Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Structural Integrity Evaluation of Copper Bonded Steam Generator

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1. Introduction

The copper bonded steam generator (CBSG) is designed to be modular type, and each module is manufactured to be integrated under high temperature and high pressure through the hot isostatic pressing (HIP) technology. Each module can be manufactured below a certain size due to the constraints of the workspace in the HIP process. The CBSG uses water and sodium as a heat transfer medium, which is a steam generator with a triple solid barrier using a copper alloy (CuCrZr) to prevent sodium-water reaction. As shown in Fig. 1, 17 modules are designed to be combined to form one device and the interior of each module consists of the porous holes such as a square tube on the sodium side and a circular tube on the water side [1]. The shape of the currently designed CBSG is a preliminary concept and the structure should be considered to be reasonable. Stress analysis is performed primarily for dead weight, pressure and steady-state thermal load in this paper. Because the CBSG has many porous holes inside each module, the analysis is complicated and it is difficult to analyze the entire model. Therefore, stress analysis is performed on the sub-models of the major parts of the CBSG three-dimensional shape.

Detailed analysis of the sub-models of CBSG was performed for the sodium connection header and steam header, respectively, and for the water connection header, it was analyzed together with the CBSG module. This is the detailed model for the CBSG selected for the proper size through the case study [2], where cross section size is 805.7 mm X 805.7 mm and thickness is 100 mm. The structural integrity evaluation of the detailed sub-models is performed.

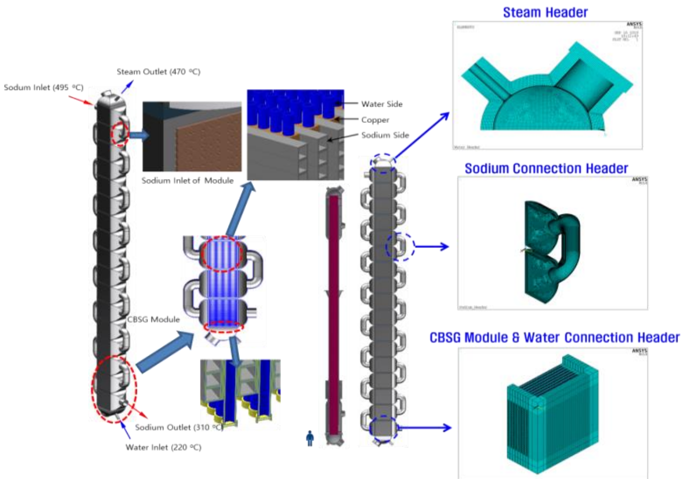


Fig. 1. Conceptual drawing of the CBSG designed by KAERI

2. Structural Integrity Evaluation of the CBSG

2.1 Sodium Connection Header

(1) Analysis Model

Fig. 2 shows the applied load and boundary condition of the sodium connection header. As shown in the figure, the internal pressure is 0.792 MPa and the temperature of sodium flowing inside is 484.1 °C. The units applied in the detailed analysis of the CBSG sub-models use kg-mm unit system and the analysis results of the stress and displacement are expressed in MPa and mm [3].

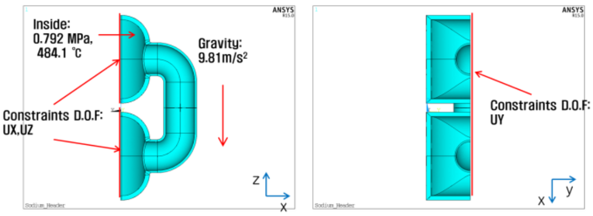


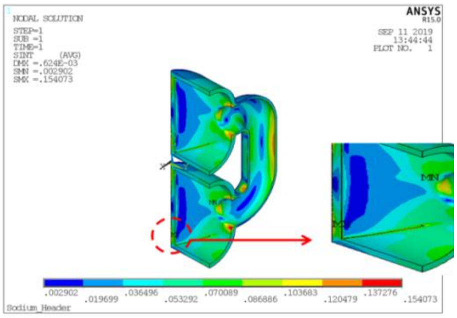
Fig. 2 Load and boundary condition of sodium connection header

(2) Analysis Results

The analysis result for the dead weight is shown in Fig. 3, and a maximum stress of 0.15 MPa is produced. Fig. 4 shows the stress analysis result for pressure. The maximum stress is calculated as 30.4 MPa in the geometrical discontinuity connected to the CBSG module. Fig. 5 shows the stress analysis result for the steady-state thermal load. The maximum thermal stress is small at 10.3 MPa because the outer part of the sodium connection header is insulated and the temperature difference is not large. The locations of the structural integrity evaluation sections for dead weight, pressure, and steady-state thermal load and the corresponding nodes are shown in Sections A through C of Figs. 3 through 5.

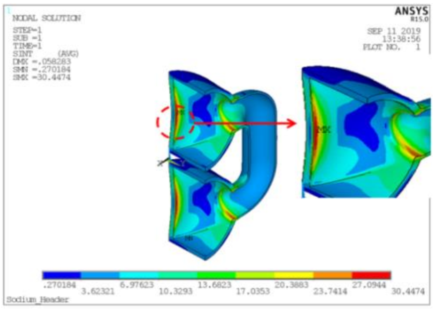
Table 1 and Table 2 show the structural integrity evaluation results of the sodium connection header for the design condition and the service level A condition, respectively. Because the maximum temperatures of the evaluation sections are maintained above the creep temperature level, ASME Sec. III, Div.5–HBB regulations are applied. The structural integrity evaluation results satisfy the ASME allowable stress limits and have the design margin of more than 6.40 for operating level A condition as shown in Table 2. The design margin in the structural integrity evaluation is defined as follows.

Design margin = (allowable stress/calculated stress)-1



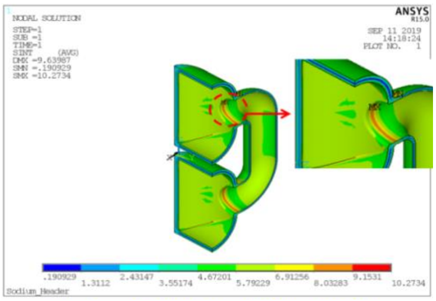
Section-A : Node (n28698 – n28606)

Fig. 3 Structural integrity evaluation section of sodium connection header (section A, dead weight)



Section-B : Node (n25504– n42645)

Fig. 4 Structural integrity evaluation section of sodium connection header (section B, pressure)



Section-C : Node (n43710– n40879)

Fig. 5 Structural integrity evaluation section of sodium connection header (section C, thermal load)

Table 1 Structural integrity check results of sodium connection header (design condition)

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress (MPa)	Margin	Temperature (°C)	C&S
Section-A	Inner (28698)	Pm	8.79	107.64	11.25	484.1	ASME Sec III Div5-HBB
		PL + Pb	14.42	161.45	10.20		
	Outer (28606)	Pm	8.79	107.64	11.25	484.1	ASME Sec III Div5-HBB
		PL + Pb	14.75	161.45	9.95		
Section-B	Inner (25504)	Pm	3.57	107.64	29.15	484.1	ASME Sec III Div5-HBB
		PL + Pb	15.24	161.45	9.59		
	Outer (42645)	Pm	3.57	107.64	29.15	484.1	ASME Sec III Div5-HBB
		PL + Pb	21.12	161.45	6.64		
Section-C	Inner (43710)	Pm	9.44	107.64	10.40	484.1	ASME Sec III Div5-HBB
		PL + Pb	12.42	161.45	12.00		
	Outer (40879)	Pm	9.44	107.64	10.40	484.1	ASME Sec III Div5-HBB
		PL + Pb	10.57	161.45	14.27		

Table 2 Structural integrity check results of sodium connection header (Service level A condition)

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress (MPa)	Margin	Temperature (°C)	C&S
Section-A	Inner (28698)	Pm	8.79	106.64	11.13	484.1	ASME Sec III Div5-HBB
		PL + Pb	14.42	159.95	10.09		
		PL + Pb/Kt	12.77	129.34	9.13		
		UFS(t/tm)	0.88E-14	1.0	1.14E+14		
		UFS(t/tb)	0.26E-13	1.0	3.85E+13		
	Outer (28606)	Pm	8.79	106.64	11.13	484.1	ASME Sec III Div5-HBB
		PL + Pb	14.75	159.95	9.84		
		PL + Pb/Kt	12.89	129.34	9.03		
		UFS(t/tm)	0.88E-14	1.0	1.14E+14		
		UFS(t/tb)	0.26E-13	1.0	3.85E+13		
Section-B	Inner (25504)	Pm	3.57	106.64	28.87	484.1	ASME Sec III Div5-HBB
		PL + Pb	15.24	159.95	9.50		
		PL + Pb/Kt	11.62	129.34	10.13		
		UFS(t/tm)	0.22E-14	1.0	4.55E+14		
		UFS(t/tb)	0.18E-13	1.0	5.56E+13		
	Outer (42645)	Pm	3.58	106.64	28.79	484.1	ASME Sec III Div5-HBB
		PL + Pb	21.12	159.95	6.57		
		PL + Pb/Kt	17.49	129.34	6.40		
		UFS(t/tm)	0.22E-14	1.0	4.55E+14		
		UFS(t/tb)	0.91E-13	1.0	1.10E+13		
Section-C	Inner (43710)	Pm	9.44	106.64	10.30	484.1	ASME Sec III Div5-HBB
		PL + Pb	12.42	159.95	11.88		
		PL + Pb/Kt	11.56	129.34	10.19		
		UFS(t/tm)	0.10E-13	1.0	1.00E+14		
		UFS(t/tb)	0.18E-13	1.0	5.56E+13		
	Outer (40879)	Pm	9.44	106.64	10.30	484.1	ASME Sec III Div5-HBB
		PL + Pb	10.57	159.95	14.13		
		PL + Pb/Kt	10.26	129.34	11.61		
		UFS(t/tm)	0.10E-13	1.0	1.00E+14		
		UFS(t/tb)	0.13E-13	1.0	7.69E+13		

2.2 Steam Header

(1) Analysis Model

Fig. 6 shows the applied load and boundary condition of the steam header. The steam of 470 °C inside the steam header exists and exits through the outlet nozzle in a high pressure (design pressure: 16.5 MPa).

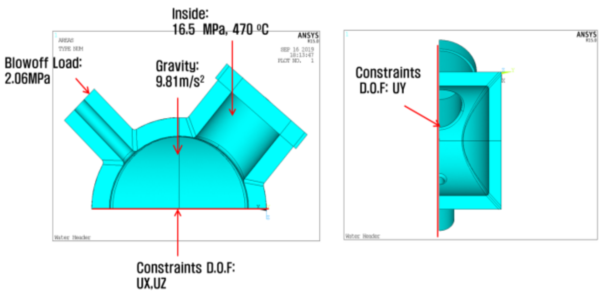
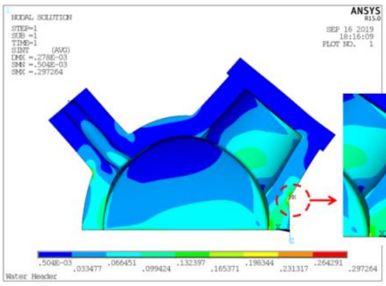


Fig. 6 Load and boundary condition of steam header

(2) Analysis Results

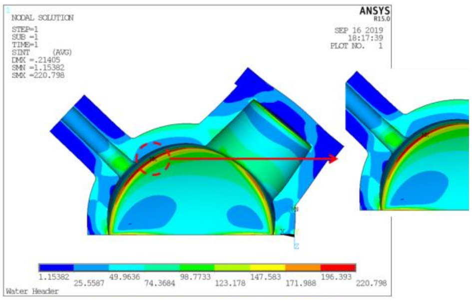
The analysis result of the dead weight is shown in Fig. 7, and a maximum stress of 0.30 MPa is produced. Fig. 8 shows the stress analysis result for the pressure. The maximum stress was calculated as 220.8 MPa in the internal discontinuity of the steam header. Fig. 9 is the stress analysis result for the steady-state thermal load and the maximum thermal stress is small as 12.90 MPa. The locations of the structural integrity evaluation sections for dead weight, pressure, and steady-state thermal load and the corresponding nodes are shown in sections A through C of Figs. 7 through 9.

Table 3 and Table 4 show the structural integrity evaluation results of the steam header for the design condition and the service level A condition, respectively. The structural integrity evaluation results satisfy the ASME allowable stress limits and have the design margin of more than 0.47 for operating level A condition as shown in Table 4.



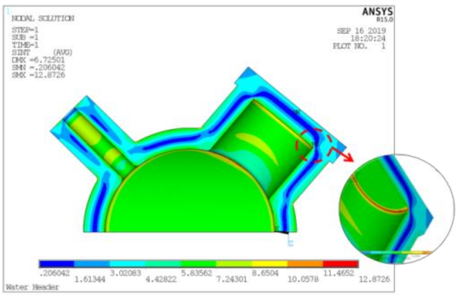
Section-A : Node (n29037 – n28087)

Fig. 7 Structural integrity evaluation section of steam header (section A, dead weight)



Section-B : Node (n20784 – n20537)

Fig. 8 Structural integrity evaluation section of steam header (section B, pressure)



Section-C : Node (n9889 – n33151)

Fig. 9 Structural integrity evaluation section of steam header (section C, thermal load)

Table 3 Structural integrity check results of steam header (design condition)

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress (MPa)	Margin	Temperature (°C)	C&S
Section-A	Inner (29037)	Pm	41.72	108.00	1.59	470	ASME Sec III Div5-HBB
		PL + Pb	62.80	162.00	1.58		
	Outer (28087)	Pm	41.72	108.00	1.59	470	ASME Sec III Div5-HBB
		PL + Pb	57.53	162.00	1.82E+00		
Section-B	Inner (20784)	Pm	31.57	108.00	2.42E+00	470	ASME Sec III Div5-HBB
		PL + Pb	44.52	162.00	2.64		
	Outer (20537)	Pm	31.57	108.00	2.42	470	ASME Sec III Div5-HBB
		PL + Pb	106.93	162.00	0.52		
Section-C	Inner (9889)	Pm	27.52	108.00	2.92E+00	470	ASME Sec III Div5-HBB
		PL + Pb	23.11	162.00	6.01E+00		
	Outer (33151)	Pm	27.52	108.00	2.92	470	ASME Sec III Div5-HBB
		PL + Pb	53.33	162.00	2.04		

Table 4 Structural integrity check results of steam header (Service level A condition)

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress (MPa)	Margin	Temperature (°C)	C&S
Section-A	Inner (29037)	Pm	41.72	107.20	1.57	470	ASME Sec III Div5-HBB
		PL + Pb	62.80	160.80	1.56		
		PL + Pb/Kt	55.44	134.62	1.43		
		UFS(t/tm)	0.15E-15	1.0	6.67E+15		
		UFS(t/tb)	0.32E-13	1.0	3.12E+13		
	Outer (28087)	Pm	41.72	107.20	1.57	470	ASME Sec III Div5-HBB
		PL + Pb	57.53	160.80	1.80		
		PL + Pb/Kt	49.17	134.62	1.74		
		UFS(t/tm)	0.88E-14	1.0	1.14E+14		
		UFS(t/tb)	0.27E-14	1.0	3.70E+14		
Section-B	Inner (20784)	Pm	31.57	107.20	2.40	470	ASME Sec III Div5-HBB
		PL + Pb	44.52	160.80	2.61		
		PL + Pb/Kt	29.53	134.62	3.56		
		UFS(t/tm)	0.28E-17	1.0	3.57E+17		
		UFS(t/tb)	0.12E-17	1.0	8.33E+17		
	Outer (20537)	Pm	31.57	107.20	2.40	470	ASME Sec III Div5-HBB
		PL + Pb	106.93	160.80	0.50		
		PL + Pb/Kt	91.83	134.62	0.47		
		UFS(t/tm)	0.28E-17	1.0	3.57E+17		
		UFS(t/tb)	0.51E-07	1.0	1.96E+07		
Section-C	Inner (9889)	Pm	27.52	107.20	2.90	470	ASME Sec III Div5-HBB
		PL + Pb	23.11	160.80	5.96		
		PL + Pb/Kt	20.92	134.62	5.43		
		UFS(t/tm)	0.56E-18	1.0	1.79E+18		
		UFS(t/tb)	0.42E-19	1.0	2.38E+19		
	Outer (33151)	Pm	27.52	107.20	2.90	470	ASME Sec III Div5-HBB
		PL + Pb	53.33	160.80	2.02		
		PL + Pb/Kt	48.11	134.62	1.80		
		UFS(t/tm)	0.56E-18	1.0	1.79E+18		
		UFS(t/tb)	0.18E-14	1.0	5.56E+14		

2.3 CBSG Module

(1) Analysis Model

Fig. 10 shows the applied load and boundary condition of the integrated CBSG module and water connection header. This is modeled with porous holes including square flow tubes on the sodium side and round flow tubes on the water side, and a total of 5,059,008 finite elements are used. As shown in Fig. 10, a high pressure load of 16.5 MPa and a steady-state thermal load are considered inside the CBSG module and the water connection header.

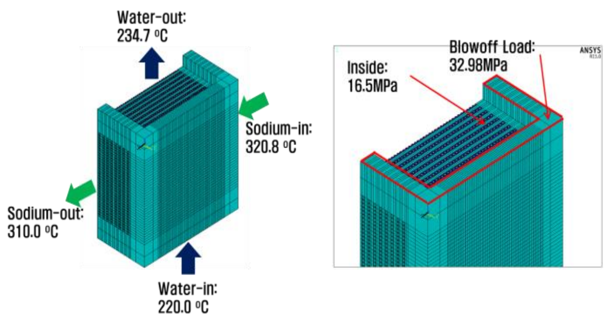
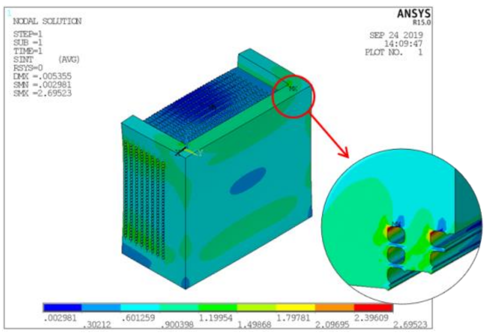


Fig. 10 Load and boundary condition of CBSG module

(2) Analysis Results

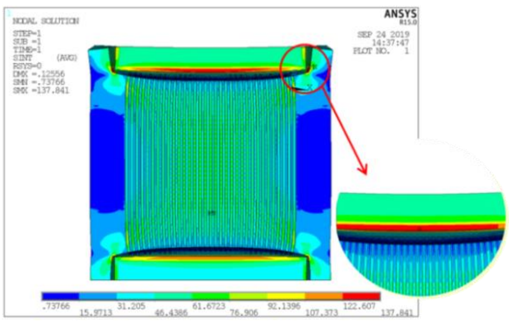
The analysis result of the dead weight is shown in Fig. 11, and a maximum stress of 2.70 MPa is produced. Fig. 12 shows the stress analysis result for the pressure. The maximum stress was calculated as 137.8 MPa in the interface where the CBSG module is connected to the water connection header. Fig. 13 shows the result of stress and displacement analysis for steady-state thermal load. A maximum stress of 249.7 MPa occurs at the topmost part of the water tube of the CBSG module. The locations of the structural integrity evaluation sections for dead weight, pressure, and steady-state thermal load and the corresponding nodes are shown in sections A through C of Figs. 11 through 13.

Table 5 and Table 6 show the structural integrity evaluation results of the CBSG module and water connection header. The structural integrity for the corresponding evaluation sections of the integrated CBSG module and water connection header is evaluated for the design condition and the service level A condition. The evaluation results satisfy the ASME allowable stress limits and have a design margin of more than 0.44 for operating level A condition as shown in Table 6.



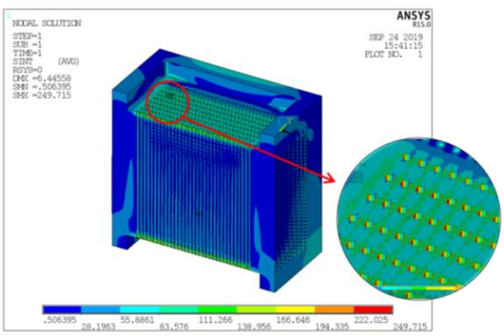
Section-A : Node (n28698 – n28606)

Fig. 11 Structural integrity evaluation section of CBSG module (section A, dead weight)



Section-B : Node (n25504 – n42645)

Fig. 12 Structural integrity evaluation section of CBSG module (section B, pressure)



Section-C : Node (n43710 – n40879)

Fig. 13 Structural integrity evaluation section of CBSG module (section C, thermal load)

Table 5 Structural integrity check results of CBSG module (design condition)

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress (MPa)	Margin	Temperature (°C)	C&S
Section-A	Inner (28698)	Pm	20.71	116.49	4.62	320.9	ASME Sec III Div5-HBA
		PL + Pb	24.30	174.74	6.19		
	Outer (28606)	Pm	20.71	116.49	4.62	320.9	ASME Sec III Div5-HBA
		PL + Pb	17.58	174.74	8.94		
Section-B	Inner (25504)	Pm	58.45	116.49	0.99	320.9	ASME Sec III Div5-HBA
		PL + Pb	104.64	174.74	0.67		
	Outer (42645)	Pm	58.45	116.49	0.99	320.9	ASME Sec III Div5-HBA
		PL + Pb	29.47	174.74	4.93		
Section-C	Inner (43710)	Pm	31.80	116.49	2.66	320.9	ASME Sec III Div5-HBA
		PL + Pb	38.00	174.74	3.60		
	Outer (40879)	Pm	31.80	116.49	2.66	320.9	ASME Sec III Div5-HBA
		PL + Pb	25.79	174.74	5.78		

Table 6 Structural integrity check results of CBSG module (Service level A condition)

Sections	Nodes	Linearized Stress	Calculated Stress (MPa)	Allowable Stress (MPa)	Margin	Temperature (°C)	C&S
Section-A	Inner (28698)	PL + Pb +Pe + Q	134.23	414.00	2.08	320.9	ASME Sec III Div5-HBA
		Thermal Ratcheting	113.18	2069.20	17.28		
	Outer (28606)	PL + Pb +Pe + Q	65.16	414.00	5.35	320.9	ASME Sec III Div5-HBA
		Thermal Ratcheting	50.59	2069.20	39.90		
Section-B	Inner (25504)	PL + Pb +Pe + Q	114.45	414.00	2.62	320.9	ASME Sec III Div5-HBA
		Thermal Ratcheting	20.35	733.14	35.03		
	Outer (42645)	PL + Pb +Pe + Q	32.78	414.00	11.63	320.9	ASME Sec III Div5-HBA
		Thermal Ratcheting	20.84	733.14	34.18		
Section-C	Inner (43710)	PL + Pb +Pe + Q	287.25	414.00	0.44	320.9	ASME Sec III Div5-HBA
		Thermal Ratcheting	249.67	1347.50	4.40		
	Outer (40879)	PL + Pb +Pe + Q	161.30	414.00	1.57	320.9	ASME Sec III Div5-HBA
		Thermal Ratcheting	136.34	1347.50	8.88		

3. Conclusions

Detailed stress analysis and structural integrity evaluation including porous holes inside the CBSG module were performed on the dimensions of the modified copper bonded steam generator. The structural integrity evaluation applies the design criteria of ASME B&PV Code Sec. III, Division 5-HBA and HBB according to the maximum temperature of the evaluation section [4,5]. As a result of the structural integrity evaluation for the design condition and the service level A condition, the modified CBSG structure satisfied the ASME allowable stress limits. For further detailed structural integrity evaluation of CBSG in the future, transient thermal analysis considering transient thermal loads and seismic analysis should be performed.

Acknowledgements

This study was supported by the National Research Foundation of Korea grant funded by the Korea government (Ministry of Science, ICT and Future Planning).

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