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CFD Analysis of Printed Circuit Heat Exchanger for the Supercritical CO_2 Brayton Cycle

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1. Introduction

The supercritical carbon dioxide (S-CO_2) Brayton cycle is one of the promising power cycles since it has high thermal efficiency in relatively low temperature range. The S-CO_2 cycle components such as turbomachinery and heat exchanger can be designed in a compact way. The Printed Circuit Heat Exchanger (PCHE) is one of the most widely used heat exchangers for the closed gas Brayton cycles including S-CO_2 cycle. The fluid with moderate heat transfer capacity such as gas or supercritical fluid can be used as a working fluid of power conversion cycle due to the technology development of compact heat exchanger.

The heat transfer and pressure drop performance are the critical factor for designing a heat exchanger. In a micro channel of the PCHE, it is very difficult to measure and obtain flow parameters. Therefore, the CFD analysis can be useful approach to obtain local flow information. In this paper, the CFD analysis result of PCHE with S-CO_2 as a working fluid is reported. The geometry and boundary conditions were determined to be the same as an experimental study of PCHE performed by Ishizuka et al. [1].

The Nusselt number and pressure drop correlations proposed in the previous experimental studies have restricted Reynolds number range since the PCHE specimen of experimental facility was constructed for a lab scale. [1][2] Thus, the correlations valid in high Reynolds number range are required to estimate a commercial size PCHE for research purpose.

In the previous numerical studies of PCHE, a single or several cases were investigated and compared with experimental results. Although the CFD results showed good agreement with the experimental results, the performance information that is required to design a PCHE is not sufficient. Therefore, the heat transfer performance of PCHE with high Reynolds number range was found and the results were compared to the correlations developed by Ishizuka et al. and tested if the existing correlations can be used in beyond the valid Reynolds number range.

2. CFD Analysis of S-CO_2 PCHE

2.1 PCHE Analysis Model

The geometry and boundary conditions of PCHE were made to be the same as the experimental study performed by Ishizuka et al. [1]. A channel configuration of two hot channels and one cold channel with vertical and horizontal periodic condition was employed for the analysis model as shown in Figure 1. The original cross sectional shape of PCHE specimen is shown in Figure 2. Since the one cold side plate is located between the two hot side plates, a unit set is composed with two hot channels and one cold channel to represent the original configuration. Hot channel and cold channel have semi-circular shaped channel, which is 1.9mm and 1.8mm in diameter, respectively. The solid material of PCHE plate is AISI 316, which has a thermal conductivity of 16.2 W/m-K. In the analysis model it is difficult to apply the periodic boundary condition if the channel angle is different between the hot side and cold side. Therefore, the channel angle of this analysis model was assumed to be 115^o in both sides. In the PCHE experiment, the channel angle is 115^o and 100^o in the hot side and cold side, respectively. The active channel length of the cold side is 10% longer than the analysis model.

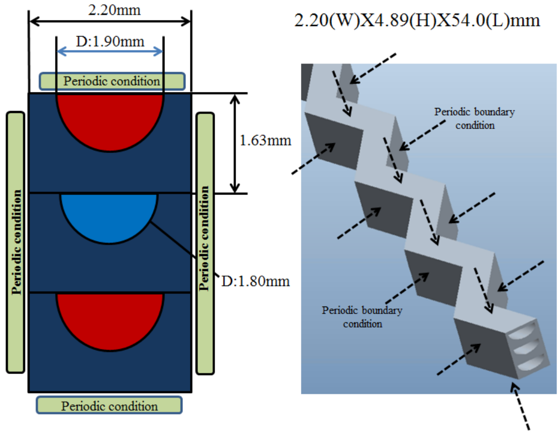

Figure 1. The geometry and boundary condition of PCHE analysis model.

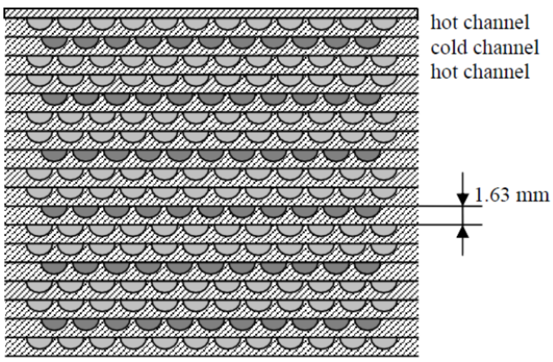

Figure 2. Cross-sectional shape of PCHE [1].

2.2 Grid generation

The volume meshing elements were generated by ICEM CFD with 18 sheets of prism layers near the wall. The y+ of the first nodes near the wall is close to 1.0. To confirm the grid independence of PCHE analysis model, grid sensitivity study was conducted and results are shown in Table 1. As the grid size exceeds 1,204,052 nodes, the channel averaged heat transfer coefficient showed converged value. Therefore, the grid with 1,204,052 nodes and 3,772,579 elements are mainly used in this CFD analysis.

Table 1. Result of grid sensitivity study.

Number of nodes	**Number of elements**	**Average Heat Transfer Coefficient (W/m^2-K)**	**Error (%)**
303,998	850,164	2,002 (Hot) 3,921 (Cold)	-13.7 -11.1
678,175	2,036,925	2,128 (Hot) 4,149 (Cold)	-8.3 -5.9
1,204,052	**3,772,579**	2,296 (Hot) 4,378 (Cold)	-1.0 -0.7
2,283,447	7,643,631	2,320 (Hot) 4,411 (Cold)	+0.0 +0.0

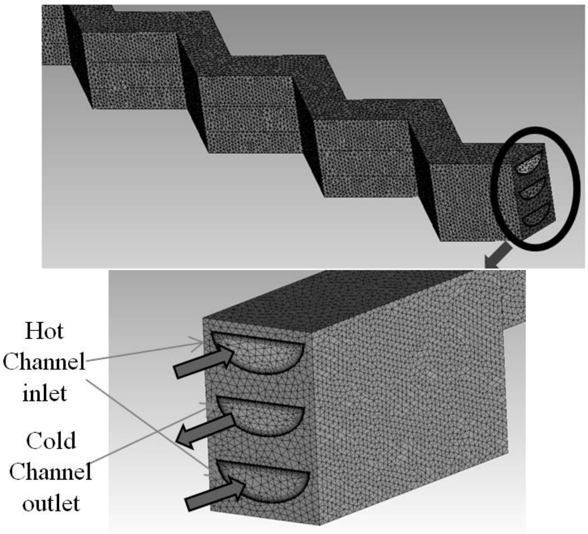

Figure 3. Grid shape of the PCHE analysis model

2.3 Fluid property implementation

The RGP (real gas property) format table was used for the CO_2 property implementation. The properties of CO_2 are taken from the NIST REFPROP 8.0 fluid property database [2]. The tables were generated in the prescribed pressure and temperature ranges. The table resolution is also prescribed by the user for the generated in-house MATLAB program. The CFX solver utilizes lookup table method to refer the CO_2 properties and calculates output value by using bilinear interpolation.

The RGP table, pressure ranging from 1MPa to 20MPa, and temperature ranging from 290K to 650K, with resolution of 500x500 was used. To estimate the error between the real properties obtained from the NIST REFPROP and calculated properties within the CFX code, a comparison was made at the mid-point of the hot side and cold side as summarized in Table 2. With 500x500 table, the density showed 1.1% of property error while other properties showed error less than 0.3%.

Table 2. Property errors of RGP table in the hot side and cold side.

Hot side (3.196MPa, 516.2K)					
	Enthalpy [kJ/kg]	**Cp [J/kg-K]**	**Viscosity [Pa-s]**	**Thermal conductivity [W/m-K]**	**Density [kg/m^3]**
CFX	703.26	1065.2	2.4929e-05	0.03577	33.787
NIST	702.59	1064.31	2.4898e-05	0.03571	33.4152
Error	**0.09%**	**0.08%**	**0.13%**	**0.19%**	**1.11%**
Cold side (10.49MPa, 410.6K)					
	Enthalpy [kJ/kg]	**Cp [J/kg-K]**	**Viscosity [Pa-s]**	**Thermal conductivity [W/m-K]**	**Density [kg/m^3]**
CFX	553.84	1315.1	2.2774e-05	0.03252	163.05
NIST	553.19	1313.9	2.2730e-05	0.03244	162.67
Error	**0.12%**	**0.09%**	**0.19%**	**0.25%**	**0.23%**

2.4 *Problem setup*

A commercial code, ANSYS CFX 14.5 was used for the CFD analysis. The k-ω SST (Shear Stress Transport) turbulence model was used. A turbulent intensity and length scale were determined automatically. The total energy equation and thermal energy equation were used for energy conservation in the fluid domain and solid domain, respectively. The conjugate heat transfer mode in the fluid and solid domain was employed in this study. The convergence criteria was determined when the RMS residual of mass, momentum and energy is less than 1.0^{-3} and imbalance of mass, momentum and energy is less than 0.5%.

2.5 Boundary conditions

Boundary conditions were determined to be the same as the experimental conditions of Ishizuka et al. [1]. The operating conditions matches with the recuperator in the S-CO_2 cycle. In this experiment, the inlet condition of hot side and cold side were 280℃, 3.2MPa and 108℃, 10.5MPa, respectively. Since the analysis model is much shorter than the experiment, inlet conditions should be corrected. If we use original boundary condition, it yields too large temperature difference between hot side and cold side. Thus, we need to know internal distribution of pressure and temperature inside the PCHE. However, pressure and temperature were measured only at the inlet and outlet of the heat exchanger, internal distribution of pressure and temperature is unknown. Therefore, the inlet temperature of cold side which is 54mm far from the hot side inlet was referred from the previous CFD results with full channel length (896mm) performed by Kim et al. [3]. The temperature distribution at the hot side and cold side was shown in Figure 4. Based on this result, the temperature condition at the cold side inlet was defined as 221.8℃.

The outlet condition was controlled to the mass flow rate from 25kg/h to 300kg/h with 25kg/h increment. Although the outlet conditions of experiment were 35-90kg/h, in order to simulate high Reynolds number condition above the valid range of correlation, the outlet condition of high mass flow rate ranging from 100kg/h to 300kg/h were applied.

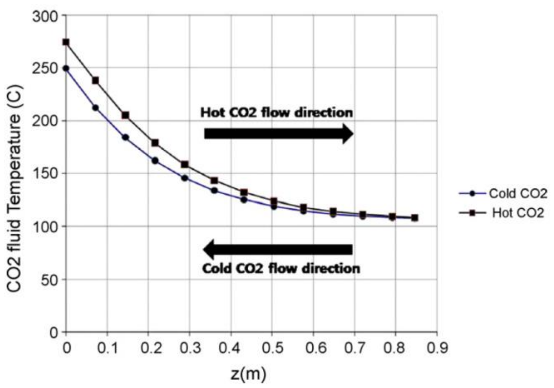

Figure 4. Results of temperature profile at the PCHE hot side and cold side conducted by Kim et al. [3].

2.6 Post-processing

In the post-processing, following expressions are used for obtain meaningful results.

The local heat transfer coefficient h was obtained by using following expression.

$$h = \frac{q''}{T_w - T_{bulk}}$$

$$where\ q'': wall\ heat\ flux, T_w: wall\ temperature,$$
$$T_{bulk}: bulk\ temperature$$

The bulk temperature T_{bulk} was obtained by using following expression.

$$T_{bulk} = \frac{\int \rho \cdot h \cdot V \cdot dA}{\int \rho \cdot C_P \cdot V \cdot dA}$$

$$where\ \rho: density, h: enthalpy, V: velocity,$$
$$C_P: Specific\ heat\ capacity\ at\ constant\ pressure$$

3. Results

3.1 Results of Nusselt number

Predicted Nusselt number in the hot side and cold side were compared to the existing correlation. The range of correlations were extended up to the Reynolds number of 50,000 and evaluated in both valid range and extended invalid range.

The local heat transfer correlation proposed by Ishizuka et al. in the hot and cold side [1]:

$$h = 0.2104Re + 44.16$$
$$(2{,}400 < Re < 6{,}000)\quad for\ hot\ side$$
$$(5{,}000 < Re < 13{,}000)\quad for\ cold\ side$$

The correlation for heat transfer coefficient developed from Ishizuka et al. was converted to the correlation for the Nusselt number by multiplying $\frac{l}{k}$, where l is a characteristic length of channel and k is a channel averaged value of thermal conductivity, and it was compared to the CFD results. In the extended Reynolds number range, the correlations are shown as dotted line.

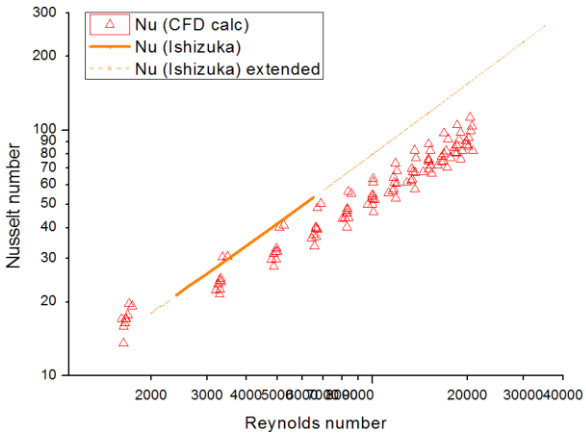

Figure 5. CFD results of Nusselt number in the hot side compared to the correlations.

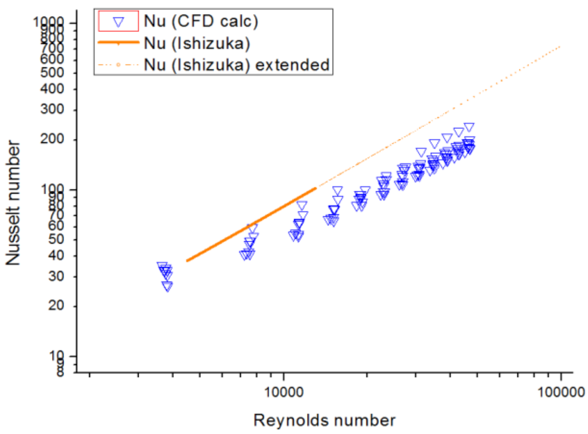

Figure 6. CFD results of Nusselt number in the cold side compared to the correlations.

Table 3. Relative difference of CFD results in comparison to the correlation.

	Ishizuka correlation (Hot side)	Ishizuka correlation (Cold side)
Relative difference in the valid range	-9.4%	-13.7%
Relative difference in the invalid range	-30.0%	-36.1%

The channel averaged results were compared to the correlations, and relative differences are summarized in Table 3. As shown in Figures 5 and 6, most of the results are below the correlation. In comparison to the correlation of Ishizuka et al., the relative differences of predicted Nusselt number in the hot side and cold side are increasing as Reynolds number is far from the valid range.

4. Conclusion and future works

The CFD analysis was performed to examine the heat transfer performance of the PCHE. The geometry was made to be the same as the experimental study conducted by Ishizuka et al. The analysis model was constructed to represent original cross-sectional configuration of the PCHE. In order to save computational time, a unit set was composed with two hot channels and one cold channel. To consider the heat transfer through the vertical and horizontal faces of a unit analysis model, periodic boundary condition was applied.

In comparison to the correlation of Ishizuka et al., the CFD results of both hot and cold sides showed reasonable agreement. However, the differences are increasing largely in the high Reynolds number range for Ishizuka correlation, which potentially indicates that utilizing Ishizuka correlation beyond the experimentally valid range can be limiting. However, it should be noted that the PCHE in the experiment had a different channel angle of 115^o and 100^o in the hot side and cold side, respectively, while the channel angle in the analysis model is set to 115^o in both hot side and cold side to create simpler analysis model. Thus, it is expected that the reason why the predicted results of Nusselt number from the CFD analysis is lower than the correlation can be due to the difference of active channel length.

The ability of turbulence model to predict the correct level of the secondary flow motion and the size of the recirculation zones can play a major role in the fluid mixing hence the heat transfer coefficient. Therefore, future work should include comparison between different models to assess their performance in the actual test case with sharp angles.

In the future study, the results of friction factor will be obtained and analyzed with the existing correlations to examine the pressure drop performance of the PCHE. Moreover, near the critical point of CO_2 operating condition of the PCHE will be analyzed with CFD to successfully design pre-cooler of the S-CO_2 power cycle.

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REFERENCES

[1] Takao Ishizuka, Yasuyoshi Kato, Yasushi Muto, Konstantin Nikitin, Ngo Lam Tri, Hiroyuki Hashimoto, *Thermal-hydraulic Characteristic of a Printed Circuit Heat Exchanger in a Supercritical CO2 Loop*, The 11th international Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, October 2-6, 2005.

[2] Eric W. Lemmon, Marcia L. Huber, Mark O. McLinden, *NIST Reference Fluid Thermodynamic and Transport Properties – REFPROP*, National Institute of Standards and Technology, 2007.

[3] Dong Eok Kim, Moo Hwan Kim, Jae Eun Cha, Seong O. Kim, *Numerical Investigation on Thermal-hydraulic Performance of New Printed Circuit Heat Exchanger Model*, Nuclear Engineering and Design 238 (2008) 3269-3276.