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Heat Performance Tests and COMSOL Analysis on 800HT Printed Circuit Heat Exchanger in HELP

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1. Introduction

. Since a VHTR has a high temperature at the outlet of the reactor above 850℃, its applications include not only high efficient electricity but also industrial heat supply such as hydrogen production, steam-methane reforming, and other industrial processes [1, 2]. The development of high temperature components for VHTR is very important because of its higher operation temperature than that of a common light water reactor and high pressure industrial process. In particular, the Intermediate Heat eXchanger (IHX) is a key-challenged high temperature component in a VHTR. Heat generated by fission reactions in the nuclear fuels is transferred from the VHTR to the intermediate loop through the IHX. A Printed Circuit Heat Exchanger (PCHE) is one of the candidates for the intermediate heat exchanger in a VHTR because its operation temperature and pressure are larger than any other heat exchanger types [3]. Mylavarapu et al. [4] fabricated a laboratory scale alloy617 PCHE and experimentally investigated its thermo-hydraulic performance in a High-Temperature Helium Facility (HTHF) at up to 800℃ and 3 MPa. Korea Atomic Energy Research Institute has developed a high temperature PCHE [5] for a VHTR and operated a very high temperature Helium Experimental LooP (HELP) to verify the performance of the high-temperature heat exchanger at the component level [5].

This paper presents a heat performance test of the 800HT PCHE in HELP. The experimental data are compared with a thermo-fluid analysis from COMSOL [6].

2. Methods and Results

2.1 HELP & 800HT PCHE

The primary goal of HELP is to maintain the component-level operation condition for the verification tests of scale-down key components in a nuclear hydrogen system. The loop consists of the primary loop and secondary loop. The primary loop and secondary loop simulate a VHTR and an intermediate loop in the nuclear hydrogen production system, respectively. The loops were designed to withstand the maximum temperature of 1000℃ as the outlet temperature of its primary high temperature heater. Its working fluid is helium as the actual coolant of the VHTR. Nitrogen can be also used as the working fluid in the low rotating speed condition of the circulator motor. The pressure transmitter and differential pressure gauge produced by Rosemount Inc. are used to measure the pressures of each system and the differential pressure drops between the inlet and outlet of the PCHE. The mass flow velocities are measured at the inlet of the pre-heaters by coriolis mass flow meters. K type thermocouples were installed to measure the gas flow temperatures in HELP.

To maximize the heat-transferred area of the PCHE, the channels in its core matrices were etched in the wavy channels. In addition, one flow channel branches off into two wavy channels and they join the outlet channel, as shown in Fig. 1. The width and depth of the semielliptical channel are 1.5 mm and 0.7 mm, respectively. The entire 800HT PCHE is composed of 60 stacks of 40 channels per stack, and each system has 30 stacks.

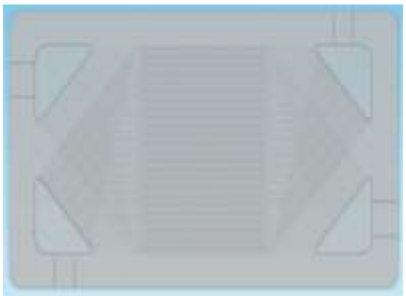


Fig. 1. Channel Design of 800HT PCHE

Four tied universal expansion joints were installed to absorb the thermal expansion of the high temperature components, since Kim et al's [7] test results showed that the thermal stress was large enough to result in a plastic windingness of the nozzles of the PCHE. To estimate the thermal performance, a thermal insulator was installed on the external surface. Fig. 2 shows the 800HT PCHE and the stainless steel 316L PCHE installed in HELP before the installation of the thermal insulator.

Fig. 2 PCHEs in HELP

2.2 COMSOL Analysis

COMSOL multi-physics software [6] is used to provide the input data for the thermal stress analysis [8] of the 800HT PCHE under the high temperature operation. The model for the 800HT PCHE is too complex to conduct a full-scale thermo-fluid simulation such as the stainless steel 316L PCHE [9]. In this study, only two stacks are simulated under the experimental conditions except for the inlet and outlet plenums, as shown in Fig. 3.

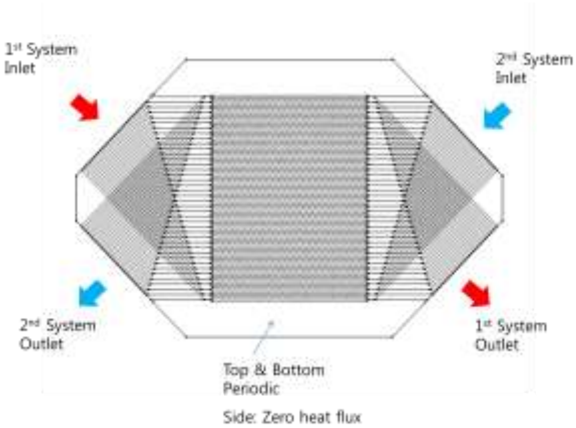


Fig. 3 COMSOL Input Model for 800HT PCHE

The finite element method (FEM) is used for discretization, and the 3D unstructured meshes (tetrahedral mesh) were used for the metal sheets, and the 1D meshes were used for all micro-channels in the 800HT PCHE using a COMSOL pipe flow module. The mass flow and temperature in the PCHE are governed by the three equations for a laminar flow using a pipe flow module in COMSOL 4.3b.

In the pipe module, two correlations for the heat transfer coefficient are used to simulate the test results in this study. The constant Nusselt number in Hesselgreaves [10] was used in the straight channel, and Kim[11]'s correlation was used in the wavy channel as the following equations.

Straight Channel $Nu = 4.089$

Wavy Channel $Nu = 4.089 + 0.03\mathrm{Re}^{0.76}$

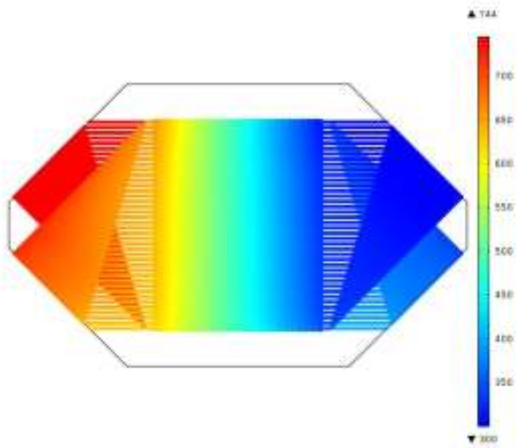
2.3 Results

Table I shows the comparison between the test data and the COMSOL analysis results for the thermal performance on 800HT PCHE. The working fluids of the primary and secondary systems were helium and nitrogen to simulate the various Reynolds number regimes. As shown in Table I, the exchanged energies calculated from the test data are always higher than those from the COMSOL analysis. Since the used correlation was developed at the longer pitch, the calculated heat transfer coefficient was lower than that at the test condition. To simulate the test results, the correlation will be developed from the CFD analysis at the same dimension of the 800HT PCHE.

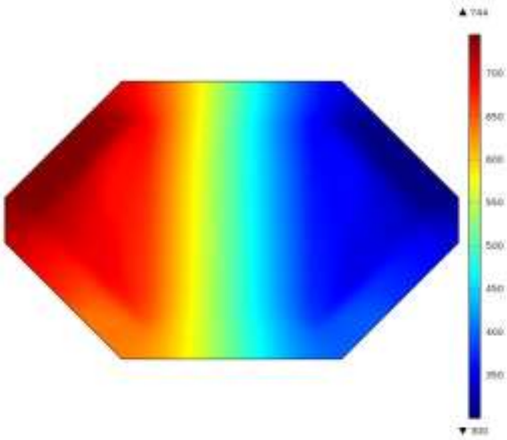
Table I Comparison between Test Results & COMSOL Analysis

Case 1	Test		COMSOL	
	1st	2nd	1st	2nd
Working Fluid	He	He	He	He
Mass Flow Rate	3.51 kg/min	3.51 kg/min	3.51 kg/min	3.51 kg/min
Inlet Temperature	471℃	27℃	471℃	27℃
Outlet Temperature	71℃	412℃	94℃	406℃
Effectiveness	0.90		0.85	
Case 2	Test		COMSOL	
	1st	2nd	1st	2nd
Working Fluid	N_2	He	N_2	He
Mass Flow Rate	14.3 kg/min	3.1 kg/min	14.3 kg/min	3.1 kg/min
Inlet Temperature	427℃	28℃	427℃	28℃
Outlet Temperature	75℃	373℃	113℃	333℃
Effectiveness	0.88		0.78	

Fig. 4 shows the temperature distributions of the fluid and the plate of the 800HT PCHE at the He-He. The temperature gradients between two plenums are always lower than the temperature gradient between two averaged fluid temperatures in each plenum. Therefore, the assumption that the plenum temperature is the same as the average fluid temperature is enough conservative to estimate the structural integrity at the high temperature condition.



(a) Fluid Temperature Distribution



(b) Plate Temperature Distribution

Fig. 4 COMSOL Analysis Results at He-He Condition (Unit: K)

3. Conclusions

The comparison with test results and COMSOL analysis shows that COMSOL analysis is useful method to estimate thermal performance and provide the input data for the thermal stress analysis. But the CFD analysis at the same dimension is required to simulate the thermal performance of the PCHE with wavy channels, because there is no correlation with considering the channel dimensions of the 800HT PCHE in HELP. In the future, the heat transfer correlation will be developed by the CFD analysis. The calculated effectiveness from COMSOL with the developed correlation will be compared with the measured effectiveness from the test results with the various Reynolds number regime.

ACKNOWLEDGMENTS

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