Structural Analysis on a Small-Scale PHE Prototype under High-Temperature Gas Loop Condition

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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 in a small-scale nitrogen gas loop at the Korea Atomic Energy Research Institute. Previous research on the 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, high-temperature structural analysis considering the mechanical properties in the weld-affected zone was performed.**

Keywords- Process Heat Exchanger; High-Temperature Structural Analysis; Heat Affected Aone; Weld

I. 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 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) [1-3].

The nuclear hydrogen program in the ROK is strongly considering producing hydrogen by employing a Sulfur-Iodine (SI) water-splitting hydrogen production process [4-5]. An intermediate loop that transports the nuclear heat to the hydrogen production process is necessitated for the nuclear hydrogen program. In the intermediate loop, whereas the hot gas duct provides a route of high-temperature gas from the nuclear reactor to the 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 [1]. The PHE of the SO_3 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.

Recently, KAERI (Korea Atomic Energy Research Institute) has established a small-scale nitrogen gas loop for the performance test of VHTR components, and also has manufactured a small-scale PHE prototype made of Hastelloy-X. A performance test on the PHE prototype is underway in the small-scale gas loop at KAERI. 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 [6-10]. By the way, recently mechanical properties, such as yield stress and tensile strength were obtained [11] using a ball indentation technique [12]. In this study, a high-temperature structural analysis considering the mechanical properties in the weld-affected zone was performed.

II. FINITE ELEMENT MODELLING

A schematic view of the inside of the PHE prototype is illustrated in Fig.1. The PHE prototype is designed as a hybrid concept to meet the design pressure requirements between a nuclear system and hydrogen production system [13]. That is to say, the hot nitrogen 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.

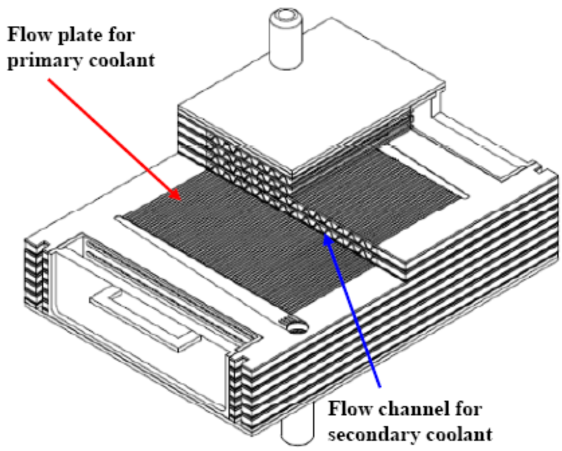

Fig. 1 Inside of a small-scale PHE prototype

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 (nitrogen 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 thickness. Fig. 2 shows the set-up of the PHE prototype in the gas loop.

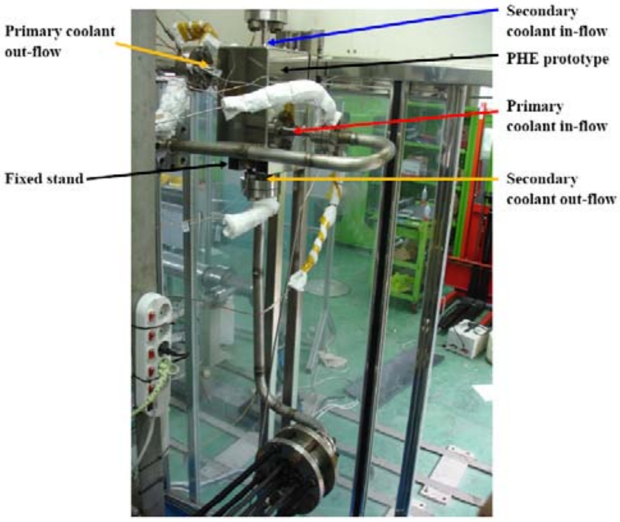

Fig. 2 Set-up of a PHE prototype in the gas loop

Fig. 3 shows the overall dimensions and each part of the PHE prototype from the 3-D CAD modelling. Based on Fig. 3, FE modelling using I-DEAS/TMG Ver. 6.1 [14] was carried out, and analyses such as a thermal analysis and structural analysis were carried out using ABAQUS Ver. 6.8 [15]. In 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 [7]. The weld-affected zones of the PHE prototype are modelled as shown in Fig.4, where the weld bead along the edges and heat affected zone (HAZ) are represented. The mechanical properties in the weld-affected zones including a HAZ were obtained by the instrumented indentation method [12].

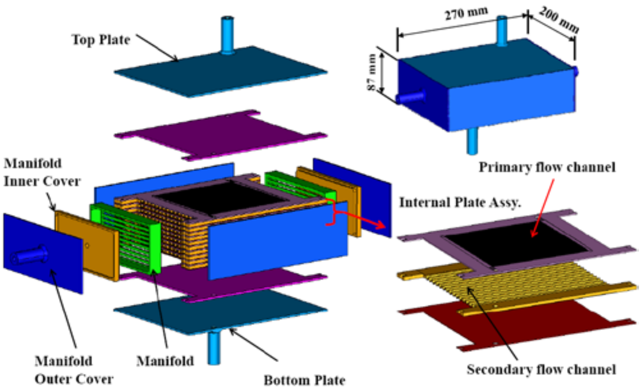

Fig. 3 Overall dimensions and parts of the PHE prototype

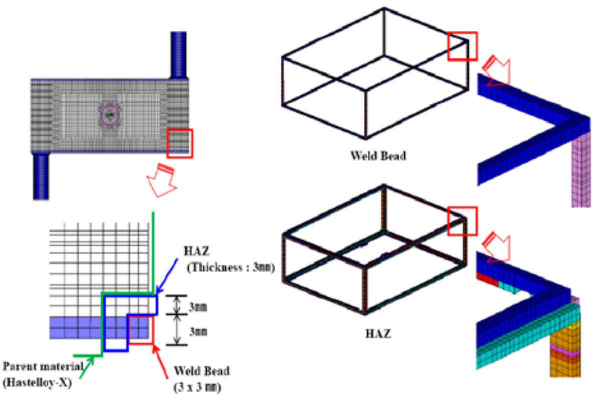

Fig. 4 Finite element model in the weld affected zone

III. ANALYSIS

A. *Thermal Analysis*

Fig. 5 shows the thermal analysis results of the PHE prototype inside/outside under the test condition of a small-scale nitrogen gas loop [7]. According to Fig. 5, the temperature distribution is nearly symmetrical along the vertical axis, and the maximum temperature of the outside is about 837.15℃. Material properties of Hastelloy-X and bilinear stress-strain curve shown in Fig. 6 are in Hastelloy-X website [16].

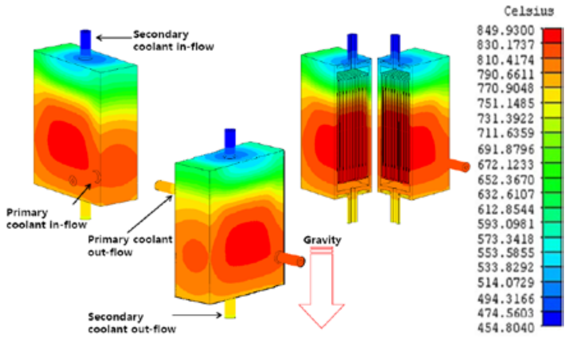

Fig. 5 Temperature contour of outside PHE prototype

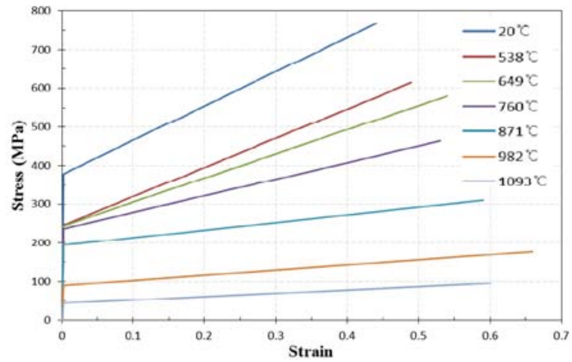

Fig. 6 Bilinear stress-strain curve of Hastelloy-X

B. *Boundary Condition for Structural Analysis*

Based on the thermal analysis results, a high-temperature elastic/elastic-plastic structural analysis was performed imposing displacement constraint condition at each end of the primary/secondary flow pipelines as shown in Fig. 7, considering the pipeline stiffness of the small-scale nitrogen gas loop [9].

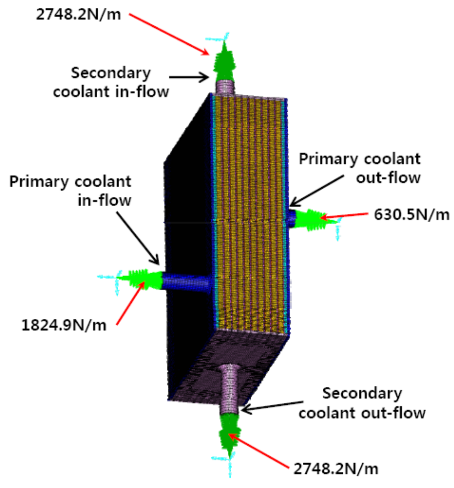

Fig. 7 Boundary condition for structural analysis

C. Pressure Boundary Condition for Structural Analysis

According to the test condition of the small-scale nitrogen gas loop, in/out-flow pressure for the primary and secondary coolant is 3.0MPa and 0.1MPa, respectively [7].

D. Structural Analysis Using Parent Material Properties

Fig. 8 shows the elastic stress contour at the pressure boundary of the PHE prototype using parent material properties of Hastelloy-X. The maximum local stress of 272.33 MPa around the edge between the top plate and side plate exceeds the yield stress of the parent material (237.9 MPa at 746℃) by 14.5%. Fig. 9 shows the elastic-plastic stress contour at the pressure boundary of the PHE prototype using parent material properties of Hastelloy-X. According to Fig. 9, the maximum local stress of 242.60 MPa around the edge between the top plate and side plate also exceeds the yield stress of the parent material (237. 6 MPa at 750℃) by 2.1%.

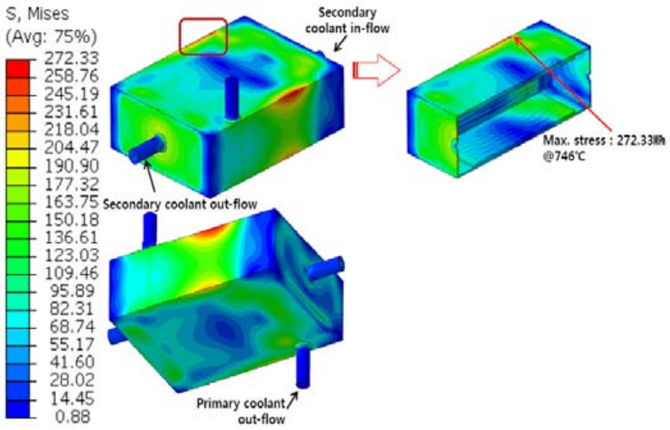

Fig. 8 Stress contour using parent material properties from an elastic analysis

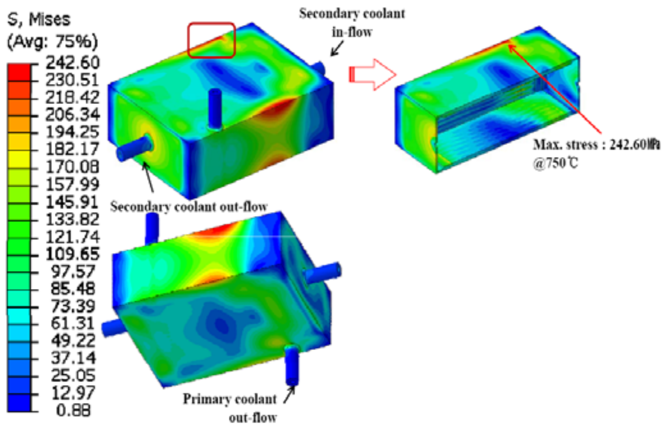

Fig. 9 Stress contour using parent material properties from an elastic-plastic analysis

E. Structural Analysis Using Weld Material Properties

Table Ⅰ represents the normalized mechanical properties of Hastelloy-X in the weld region obtained [11] using an instrumented indentation technique. The stress distribution at the pressure boundary of the PHE prototype using material properties of Hastelloy-X in the weld zone is the same as that shown in Fig.8 because of the use of the same elastic 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 (262.9 MPa at 746) by only 3.6%.

TABLE Ⅰ

NORMALIZED MECHANICAL PROPERTIES OF HASTELLOY-XIN WELD-AFFECTED ZONE

	Yield Stress	Tensile Strength
Parent Material	1.000	1.000
Heat Affected Zone	0.962	0.998
Weld Zone	1.094	1.120

Fig. 10 shows the elastic-plastic stress contour at the pressure boundary of the PHE prototype using mechanical properties of Hastelloy-X in the weld-affected zone. According to Fig. 10, the maximum local stress of 266.19 MPa around the edge between the top plate and side plate also exceeds the yield stress of the weld material (263.2 MPa at 740.70℃) by 1.1%.

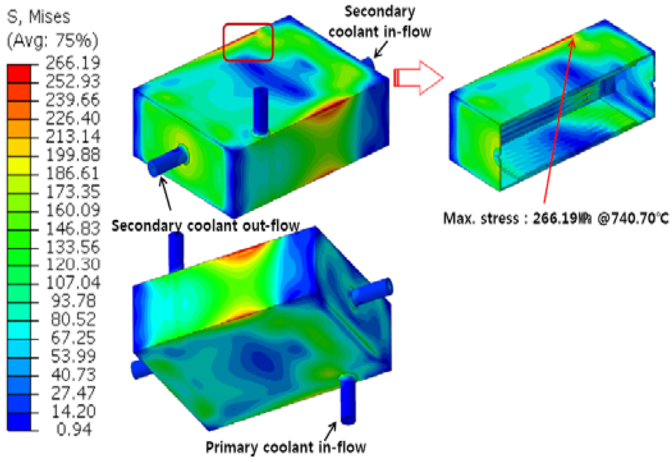

Fig. 10 Stress contour using weld material properties from an elastic-plastic analysis

F. Discussion on the Analysis Results

From the above analysis results, the following interesting observation was found. When we consider the mechanical properties of Hastelloy-X in the weld-affected zone, the degree of exceeding the yield stress becomes smaller due to the increase of yield stress of the weld material. Therefore, considering the design margin or safety margin, a different judgment may be made when considering the mechanical properties of Hastelloy-X in the weld zone.

IV. SUMMARY

A high-temperature structural analysis considering the mechanical properties of Hastelloy-X in the weld-affected zone was performed, and the results were compared with those using the parent material properties of Hastelloy-X. As the result of the analysis, the following conclusions were drawn:

1. The degree of exceeding the yield stress becomes smaller due to the increase of yield stress of Hastelloy-X at weld bead.

2. Considering the design margin or safety margin, a different judgment may be made when considering the mechanical properties of Hastelloy-X in the weld zone.

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