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Effect of Weld Properties on the Thermo-Mechanical Structural Analysis of Prototype Process Heat Exchanger

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Abstract: A PHE (Process Heat Exchanger) is a key component in transferring the high temperature heat generated from a VHTR (Very High Temperature Reactor) to the chemical reaction for the massive production of hydrogen. A performance test on a small-scale PHE prototype made of Hastelloy-X is currently under way a small-scale gas loop at the Korea Atomic Energy Research Institute. Previous research on the elastic high-temperature structural analysis of the small-scale PHE prototype has been performed using the parent material properties over the whole region. In this study, an elastic-plastic high-temperature structural analysis considering the mechanical properties in the weld-affected zone was performed, from a macroscopic viewpoint.

Keywords: Process Heat Exchanger (PHE), High-Temperature Structural Analysis, Very High Temperature Reactor (VHTR), Mechanical Properties in Weld-Affected Zone

1 Introduction

Hydrogen is considered a promising future energy solution because it is clean, abundant, and storable, and has high-energy density. One of the major challenges in establishing a hydrogen economy is how to produce massive quantities of hydrogen in a clean, safe, and economical way. Among the various hydrogen production methods, nuclear hydrogen production is garnering attention worldwide since it can produce hydrogen, a promising energy carrier, without an environmental burden. Research demonstrating the massive production of hydrogen using a VHTR (Very High Temperature Reactor) designed for operation at up to 950° has been actively carried out worldwide, including in the USA, Japan, France, and the Republic of Korea (ROK). See Lee(2009), US DOE(2009), and AREVA(2007).

The nuclear hydrogen program in the Republic of Korea (ROK) is strongly considering producing hydrogen by employing a Sulfur-Iodine (SI) water-splitting hydro-

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gen production process. See Chang(2007) and Shin(2009). An intermediate loop that transports the nuclear heat to the hydrogen production process is necessitated for the nuclear hydrogen program as shown in Fig. 1. In the intermediate loop, whereas the HGD (Hot Gas Duct) provides a route of high-temperature gas from the nuclear reactor to the IHX (Intermediate Heat Exchanger), the PHE (Process Heat Exchanger) is a component that utilizes the nuclear heat from the nuclear reactor to provide hydrogen. PHE is used in several processes such as nuclear steam reforming, nuclear methanol, nuclear steel, nuclear oil refinery, and nuclear steam. See Lee(2009). The PHE of the SO3 decomposer, which generates the process gas such as H_2O, O_2, SO_2, and SO_3 at a very high-temperature, is a key component in the nuclear hydrogen program in the ROK.

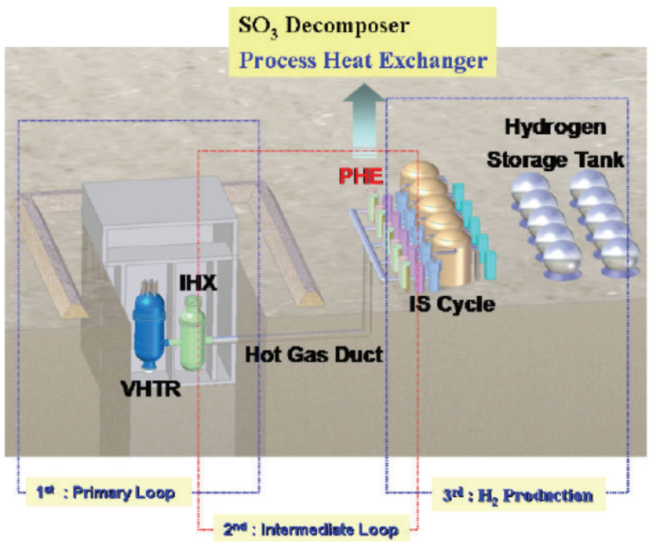

Figure 1: Nuclear hydrogen system

Recently, KAERI (Korea Atomic Energy Research Institute) established a small-scale gas loop for the performance test of VHTR components and also manufactured a small-scale PHE prototype made of Hastelloy-X. A performance test on the PHE prototype is under way in the small-scale gas loop at KAERI as shown in Fig. 2. To evaluate the high-temperature structural integrity of the PHE prototype under the test condition of the gas loop, a series of structural analyses on the PHE prototype was carried out using parent material properties over the whole region. See Song(2010,2011a,2011b). In this study, a high-temperature structural analysis considering mechanical properties in the weld affected zone was performed.

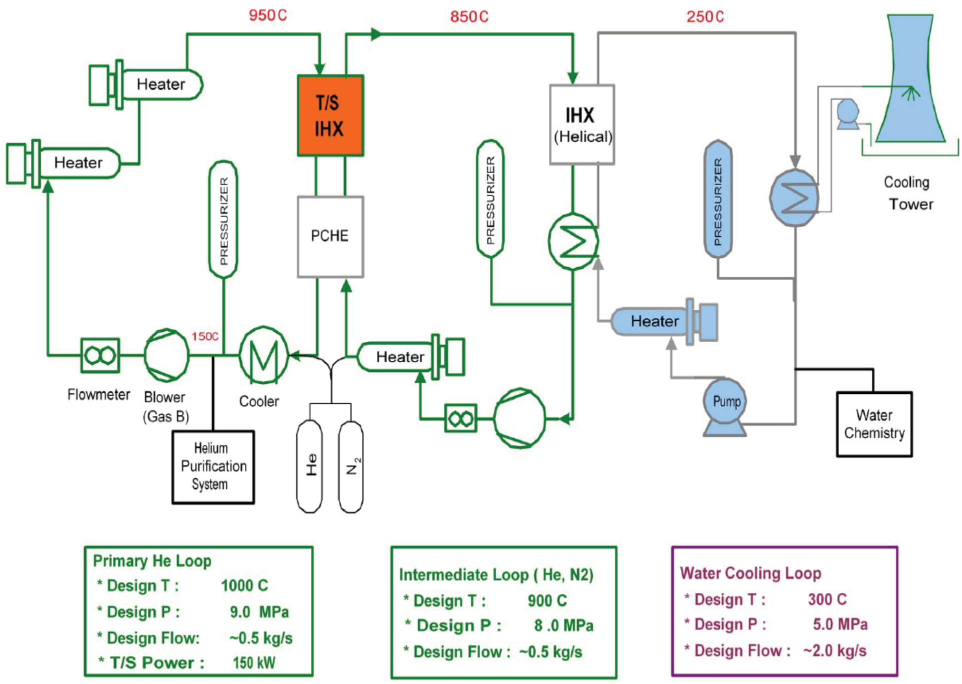

Figure 2: KAERI's small-scale gas loop

2 FE modeling

2.1 Structure of a PHE prototype

A schematic view of the inside of the PHE prototype is illustrated in Fig. 3, and detailed shapes of the flow plates for the primary and secondary flows are shown in Fig. 4. The PHE prototype is designed as a hybrid concept to meet the design pressure requirements between a nuclear system and hydrogen production system. See Kim(2008). That is to say, the hot helium gas channel has a compact semicircular shape, similar to a printed circuit heat exchanger, and is designed to withstand the high-pressure difference between loops, while the sulfuric acid gas channel has a plate fin shape with sufficient space to install and replace the catalysts for sulfur trioxide decomposition.

All parts of the PHE prototype are made of Hastelloy-X of high-temperature alloy. Grooves of 1.0 mm diameter are machined into the flow plate for the primary coolant (helium gas). Waved channels are bent into the flow plate for the secondary coolant (SO_3 gas). Twenty flow plates for the primary and secondary coolants are stacked in turn, and are bonded along the edge of the flow plate using a solid-state diffusion bonding method. After stacking and bonding the flow plates, the outside of the PHE is covered with a Hastelloy-X plate of 3.0 mm in thickness. Figure 5 shows the set-up of the PHE prototype in the gas loop.

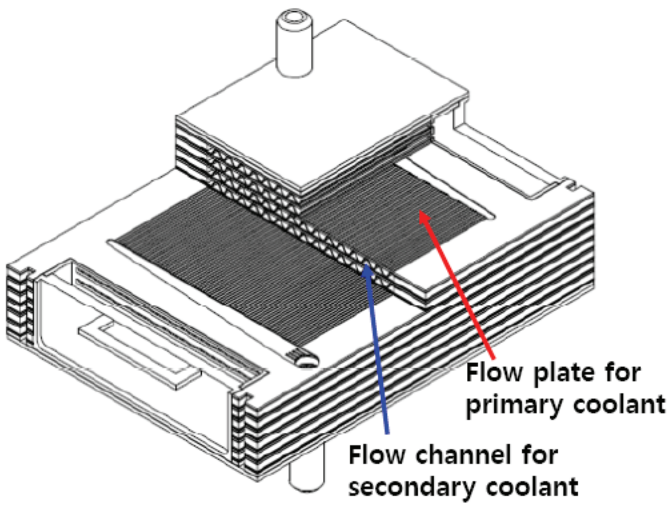

Figure 3: Inside of process heat exchanger

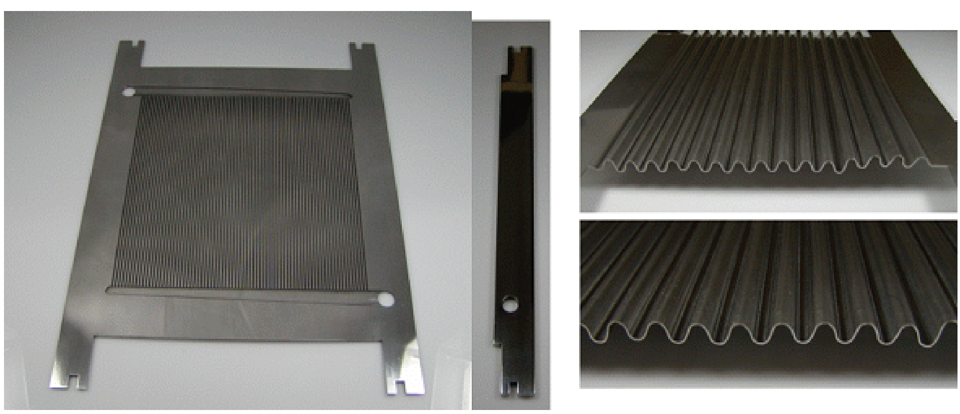

Figure 4: Flow plates

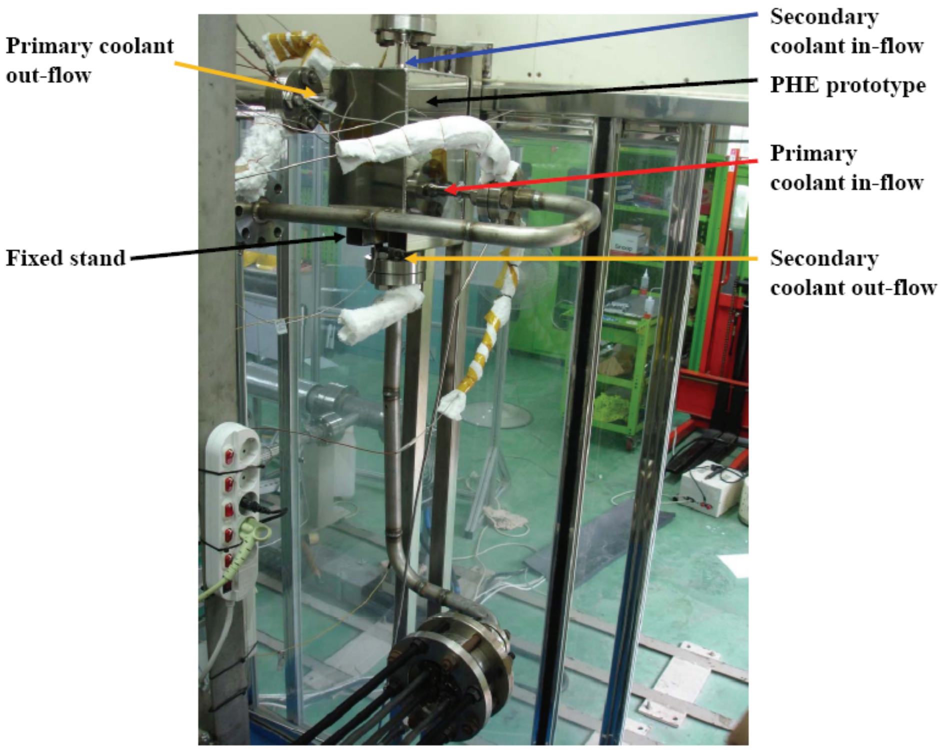

Figure 5: Set-up of PHE prototype in the gas loop

2.2 FE modeling

Figure 6 shows the overall dimensions and each part of the PHE prototype from the 3-D CAD modeling. Based on Fig. 6, FE modeling using I-DEAS/TMG Ver. 6.1 was carried out and analyses such as a thermal analysis and structural analysis were carried out using ABAQUS Ver. 6.8. See ABAQUS (2009) and I-DEAS/TGM(2009). For the sake of simplicity and an understanding of the overall behavior of the PHE prototype, the FE model is composed of 546,764 2-D linear quadrilateral shell elements and 911,012 3-D linear solid elements made of 830,304 brick elements, 80,348 wedge elements, and 360 tetrahedron elements.

For the FE model, the inflow/outflow of the primary and secondary coolants and the boundary conditions of the primary/secondary flow plates for a thermal analysis under a test condition of 850° were shown in Song(2010).

The weld-affected zones of the PHE prototype are modeled as shown in Fig. 7,

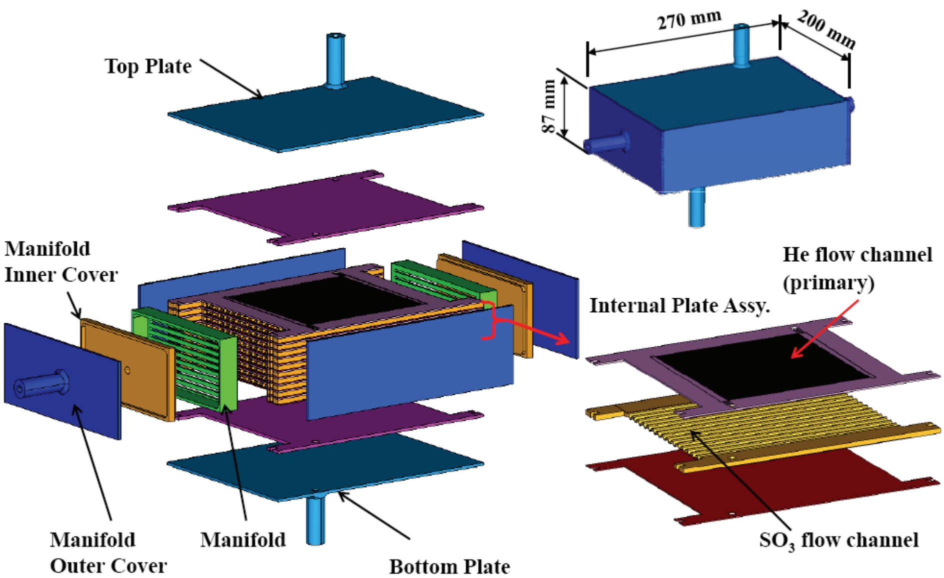

Figure 6: Parts of the PHE prototype

where the weld bead along the edges and heat affected zone (HAZ) are represented. The mechanical properties in the weld-affected zones including a heat affected zone were obtained by the instrumented indentation method. See Song(2011c) and ISO TR29381(2008).

According to the test condition of the helium gas loop, in/out-flow pressures for the primary and secondary coolant are 3.0MPa and 0.1MPa, respectively.

3 Analysis

3.1 Thermal analysis

Figure 8 shows the thermal analysis results of the PHE prototype inside/outside under the fixed test condition of the helium gas loop. According to Fig. 8, the temperature distribution is nearly symmetrical along the vertical axis, and the maximum temperature of the outside represents about 837.15°.

3.2 High temperature elastic/elastic-plastic structural analysis using parent material properties

Table 1 and Fig. 9 show the mechanical properties of Hastelloy-X and bilinear stress-strain curve, respectively. See the Hastelloy-X website. Based on the thermal

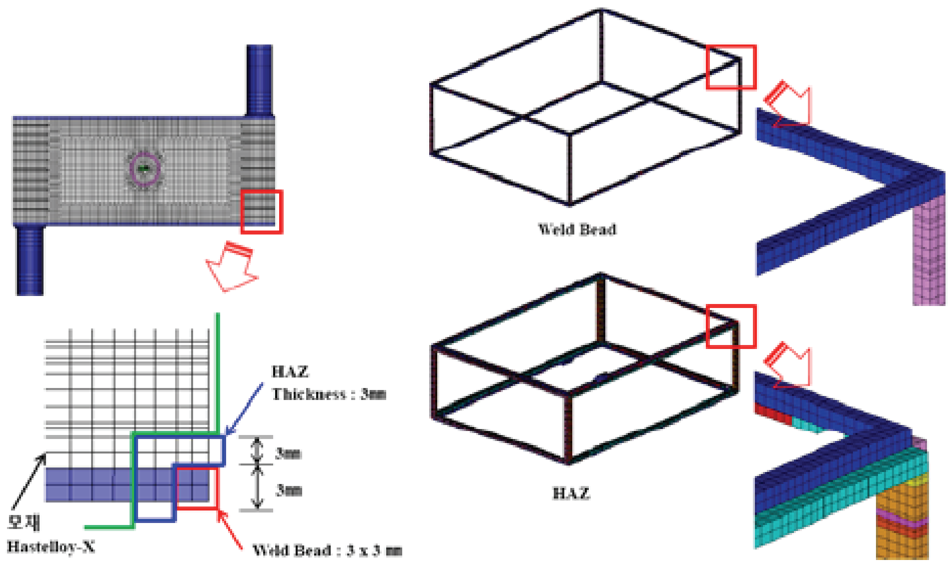

Figure 7: FE model in the weld affected zone

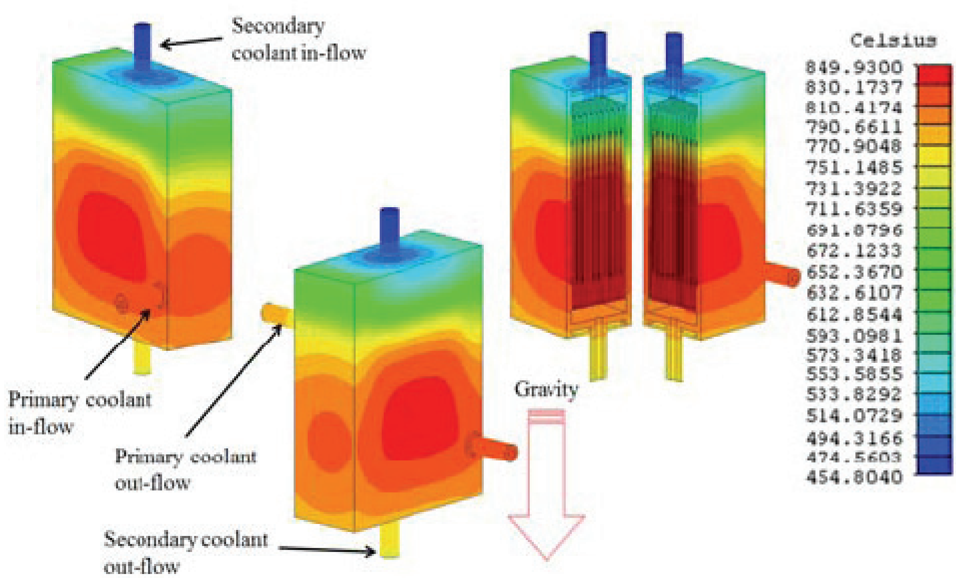

Figure 8: Temperature distribution of outside PHE

analysis results, a high-temperature elastic structural analysis was performed by imposing a displacement constraint condition at each end of the primary/secondary flow pipelines as shown in Fig. 10, considering the pipeline stiffness of the small-scale gas loop. See Song(2011b).

Table 1: Mechanical properties of Hastelloy-X

Average Tensile Data*

Form	Condition	Test Temperature °F	Test Temperature °C	Ultimate Tensile Strength Ksi	Ultimate Tensile Strength MPa	Yield Strength at 0.2% Offset Ksi	Yield Strength at 0.2% Offset MPa	Elongation in 2 in. (50.8 mm) %
Sheet 0.045-0.060 in. (1.1 1.5 mm) thick	Bright Annealed at 2150°F (1177°C), Hydrogen Cooled	Room		111.2	767	54.9	379	44
		1000	538	89.0	614	35.6	245	49
		1200	649	84.2	581	35.4	244	54
		1400	760	67.1	463	34.4	237	53
		1600	871	44.9	310	28.1	194	59
		1800	982	25.6	177	13.2	91	66
		2000	1093	14.0	97	6.3	43	60

* Strain rate was 0.005-inch/inch/minute to 0.2% yield point and 0.5-inch/inch/minute to failure.

Figure 11 shows the elastic stress distribution at the pressure boundary of the PHE prototype using parent material properties. The maximum local stress of 272.33 MPa occurs around the edge between the top plate and side plate exceeds the yield stress of the parent material (239.7 MPa at 746°) by 13.6%.

Figure 12 shows the elastic-plastic stress distribution at the pressure boundary of the PHE prototype using parent material properties. According to Fig. 12, the maximum local stress of 242.60 MPa occurs around the edge between the top plate and side plate also exceeds the yield stress of the parent material (237.63 MPa at 750°) by 2.09%.

3.3 High temperature elastic/elastic-plastic structural analysis using mechanical properties in weld-affected zone

Based on the thermal analysis results, a high-temperature elastic structural analysis was performed using mechanical properties in the weld affected zone. Table 2 shows the normalized mechanical properties of Hastelloy-X in the weld region obtained by the instrumented indentation technique. See Song(2011c).

The stress distribution at the pressure boundary of the PHE prototype using material properties in the weld zone is same as Fig. 11 because of using a same elastic

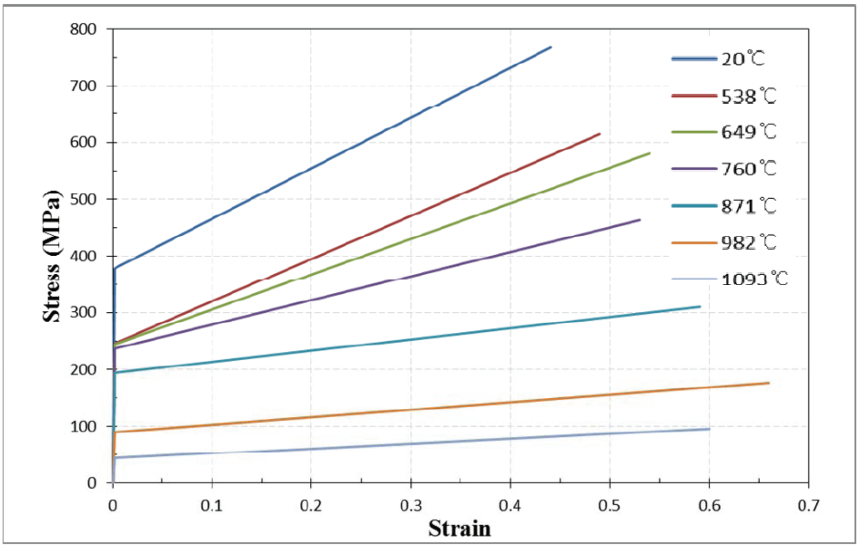

Figure 9: Bilinear stress-strain curves for elastic-plastic analysis

Table 2: Normalized mechanical properties of Hastelloy-X in weld region

	Yield stress	Tensile strength
Parent material	1.000	1.000
Heat affected zone (HAZ)	0.962	0.998
Weld	1.094	1.120

modulus in the elastic analysis. The maximum local stress of 272.33 MPa around the edge between the top plate and side plate exceeds the yield stress of the weld material (269.5 MPa at 746) by only 1.02%. The degree of exceeding the yield stress in the weld zone is decreased for the elastic analysis using the weld material properties. The reason for this is attributed to a larger yield stress in the weld than in the parent material.

Figure 13 shows the elastic-plastic stress distribution at the pressure boundary of the PHE prototype using the mechanical properties in the weld-affected zone. According to Fig. 13, the maximum local stress of 266.19 MPa occurs around the edge between the top plate and side plate, in that exceeds the yield stress of the weld material (263.23 MPa at 740.70°) by 1.12%. The degree of exceeding the

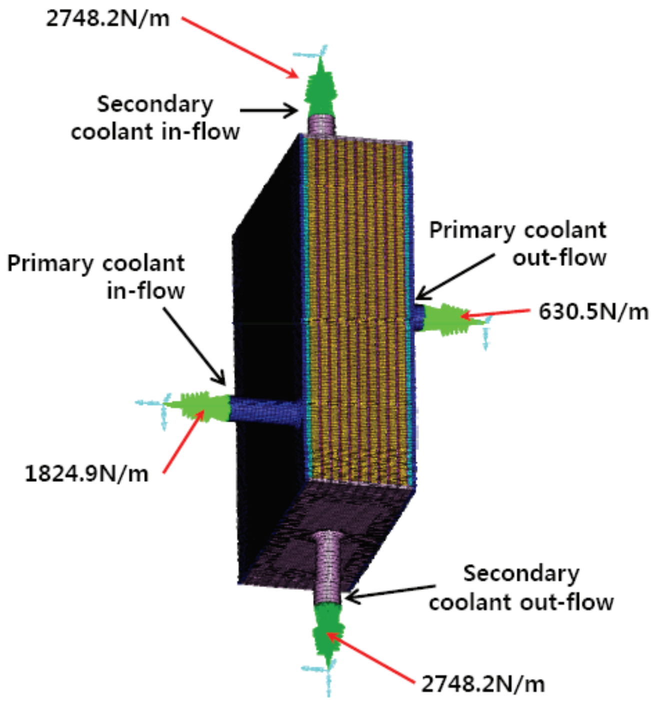

Figure 10: Displacement constraints for structural analysis

yield stress in weld zone is decreased for the elastic-plastic analysis using weld material properties, when compared to the result using parent material properties shown in Fig. 12. The reason for this is also attributed to larger yield stress in weld than in parent material.

4 Summary

To find the high-temperature structural integrity of the PHE prototype from a macroscopic viewpoint, a series of structural analyses on the PHE prototype was carried out using the parent material properties over the whole region. In this study, an elastic/elastic-plastic high-temperature structural analysis considering the mechanical properties in the weld-affected zone was performed, and the results compared with those using the parent material properties. As a result of the analysis, the following conclusions are drawn.

1. When using the mechanical properties in the weld-affected zone, the maximum stress may be different from using parent material properties.

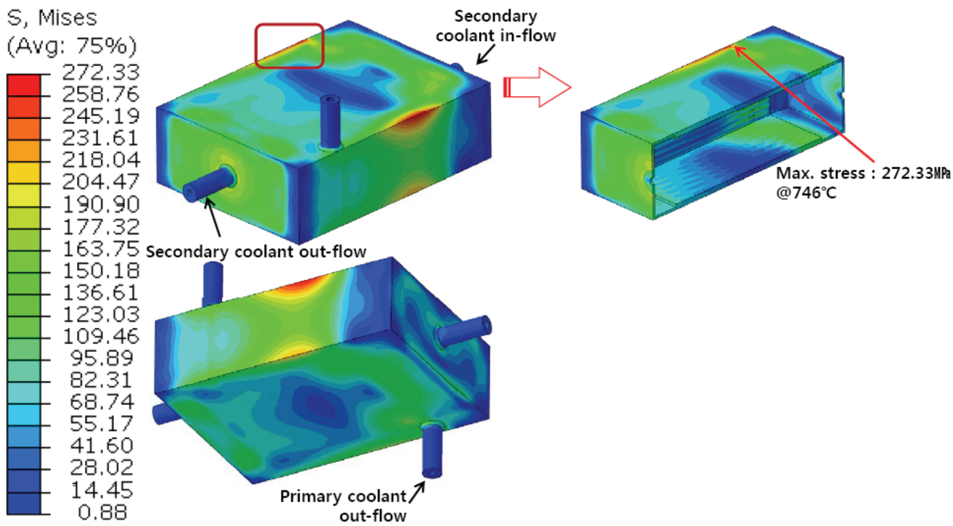

Figure 11: Elastic stress contour using parent material properties

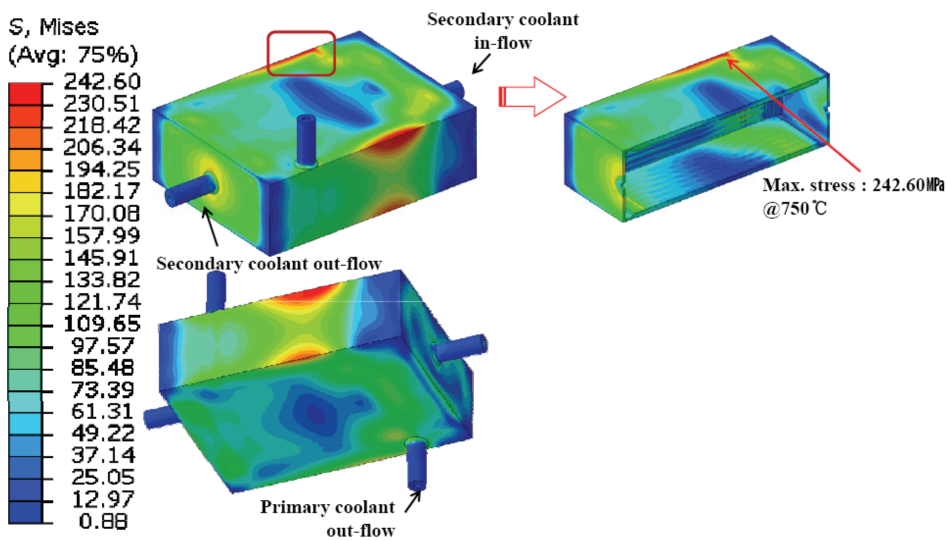

Figure 12: Elastic-plastic stress contour using parent material properties

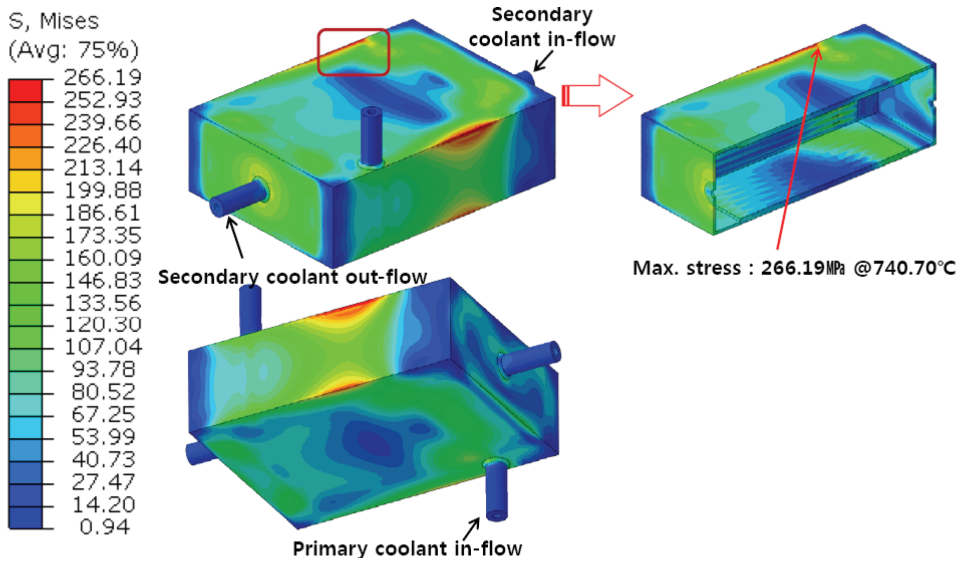

Figure 13: Elastic-plastic stress contour using mechanical properties in the weld-affected zone

2. The degree of exceeding the yield stress becomes smaller due to the increase of yield stress of the weld material.

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