CFD Analysis on the S-shaped PCHE Recuperator installed in the Autonomous Brayton Cycle (ABC) test loop

Jeong Yeol Baek, Jae Jun Lee, Jeong Ik Lee[*]
Dept. Nuclear & Quantum Eng., KAIST, 291 Daehak-ro, Yuseong-Gu, Daejeon 34141, Republic of Korea
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

Recently, the supercritical carbon dioxide (S-CO₂) cycle has attracted attention as the promising power conversion system for many power applications. Many research institutions and industries have built experimental facilities, and some countries have established pilot or commercial scale facilities. For the interest in the commercialization of the S-CO₂ system, the development of printed circuit heat exchanger (PCHE) played a key role for a recuperator due to its compactness and high effectiveness. In order to design and analyze PCHE, it is required to develop an empirical correlation that can predict heat transfer and flow characteristics correctly. PCHE may show different performance depending on geometric information such as channel shape, diameter, spacing, and thickness. In addition, when applied to the S-CO₂ system, it may show different characteristics depending on the operating conditions due to dramatic changes in physical properties. Therefore, it is necessary to develop empirical correlations suitable for target geometry and operating conditions.

Currently, the KAIST research team has improved existing S-CO₂ experimental facility (SCO₂PE) to build a new facility by adding a recuperator and a heater to test automatic control capability of the S-CO₂ power cycle, namely Autonomous Brayton Cycle (ABC) test loop. The recuperator for this facility has a PCHE with S-shape channels. However, the operating conditions of the recuperator has lower pressure and temperature than the commercial scale facilities due to the limitations of the university environment. In this study, a CFD analysis is used to derive correlations that can predict heat transfer and friction coefficients of the target PCHE and compare them with existing correlations before the test is conducted. Correlations derived in this study will be experimentally validated after the construction of the experimental facility is completed.

2. Methods and Results

2.1 Experimental Loop and Recuperator

Fig. 1 shows the layout and design points of the experimental facility. It consists of turbo alternator compressor (TAC), 32 kW electric cartridge heater, recuperator, and a cooler. The recuperator is an S-shape PCHE and designed using Kim et al. correlations which was developed under 32.5° fin angle zigzag PCHE and the recuperator conditions for KAIST-MMR [1]. Fig. 2

shows the recuperator mounted in the experimental loop and Fig. 3 describes detailed channel geometry. Hot and cold channels are designed to have the same geometry which is a semicircular channel.
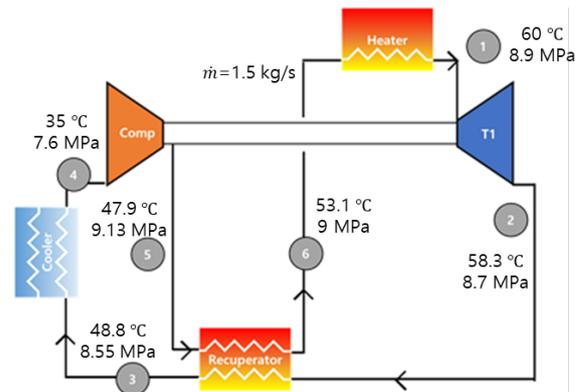
Fig. 1. Schematic diagram of experimental facility and design conditions.
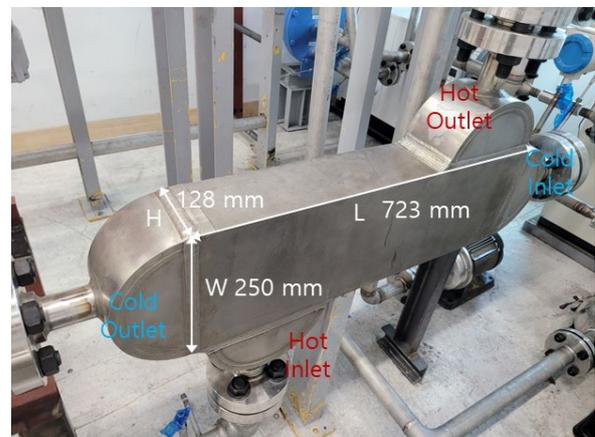
Fig. 2. PCHE recuperator in experimental loop.
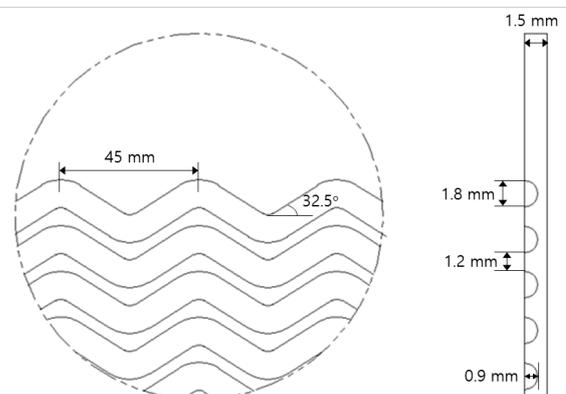
Fig. 3. Detailed channel geometry of PCHE recuperator.

2.2 CFD Analysis

A commercial CFD code, Ansys CFX 19.2 was used to analyze heat transfer and flow characteristics of the target PCHE. The turbulence model was selected to be k-ω shear stress transport (SST) model since standard k-ε model may underestimate pressure loss as reported in the previous studies [1]. For the physical properties, a real gas format table was used. The table was generated from the NIST REFPROP 9.1 fluid property database with 20,000 data points resolution within the simulation ranges [3]. The simulated temperature and pressure range were the operating conditions at each side and mass flow rate is adjusted to analyze wide Reynolds number range. Grid sensitivity test was performed as shown in Table I. Since the increase in the number of nodes in the computation domain does not show a dramatic decrease in error, the case of 1,328,100 nodes was selected in consideration of computational efficiency. Fig. 4 shows the calculation domain and boundary conditions. The counter current flow for a single channel was modeled and periodic boundary condition was applied to top, bottom, left, and right sides.
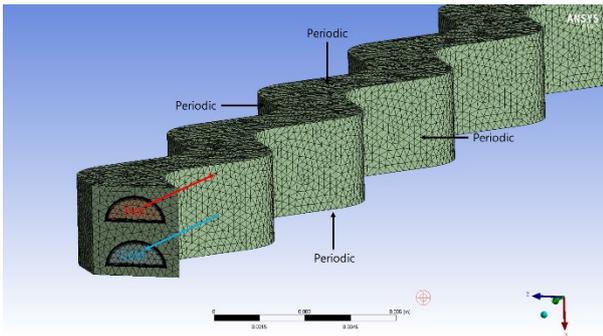
Fig. 4. Computational domain and boundary conditions.

Table I: Grid test results

Number of nodes	Number of elements	Average h $[W/m^2 \cdot K]$	Error [%]
1,328,100	616,482	5429.1 (hot)	-1.5
		6717.4 (cold)	-2.4
2,109,861	1,006,185	5484.8 (hot)	-0.5
		6740.3 (cold)	-2.0
9,668,600	4,962,724	5513.8 (hot)	0
		6879.2 (cold)	0

To obtain local variables, planes were generated and placed on certain locations in the fluid domain. Physical properties and flow parameters are read from these planes so that bulk properties can be obtained. Entrance region at each side was excluded and only fully developed regions were analyzed. The local heat transfer coefficient was calculated by using the below expression.

$$h = \frac{q''}{T_{wall} - T_{bulk}}, \bar{h} = \frac{1}{n}\sum_{i=1}^{k} h_i$$

q'': wall heat flux
T_{wall}: wall temperature
T_{bulk}: bulk temperature
$\bar{h}$: channel averaged local heat transfer coefficient

The bulk temperature and other properties were obtained using area averaged pressure and mass flow averaged enthalpy from CFX CEL expression. Nusselt number and Fanning friction factor can be derived from the following expressions.

$$Nu = \frac{h_{local}l}{k}, \overline{Nu} = \frac{1}{n}\sum_{i=1}^{k} Nu_i$$

$$f = \frac{\Delta P_k}{2\rho_k v_k^2}\cdot\frac{D_h}{L_k}, \bar{f} = \frac{1}{n}\sum_{i=1}^{k} f_i$$

Fig. 5 and 6 shows results of Nusselt number and Fanning friction factor. Although the temperature and pressure ranges cover lower values than those of the commercial system, the thermodynamic state is not close to the critical point too much. Thus, there is very limited Prandtl number effect on the heat transfer. The newly developed correlations for S-shaped PCHE recuperator are as following.

$$12,000 < \text{Re} < 67,000 \ (1.5 < \text{Pr} < 2.5)$$
$$Nu = 0.0391\, Re^{0.8198}$$
$$f = 0.2688\, Re^{-0.2812}$$
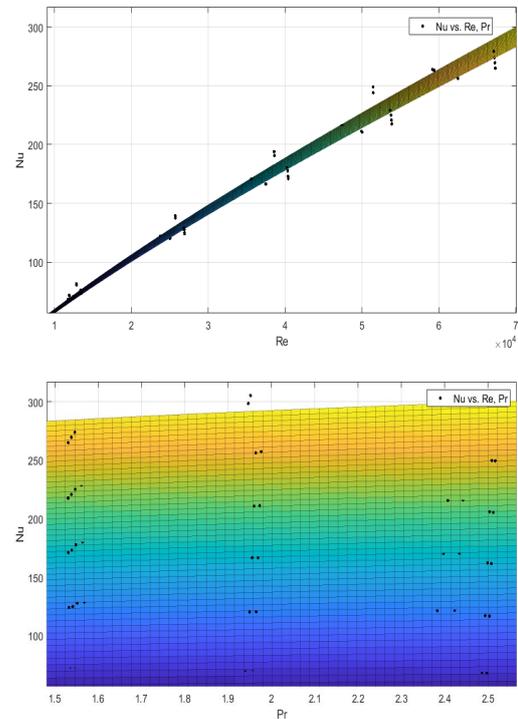
Fig. 5. Relationship between Reynolds number, Prandtl number, and Nusselt number.
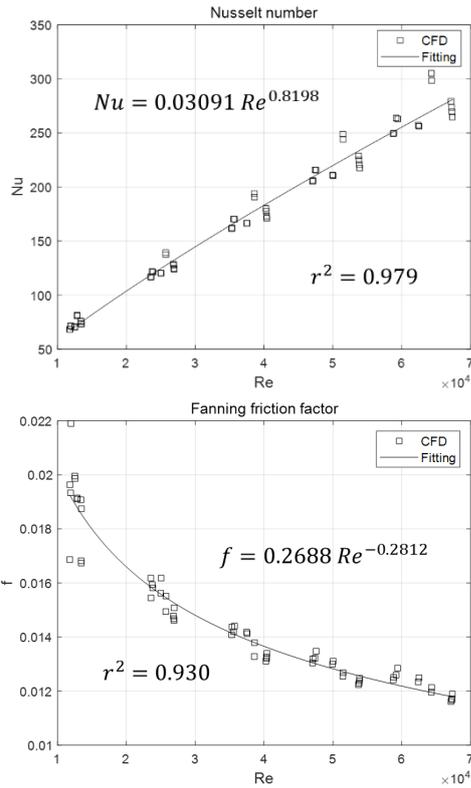
Fig. 6. Results of Nusselt number and Fanning friction factor.

2.3 Comparison with existing correlations

The authors selected two PCHE correlations to compare the newly developed correlations [1 & 4].

- Kim correlation (32.5° zigzag PCHE, for recuperator)
  $2,000 < Re < 58,000 \ (0.7 < Pr < 1.0)$
  $$Nu_{Kim} = 0.0292 \, Re^{0.8138}$$
  $$f_{Kim} = 0.2515 \, Re^{-0.2031}$$

- Baik correlation (32.5° zigzag PCHE, for precooler)
  $15,000 < Re < 85,000 \ (2 < Pr < 33)$
  $$Nu_{Baik} = 0.8405 \, Re^{0.5704} Pr^{1.08}$$
  $$f_{Baik} = 0.0748 \, Re^{-0.19}$$

Both correlations were chosen because they were derived from a PCHE with very similar geometric conditions to the current PCHE except for the channel shape. Fin angle and channel diameter are the same, but they were developed for the zigzag channel, not the S-shape channel.

Fig. 7 shows the comparison of Nusselt number correlations. Since the Baik correlation was developed near the critical point for the precooler, it has a large Prandtl number effect and may overestimate the heat transfer coefficient. This is due to its high density and liquid-like properties near the critical point of CO_2. It shows quite similar results to Kim correlation, which is believed to have a similar heat transfer mechanism because it is far from the critical point even though the temperature range is different.
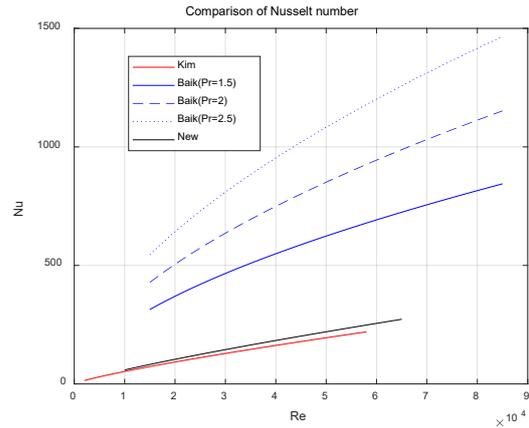
Fig. 7. Comparison of Nusselt number correlations.

Fig. 8 shows the comparison of Fanning friction factor correlations. Baik correlation tends to underestimate friction factor, because it was developed in more dense areas. Unlike the heat transfer correlation, the newly obtained result in this study is also quite different from the Kim correlation, which is thought to be because the S-shape channel has a smoother corner than the sharp zigzag channel.

As a result, in the case of S-shaped PCHE, the heat transfer coefficient is similar to that of the zigzag channel, but it is expected to be a better option due to smaller friction coefficient.
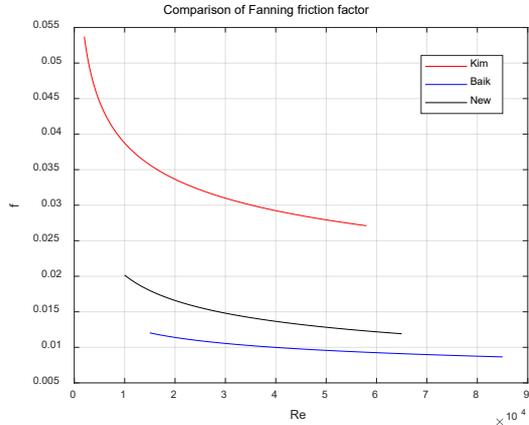
Fig. 8. Comparison of Fanning friction factor correlations.

3. Summary and Further Works

In this study, heat transfer and friction factor correlation for the S-shaped PCHE were developed to apply for S-CO_2 recuperator. CFD analysis was used to derive correlations and the newly developed correlations were compared to existing correlations. As a result of the comparison, it was confirmed that the newly developed correlation is similar to the Kim correlation in terms of heat transfer but there is a difference in the friction factor. In the future, the correlations derived in this study will be validated with experimental results obtained from the newly constructed facility namely Autonomous Brayton Cycle (ABC) test loop.

ACKNOWLEDGEMENT

REFERENCES

[1] S. G. Kim, Y. Lee, Y. Ahn, and J. I. Lee, "CFD aided approach to design printed circuit heat exchangers for supercritical CO_2 Brayton cycle application," *Annals of Nuclear Energy*, vol. 92, pp. 175-185, 2016.

[2] ANSYS, 2011. ANSYS CFX-Solver Theory Guide, Release 14.0. Tech., rep., November.

[3] E. W. Lemmon, M. L. Huber, and M. O. McLinden, "REFPROP, NIST Standard Reference Database 23, v. 9.1," Natl. Inst. Stand. Gaithersburg, MD, USA, 2010.

[4] S. Baik, S. G. Kim, J. Lee, and J. I. Lee, "Study on CO_2–water printed circuit heat exchanger performance operating under various CO_2 phases for S-CO_2 power cycle application," *Appl. Therm. Eng.,* vol. 113, pp. 1536-1546. 2017