Convective Heat Transfer Correlation for 800HT Printed Circuit Heat Exchanger with Wavy Channel in HELP

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1. Introduction

VHTR can be a future industrial heat supplier for hydrogen production, steam-methane reforming, high temperature steam production, and other industrial processes because of its outlet temperature above 850℃ [1, 2]. Since its operating temperature is higher than that of a common light water reactor and high pressure industrial process, the development of high temperature components for VHTR is very important to demonstrate the nuclear system. Especially, the intermediate heat exchanger is a key-challenge to demonstrate a VHTR. It is used to transfer heat, generated by fission reactions in the nuclear fuels from the VHTR, to the intermediate loop. A Printed Circuit Heat Exchanger (PCHE) is one of the candidates for the intermediate heat exchanger in a VHTR because its operating temperature and pressure range are larger than any other compact heat exchanger types [3].

Mylavarapu et al. [4] fabricated a laboratory scale alloy617 PCHE and experimentally investigated its thermal 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]. The test results were compared with COMSOL & GAMMA+ analysis results at the steady state and the transient behaviors, respectively [6, 7].

In this study, the heat transfer correlation of 800HT PCHE wavy channel is obtained from the experimental data and the correction factor from COMSOL analysis. The alternative correlation is developed by FLUENT analysis.

2. Methods and Results

2.1 800HT PCHE and Test Conditions

To maximize the heat-transferred area of the 800HT PCHE, the channels in its core matrices were etched in the wavy flow paths. In addition, one flow channel branches off into two wavy channels and they join the outlet channel. 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 fluid system has 30 stacks. The width and length of the stack including the plenums are 320 mm and 600 mm, respectively. Fig. 1 shows the 800HT PCHE and the stainless steel 316L PCHE installed in Helium Experimental LooP (HELP) before the installation of the thermal insulator. The working fluids are the gas mixture of helium and nitrogen including pure helium and nitrogen. That is to obtain the wide Reynolds number range.

Fig. 1 PCHEs in HELP

2.2 Correction Factor from COMSOL Analysis

COMSOL multi-physics software [8] is used to provide the input data for the thermal stress analysis [9] 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. In this study, only two stacks are simulated under the experimental conditions except for the inlet and outlet plenums, as shown in Fig. 2.

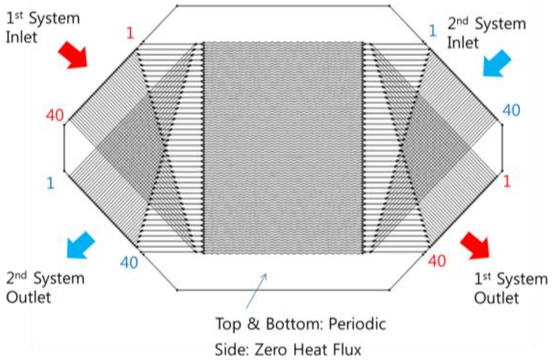

Fig. 2 COMSOL Input Model for 800HT PCHE

The finite element method (FEM) is used for discretization, and the 3-dimensional 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 from GAMMA+ steady-state analysis [7].

Straight Channel $Nu = 4.089, Dittus \,\&\, Boelter$ (1)

Wavy Channel $Nu = 4.089 + 0.03\mathrm{Re}^{0.76}$ (2)

Fig. 3 and Fig.4 show the temperature profiles according to the arclength of the PCHE channels. Most of the heat energy is exchanged in the wavy channel regions. Its fraction is dependent on the channel number, but the bounding value is between 83~87 %.

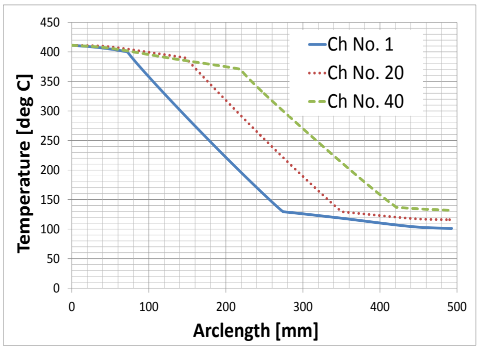

Fig. 3 Gas Flow Temperature Profiles According to the Arclength of 1st System (N_2-N_2 case)

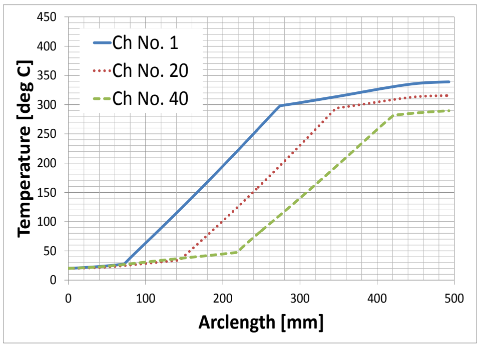

Fig. 4 Gas Flow Temperature Profiles According to the Arclength of 2nd System (N_2-N_2 case)

As shown in Fig. 2, the 800HT PCHE is the connected type of two cross flow heat exchangers and one counter current heat exchanger. The area fraction of the counter current heat exchanger region with wavy channels is 67.6% of the total heat transferred area. The COMSOL analysis results give us the correction factor for the thermal analysis of the 800HT PCHE as the following equations.

$$Q = (UA)_{tot} F\Delta T_{LMTD} \tag{3}$$

$$(UA)_{tot}^{-1} = \sum_i \left(\frac{1}{h_{wavy} A_{wavy}} \right)_i + R_{cond.} \tag{4}$$

Table 1 shows the heat transfer coefficients and the correction factor for 800HT PCHE based on the COMSOL analysis results at the He-He and N_2-N_2 conditions.

Table 1 Convective Heat Transfer Coefficient and Correction Factor from COMSOL Analysis

Test Case	Wavy Ch. HTC of 1st / 2nd System [W/m K]	Straight Ch. HTC of 1st / 2nd System [W/m K]	Correction Factor
N_2 / N_2	691/651	800/783	0.8
He / He	2380/2264	1076/987	0.8

2.3 Heat Transfer Correlation Based on Test Results

Kim et al.[3] suggested the exponent of Reynolds number. Adopting the exponent of Reynolds number, the following Nusselt number correlation was obtained from the test results with pure helium and nitrogen test cases.

$$Nu = 4.089 + 0.009945\,\mathrm{Re}\,\mathrm{Pr} \tag{5}$$

Table 2 shows the comparison between the measured and predicted heat exchanger powers including not only pure gas but also gas mixture with nitrogen and helium. All the heat exchanger power predicted by Eq. (5) is predicted within 5% error of all the test results in helium, nitrogen, and helium 36% / nitrogen 64% cases. The predicted errors in the case of helium 75% / nitrogen 25% case are about 15~20%, because the uncertainty of the measured mass flow of helium was large at the low mass flow rate condition and the uncertainty of thermal conductivity of gas mixture was large at the helium 75% and nitrogen 25%.

Table II Comparison with Heat Exchanger Power

1st/2nd System Working Fluid	1st / 2nd Average Re @Wavy Ch.	LMTD [℃]	Measured / Predicted Q[kW]
He/He	876/932	43.34	102.8 / 103.8
N_2/He	3795/868	50.41	94.3 / 92.2
N_2/N_2	2492/2755	54.24	55.3 / 55.8
He(75%)N_2(25%)/He	1722/796	41.48	88.5 / 78.8
He(36%)N_2(64%)/N_2	1358/1750	59.15	43.9 / 46.0

2.4 Heat Transfer Correlation from FLUENT Analysis

FLUENT was utilized to obtain Nusselt number correlation for the wavy channel of 800HT PCHE. A pair of channels, comprising a hot channel and cold channel, was modeled. The modeled channel length was a pitch length. All the fluid properties were fixed to simplify developing Nusslet number correlation. Inlet thermal conditions were constant temperature conditions and fully developed velocity profiles. Mass flow rate was the same in hot and cold channel.

Bulk mean temperature was average value of mean temperature at inlet and outlet surfaces.

$$T_g = \frac{T_{in,mean} + T_{out,mean}}{2} \quad (6)$$

The heat flux was calculated by dividing energy loss through a hot channel by surface area of hot channel.

$$q'' = \frac{\left|\dot{m}c_p\left(T_{in} - T_{out}\right)\right|_{1st}}{A_s} \quad (7)$$

Average wall temperature was area-weighted average wall temperature.

$$T_S = \frac{1}{A_s}\int TdA \quad (8)$$

Heat transfer coefficient was calculated as following equation.

$$h = \frac{q''}{T_g - T_S} \quad (9)$$

Nusselt numbers were obtained at Reynolds number range of 521 to 1824. Adopting the exponent of Reynolds number as the above section, the following Nusselt number correlation was obtained from FLUENT analysis, when the Prandtl number was 0.68.

$$Nu = 4.28 + 0.0048\,\mathrm{Re} \quad (10)$$

Fig. 5 shows the comparison between Nusselt numbers from equations (5) and (10). Nusselt number from test results is always higher than that from FLUENT analysis. Kim et al's test results [12] showed that the dimensionless pressure drop of single channel test results from stainless 316L wavy channels is much lower than that of 800HT PCHE. It means that the surface roughness, the lower etched depth, and the decreased flow area result in the increase of Nu and friction factor.

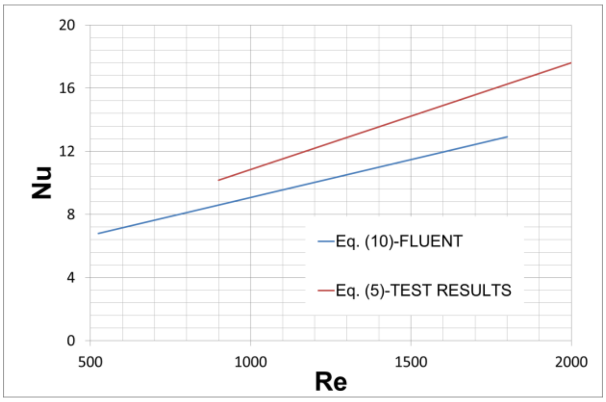

Fig. 5 Nusselt Numbers
from Test Results & FLUENT Analysis

3. Conclusions

The comparison with test results and COMSOL analysis shows that the heat transfer correlation from test results is good to predict thermal performance of 800HT PCHE in HELP. It means that the estimation of the correction factor is necessary to develop the heat transfer correlation from the test results. If the etching process and the diffusion bonding process are very good to exclude the surface roughness and the decrease of the flow area, the CFD analysis can be the useful method to develop the heat transfer correlation.

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REFERENCES

[1] J. H. Chang, Y. W. Kim, K. Y. Lee, Y. W. Lee and W. J. Lee, "A Study of a Nuclear Hydrogen Production Demonstration Plant," Nuclear Engineering and Technology, Vol. 39, No. 1, p. 9, 2007.

[2] W. J. Lee, Y. W. Kim, and J. H. Chang "Perspectives of Nuclear Heat and Hydrogen," Nuclear Engineering and Technology, Vol. 41, No. 4, p. 419, 2009.

[3] I. H. Kim and H. C. Noh, "Thermal Hydraulic Performance Analysis of the Printed Circuit Heat Exchanger Using a Helium Test Facility and CFD calculation," Nuclear Engineering and Design, Vol. 239, No. 11, p. 2399 (2009).

[4] S. K. Mylayarapu et al., "Fabrication and Design Aspects of High-Temperature Compact Diffusion Bonded Heat Exchangers, Nuclear Engineering and Design, Vol. 249, p. 49, 2012.

[5] C. S. Kim, B. H. Park, E. S. Kim, Very High Temperature Test of Alloy617 Compact Heat Exchanger in Helium Experimental Loop, Transactions

of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 12-13, 2016.

[6] C. S. Kim, B. H. Park, E. S. Kim, J. S. Shim, Heat Performance Tests and COMSOL Analysis on 800HT Printed Circuit Heat Exchanger in HELP, Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 27-28, 2016.

[7] B. H. Park, C. S. Kim, E. S. Kim, Steady-state and Transient Analysis of a Printed Circuit Heat Exchanger, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 12-13, 2016.

[8] COMSOL 4.3 b

[9] K. N. Song et al., Macroscopic High-temperature Structural Analysis on an Alloy800HT PCHE Prototype, Transactions of the Korean Nuclear Society Spring Meeting, May 29-30, 2014, Jeju, Korea.

[10] J. E. Hesselgreaves, Compact Heat Exchangers: Selection, Design and Operation, 1st edition, Ch. 5, Pergamon, London, UK, 2001.

[11] I. H. Kim, Experimental and Numerical Investigations of Thermal-Hydraulic Characteristics for the Design of a Printed Circuit Heat Exchanger (PCHE) in HTGRs, Ph. D. Dissertation, Department of Nuclear and Quantum Engineering, KAIST, 2012.

[12] C. S. Kim, S. D. Hong, J. S. Shim, M. H. Kim, High-Temperature Test of 800HT Printed Circuit Heat Exchanger in HELP, Proceedings of the HTR2014, Weihai, China, October 27-31, 2014.