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Structural Behavior Analysis on a Small-scale PCHE Prototype under High-temperature Gas Loop Conditions

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Abstract: The IHX (Intermediate Heat Exchanger) of a VHTR (Very High Temperature Reactor) transfers 950° heat generated from the VHTR to a hydrogen production plant. The Korea Atomic Energy Research Institute (KAERI) has manufactured a small-scale prototype of a PCHE (Printed Circuit Heat Exchanger) under consideration as a candidate of the IHX. In this study, as a part of high-temperature structural integrity evaluation of the small-scale PCHE prototype, we carried out a macroscopic structural behavior analysis including structural analysis modeling and thermal/elastic structural analysis under small-scale gas loop test conditions as a precedent study to a performance test. The results obtained in this study will be compared with the test results of the small-scale PCHE and also will be applied to the design of a medium-scale PCHE prototype.

Keywords: Printed Circuit Heat Exchanger (PCHE), High-temperature Structural Analysis, Very High Temperature Reactor (VHTR), Intermediate Heat Exchanger (IHX)

1 1 Introduction

Hydrogen is considered a promising future energy solution as 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 various hydrogen production methods, nuclear hydrogen production is garnering worldwide attention since it can produce hydrogen without environmental burden. Researches to demonstrate 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).

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The nuclear hydrogen program in the ROK is strongly considered for the production of hydrogen by sulfur-iodine water-split hydrogen production processes. 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, the IHX (Intermediate Heat Exchanger) of the VHTR transfers 950° heat generated from the VHTR to a hydrogen production plant through a hot gas duct, while the PHE (Process Heat Exchanger) is a component that utilizes the nuclear heat from the nuclear reactor to produce hydrogen. A PCHE (Printed Circuit Heat Exchanger) is considered as a candidate of the IHX of the nuclear hydrogen system in the ROK.

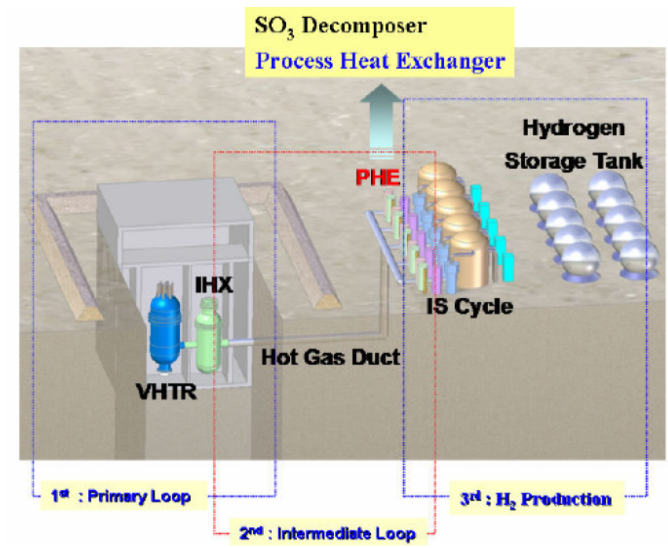

Figure 1: Nuclear Hydrogen System

Recently, the Korea Atomic Energy Research Institute (KAERI) has established a small-scale gas loop for a performance test of VHTR components, as shown in Fig. 2, and has manufactured a small-scale prototype of the PCHE for testing in a gas loop.

In this study, to investigate the macroscopic structural characteristics and behavior of the PCHE prototype under the test conditions of a small-scale gas loop, FE (finite element) modeling, thermal analysis, and structural analysis on the PCHE prototype are conducted as a precedent study. The results obtained in this study will be compared with the test results of the small-scale PCHE and also applied to the design of the medium-scale PCHE prototype.

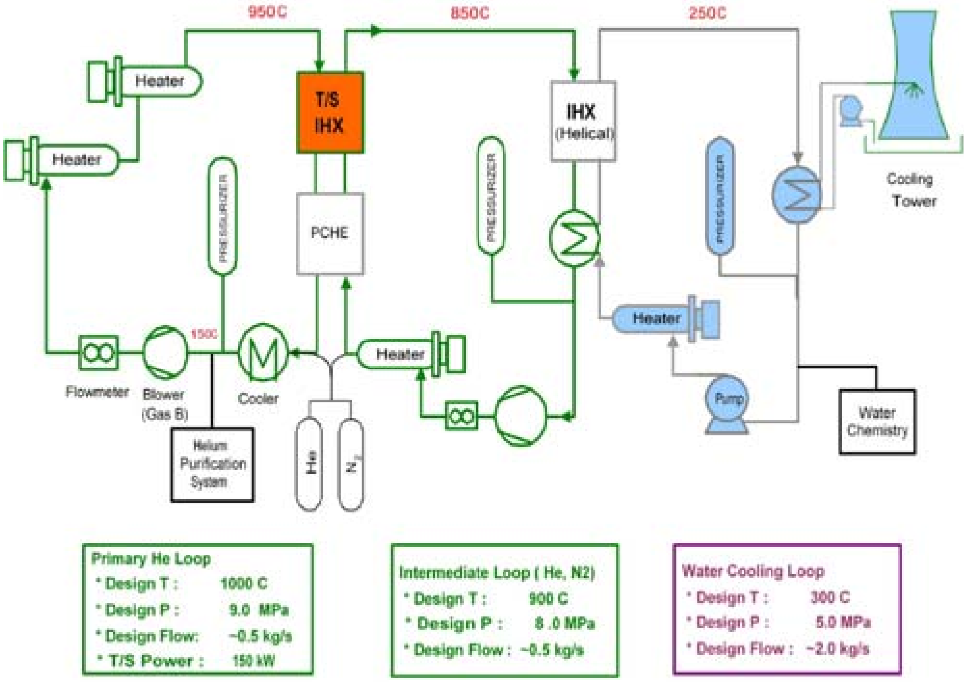

Figure 2: KAERI's Small-scale Gas Loop

2 FE modeling

A schematic view of the PCHE prototype from 3-D CAD modeling is illustrated in Fig. 3.

All parts of the PCHE prototype are made from Stainless Steel and Inconel800HT of very high temperature material. Grooves are formed by chemical etching in the flow plates, which are shown in Figs. 4 and 5, respectively. For the sake of simplicity and computational efficiency, the real flow plates with a zigzag flow path are simplified as shown in Figs. 6 and 7 with a straight path in an FE model of the PCHE prototype. And for the simplified flow plate models temperature distribution mappings, as shown in Figs. 8 and 9, are used as input data for thermal analysis.

Based on Fig. 3, FE modeling using I-DEAS/TMG Ver. 6.1 is carried out as shown in Fig. 10 and analyses such as thermal analysis and thermal expansion/structural analysis are carried out using ABAQUS Ver. 6.8. See I-DEAS/TGM(2009) and ABAQUS (2009).

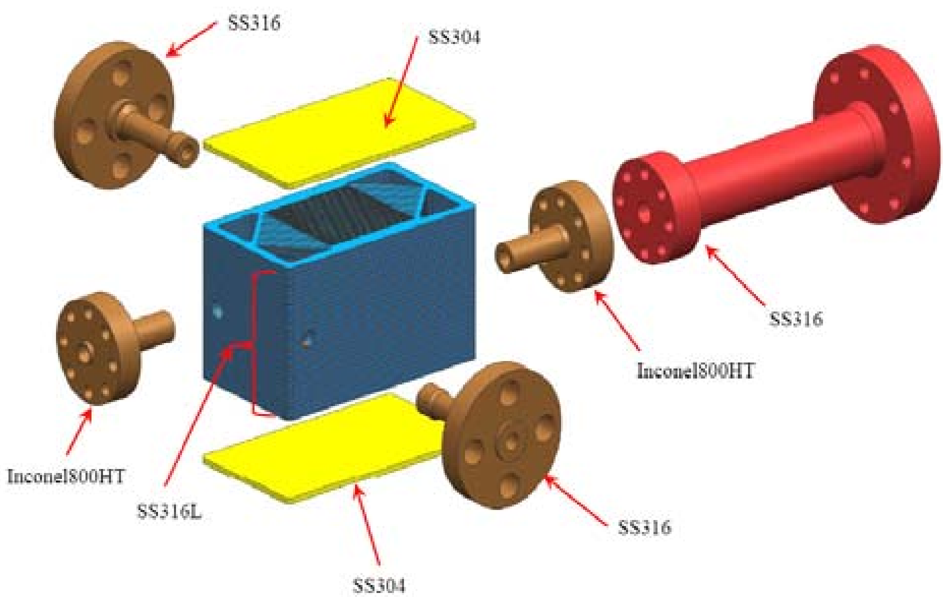

Figure 3: Parts of PCHE prototype

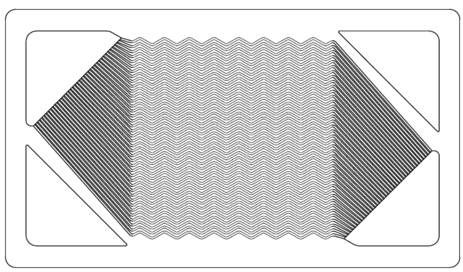

Figure 4: Flow plate for high temperature gas

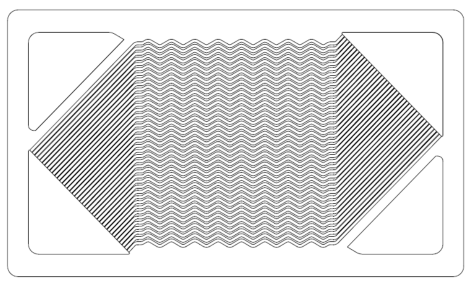

Figure 5: Flow plate for water

3 Analysis

3.1 Thermal analysis

Figure 11 shows the thermal analysis results of the PCHE prototype outside under the test conditions of a gas loop. See Song(2010). According to Fig. 11, the maximum temperature of the PCHE pressure boundary is about 620°C except for the gas inlet pipe and flanges.

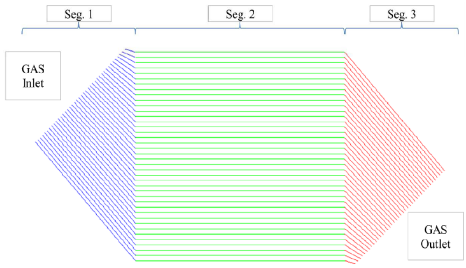

Figure 6: Simplified flow plate for gas

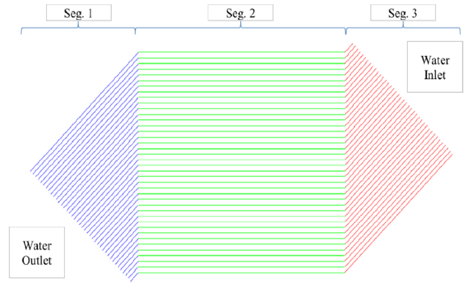

Figure 7: Simplified flow plate for water

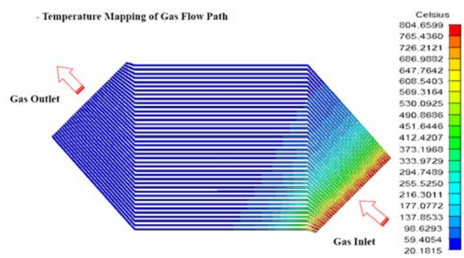

Figure 8: Temperature mapping of gas flow

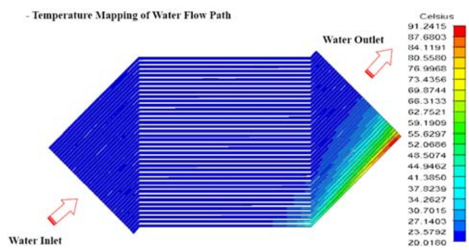

Figure 9: Temperature mapping of water flow

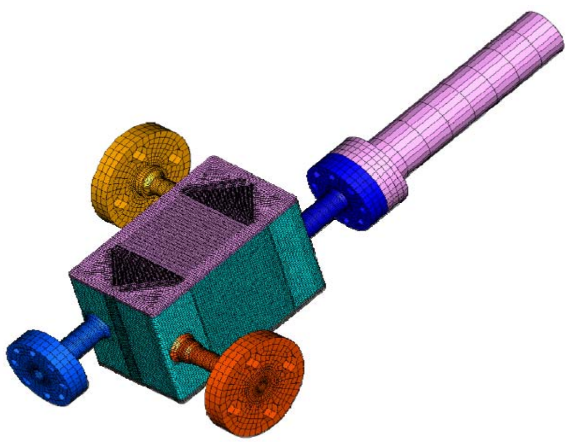

Figure 10: FE model of PCHE prototype

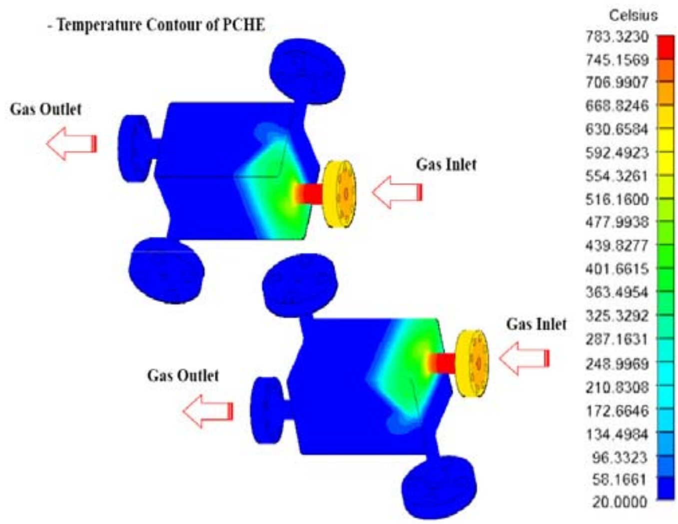

Figure 11: Temperature contour of PCHE

3.2 *Structural boundary condition*

Figure 12 shows the boundary condition for the high-temperature structural analysis, where all DOFs at the end of the gas inlet pipe are fixed, and the DOFs at the other flanges are assumed as free end due to the connection of very flexible pipes.

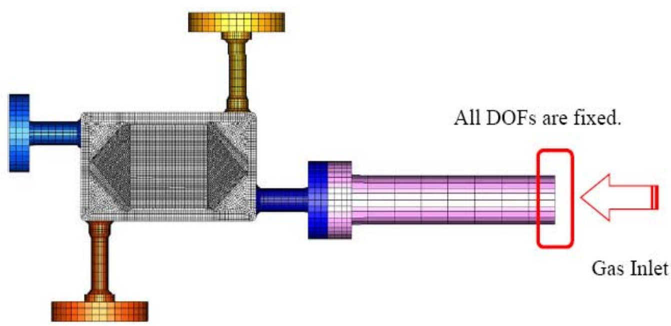

Figure 12: Structural boundary condition

3.3 *High-temperature structural analysis*

Using the structural boundary condition shown in Fig. 12 and the temperature contour of PCHE prototype shown in Fig. 11, we carried out an elastic structural analysis under the test condition of the PCHE prototype. In this study, we used a de-coupled method in the elastic structural analysis because our workstation did not work due to too many meshes in the FE model. Figure 13 shows the overall stress distribution at the pressure boundary of the PCHE prototype, and Fig. 14 shows the stress distribution on the top plate under the tested temperature condition. According to Fig. 14, high stress occurred near the gas inlet chamber on the top plate of the PCHE prototype, and the maximum local stress on the top plate was about 689.7 MPa. Fig. 15 shows the detailed stress distribution in the gas inlet chamber. According to Fig. 15, a very high stress of 1,105 MPa occurred in a local area near the connection part of the gas inlet pipe/gas inlet chamber.

Figure 16 shows the overall stress distribution at the pressure boundary of the PCHE prototype under the tested pressure condition. A maximum local stress of 61.6 MPa occurred on the gas inlet pipe, as shown in Fig. 16, is much more below when compared with maximum stresses, as shown in Figs. 13 and 14.

Fig. 17 shows the stress distribution on the bottom plate under the tested pressure condition. According to Fig. 17, very low stress level occurred on the bottom plate of the PCHE prototype compared with Fig. 14.

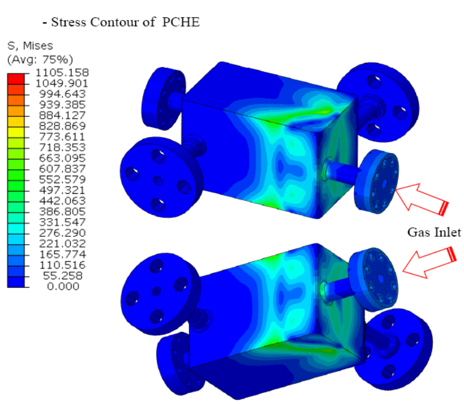

Figure 13: Stress contour under test temperature condition

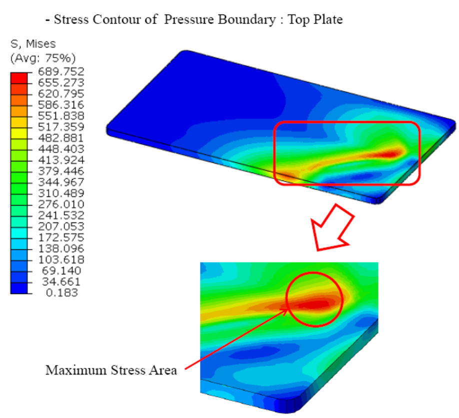

Figure 14: Stress contour on the top plate

4 Summary

In an effort to investigate the macroscopic structural characteristics and behavior of a PCHE prototype under the test conditions of a small-scale gas loop prior to an actual performance test, FE modeling, thermal analysis, and high-temperature

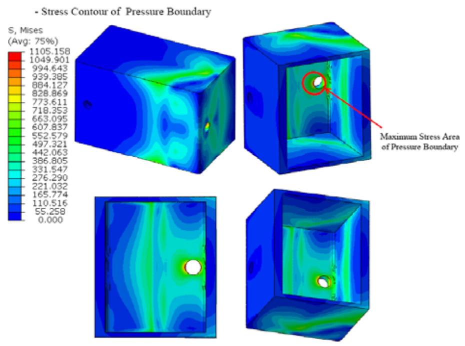

Figure 15: Stress contour around gas inlet chamber

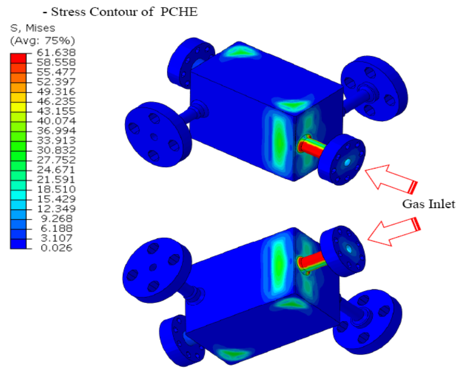

Figure 16: Stress contour under the tested pressure condition

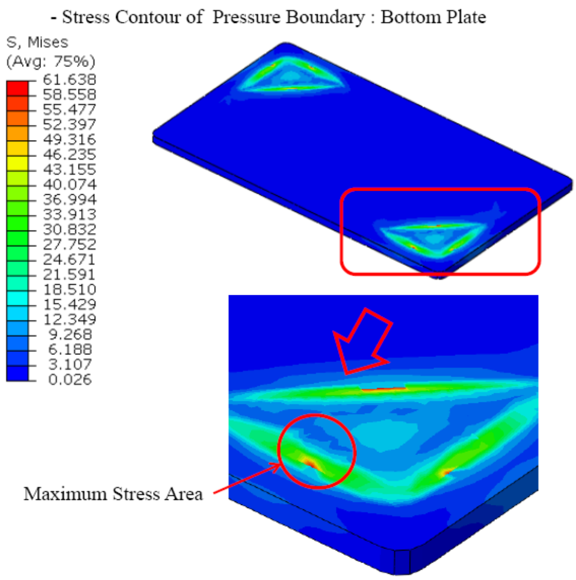

Figure 17: Stress contour on the bottom plate under the tested pressure condition

structural analysis on the PCHE prototype are carried out. A summary of the analysis results is as follows:

1. Under the tested temperature condition, the maximum stress at the pressure boundary of the PCHE prototype was about 689.7 MPa. Thus, some measure to strengthen the structural integrity of the PCHE prototype should be determined.

2. The temperature condition is a far more effective condition to the structural in-

tegrity of the PCHE prototype than the pressure condition. Thus, thermal expansion is very important for a structural integrity evaluation of the PCHE prototype in a gas loop.

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