Preliminary Study of Printed Circuit Heat Exchanger (PCHE) for various power conversion systems for SMART

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1. Introduction

SMART (System-integrated Modular Advanced ReacTor) is a promising advanced small nuclear power reactor. It is a 330 MWth integral type reactor developed by KAERI (Korea Atomic Energy Institute) for multipurpose utilization, which incorporated inherent safety systems, system simplification and component modularization.

The steam-Rankine cycle was the most widely used power conversion system for a nuclear power plant. The size of the heat exchanger is important for the modulation. Such a challenge was conducted by Kang et al [1]. They change the steam generator type for the SMART from helical type heat exchanger to Printed Circuit Heat Exchanger (PCHE).

Recently, there has been a growing interest in the supercritical carbon dioxide (S-CO_2) Brayton cycle as the most promising power conversion system. The reason is high efficiency with simple layout and compact power plant due to small turbomachinery and compact heat exchanger technology. That is why the S-CO_2 Brayton cycle can enhance the existing advantages of Small Modular Reactor (SMR) like SMART, such as reduction in size, capital cost, and construction period.

The objective of this paper is comparing the size of PCHE in case of steam Rankine cycle and in case of the S-CO_2 Brayton cycle.

2. Methods and Results

2.1 PCHE

PCHE, developed by Heatric Division of Meggitt (UK), is a promising heat exchanger because it is able to withstand pressures up to 50 MPa and temperatures from cryogenic condition to 700 ℃. It is extremely compact and has high efficiency. Fluid flow channels are etched chemically on metal plates. The channels are semicircular with 1-2mm diameter. Etched plates are stacked and diffusion bonded together to fabricate as a block. These process are shown in Fig. 1. Also, for the same thermal duty and pressure drop, a PCHE is up to 85% smaller than an equivalent shell and tube heat exchanger. A relative size comparison is shown in Fig. 2. [2]

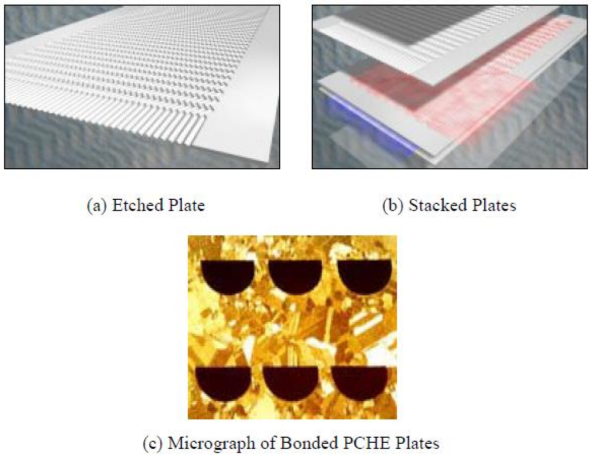

Figure 1. PCHE Plates and Diffusion Bond [2]

Figure 2. Size comparison of PCHE and shell and tube heat exchanger [2]

2.2 KAIST_HXD

To design and analyze the PCHE, the KAIST research team developed an in-house code of which the name is KAIST_HXD. It is well validated with experimental data from KAIST S-CO_2 pressurizing experiment (S-CO2PE) facility. Since the detailed structure and the verification of the PCHE code were already well summarized by Baik et al. (2014) [3], it will not be repeated here in detail. The differences are heat transfer correlation and friction factor correlation at the hot side (water side). The Dittus-Boelter correlation (1) is used as heat transfer correlation, which is the best known and most widely used correlation. This equation can be used above 10,000

Reynolds number. For smooth pipe turbulent flow, the following friction factor equations (2) and (3) are used.

$$Dittus-Boelter\ : Nu = 0.023\,\mathrm{Re}_b^{0.8}\,\mathrm{Pr}_b^{0.3}$$

(1)

$$f = \frac{0.316}{\mathrm{Re}^{0.25}} \quad 3,000 < \mathrm{Re} < 100,000$$

(2)

$$f = \frac{0.184}{\mathrm{Re}^{0.2}} \quad \mathrm{Re} > 100,000$$

(3)

2.3 Design condition of the S-CO_2 Brayton cycle

For SMART with a steam Rankine cycle, thermal hydraulic parameters of the Printed Circuit Steam Generator (PCSG) was shown at Table 1, which is adopted from Kang et al. [1] work. First of all, to compare the heat exchanger volume at the same capacity, the KAIST research team tried to match the same heat duty. The primary mass flow rate and inlet temperature was set to 174 kg/sec and 323 °C respectively. The same inlet pressure was assumed.

For the secondary side (CO_2 side), the design parameters were obtained through a sample calculation based on previous works (Dostal et al. [3], 2004; Jeong et al. [4], 2010) and these obtained values are set as the reference design values (secondary side : mass flow rate, inlet temperature and inlet pressure) for this paper. However, the results from the previous works are different. The result of previous works is shown at Table 1 with the result of this study.

The outlet temperature is almost the same for both cases around 1 °C difference at the primary side. Furthermore, there is a little difference at the pressure drop values. That is why the heat duty of heat exchanger is almost the same for 2 cases. With respect to the secondary side, mass flow rate difference is very large. There are 2 reasons. 1: the specific heat of CO_2 is almost one-fourth of the specific heat of the water. 2: the water has the huge latent heat when the water accompany the phase-change at the heat transfer process.

The inlet pressure of PCHE at secondary side is much higher than PCSG because the critical pressure of CO_2 is almost 7.38MPa, such a critical point should be placed at the compressor inlet condition to increase the efficiency of the cycle. After passing the compressor, the CO_2 pressure increases up to 15 MPa.

2.4 Comparison of the design results

The volume of a PCHE can be easily found by equation (4). The results show that the heat exchanger for water to S-CO_2 is smaller than PCSG. The volumes of CO_2 heat exchanger should be larger than water heat exchanger due to less heat transfer capability. However, in this case, the PCSG was used for super-heated steam Rankine cycle. The PCSG needs larger size heat exchanger than S-CO_2 PCHE because the water vapor has lower capability to transfer heat and smaller density than S-CO_2.

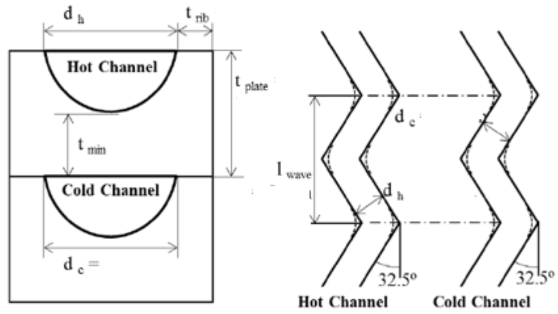

Figure 3 Schematic PCHE geometry

$$Volume = 2(d_h + 2t_{rib})\,\mathrm{t}_{\mathrm{plate}}\mathrm{l}_{\mathrm{wave}}\,N_{channel} \qquad (4)$$

Table I: Comparison of thermal hydraulic parameters of PCSG with PCHE

Parameters	PCSG	PCHE
Power [MW]	27.5	27.5
Number	12	12
Primary Side		
Mass flow rate [kg/sec]	174	174
Inlet temperature [°C]	323	323
Outlet temperature [°C]	294.5	295.65
Inlet Pressure [MPa]	15	15
Pressure drop [kPa]	191	15.88
Secondary Side		
Fluid	Water	CO_2
Mass flow rate [kg/sec]	13.4	182.77
Inlet temperature [°C]	200	200
Outlet temperature [°C]	290.5	322.74
Inlet Pressure [MPa]	5.2	15
Pressure drop [kPa]	119	116.65
Geometry		
Volume [m3]	0.66	0.53771
Length [m]	1.5	0.506

3. Summary and Conclusions

Thermal hydraulic and geometric parameters of a PCHE for the S-CO_2 power cycle coupled to SMART. The results show that the water - CO_2 printed circuit heat exchanger size is smaller than printed circuit steam generator for the superheated steam Rankine cycle. This results show the potential benefit of using the S-CO_2 Brayton power cycle to a water-cooled small modular reactor. Further study will be conducted to optimize the small modular reactor power cycle and its performance.

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