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Structural Analysis of a Lab-Scale PCHE Prototype under the Test Conditions of HELP

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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 lab-scale PCHE (Printed Circuit Heat Exchanger) prototype made of SUS316L under consideration as a candidate. In this study, as a part of a high-temperature structural integrity evaluation of the lab-scale PCHE prototype, a macroscopic structural behavior analysis including structural analysis modeling and a thermal/elastic structural analysis was carried out under the test conditions of a helium experimental loop (HELP) as a precedent study for a performance test. The results obtained in this study will be compared with the test results of the lab-scale PCHE prototype.

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

1 Introduction

Hydrogen is considered a promising future energy solution, as it is clean, abundant, and storable, and has a 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 gathering attention worldwide since it can produce hydrogen, a promising energy carrier, without any environmental burden. Researches to demonstrate the massive production of hydrogen using a VHTR (Very High Temperature Reactor) designed for operation at up to 950° have been actively carried out worldwide including in the USA, Japan, China, France, and the Republic of Korea (ROK). See Lee (2009), US DOE (2009).

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The nuclear hydrogen program in the ROK has been strongly considered for the production of hydrogen using 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 a 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 a candidate of the IHX of the nuclear hydrogen system in the ROK.

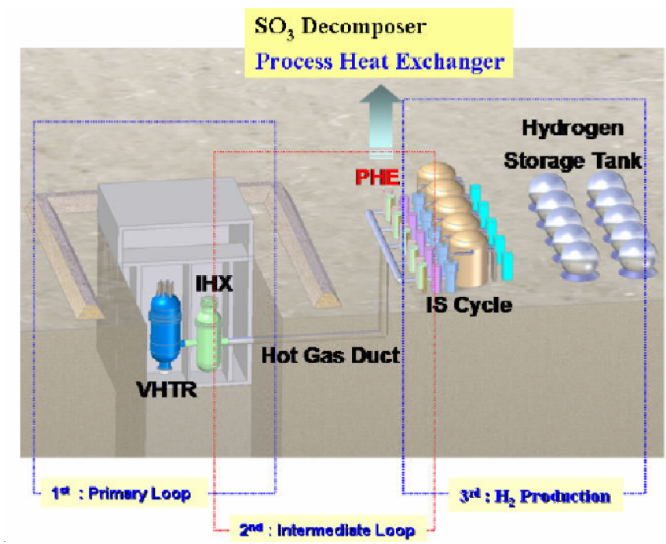

Figure 1: Nuclear Hydrogen System

Recently, the Korea Atomic Energy Research Institute (KAERI) established a helium experimental loop (HELP) for a performance test of VHTR components such as PCHE, IHX and Hot Gas Duct components as shown in Fig. 2. The design specification of HELP is summarized in Table 1. In addition, KAERI has manufactured a lab-scale PCHE prototype made of SUS316L to be tested in HELP.

In this study, to investigate the macroscopic structural characteristics and behavior of a lab-scale PCHE prototype under the test conditions of HELP, FE (finite element) modeling, a thermal analysis, and a structural analysis on the PCHE prototype are conducted as a precedent study for a performance test. The results obtained in this study will be compared with the test results of the lab-scale PCHE prototype.

Table 1: Design specification of HELP

	Pressure (MPa)	Temperature (°C)	Flow rate (kg/s)
Primary loop	9.0	1000	0.1
Secondary loop	9.0	500	0.1

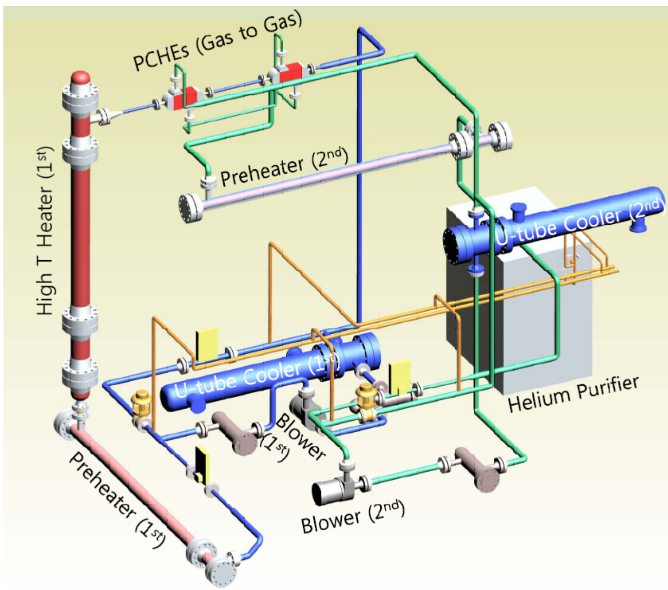

Figure 2: KAERI's helium experimental loop (HELP)

2 FE modeling

A schematic view of a lab-scale PCHE prototype, which is generated from a finite element (FE) model, is illustrated in Fig. 3. The approximate dimensions of the lab-scale PCHE prototype are also shown in Fig.3. The FE models of the lab-scale PCHE prototypes are formulated with linear solid elements including 3,357,896 linear hexahedral elements and 34,272 linear wedge elements. The maximum node number of the FE model is 4,355,684. All parts of the lab-scale PCHE prototype are made of SUS316L. For the sake of simplicity and computational efficiency, the real flow plates were modeled, as shown in Fig. 4, in the FE model of the lab-scale PCHE prototype. The flow paths are straight, as shown in Fig. 4a, for the primary flow plate because the chambers and pipes are in-lined for a primary flow, as shown in Fig. 3. On the other hand, the flow paths are cranked, as shown in Fig.

4b, for the secondary flow plate because the chambers and pipes are not in-lined for a secondary flow, as shown in Fig. 3. In addition, the thermal boundary conditions of the lab-scale PCHE prototype under the test condition of HELP, as shown in Fig. 5, are used as input data for the thermal analysis. Table 2 shows the test conditions of HELP.

Table 2: KAERI's helium experimental loop (HELP)

	Primary Coolant	Secondary Coolant
Fluid	He	He
Inlet Temperature (°C) Outlet Temperature (°C)	550 411	300 438
Pressure (MPa)	6.0	4.0

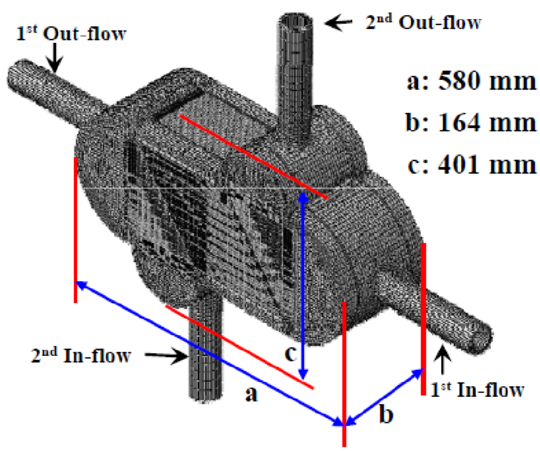

Figure 3: Schematic view of a lab-scale PCHE prototype

Based on the finite element model of the lab-scale PCHE prototype, as shown in Fig. 3, thermal and structural analyses are carried out using ABAQUS Ver. 6.9 with thermal insulation on the outside of the lab-scale PCHE prototype. See ABAQUS (2011).

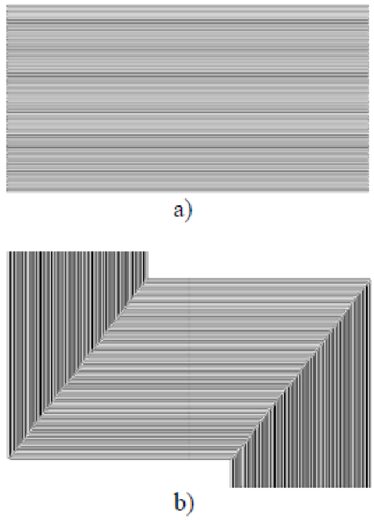

Figure 4: FE model of flow plates: a) primary and b) secondary flow plates

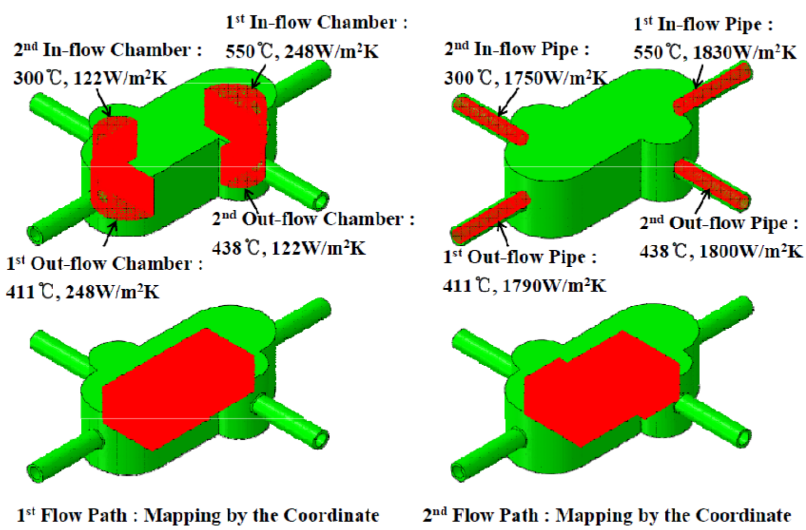

Figure 5: Thermal boundary conditions

3 Analysis

3.1 Material properties of SUS316L

All parts of the lab-scale PCHE prototype are made of SUS316L, whose mechanical properties and chemical composition are shown in Tables 3 and 4, respectively. See ASME (2001).

Table 3: Material properties of SUS316L

Temperature (°C)	Modulus of Elasticity (Gpa)	Poisson's Ratio	Thermal Conductivity (W/m·°C)	Specific Heat (J/kg· K)	Coefficient of Thermal Expansion (10^{-6}/°C)
20	192	0.3	13.94	470	15.9
100	186	0.3	15.08	486	16.4
200	178	0.3	16.52	508	17.0
300	170	0.3	17.95	529	17.5
400	161	0.3	19.39	550	17.9
500	153	0.3	20.82	571	18.3
600	145	0.3	22.25	592	18.7
700	137	0.3	23.69	613	19.0

Table 4: Chemical composition of SUS316L

Alloying element (≤wt%)							
C	Si	Mn	P	S	Ni	Cr	Mo
0.03	1.00	2.00	0.045	0.03	12-15	16-18	2.0-3.0

3.2 Thermal analysis

Figure 6 shows the temperature contours of a lab-scale PCHE prototype from the thermal analysis results. See Song (2012). According to Fig. 6, the maximum temperature at the pressure boundary of the lab-scale PCHE prototype is about 550°.

3.3 Structural boundary condition

Figure 7 shows the structural boundary conditions for the high-temperature structural analysis, where all DOFs at each end of the inlet/outlet pipes are fixed and

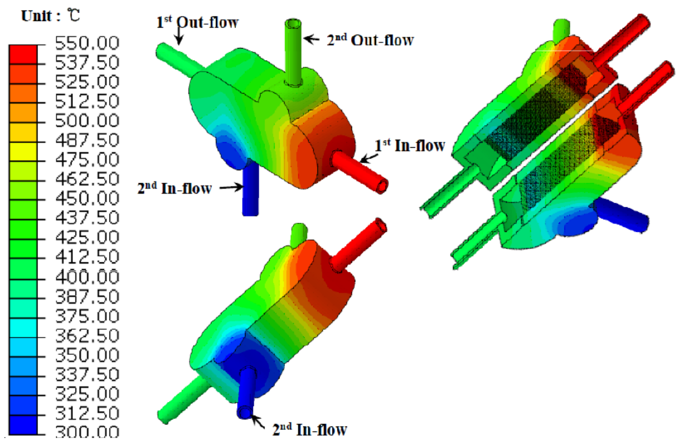

Figure 6: Temperature contours of the lab-scale PCHE

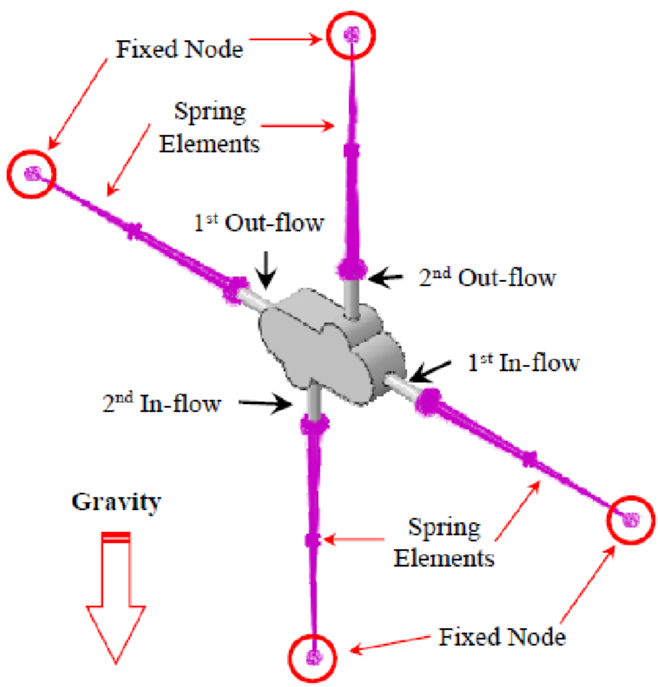

Figure 7: Structural boundary conditions

each pipeline, such as a straight pipeline, elbow, and U-tube, connecting to the lab-scale PCHE prototype in HELP are assumed as spring elements considering the pipeline stiffness. The spring stiffness of the spring elements is shown in Table 5. See Song (2012, 2013a).

Table 5: Spring stiffness at pipelines

Position	*K (N/mm)*
1^{st} Inlet	82925.3
1^{st} Outlet	194.2
2^{nd} Inlet	277.6
2^{nd} Outlet	2395.6

3.4 High-temperature structural analysis

Based on the structural boundary conditions shown in Fig. 7 and the temperature contours shown in Fig. 6, an elastic structural analysis of a lab-scale PCHE prototype was carried out considering the primary/secondary coolant pressures as shown in Fig. 8 and Table 2. Figure 9 shows the overall stress distributions at the pressure boundary of the lab-scale PCHE prototype. According to Fig. 9, high stress occurred near the weld connection of the main body of the lab-scale PCHE prototype and 2^{nd} in-flow chamber, and the maximum local stress was about 229.5 MPa, which exceeds the yield stress of 117.1 MPa. However, since the maximum local stress represents the primary stress and secondary stress such as the peak stress, it is necessary to evaluate the strength integrity according to ASME Sec. III. See ASME (2012). The maximum local stress of 229.5 MPa is equivalent to a Tresca stress of 221.8 MPa. When evaluating the maximum local stress according to ASME Sec. III T-1300, NB-3222, the maximum Tresca stress of 221.8 MPa is far below the allowable stress limit ($3S_m$) of 283.3 MPa when considering the peak stress.

Meanwhile, it was found that the mechanical properties, such as yield stress and ultimate tensile strength, in the weld zone are a little lower than those of the base material. See Song (2013b). When considering the mechanical properties in the weld zone, the maximum Tresca stress of 221.8 MPa is far below the allowable stress limit of 263.2 MPa in the weld zone ($3S_m$). Therefore, the structural integrity of the lab-scale PCHE prototype under the test conditions of HELP seems to be maintained from the view point of peak stress.

When evaluating the structural integrity of an actual PCHE after a lengthy operation, it is necessary to evaluate the structural integrity in detail from the additional viewpoint of fatigue-creep.

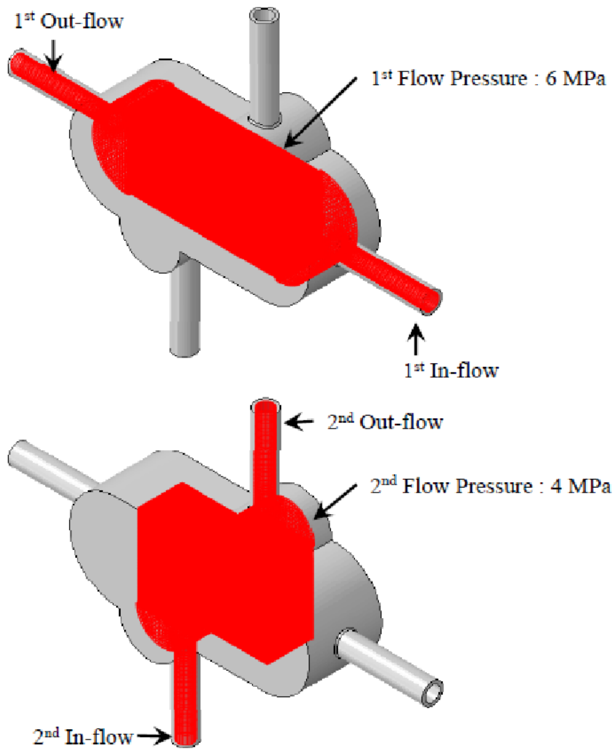

Figure 8: Primary/Secondary coolant pressures

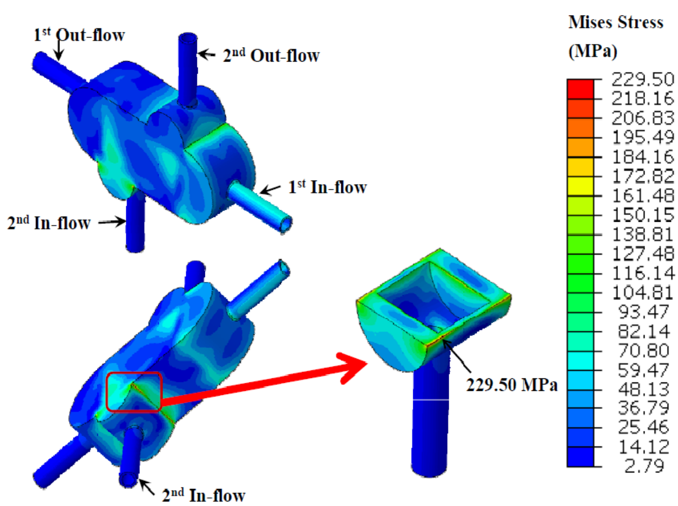

Figure 9: Stress contours of the PCHE outside

4 Summary

In an effort to investigate the macroscopic structural characteristics and behavior of a lab-scale PCHE prototype made of SUS316L under the test conditions of HELP prior to an actual performance test, FE modeling, a thermal analysis, and a high-temperature structural analysis on the lab-scale PCHE prototype were carried out. A summary of the analysis results is as follows:

1. Under the test conditions of HELP, the maximum local stress occurring at the pressure boundary of the PCHE prototype was about 229.5 MPa.

2. When evaluating the maximum local stress according to ASME Sec. III T-1300, NB-3222, the maximum Tresca stress was far below the allowable stress limit when considering the peak stress.

3. Therefore, the structural integrity of the lab-scale PCHE prototype under the test condition of HELP seems to be maintained from the viewpoint of peak stress

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