Hindawi Publishing Corporation
Science and Technology of Nuclear Installations
Volume 2013, Article ID 520145, 7 pages
http://dx.doi.org/10.1155/2013/520145

Research Article

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

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Received 31 July 2013; Revised 14 November 2013; Accepted 14 November 2013

Academic Editor: Eugenijus Ušpuras

The intermediate heat exchanger (IHX) of a very high temperature reactor (VHTR) transfers 950°C heat generated from the VHTR to a hydrogen production plant. The korea atomic energy research institute (KAERI) has manufactured a lab-scale printed circuit heat exchanger (PCHE) 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.

1. Introduction

Hydrogen is considered as 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 very high temperature reactor (VHTR) designed for operation at up to 950°C have been actively carried out worldwide including USA, Japan, China, France, and the Republic of Korea (ROK) [1].

The nuclear hydrogen program in the ROK has been strongly considered for the production of hydrogen using sulfur-iodine water-split hydrogen production processes [2, 3]. An intermediate loop that transports the nuclear heat to the hydrogen production process is necessary for a nuclear hydrogen program, as shown in Figure 1. In the intermediate loop, the intermediate heat exchanger (IHX) of the VHTR transfers 950°C heat generated from the VHTR to a hydrogen production plant through a hot gas duct. Process heat exchanger (PHE) is a component that utilizes the nuclear heat from the nuclear reactor to produce hydrogen. A printed circuit heat exchanger (PCHE) is a compact-type heat exchanger available as an alternative to shell and tube heat exchangers. Its name is derived from the procedure used to manufacture the flat metal plates that form the core of the heat exchanger which is done through chemical milling. These plates are then stacked and diffusion bonded, converting the plates into a solid metal block containing precisely engineered fluid flow passages. A PCHE is considered a candidate of the IHX of the nuclear hydrogen system in the ROK.

Recently, the Korea Atomic Energy Research Institute (KAERI) has 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 Figure 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. Figure 3 shows the lab-scale PCHE prototype attached in HELP to perform the performance test. As shown in Figure 3, the main

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

Table 2: Test conditions of HELP.

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

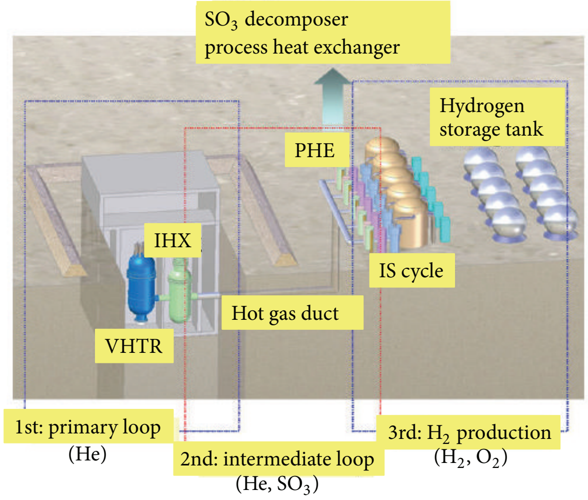


Figure 1: Nuclear hydrogen system.

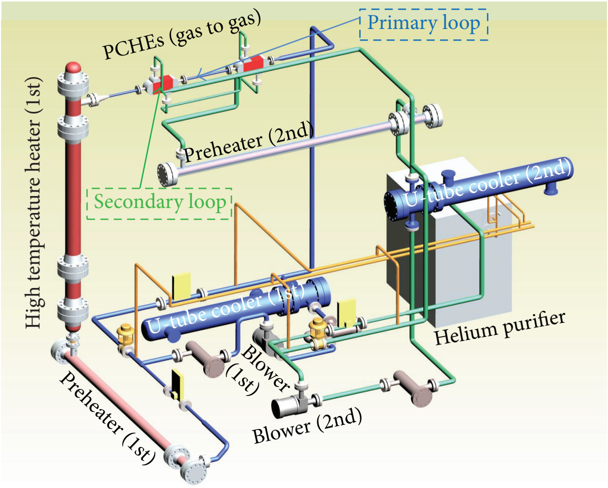


Figure 2: KAERI's helium experimental loop (HELP).

body of PCHE is welded to the chambers. It is known that the microstructures in the weld zone, including the weld and heat affected zone (HAZ), are different from those in the base material [4]. Consequently, the mechanical properties in the weld zone are different from those in the base material to a certain degree owing to different microstructures and residual welding stresses.

In this study, to investigate the macroscopic structural characteristics and behavior of a lab-scale PCHE prototype welded to the chambers under the test conditions of HELP, finite element (FE) modeling, a thermal analysis, and a structural analysis/integrity evaluation on the PCHE prototype were conducted as a precedent study for performance test when considering the base material properties of the SUS316L plate. In addition, a structural integrity evaluation is carried out considering the weld material properties of the SUS316L plate.

2. FE Modeling

A schematic view of a lab-scale PCHE prototype, which is generated from a finite element (FE) model, is illustrated in Figure 4. The approximate dimensions of the lab-scale PCHE prototype are also shown in Figure 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 Figure 4, in the FE model of the lab-scale PCHE prototype. The flow paths are straight for the primary flow plate because the chambers and pipes are in-line for a primary flow, as shown in Figure 4. On the other hand, the flow paths are cranked for the secondary flow plate because the chambers and pipes are not in-line for a secondary flow, as shown in Figure 4. In addition, the thermal boundary conditions of the lab-scale PCHE prototype under the test condition of HELP, as shown in Figure 5, are used as input data for the thermal analysis. Table 2 shows the test conditions of HELP.

Based on the finite element model of the lab-scale PCHE prototype, as shown in Figure 4, thermal and structural analyses were carried out using ABAQUS Version 6.9 [5] with thermal insulation on the outside of the lab-scale PCHE prototype.

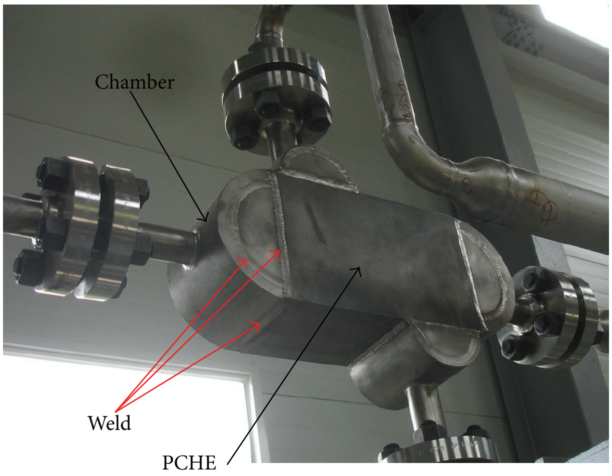
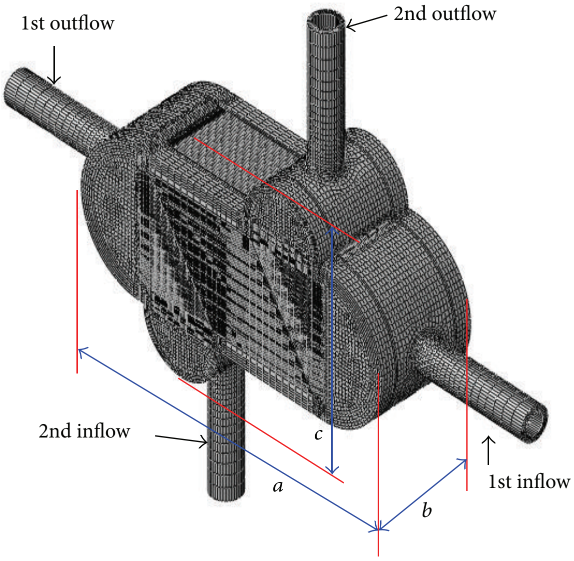


Figure 3: Lab-scale PCHE attached in HELP.



a: 580 mm

b: 164 mm

c: 401 mm

Figure 4: Schematic view of a lab-scale PCHE prototype.

3. Analysis

3.1. Material Properties of SUS316L. All parts of the lab-scale PCHE prototype are made of SUS316L, whose material properties and chemical composition are shown in Tables 3 and 4, respectively [6].

3.2. Mechanical Properties of SUS316L. When a welded structure is loaded, the mechanical behavior of the welded structure might differ from the case of a structure with homogeneous mechanical properties. Usually, the general way to obtain the mechanical properties in the weld zone is by taking tensile test specimens from the fusion zone and HAZ, and by performing a standard tensile test. However, when the weld zone is very narrow and the interfaces are not clear, it is difficult to take tensile test specimens from the weld zone. As an aside, it has recently been determined that the ball indentation technique has the potential to be an excellent substitute for a standard tensile test, especially in the case of small specimens or property gradient materials such as welds [7–11]. The weld mechanical properties of the SUS316L plate were then obtained [12] using an instrumented indentation technique.

Figure 6 shows the specimens taken from the welded SUS316L plate and their indented positions for determining the mechanical properties of the base material, weld, and HAZ of the SUS316L strip with a 5 mm thickness. Since the measured mechanical properties, such as the yield stress and ultimate tensile strength (UTS), have certain variations in each zone, as shown in Figure 7, it is necessary to set a reference value in each zone. In this study, an average value is set as the reference value in each zone. The average values of the mechanical properties in the base material, weld, and HAZ of the welded SUS316L strip are obtained using the measured data. Based on the average mechanical properties in the base material of the SUS316L strip, normalizing factors are obtained in the weld and HAZ to be later utilized in a strength analysis. Table 5 shows the normalizing factors, in other words, the normalized mechanical properties of the base material, weld, and HAZ on the weld cross-section of the weld mock-up [12]. According to Table 5, the mechanical properties in the weld, HAZ, and base material differ to a certain degree and therefore might affect the structural behavior of the lab-scale PCHE prototypes when considering the weld mechanical properties. The measured weld mechanical properties used in this study, such as the yield stress and UTS, therefore include the effect of different microstructures as well as the residual welding stress, as they were obtained from the weld specimen. Consequently, the effect of residual welding stress is considered in a strength analysis of the PCHE prototype to some extent as far as the measured weld mechanical properties are used as input data in the strength analysis.

3.3. Thermal Analysis

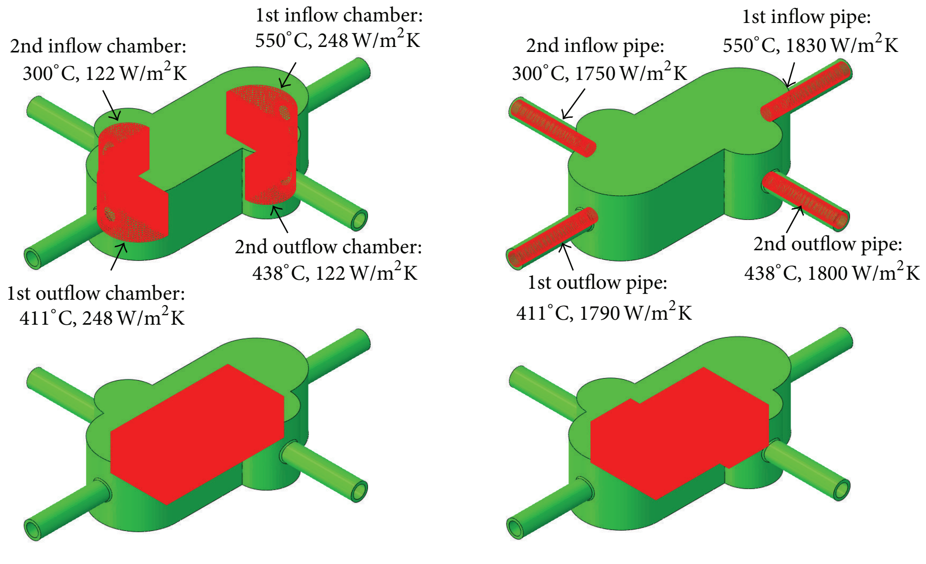
3.3.1. Validity Check of Thermal Analysis. As a validity check of a thermal analysis, the temperature contours of the PCHE prototype outside were measured using an infrared camera, and a thermal analysis was carried out under radiation and convection conditions. Table 6 shows the test conditions of HELP for measuring the temperature contours. Figure 8 shows the measured temperature contours [13], and Figure 9 shows the thermal analysis results. According to Figures 8 and 9, the temperature patterns from the measured contours are similar to those of the analysis results even when considering the limited performance of the infrared camera, whose maximum temperature that can be measured is up to around 450°C [13].

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



1st flow path: mapping by the coordinate

2nd flow path: mapping by the coordinate

Figure 5: Thermal boundary conditions.

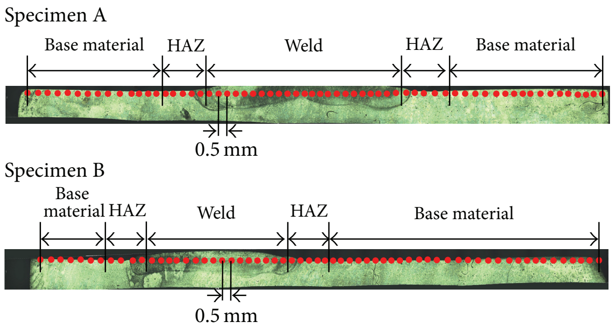
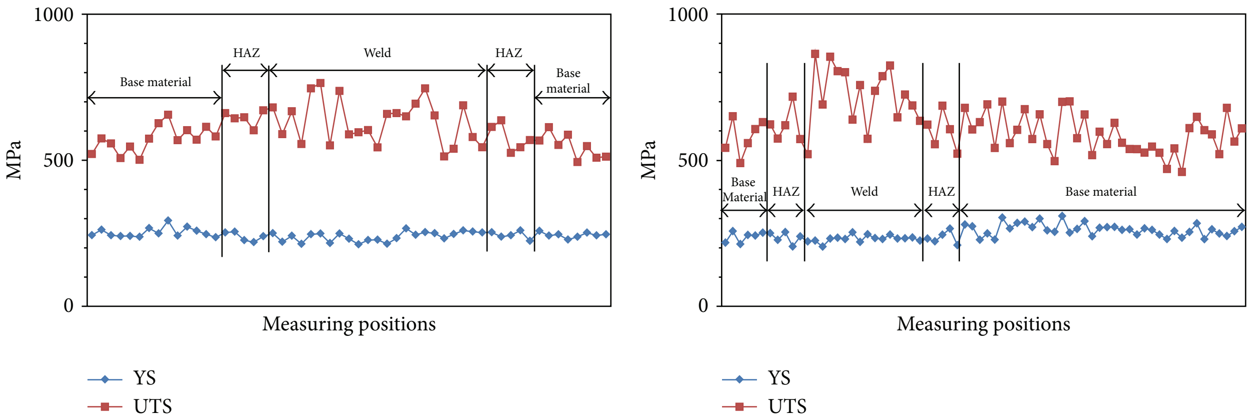


Figure 6: Weld specimens of SUS316L strip and their indented positions.



(a) Specimen A

(b) Specimen B

Figure 7: Variation of mechanical properties at the indented positions of specimens A and B.

Table 5: Normalized mechanical properties of SUS316L weld strap based on 95% lower confidence average.

	Base material	HAZ	Weld
Yield stress	1.000	0.969	0.929
Ultimate tensile strength (UTS)	1.000	1.040	1.159

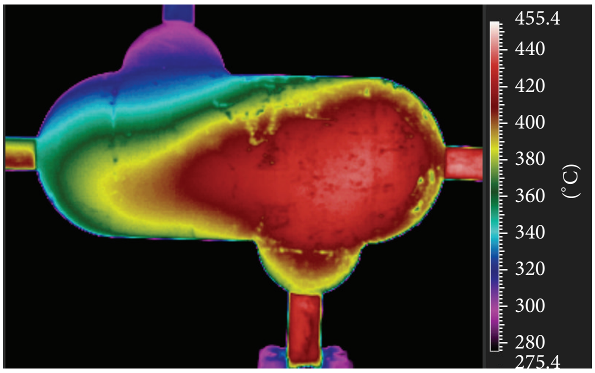


Figure 8: Measured temperature contours [13].

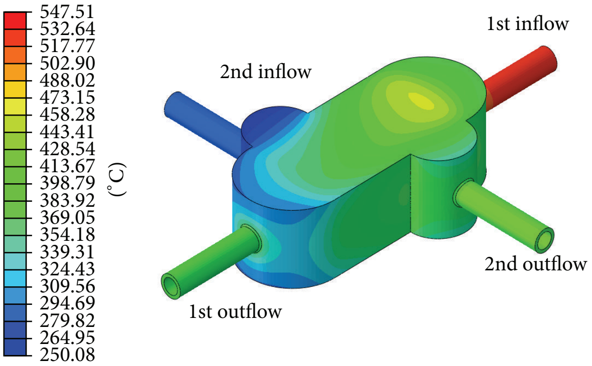


Figure 9: Temperature contours of the lab-scale PCHE outside.

3.3.2. Thermal Analysis under an Insulation Condition. Figure 10 shows the temperature contours of a lab-scale PCHE prototype from the thermal analysis results under an insulation condition using the boundary condition of Figure 5 and the test condition of HELP in Table 2 [14]. According to Figure 10, the maximum temperature at the pressure boundary of the lab-scale PCHE prototype is about 550°C.

3.4. Structural Boundary Condition. Figure 11 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 each pipeline, such as a straight pipeline, elbow, and U-tube, connecting to the lab-scale PCHE prototype in HELP is assumed as a spring element considering the pipeline stiffness. The spring stiffness of the spring elements is shown in Table 7 [15].

3.5. High Temperature Structural Analysis. Based on the structural boundary conditions shown in Figure 11 and the temperature contours shown in Figure 10, an elastic structural analysis of a lab-scale PCHE prototype was carried out considering the primary/secondary coolant pressures, as shown in Figure 12 and Table 2. Figure 13 shows the overall stress distributions at the pressure boundary of the lab-scale PCHE prototype. According to Figure 13, high stress occurred near the weld connection of the main body of the lab-scale PCHE prototype and 2nd 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

Table 6: Test condition of HELP for measuring temperature contours of a PCHE prototype outside.

	Primary coolant	Secondary coolant
Fluid	He	N_2
Inlet temperature (°C)	413.0	264.2
Outlet temperature (°C)	300.0	385.6
Pressure (MPa)	2.530	2.283

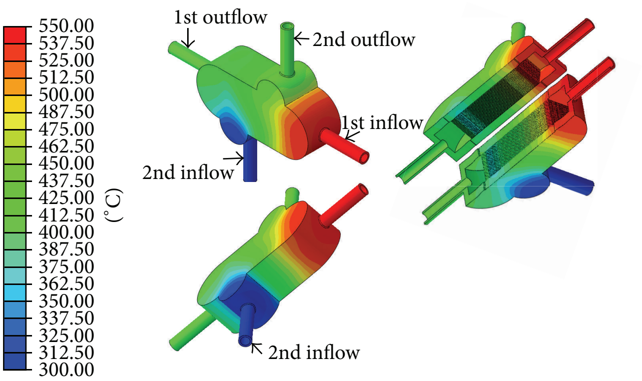


Figure 10: Temperature contours of the lab-scale PCHE.

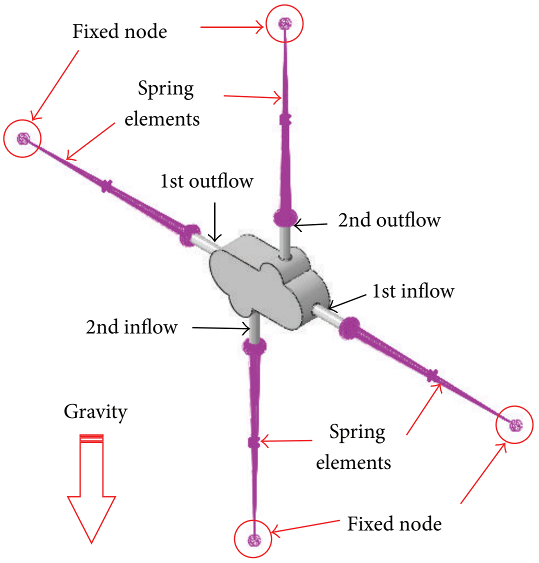


Figure 11: Structural boundary conditions.

Table 7: Spring stiffness at pipelines.

Position	K (N/mm)
1st inlet	82925.3
1st outlet	194.2
2nd inlet	277.6
2nd outlet	2395.6

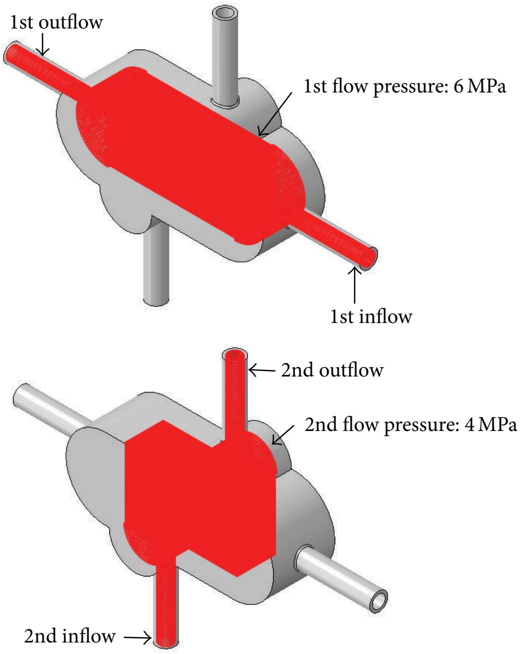


Figure 12: Primary/Secondary coolant pressures.

integrity according to ASME Sec. III [16]. 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 sufficiently 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, in the weld zone are a little lower than those of the base material, as shown in Table 5 [12]. 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 viewpoint 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.

4. Summary

In an effort to investigate the macroscopic structural characteristics and behavior of a lab-scale PCHE prototype made

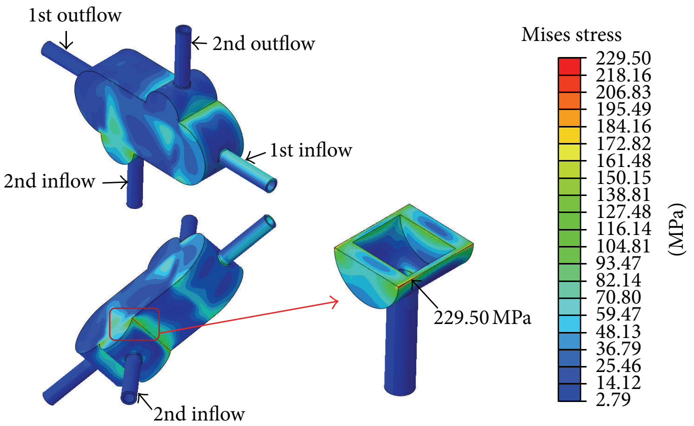


FIGURE 13: Stress contours of the PCHE outside.

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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