current flow heat exchanger with serpentine (M-shape) finned-tube arrangement.

Three-dimensional finite element analyses were conducted for the FHX, and primary stress, inelastic strain and creep-fatigue damage at several locations were evaluated according to the elevated temperature design codes, ASME Code B&PV Section III Division 5. The present design of the FHX was shown to be acceptable for a transient condition according to the design code. The highest stress intensity under self-weight and pressure loading were calculated to be 58.8 MPa at the chamber support structure and 45.2 MPa at nozzle. The maximum thermal stress during transient is 62 MPa at the hot chamber.

Structural integrity evaluation was carried out for low and high temperature conditions according to the ASME code. In the low temperature condition, only the primary stress was evaluated. In the high temperature condition, not only the primary stress limits but also the inelastic strain and creep-fatigue damage were evaluated. The calculated values satisfy all limits with sufficient margin. Evaluation results of the creep-fatigue damage for the FHX showed that damage under creep and fatigue loading was negligible and the structural integrity of the FHX was confirmed.

Acknowledgements

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