Validation of Printed Circuit Heat Exchanger Design Code KAIST_HXD

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1. Introduction

Among the generation IV reactors, sodium-cooled fast reactor (SFR) has received worldwide attention since it operates near atmospheric pressure with passive safety and reduces high-level radioactive wastes. However combination with conventional steam Rankine cycle faces the problem of violent sodium-water reaction. Thus supercritical carbon dioxide (S-CO_2) Brayton cycle has been suggested for the SFR due to the relatively mild sodium-CO_2 interaction. The S-CO_2 power conversion cycle can achieve not only high safety but also high efficiency with SFR core thermal condition.

However, due to the dramatic property change near the critical point, the inlet pressure and temperature conditions of compressor can have significant effect on the overall cycle efficiency. To maintain the inlet condition of compressor, a sensitive precooler control system is required for stable operation. Therefore understanding the precooler performance is essential for the S-CO_2 power conversion system.

2. In-House Heat Exchanger Design Code and Experimental Facility

The printed circuit heat exchanger (PCHE) is the most suggested heat exchanger for high pressure S-CO_2 cycle. In order to design PCHE, KAIST research team developed a methodology of designing PCHE for the S-CO_2 system. In this paper the in-house PCHE design code KAIST_HXD will be validated by comparing the design result and experimental data from KAIST S-CO_2 pressurizing experiment (S-CO_2PE) facility.

2.1 Heat Transfer Modeling in KAIST_HXD

The KAIST_HXD is a MATLAB based PCHE core design code. Since a PCHE has a characteristic of having repeated similar channels, the total heat transfer in PCHE can be estimated by analyzing a set of representative channels. To calculate heat transfer and pressure drop through the channel, total length of the channel is discretized for nodalized calculation [1].

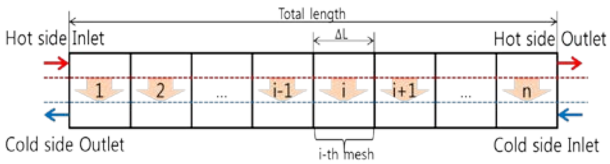

Fig. 1. Concept of channel nodalization [1]

Fig. 1 shows the nodalization concept in a set of channels. Heat transfer in each mesh can be calculated by equation (1). In this two dimensional heat transfer model, the temperature difference is defined with a fluid bulk temperature by equations (2) and (3).

$$Q = U\,A\,\Delta T = \frac{1}{R_{conv.Hot} + R_{cond} + R_{conv.Cold}}\,A\,\Delta T = \frac{1}{\frac{1}{h_{Hot}} + \frac{t}{k_{cond}} + \frac{1}{h_{Cold}}}\,A\,\Delta T \quad (1)$$

$$\Delta T = T_{bulk.Hot} - T_{bulk.Cold} \quad (2)$$

$$T_{bulk} = \frac{\int \rho v c_P T dA}{\int \rho v c_P dA} \quad (3)$$

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

To estimate the pressure drop of the channel, the equation (4) is used with fanning friction factor. The convective heat transfer coefficient in equation (1) and friction factor in equation (4) are obtained from the other research reports [4, 5]. The correlations are tabulated with restriction in Table I. However, those correlations are function of Reynolds number and channel geometry. So the special caution is needed for designing a PCHE.

Table I : Heat transfer correlation and Friction factor in KAIST_HXD [4&5]

Hot side (CO_2 side)	
Reynolds number	2,000 < Re < 58,000
Nusselt number	Nu = 0.0293 $Re^{0.814}$
Friction factor	f = 0.2515 $Re^{-0.203}$
Cold side (water side)	
Reynolds number	30 < Re < 400
Heat transfer coeff. [W/m^2k]	h = 11.04 Re + 570.36
Friction factor	f = 1.3856 $Re^{-0.482}$

2.2 S-CO_2PE Experimental Facility and Designed PCHE

The S-CO_2PE is an experimental S-CO_2 cycle demonstration facility in KAIST. Fig. 2 shows the total view of the facility. The facility is consisted of a compressor, a heater, an expansion valve and a precooler. The expansion valve plays a turbine role as well as a main flow controller. The precooler is a designed PCHE by KAIST_HXD code. The detailed design parameters are shown in Fig. 3, 4. Each side of heat exchanger consists of 896 semi-circular channels.

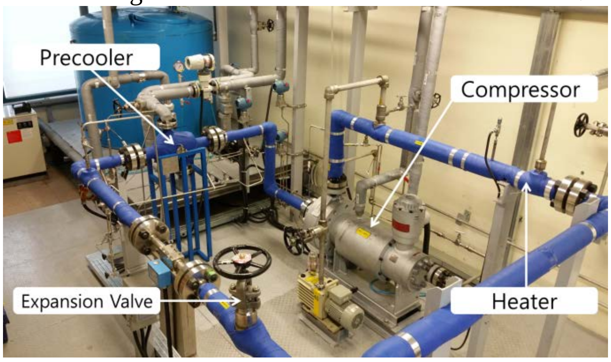

Fig. 2. Total view of S-CO_2PE experimental facility

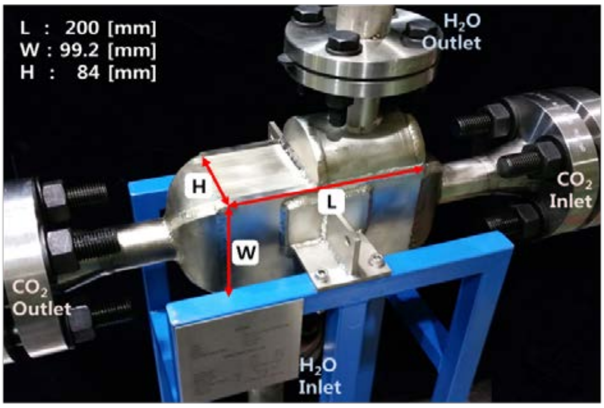

Fig. 3. Designed PCHE by KAIST_HXD

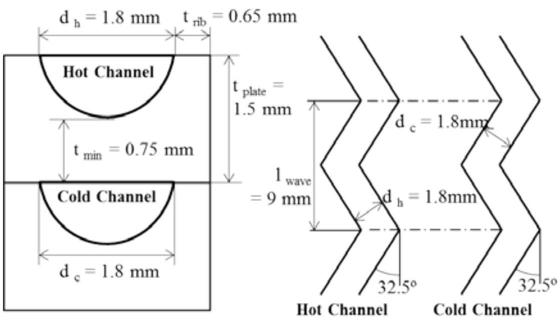

Fig. 4. Designed PCHE channel geometry information

3. Results

To validate the KAIST_HXD code, designed PCHE is tested in various conditions. To compare the performance in each case, the experiment was conducted with the same cooling water temperature at 15℃. From obtained data in 14 different cases, the heat exchanger performance was classified by density of hot side inlet condition. The tested cases are shown with density contour in Fig. 5.

From inlet to outlet, the measured temperature and pressure are plotted. Through a heat exchanger channel, the hot side fluid CO_2 gas gives heat to the cold side water. In this viewpoint, it is obvious that the CO_2 density of the outlet is larger than inlet.

From the same inlet condition of each side, KAIST_HXD simulation study was conducted.

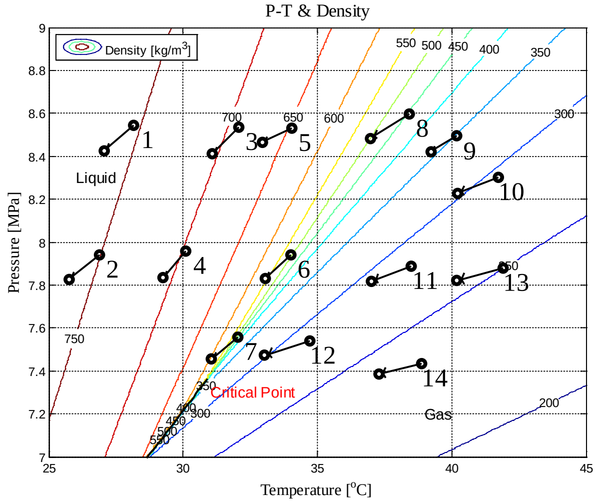

Fig. 5. Test cases with density contour

From a mesh test in 200mm core, minimum 500 mesh is needed to obtain reliable result. Figs. 6 and 7 show the heat transfer performance comparisons. The heat load is based on water side measurement to avoid large uncertainty in the CO_2 side. The hydraulic performance comparisons are showen in Figs 8 and 9. High density cases showed large amount of heat transfer and large pressure drop.

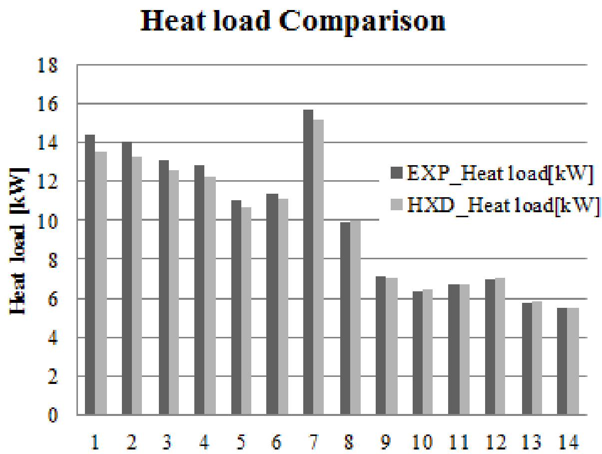

Fig. 6. Heat transfer performance comparison

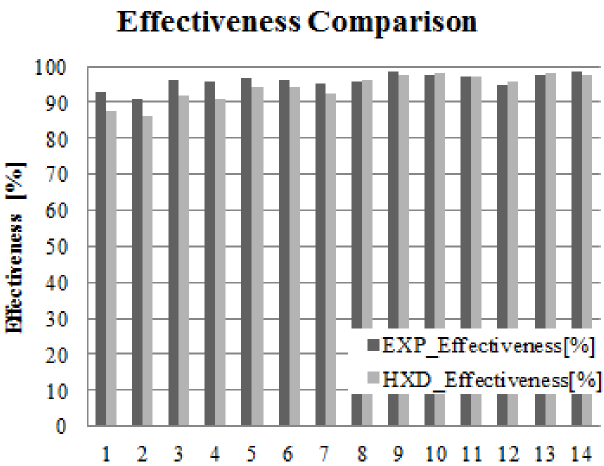

Fig. 7. Heat transfer performance comparison

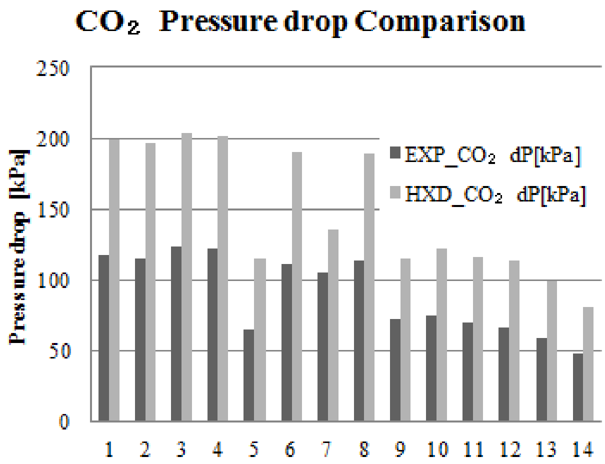

Fig. 8. Pressure drop of CO_2 side comparison

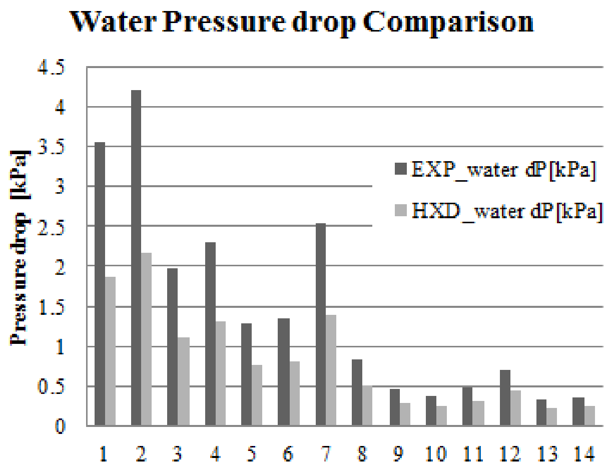

Fig. 9. Pressure drop of water side comparison

4. Conclusions and Further works

According to experimental result, designed PCHE showed high effectiveness in various operating regions. Comparing the experimental and the design data, heat transfer performance estimation showed less than 6% error. On the other hand, the pressure drop estimation showed large gap. The water side pressure drop showed 50~70% under estimation. Because the form losses were not included in the design code, water side pressure drop estimation result seems reliable.

However, the CO2 side showed more than 70% over estimation in the pressure drop from the code. The authors suspect that the differences may have occurred by the channel corner shape. The real channel has round corners and smooth edge, but the correlation is based on the sharp edged zig-zag channel. Further studies are required to understand and interpret the results correctly in the future.

The uncertainty analysis will be conducted. Also the heat transfer and friction factor correlations modification and comparison with other research will be followed

Additionally, the two dimensional numerical approach in heat transfer core plate will be utilized to analyze the header distribution effect.

Consequently the KAIST_HXD code will be upgraded by adding the hydraulic analysis in header section.

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