

Printed Circuit Heat Exchanger Design, Analysis and Experiment

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ABSTRACT

The supercritical carbon dioxide (S-CO₂) Brayton cycle has been receiving worldwide attention because of the high thermal efficiency at moderate turbine inlet temperature (450~650 °C) due to relatively low compression work near the CO₂ critical point (30.98 °C, 7.38MPa). Recently, the compact heat exchanger design for the S-CO₂ cycle has been one of the main engineering issues. The heat transfer performance and the pressure drop of a heat exchanger need to be precisely predicted for optimizing the S-CO₂ Brayton cycle. To predict the thermal hydraulic performance of a heat exchanger, KAIST research team developed a printed circuit heat exchanger (PCHE) design and analysis code; namely KAIST_HXD. For the realistic design, the Reynolds number range of previous experimental correlation for zig-zag channel was extended to 2,000-58,000 by a commercial CFD code. A small size of PCHE designed by KAIST_HXD was manufactured to test the accuracy of the design code. From the experimental result, the designed PCHE showed not only sufficient performance but also small pressure losses. This paper will describe the experimental result of the designed PCHE and the applicability to the S-CO₂ cycle.

KEYWORDS

Supercritical CO₂, S-CO₂ Brayton Cycle, Printed Circuit Heat Exchanger, CFD.

1. INTRODUCTION

An eco-friendly and highly efficient power conversion system has received worldwide attention due to increasing concerns on rising energy demand and global warming issues. Among the state of the art alternative energy technologies, sodium-cooled fast reactor (SFR) has strong potential to be a key technical solution in the near future. The SFR has several advantages, which are passive safety and reduction of high-level radioactive wastes. However, applying the conventional steam Rankine cycle to SFR raises issues on violent sodium-water reaction problem.

In order to reduce the accident possibility, the supercritical carbon dioxide (S-CO₂) Brayton cycle has been suggested due to the relatively mild sodium-CO₂ interaction. The S-CO₂ power conversion cycle can achieve not only high safety but also high efficiency with SFR core thermal condition. According to previous research [2], the S-CO₂ cycle can achieve high efficiency compared to conventional complex reheat steam cycle. Moreover, main component of power cycle such as turbo machinery and heat exchanger can be designed in compact size due to high density of S-CO₂.

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. Since the temperature control of the compressor inlet condition is solely dependent on the precooler performance, the role of precooler became very important. For the stable cycle operation, a sensitive precooler control system is

required to maintain the compressor inlet condition. Therefore designing a heat exchanger and understanding the heat exchanger performance near the critical point are essential for the S-CO₂ power conversion system. In this research, the methodology of designing compact heat exchanger and experimental performance tests are covered.

2. IN-HOUSE HEAT EXCHANGER DESIGN CODE AND EXPERIMENTAL FACILITY

In gas heat transfer, the large heat transfer area is needed due to relatively poor fluid heat transfer characteristics. To obtain large surface area in a heat exchanger, compact heat exchangers are often used. The printed circuit heat exchanger (PCHE) is one of the compact heat exchangers that can sustain high pressure difference while having high effectiveness. The PCHE is manufactured by chemical etching process and diffusion bonding process. The micro channels are chemically etched on the steel heat transfer plate and stacked plates are diffusion bonded into single solid structure under high temperature and pressure conditions. The fabrication process is illustrated in Figure 1.

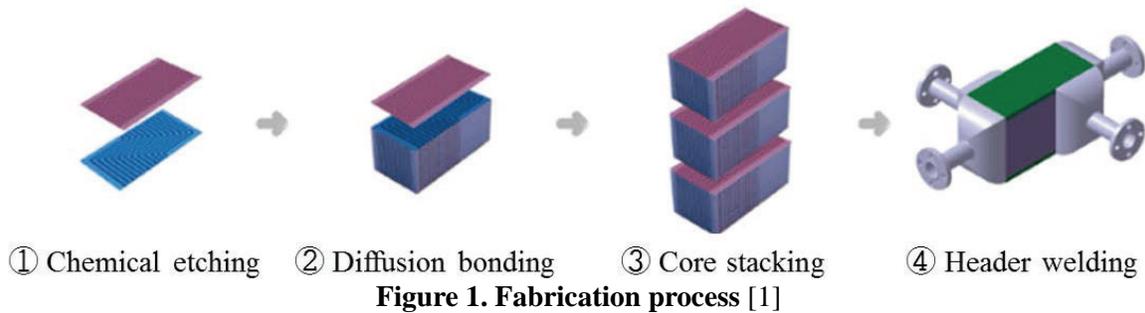


Figure 1. Fabrication process [1]

Since the PCHE can be operated under high pressure condition, the PCHE was suggested for the S-CO₂ cycle heat exchanger. By utilizing a compact heat exchanger technology such as PCHE, the S-CO₂ cycle can be compact. In order to design a PCHE, KAIST research team developed a heat exchanger design methodology for the S-CO₂ system. The developed PCHE design code KAIST_HXD will be validated by comparing the design result to the experimental data from KAIST S-CO₂ pressurizing experiment (S-CO₂PE) facility.

2.1. KAIST_HXD Algorithm

The KAIST_HXD is a MATLAB based PCHE core design code. Since a PCHE has repetitive channel configuration, the total thermal hydraulic performance in PCHE can be estimated by analyzing a set of representative channels. To calculate the heat transfer through the channel, total length of the channel is discretized for the calculation [2]. The nodalization is illustrated in Figure 2.

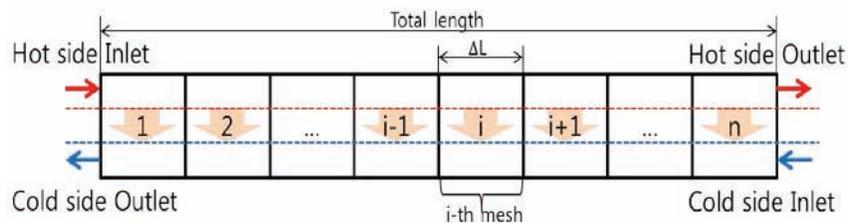


Figure 2. Channel nodalization

Figure 3 shows the flow chart of the KAIST_HXD code. From the given geometry, the code shows calculated heat transfer performance and pressure drop of whole heat exchanger. By prescribing the range of the geometry, optimized design parameters can be obtained. By fixed geometry, on the other hand, the steady state thermal hydraulic performance can be obtained as the calculation result. The following equations are the main equations for the KAIST_HXD.

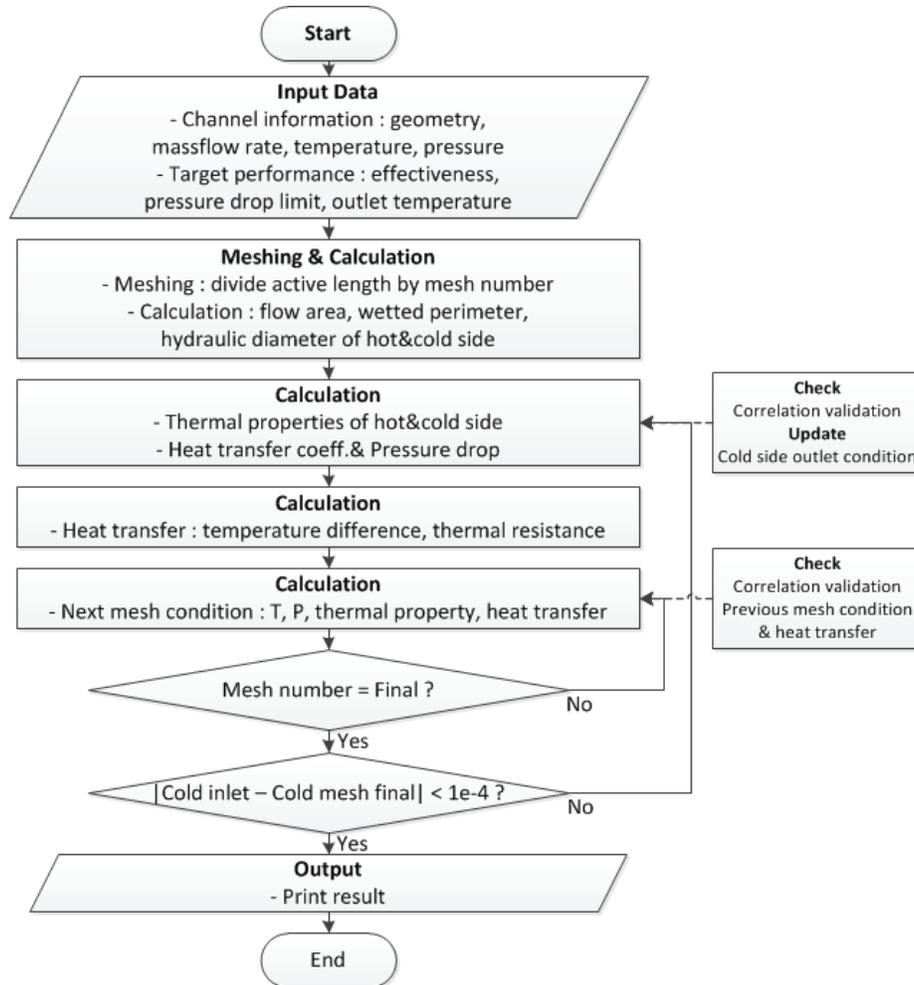


Figure 3. KAIST_HXD algorithm

Through the hot and cold channel, analysis single mass flowrate value is used which automatically satisfies the continuity equation. The heat transfer in each mesh can be calculated with equation (1). In this one dimensional heat transfer approach, the temperature difference is defined with a fluid bulk temperature by equations (2) and (3). To estimate the pressure drop of the channel, equation (4) is used with Fanning friction factor.

In order to close the equations, correlations for friction factor (f_{Fanning}) and heat transfer coefficients (h_{Hot} , h_{Cold}) in each channel are needed. The convection heat transfer coefficient in equation (1) and friction factor in equation (4) are obtained from the previous studies [5-6]. The detailed information of correlation used in KAIST_HXD is introduced in the following. For the realistic estimation, the REFPROP 8.0 real gas property database was used.

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

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

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

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

2. 2. Correlations in KAIST_HXD

Most conventional PCHE designs for working fluid of S-CO₂ require an extension of valid Reynolds number limits (2400-6000) of experimental correlations [3-4]. Therefore, commercial CFD code ANSYS was used to explore the validity of existing correlation beyond tested Reynolds number range. It is noted that the set of correlations with wide Reynolds number range (2,000-58,000) which was obtained from CFD analysis was verified with experiment. By comparing with other experimental correlations, extended correlation is suggested for designing an S-CO₂ heat exchanger [5].

For the water side calculation, previous PCHE water to water heat transfer correlations are used [6]. The Reynolds number range for the water side correlation is wide enough for the present study, thus the correlation was used without CFD study.

The utilized heat transfer and pressure drop correlations are tabulated with restriction in Table I.

Table I. Thermal hydraulic correlations in KAIST_HXD [5], [6]

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 ² ·K]	h = 11.04 Re + 570.36
Friction factor	f = 1.3856 Re ^{-0.482}

2.3. Designed PCHE for S-CO₂ to water heat exchanger

With developed KAIST_HXD code, the S-CO₂ to water heat exchanger was designed. According to Lee et al., mechanical stress induced by pressure loading is predominant rather than thermal stress in a normal PCHE [8]. Therefore the mechanical stress at the internal wall has to satisfy the pressure load limit. The minimum wall thickness was set to 0.75mm at 20MPa, which corresponds to the ASME pressure vessel standard. The detailed channel geometry of zig-zag channel is shown in Figure 5.

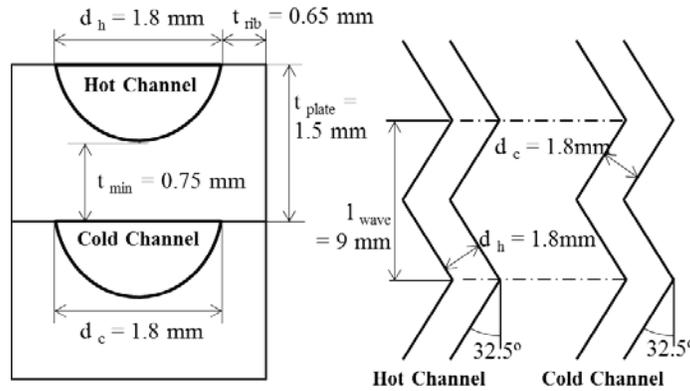


Figure 5. Channel geometry of designed S-CO₂ to water heat exchanger

Flow distribution header in the heat exchanger is another important design parameter which KAIST research team is focusing on. The pressure loss can be reduced by minimizing the local flow velocity change. In this manner, to minimize the pressure loss at the header section, the number of total channel is decided to be 896. With 896 semi-circular channels, the total flow area is equal to the main inlet pipe area.

In each plate, 32 flow channels are chemically etched. Stacking total 56 rows of 1.5mm thick SS316L heat transfer plate, the total core size is 200 mm × 99.2 mm × 84 mm. The physical shape of designed PCHE is shown in Figure 6.

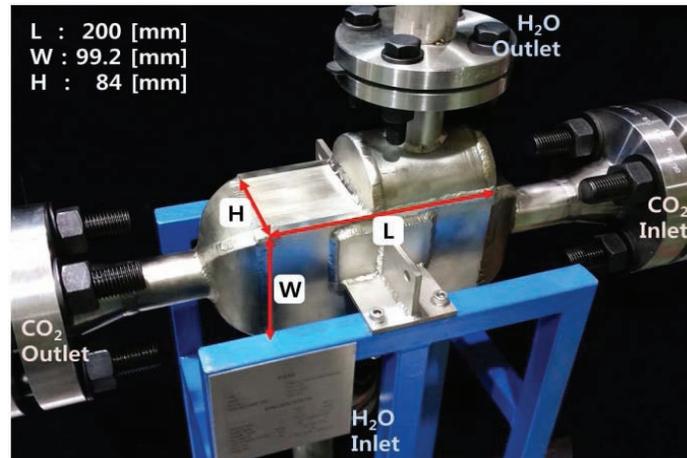


Figure 6. Designed PCHE by KAIST_HXD

For the summarized information, the specifications of designed PCHE are tabulated in Table II. The compactness of the designed heat exchanger is one of indicative parameter for comparison and it is defined with equation (5).

$$\text{Compactness} \left[\frac{\text{m}^2}{\text{m}^3} \right] = \frac{\text{Total heat transfer area} [\text{m}^2]}{\text{Total volume} [\text{m}^3]} \quad (5)$$

Table II. Specification of Designed PCHE

Designed PCHE	
Heat transfer area [m ²]	0.8
Volume [m ³]	0.003
Compactness [m ² /m ³]	267

2. 4. S-CO₂PE Experimental Facility

The S-CO₂PE is an experimental S-CO₂ simple cycle demonstration facility in KAIST. Figure 7 shows the total view of the facility. The main purpose of the facility is to evaluate the S-CO₂ compressor and precooler performance. The facility consists of a compressor, a heater, an expansion valve and a precooler. The expansion valve plays a turbine role as well as the main flow controller.

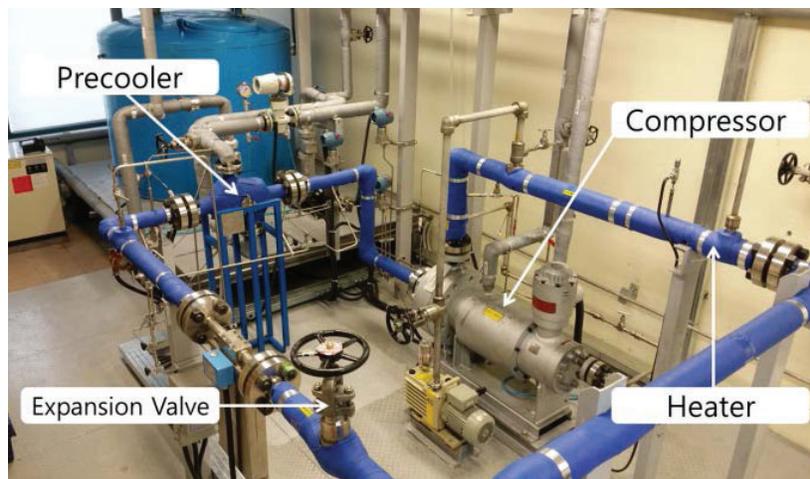


Figure 7. Overall view of the S-CO₂PE facility

2.5. Specification of S-CO₂PE facility

Since CO₂ is pseudo-incompressible fluid near the critical point, a 26kW seal free canned motor pump type compressor was utilized for pressurization and system circulation. High pressure globe valve is used for the main flow control. At the same time the globe valve induces large pressure drop due to the complex internal shape. The newly designed PCHE type heat exchanger was installed for the performance test. The total 28kW cooling capacity of chilling device was utilized for the cycle heat removal system. For the performance evaluation, accurate measurement devices were installed at the inlet and the outlet points of each component. Due to substantial property change near the critical point, the accuracy of measurement is an important parameter for the data. The accuracy of each sensor is listed in Table III.

Table III. Accuracy of measurement devices

Sensor type	Accuracy
RTD (CO ₂ , water)	± 0.2°C
Pressure transmitter (CO ₂)	± 0.05%
Differential pressure gauge (CO ₂)	± 0.065%
Differential pressure gauge (water)	± 0.04%
Mass flow meter (CO ₂)	± 0.16%
Mass flow meter (water)	± 0.5%

3. EXPERIMENTAL RESULTS

In order to validate the KAIST_HXD code, designed PCHE was tested under various conditions. To compare the performance in each case, the experiment was conducted under the condition which the cooling water temperature was maintained at 15°C. From the obtained 16 different test cases, the heat exchanger performance is shown on the density contour in Figure 8. In this figure, the measured temperature and pressure are plotted from inlet to outlet. From case 1 to case 6, the operating conditions have high density. The experimental condition of case 9 is the closest to the CO₂ critical point. Through a heat exchanger channel, the hot side fluid CO₂ gas transfers heat to the cold side water. In this cooling process, it is obvious that the CO₂ density is increasing.

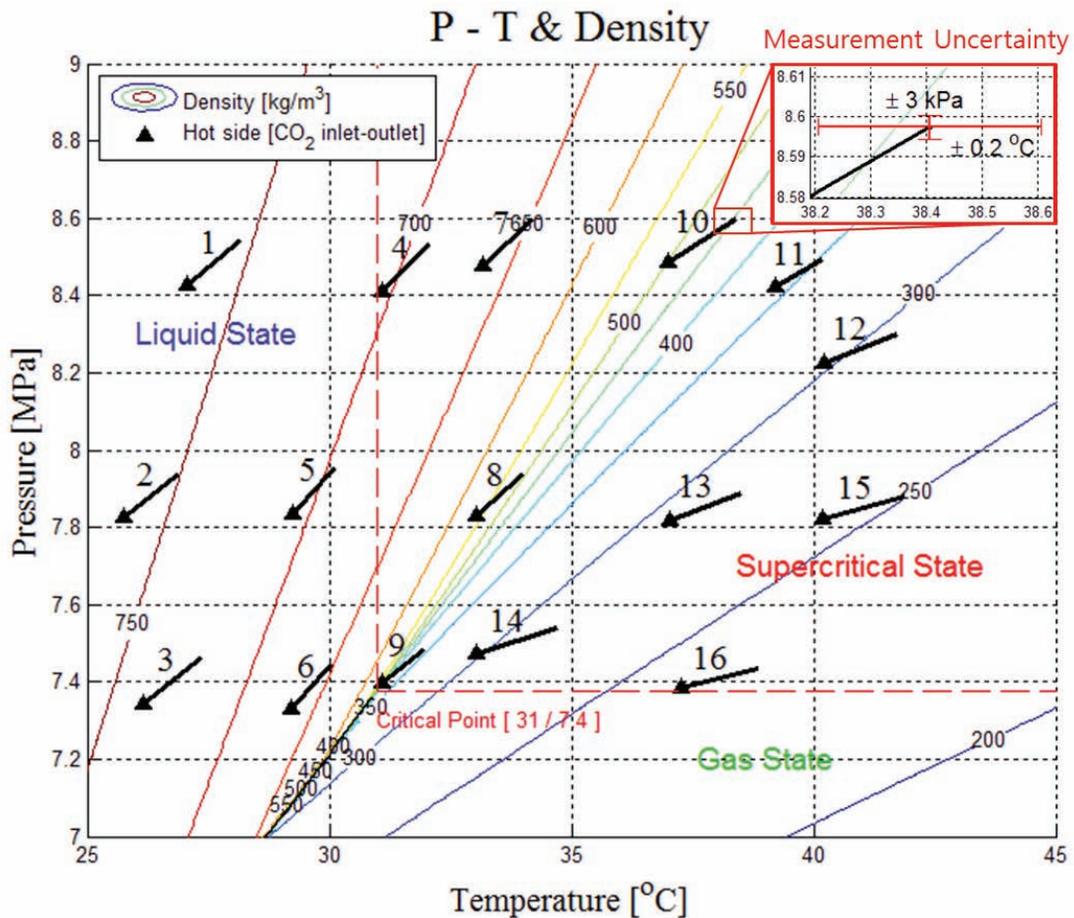


Figure 8. S-CO₂ inlet-outlet condition of tested cases

From the same inlet condition of hot and cold side, KAIST_HXD analyses were conducted. Compare to the experiment, the results from the KAIST_HXD at hot side outlet shows consistent differences. The pressure drop was overestimated for the CO₂ side in KAIST_HXD code for most cases. However, the temperature difference was relatively small between the KAIST_HXD and the experiment. Figures 9 and 10 show the heat transfer performance comparisons. The heat load calculation is based on the water side measurement to avoid large uncertainty in the CO₂ side near the critical point. Comparing the experimental data and the analysis result, heat transfer performance estimation showed less than 7% error. And the PCHE experimental data showed over 90% high effectiveness in various operating regions.

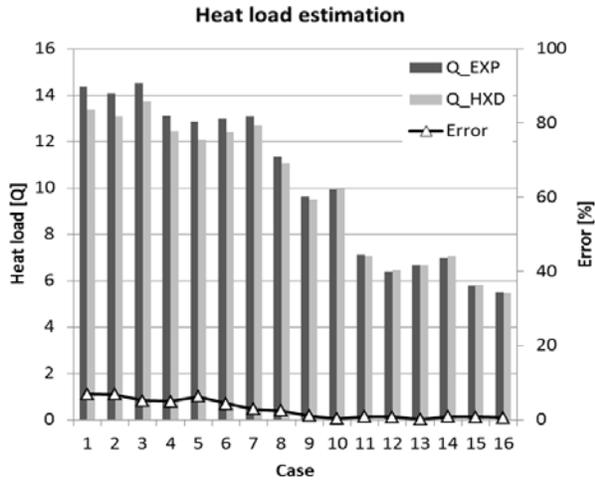


Figure 9. Heat load comparison

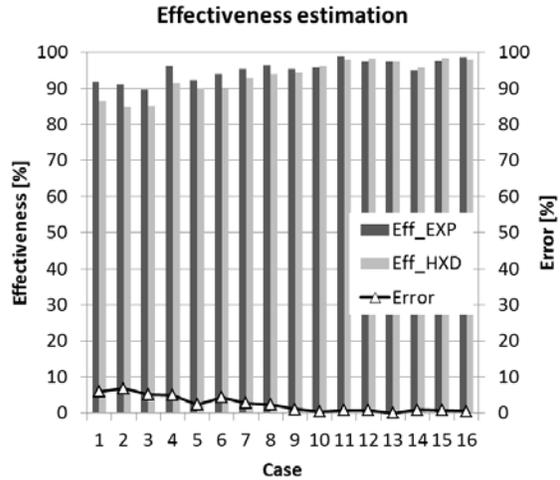


Figure 10. Effectiveness comparison

As mentioned above, the pressure drop estimation showed significant error. The hydraulic performance comparisons are shown in Figure 11. By comparing the code analysis result to the data, it was identified that the CO₂ side showed 40% over estimation on the pressure drop with the KAIST_HXD code. The water side showed 50~60% under estimation for the KAIST_HXD code result. The water side difference is understandable since the form loss in the header section is not evaluated in the KAIST_HXD code. However, the CO₂ side over estimation was unexpected and further studies are necessary to understand the reason.

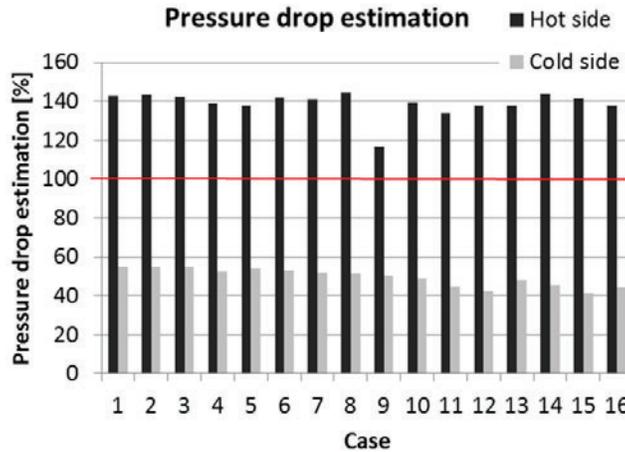


Figure 11. CO₂ and Water side pressure drop comparison

4. CONCLUSIONS AND FURHER WORKS

This study was conducted to check the validity of the PCHE design code with a simple experiment and understand the heat exchanger performance under various operating conditions other than the design point. From the experimental study, designed PCHE showed sufficient heat transfer performance. The most experimental data showed over 90% high effectiveness within 200mm small core and the design code also predicted the similar performance. The water side pressure drop estimation seems reliable even though some differences were observed from the code and the data, since the form losses were not included in the design code.

However, the CO₂ side showed more than 70% over estimation in the pressure drop from the code. So far, the authors suspect that the differences may have occurred by the difference in the channel edge 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.

For the KAIST_HXD to become a reliable code, the CO₂ side hydraulic performance has to be upgraded. The pressure drop correlation of both hot and cold sides will be re-studied with more detailed CFD simulation with realistic channel geometry. Also the header part pressure losses will be evaluated from the CFD.

The KAIST_HXD code can calculate not only the temperature and pressure profiles but also the thermo dynamic property change through the channel. After the code modification and CFD result, the heat transfer study depending on the property change near the critical point will be followed.

Additionally, the two dimensional numerical approach in heat transfer plate will be investigated to analyze the header distribution and cross flow region effect.

NOMENCLATURE

Q : Heat transfer rate [kW]

U : Overall heat transfer coefficient [kW/m²·K]

A : Heat transfer area [m²]

ΔT : temperature difference [°C]

Nu : Nusselt number

Re : Reynolds number

R_{conv} : Convective thermal resistance [K/kW]

R_{cond} : Conductive thermal resistance [K/kW]

h : Convective heat transfer coefficient [kW/m²·K]

k_{cond} : Conductive heat transfer coefficient [kW/m·K]

t_{plate} : Heat transfer plate thickness [mm]

l : Channel length [mm]

D : Hydraulic diameter [mm]

ρ : Density [kg/m³]

v : Fluid velocity in channel [m/s]

f_{Fanning} : Fanning friction factor

ΔP : Pressure drop [kPa]

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