Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

Experimental and CFD Analysis of Printed Circuit Heat Exchanger for Supercritical CO_2 Power Cycle Application

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1. Introduction

The sodium-cooled fast reactor (SFR) has received worldwide attention among the next generation reactors. The SFR not only operates at atmospheric pressure condition, but also reduces the high-level radioactive wastes. However the SFR faces violent sodium-water reaction problem when using the steam Rankine cycle [1].

The supercritical carbon dioxide (S-CO_2) power cycle has been suggested as an alternative for the SFR power generation system. First of all, relatively mild sodium-CO_2 interaction can reduce the accident probability. Also the S-CO_2 power conversion cycle can achieve high efficiency with SFR core thermal condition. Moreover, the S-CO_2 power cycle can reduce cycle footprint due to high density of the working fluid.

Recently, various compact heat exchangers have been studied for developing an optimal heat exchanger [2, 3, 4, 5 for the S-CO_2 cycle]. In this paper, the printed circuit heat exchanger was selected for S-CO_2 power cycle applications and was closely investigated experimentally and analytically.

2. PCHE Experiment and CFD analysis

From the 2014, KAIST research team conducted a PCHE performance test to evaluate the PCHE applicability for S-CO_2 system [6, 7, 8]. The PCHE was designed by a developed in-house code KAIST_HXD and it was manufactured by a Korean vendor. The testing facility and PCHE channel configurations are shown in t Fig. 1 and Fig. 2. The PCHE was installed as a precooler, which transfers waste heat to the heat sink, i.e. water side.

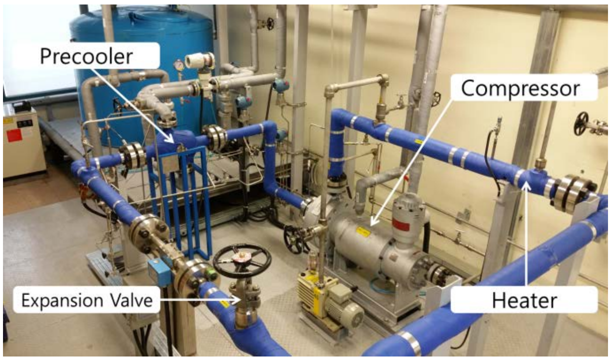

Fig. 1. Overall view of the S-CO_2PE facility [8].

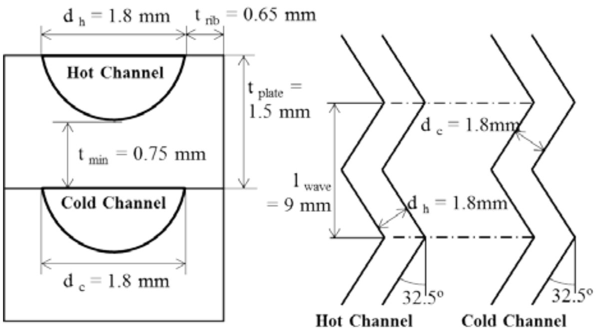

Fig. 2. Channel geometry of designed PCHE [8]

2.1 PCHE experimental conditions

The performance tests were conducted under various conditions near the CO_2 critical points (31℃, 7.4MPa). Total 16 test points were explored by varying the CO_2 mass flowrate. The experimental conditions were plotted with density contour line in Fig. 3. From this figure, the CO_2 pressure and temperature decrease due to the cooling process.

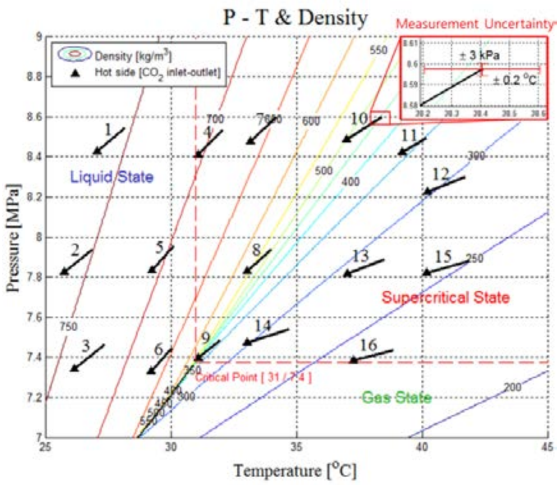

Fig. 3. CO_2 conditions of test cases (inlet to outlet). [8]

The S-CO_2 cycle efficiency has significant effect on compressor inlet condition due to the dramatic property change near the critical point. Therefore to maintain the compressor inlet condition steadily requires a sensitive precooler control. Consequently CFD analysis was conducted to understand the precooler performance and thermal response.

2.2 CFD problem set up

It was not possible to measure the temperature and pressure inside the channel, a set of representative channel was simulated by CFD commercial code. Ansys-CFX 14.5v was utilized with RGP table implementation. The calculation domain and boundary conditions are shown in Fig 4. The real scale 20 pitches of 9mm zig-zag channel were considered and the zig-zag channel corner was rounded with radius of 1mm.

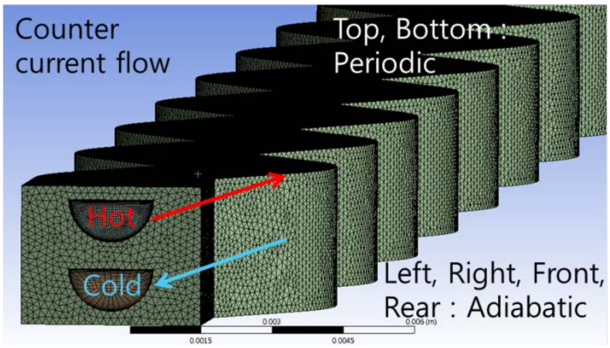

Fig. 4. Calculation domain and boundary conditions.

The water side flow was laminar region, but the hot CO_2 side was high Reynolds number (20,000 ~ 80,000) turbulent region. For the precise calculation, the k-ω SST (shear stress transport) turbulence model was used. As a fluid part boundary condition, each side inlet and outlet side was set as experiment conditions. The test cases 7, 15 are simulated with 9 different mass flowrate cases.

2.3 CFD analysis results

From the CFD results, local flow motion and temperature, pressure were obtained. Fig 5 shows the 7-1 case temperature profiles along the channel.

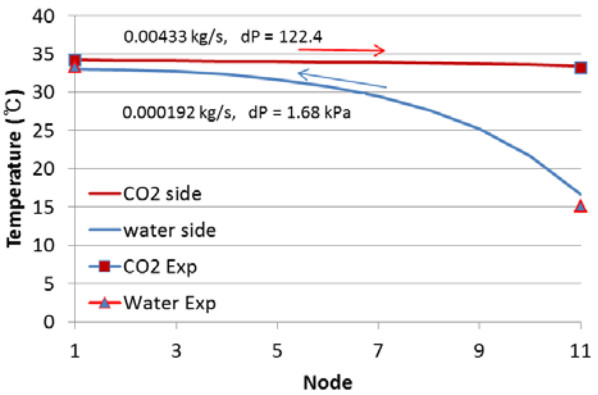

Fig.5. Case 7-1 CFD simulation results validation

In order to predict the PCHE thermal hydraulic performances, pressure drop and heat transfer correlations are needed. The fluid domains are divided in to pitches to develop a pitch-averaged correlation.

2.4 Development of pressure drop and heat transfer correlations

For the hydraulic parts, pressure drop in each section are transformed to normalized friction factor by the following equation (1).

$$f_{Fanning} = \frac{1}{4}\,\Delta P\,\frac{D}{l}\frac{2}{\rho v^2} \quad (1)$$

Along with the hydraulics, heat transfer rate and averaged wall temperatures are obtained. By following equations (2) and (3), Nusselt numbers are obtained.

$$h = \frac{W}{A\,(T - Twall)} \quad (2)$$

$$Nu = \frac{hD}{k} \quad (3)$$

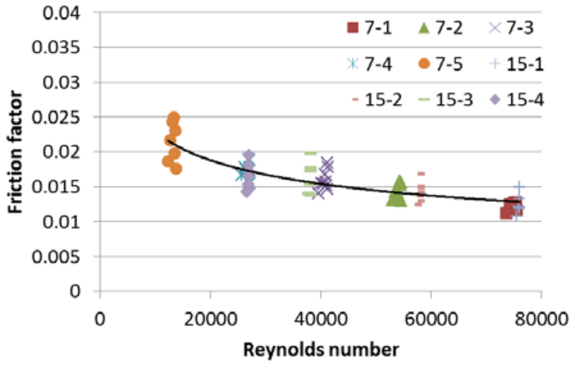

Fig. 6. Friction factor correlation for CO_2 side.

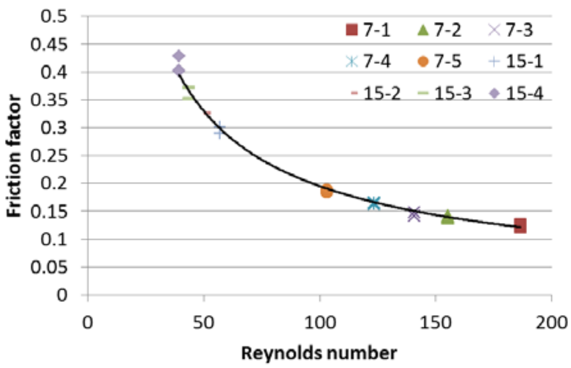

Fig. 7. Derived friction factor correlation for water side.

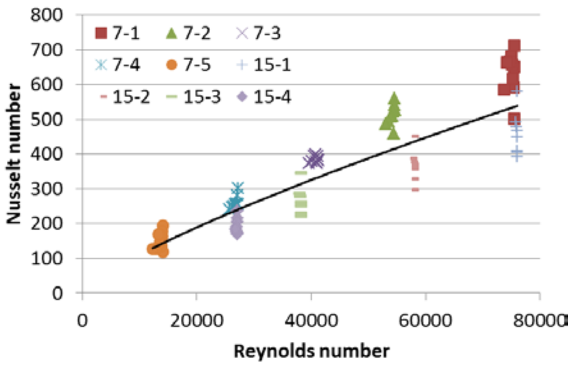

Fig. 8. Nusselt number correlation for CO_2 side.

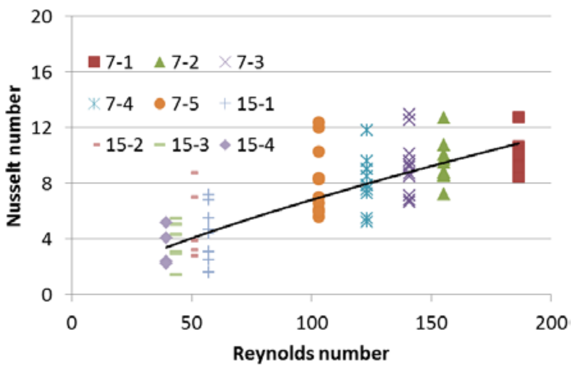

Fig. 9. Nusselt number correlation for water side.

Two sets of friction factor and Nusselt number correlations are obtained through the analysis. The Reynolds number range of water side was 40-190 and CO_2 side was 12,000-75,000. The derived correlations are tabulated in table 1 with R^2 values.

Table I: Derived correlations

	Correlation	R^2
CO_2	$f = 0.3224\ Re^{-0.287}$	0.706
	$Nu = 0.0792\ Re^{0.7852}$	0.8329
Water	$f = 6.4064\ Re^{-0.758}$	0.9976
	$Nu = 0.1568\ Re^{0.8012}$	0.7404

3. Conclusions

Recently, design and performance prediction of PCHE received attention due to its importance in high pressure power systems such as S-CO_2 cycle. To evaluate a PCHE performance with CO_2 to water, KAIST research team designed and tested a lab-scale PCHE. From the experimental data and CFD analysis, pressure drop and heat transfer correlations are obtained. For the CFD analysis, Ansys-CFX commercial code was utilized with RGP table implementation.

In near future, the turbulence model sensitivity study will be followed. Also the suggested correlations will be compared with conventional micro channel correlations.

In addition, header part design optimization will be studied for more precise PCHE design. Two dimensional PCHE design methodology will be examined for flow distribution effect analysis.

ACKNOWLEDGEMENT

Authors gratefully acknowledge that this research is supported by the National Research Foundation of Korea (NRF) and funded by the Korean government. (No. 2013M2A8A1041508)

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