Review of compact heat exchangers for supercritical CO_2 power system

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1. Introduction

Recently, the supercritical carbon dioxide (S-CO_2) Brayton cycle has received attention as the most promising power conversion system for future nuclear system. The reason is due to high thermal efficiency for mild turbine inlet temperature range (450ºC – 750ºC) with simple layout and compact power plant. These unique characteristics of S-CO_2 system can be established by reduced compression work compared to an ideal gas and high minimum cycle pressure contributing to more compact turbomachinery and heat exchangers [1].

To enhance advantages of S-CO_2 system, researches on heat exchangers have been conducted because the performance of that has great impact on system thermal efficiency and economics. Especially, compact heat exchangers that can extremely reduce the system size are the main research area. Compact heat exchanger are characterized by high area density, which is defined as a heat transfer area divided by the heat exchanger volume. High area density heat exchanger naturally has small hydraulic diameter and many channels for heat transfer. Thus, the inventory of working fluid and physical size of power system can be minimized. For instance, heat exchanger is up to 85% smaller than the conventional shell and tube heat exchangers as shown in Figure 1 [2].

There are two important considerations for selecting heat exchangers among various options. One is satisfying the service conditions of the plant environment (e.g. temperature, pressure and corrosion). The other is maintainability, which involves cleaning, repairing, and replacing [3]. The S-CO_2 system usually operates at high temperature (up to 600ºC) and high-pressure (up to 20 MPa) condition. It means excellent structural integrity is required for harsh condition. Moreover, periodic inspection and maintenance should be possible for not only safe operation but also economics.

Therefore, the goal of this study is to summarize the characteristics of existing viable compact heat exchangers for S-CO_2 system application since the area has evolved very rapidly in the last decade.

Fig. 1. Size comparison of PCHE (one of compact heat exchangers) and shell and tube heat exchanger [2]

2. Various compact heat exchangers

2.1 Printed Circuit Heat exchanger (PCHE)

PCHE, which is developed by Heatric of Meggitt (UK), is a widely-used heat exchanger owing to excellent structural rigidity, which can withstand pressures up to 50 MPa and temperatures from cryogenic condition to 700 ºC. Fluid flow channels are etched chemically on metal plates. The channels are semicircular with 0.5-2mm diameter. Typical area density has 1300 m^2/m^3 at 10 MPa and 650 m^2/m^3 at 50 MPa [2]. Etched plates are stacked and diffusion bonded together to fabricate as a block. The configuration of PCHE is shown in Figure 2.

This type has been investigated experimentally and numerically to obtain the optimum fin arrangement between heat transfer and pressure loss. Baik performed the experimental study of the zigzag channel PCHE with semi-circular cross section. The author suggested the heat transfer and pressure drop semi empirical-correlation under various operation condition of S-CO_2 [4]. In an attempt to reduce the pressure drop, S-shaped and airfoil-type PCHE studies were conducted [5, 6]. They described that PCHE in airfoil form has the lowest pressure drop. Moreover, structural rigidity was assessed for Sodium-cooled Fast Reactor attached to S-CO_2 system. The obtained computational data suggested that 1 mm of plate thickness without channel radius guarantees longer than 34 years of service time if SS316 is applied [7].

However, it is difficult to determine whether damage exists inside the heat exchanger due to a completely welded body from core to header. With the same reason, cleaning and maintenance are rising problems of this type heat exchanger.

Fig. 2. The picture of cross-flow type PCHE [2]

2.2 Plate Fin Heat Exchanger (PFHE)

The history of PFHE is originated from aircraft industry 1940s thanks to the high area density. It consists of corrugated fin and flat metal plate on the top and bottom of fin. The side is enclosed by side bar as shown in Figure 3. The fin and plates are assembled by brazing in a vacuum furnace. The fin inside PFHE has two function. (1) Extension of heat transfer area, which can makes hydraulic diameter and thermal resistance smaller. (2) Withstanding the pressure difference between high-pressure side fluid and low-pressure side fluid. Accordingly, various types of fins have been studied to obtain optimum shape like perforated, serrated, and so on [3].

Conventional PFHE, which is made of aluminum, can withstand up to 13 MPa of pressure and melting point is about 660 ^{o}C [8]. To overcome the limitation, Brayton Energy, LLC was developed a novel concept of PFHE with inconel 625 for application on concentrated solar power that uses S-CO_2 as a working fluid. It is expected that this PFHE can endure up to around 750 ^{o}C and 27.7 MPa based on fatigue and creep test (it is not described specifically). The structural integrity was achieved by the configuration that high-pressure side fin is enclosed by fully welded pressure containment and low-pressure side fin is attached to the top and bottom of the containment as shown in Figure 4. The integrated assembly with fin and containment is called as unit cell. The area density of this heat exchanger is about 3300 – 4500 m^2/m^3. Moreover, it has high degree of geometric flexibility in the design of the unit cell because unit cell is not bonded each other as shown in Figure 5 [10].

Bechtel Marine Propulsion Corporation and Brayton Energy, LLC have developed wire-mesh heat exchanger for application to the recuperator of S-CO_2 system. This has similar configuration with the PFHE, which the fin of that is replaced by a wire mesh. The schematic rendering image is shown in Figure 6. This type is expected to have an area density about 7000 – 8000 m^2/m^3. It means wire-mesh heat exchanger has excellent heat transfer performance among compact heat exchangers. However, there are two disadvantages for this. Firstly, large pressure drop is occurred due to high density of wire-mesh. Secondly, fabrication is uncontrolled. The wire-mesh material is hard to cut clearly without plastic deformation and compaction factor of this is not constant [11].

The main weakness is that PFHE tends to be fouled easily due to small channel diameter same as PCHE. It cannot be mechanically cleaned. As a result, PFHE can be used with relatively clean process stream with filter system. Furthermore, repair is almost impossible in case of failure or leakage between flow paths.

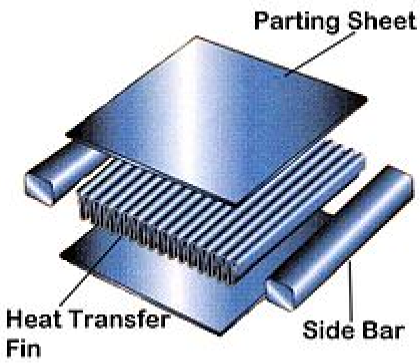

Fig. 3. Schematic diagram of typical PFHE [9]

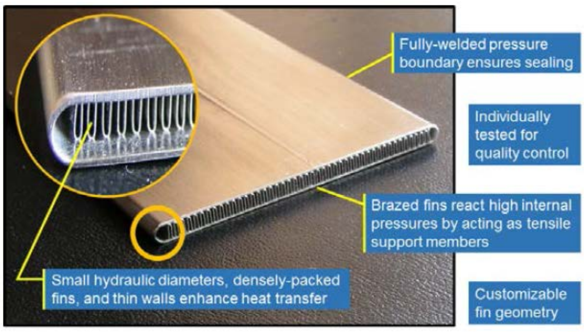

Fig. 4. High-pressure side fin is enclosed by fully-welded pressure boundary [10]

Fig. 5. Many unit cells are connected to manifold [10]

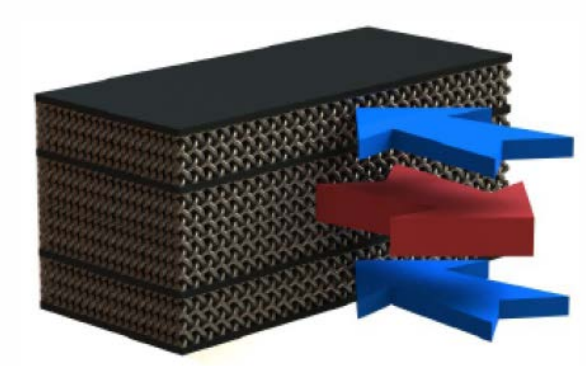

Fig. 6. Rendering of a detail of the wire-mesh heat transfer surface and the associated flows [11]

2.3 Additive Manufacturing Heat Exchanger (AMHE)

The name of 'Additive manufacturing' came from the technologies that makes the 3-D object by adding the material layer by layer. There are many strengths of this method. (1) There is no need to be weld and brazed at the joint because it is monolithic. (2) There is no restriction by geometry, material, and detailed design. (3) It has excellent scalability due to modular design and can provide rapid customizable solutions [12].

In the University of California, Davis, the primary heat exchanger (PHX) for S-CO_2 waste heat recovery cycle has been developed by using an Inconel 718 as an additive material [13]. The concept for PHX is made up of several cold plates spaced a certain distance apart (where the fin for hot fluid gas is) and connected to S-CO_2 side manifolds. Micro-pin fin is placed inside the cold plate to increase heat transfer performance. The design of heat exchangers is shown in Figure 7.

The author studied the hydrodynamic loss under laminar flow condition to validate with a laminar theory. In addition, the pressure test was performed under PHX condition around 550 °C and 20 MPa. The results show the slight change of pressure at 20 MPa due to a leak in the fitting connection to the regulator. Since there are not many ongoing researches, additional studies on fin configuration, header, and performance are required to apply to S-CO_2 system.

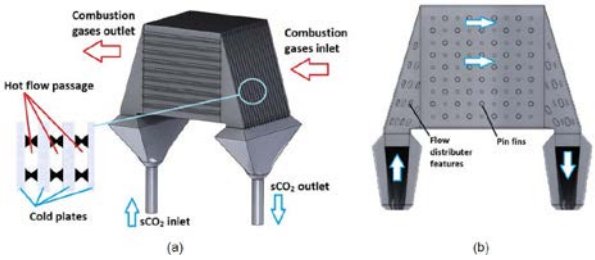

Fig. 7. 3D model proposed for PHX a) overall view illustrating several cold plates with specified spacing connected to inlet and outlet plena. b) view of micro features within a cold plate [13]

2.4 Micro shell and tube heat exchanger

Micro shell and tube heat exchanger is same concept with a conventional shell and tube design except for tube diameter. It is developed at the Thar Energy LLC for S-CO_2 power cycle recuperator. The high-pressure fluid is allocated to micro-sized tube and low-pressure fluid is allocated to the shell. The microtube bundle area density is 4500 m^2/m^3 and is implemented in a pressure vessel utilizing a new single flange design. The advantages include high heat transfer efficiency, the floating tube sheet accommodates high thermal stresses, and a removable microtube bundle allows for ease of maintenance. Moreover, it can meet the high temperature high differential pressure criteria experimentally. As shown in Figure 8, tubes are arranged to counter-current type without baffles. However, this unique geometry can induce tube-buckling issues when the tube length is sufficiently long. To conserve a high area density, tube should be packed densely. It makes it possible to use it only for recuperator. Additionally, it can be expected that the economy is not desirable due to thick tube thickness to withstand high pressure.

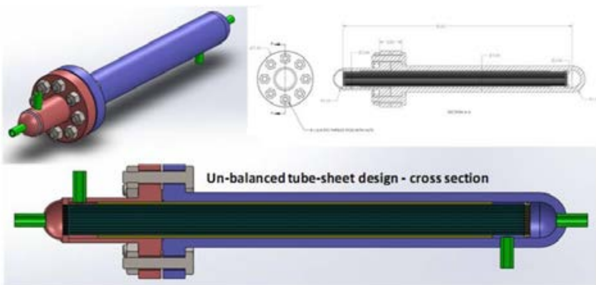

Fig. 8. Single Flange 100 kW Recuperator HX Design – 1000 microtube [14]

3. Conclusions

Compact heat exchangers play important role in efficient thermal system and economics. It can further improve the advantage of S-CO_2 system such as high thermal cycle efficiency and small footprint. The major emphasis of this paper is introducing the structure and characteristics of respective compact heat exchangers that can be applied to high temperature and pressure condition. Moreover, the current research status are also suggested in this study.

Through the summary, it can be found that every compact heat exchangers except for Micro shell and tube heat exchanger has same weak point. They are easily fouled and inspection (by non-destructive way and ultrasonic wave) is impossible due to small hydraulic diameter. Furthermore, if there is a damage inside the component, the only way to repair it is to replace the heat exchanger including a header part. This is a big challenge for compact heat exchanger. Even the priced is expected to high, Micro shell and tube heat exchanger is appropriate compact heat exchanger for S-CO_2 recuperator.

ACKNOWLEDGEMENTS

This study was conducted with the support of Korea Evaluation Institute of Industrial Technology (Project No.: 10063187, Engineering Technique for Power Generation System Design using Industry Waste Heat) as part of the core industrial technology development project supported by the Ministry of Trade, Industry and Energy, which is gracious acknowledged.

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