Heat transfer performances of printed circuit heat exchangers with airfoil and straight channels for helium Brayton cycle recuperator designs

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1. Introduction

In helium Brayton cycles for high temperature gas-cooled reactors, recuperators, gas-to-gas heat exchange type, are essential components to increase the cycle thermal efficiency. However, it required a very high volume and heat transfer area because of the high thermal duty and similar heat capacitances of hot and cold sides. Also, due to the low density of helium, heat exchangers in helium Brayton cycles were normally designed at the relatively low Reynolds number conditions compared to the supercritical carbon dioxide Brayton cycles and nitrogen Brayton cycles [1-5].

A printed-circuit heat exchanger (PCHE) has been considered as the most suitable heat exchanger type due to its high compactness and wide operating ranges [3]. There are various PCHE channels shapes such as straight, zigzag, S-shape, and airfoil fin with different thermal-hydraulic performances. Airfoil PCHE has been developed and considered as the competitive channel shape at the low Reynolds number conditions [4]. However, there was not sufficient experimental data of airfoil PCHE at the low Reynolds number and gas conditions.

For this reason, the heat transfer performance of airfoil PCHE was investigated through experimental data. Straight PCHE experiments were performed to confirm the results based on nitrogen could be applied to the heat exchanger design of the helium Brayton cycle. In addition, the results of the Nusselt number for airfoil PCHE in terms of Reynolds number will be discussed in this paper.

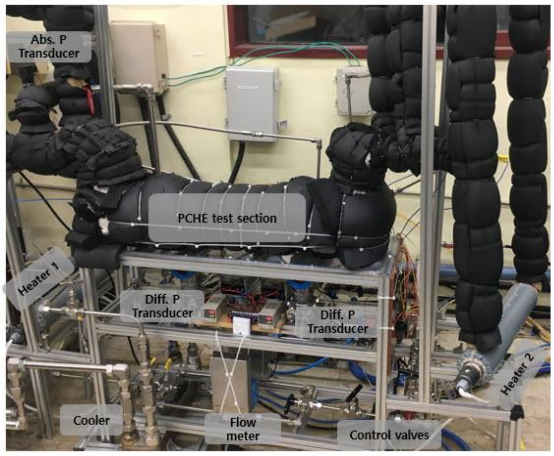

Fig. 1. Experimental loop installed at POSTECH.

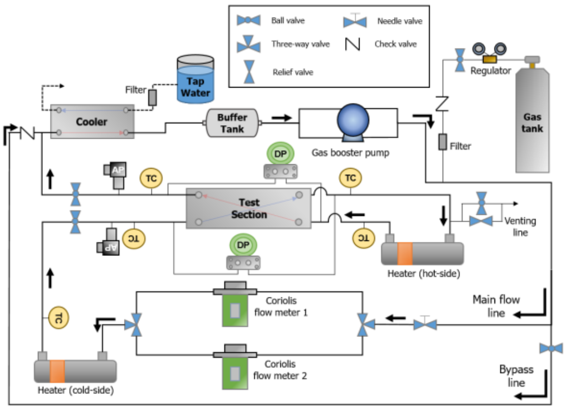

Fig. 2. Schematic diagram of the experimental loop.

2. Experimental setup

2.1. Experimental loop

To investigate the performance of airfoil PCHE at the low Reynolds number and gas conditions, a gas-to-gas heat exchanger experimental loop was developed at POSTECH (Fig. 1). The experimental loop is a closed system and once-through heat exchange type which means mass flow rates of the hot and cold sides are considered as the same value. The two heaters were installed to set the inlet temperature conditions for hot and cold with a maximum 1.2 kW heat capacity. A gas booster pump was used to circulate the working fluid in the experimental loop. In this study, nitrogen was adopted as a working fluid in the experiments. The temperatures and pressures were measured at the inlet and outlet of each hot and cold side with K-type thermocouples, absolute pressures, and differential pressures. The schematic diagram of the experimental loop is shown at Fig. 2.

2.2. PCHE test section

Two PCHE test sections for airfoil and straight channels were manufactured to have the same hydraulic diameter as 1.1 mm (Fig. 3). Both test sections were designed as the counter-flow type, single banking method, and the same geometries of the hot/cold sides. In the case of straight PCHE, the plate thickness was 1.8 mm with 1.8 mm of semi-circular diameter, and 0.9 mm of etching depth. On the other hand, the airfoil PCHE test section had 1.5 mm of plate thickness, 6 mm chord length of NACA0020 airfoil fin, and 0.7 mm etching depth.

Fig. 3. Configuration of PCHE channel.

3. Experimental results

The airfoil PCHE experiments were performed under the range of Reynolds number in 400 to 2,500. The inlet temperature conditions were set as the same values in the airfoil and straight PCHE experiments as 90°C for the hot side and 40°C for the cold side. In this study, the losses of experiments were less than 10% as shown in Fig. 4.

Due to the small thickness of the unit plate and the high thermal conductivity of solid material, the Biot number was not over than 0.1 in this study. Therefore, the conduction resistance of the wall was neglected by the lumped capacitance method. Since the differences of Reynolds number and Prandtl number between hot and cold sides were less than 2% in this study, the Nusselt numbers could be derived with an assumption [5] called the direct method which considered as the heat transfer coefficients of hot and cold sides are same.

The results of the Nusselt number based on the experimental data were shown in Fig. 5. For applying the experimental data based on nitrogen to the helium Brayton cycle heat exchanger designs, the experimental data of straight PCHE were compared to the predicted results by Chen correlation which is based on the helium-to-helium straight PCHE experiments with 1,200 to 1,850 of Reynolds number range [5]. The Chen correlation is shown as the orange solid line in Fig. 5 and the correlation is as follows.

$$Nu = 0.047516\,\mathrm{Re}^{0.633151},\ 1200<\mathrm{Re}<1850 \qquad (1)$$

The compared results showed that the maximum error between experimental data of nitrogen and the predicted Nusselt number was less than 6%. When the Reynolds number is extended on Chen correlation as shown as the orange dash line in Fig. 5, it had about 15% maximum error compared to the straight PCHE results. In the case of the Prandtl number, the difference between helium and nitrogen was less than 10% in experiments. Also, the results of $Nu/Pr^{1/3}$ had a maximum difference of less than 13% in the experimental range of Reynolds numbers. For these reasons, the results of experiments based on nitrogen could be expected to be used for the helium Brayton cycle heat exchanger designs.

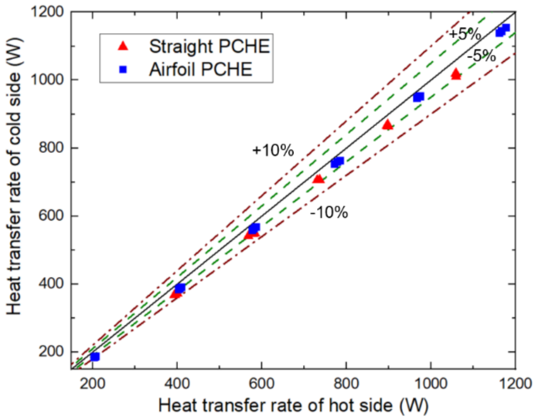

Fig. 4. Results of heat balance in experiments.

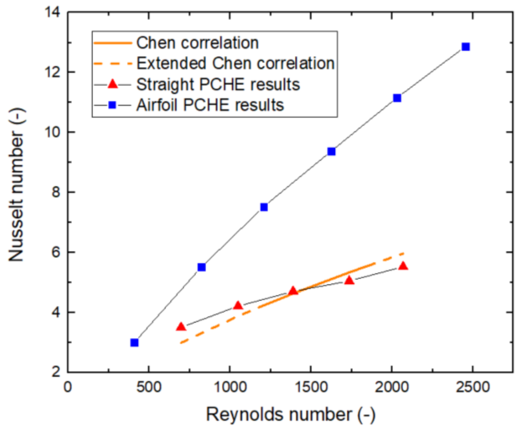

Fig. 5. Nusselt number in terms of Reynolds number.

The results of airfoil PCHE showed that it had much higher heat transfer performances than straight PCHE. It was almost twice of straight PCHE heat transfer performance at the same Reynolds number. In addition, the increasement rate of Nusselt number in terms of Reynolds number was higher than straight PCHE.

In the next research, the heat transfer correlation will be developed with experimental data and it will be used to design the gas-to-gas heat exchangers at the low Reynolds number range such as recuperators of helium Brayton cycles.

4. Conclusion

In this paper, the heat transfer performance of airfoil and straight PCHE were evaluated at the low Reynolds number and gas conditions with experimental data. The experimental Nusselt number was obtained from the developed experimental loop and the direct method. The Nusselt numbers of straight PCHE experiments based on nitrogen were enough to reflect the heat transfer performance of the previous study correlation based on the helium experiments. The airfoil PCHE had a higher Nusselt number than straight PCHE at the same Reynolds number. In the next research, the heat transfer correlation for airfoil PCHE will be developed and used to design the helium Brayton cycle heat exchangers.

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