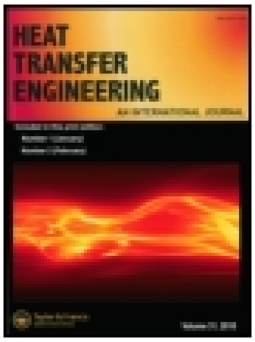

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Recent Progress on High Temperature and High Pressure Heat Exchangers for Supercritical CO_2 Power Generation and Conversion Systems

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ABSTRACT

Heat exchangers for supercritical CO_2 power generation and waste heat to power conversion systems have a significant impact on the overall cycle efficiency and system footprint. Key challenges for supercritical CO_2 heat exchangers include ability to withstand high temperature and high pressure (typical temperature range of heat source 350 to 800 °C and typical required operating pressure range 150 to 300 bars), and large pressure differential between fluid streams. Other requirements are low pressure drop, high effectiveness and high reliability under thermal cycling. This paper presents recent developments in supercritical CO_2 heat exchangers in terms of material selection, design, manufacture, and operation. Since heat exchangers represent a significant portion of the total system cost, another key challenge is to find a compromise between the heat exchanger type, cost, durability, and performance. This paper explores heat exchanger technologies, manufacturing techniques and materials for high temperature and high pressure heat exchangers for supercritical CO_2 applications. It also identifies technology gaps and research needs to accelerate the development of effective designs to facilitate the commercialization of both supercritical CO_2 heat exchanger technologies and power cycles.

Introduction

Supercritical CO_2 systems offer the potential benefits of higher thermal efficiencies and greater power density than traditional steam and gas power cycles. The high-pressure operation throughout the system leads to smaller equipment sizes, smaller plant footprint and better operational flexibility that also led to the potential for lower capital cost. Alongside recent developments in high-temperature materials and compact heat exchanger designs, supercritical CO_2 power generation and conversion systems are being investigated as a promising technology for many applications including waste heat recovery, concentrated solar power, fossil fuel and nuclear power generation amongst others [1–4]. The Sandia National Laboratory and the Knolls Atomic Power Laboratory in the USA and the Institute of Applied Energy in Japan are amongst the first to test small scale supercritical CO_2 integrated systems alongside the development of important components such as turbomachinery and heat exchangers [4–6]. Demonstration of small-scale integrated systems has also taken place in the USA, Japan, Korea, Europe and China. A supercritical CO_2 Brayton cycle developed at Brunel University London, UK, is shown in Figure 1(a). The design nominal power output of the integrated system is approximately 50 kW. The flue gas stream is employed to simulate the typical waste heat source. The cycle temperatures and pressures at design conditions are shown in Figure 1(b).

Supercritical CO_2 systems, depending on their configuration, can involve many heat exchangers: the heater absorbing heat from the heat source, the recuperator transferring heat from the low-pressure stream to the high-pressure stream, and the cooler rejecting heat to the environment [1, 2]. These heat exchangers have a significant impact on system efficiency. This is primarily due to the requirement to maintain cycle compactness, withstand the high temperature and pressure differentials between the fluid streams, and the demands of low pressure drop, high effectiveness and high reliability under thermal cycling. These prerequisites pose significant

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Nomenclature

ASMR	advanced small modular reactors
ARD	advanced reactor designs
CFD	computational fluid dynamics
CSP	concentrated solar power
c	coefficient
$\bar{c}_p$	integrated mean specific heat, J/(kg K)
c_p	specific heat, J/(kg K)
DHFF	direct heating fossil fuel
D_h	hydraulic diameter, m
f	friction factor
G	mass flux, kg/(m^2 s)
GE	General Electric
Gr	Grashof number, $Gr = \frac{(\rho_b - \rho_w)\rho_b g D_h^3}{\mu_b^2}$
GT	geothermal
GTB	gas turbine bottoming
g	gravity acceleration, 9.81 m/s
h	heat transfer coefficient, W/(m^2 K)
IHFF	indirect heating fossil fuel
k	thermal conductivity, W/(m K)
LMTD	log mean temperature difference, K
L_p	pitch length, m
l	length, m
Nu	Nusselt number, $Nu = \frac{hD_h}{k_b}$
NTU	number of transfer unit
P	pressure, Pa
PCHE	printed circuit heat exchanger
PCHEs	printed circuit heat exchangers
PCHE-AF	printed circuit heat exchanger with airfoil fins
PCHE-SC	printed circuit heat exchanger with straight channels
PCHE-SF	printed circuit heat exchanger with S-shaped fins
PCHE-ZC	printed circuit heat exchanger with zigzag channels
Pr	Prandtl number, $Pr = \frac{\mu_b c_{p,b}}{k_b}$
Re	Reynolds number, $Re = \frac{GD_h}{\mu_b}$
r_b	fillet radius, m
SHP	shipboard house power
SP	shipboard propulsion
T	temperature, K
WHR	waste heat recovery
1D	one-dimensional
3D	three-dimensional

Greek symbols

β	inclined angle, °; fin thickness, m
ε	effectiveness
ρ	density, kg/m^3
μ	dynamic viscosity, Pa·s

Subscripts

b	bulk
w	wall

mechanical, thermomechanical, and thermohydraulic challenges on heat exchanger design [7–11]. In the last couple of decades there has been a prolific increase in research and development of heat exchangers for supercritical CO_2 systems. However, most research to date has focused on printed circuit heat exchangers (PCHEs) for recuperator or cooler applications. The development of the heater, particularly for "dirty" exhausts, lags considerably behind recuperator development due to the much higher operating temperatures, larger pressure differential between the hot and cold fluids and fouling issues.

To outline state of the art and highlight challenges to be addressed, this paper presents recent progress on the development of supercritical CO_2 heat exchangers and discusses challenges associated with materials, design, manufacture, and operation. The objective is to identify knowledge gaps and research and development needs to address them thus contributing to the global efforts aimed at the further development and commercialization of supercritical CO_2 heat to power systems.

Key issues for high temperature and pressure heat exchangers

To facilitate the further development of heat exchangers for supercritical CO_2 power generation and conversion systems, it is essential to understand the performance of technologies that have already been commercialized or are close to commercialization, and to resolve key issues of cost and economic viability for commercial-scale deployment. Research to date has shown that the heat exchangers can represent 40-50% of the total system cost [12], leading to another key challenge of finding a compromise between the heat exchanger type, cost, durability, and performance. Moreover, different heat sources and different supercritical CO_2 power system layouts impose unique constraints on the heat exchanger design. Figure 2(a) shows the operating temperature range and Figure 2(b) shows the required operating pressure range for potential applications of the supercritical CO_2 Brayton cycle. The maximum temperature of the heat source can be up to 1500 °C and the operating pressure up to 400 bars. However, due to strength of materials challenges and high cost, current designs of supercritical CO_2 Brayton cycles are limited to temperatures below 800 °C and pressures below 300 bars [2, 4].

Heater

Depending on the heat source, two types of heat exchanger are typically employed: one absorbing the thermal energy from the heat source by combining radiation and convection while the other relying mainly on heat transfer by convection [2]. A heater combining radiation and convection heat transfer has been proposed for coal fired supercritical CO_2 power plants [13, 14]. Heaters relying only on heat transfer by convection, have been proposed mainly for waste

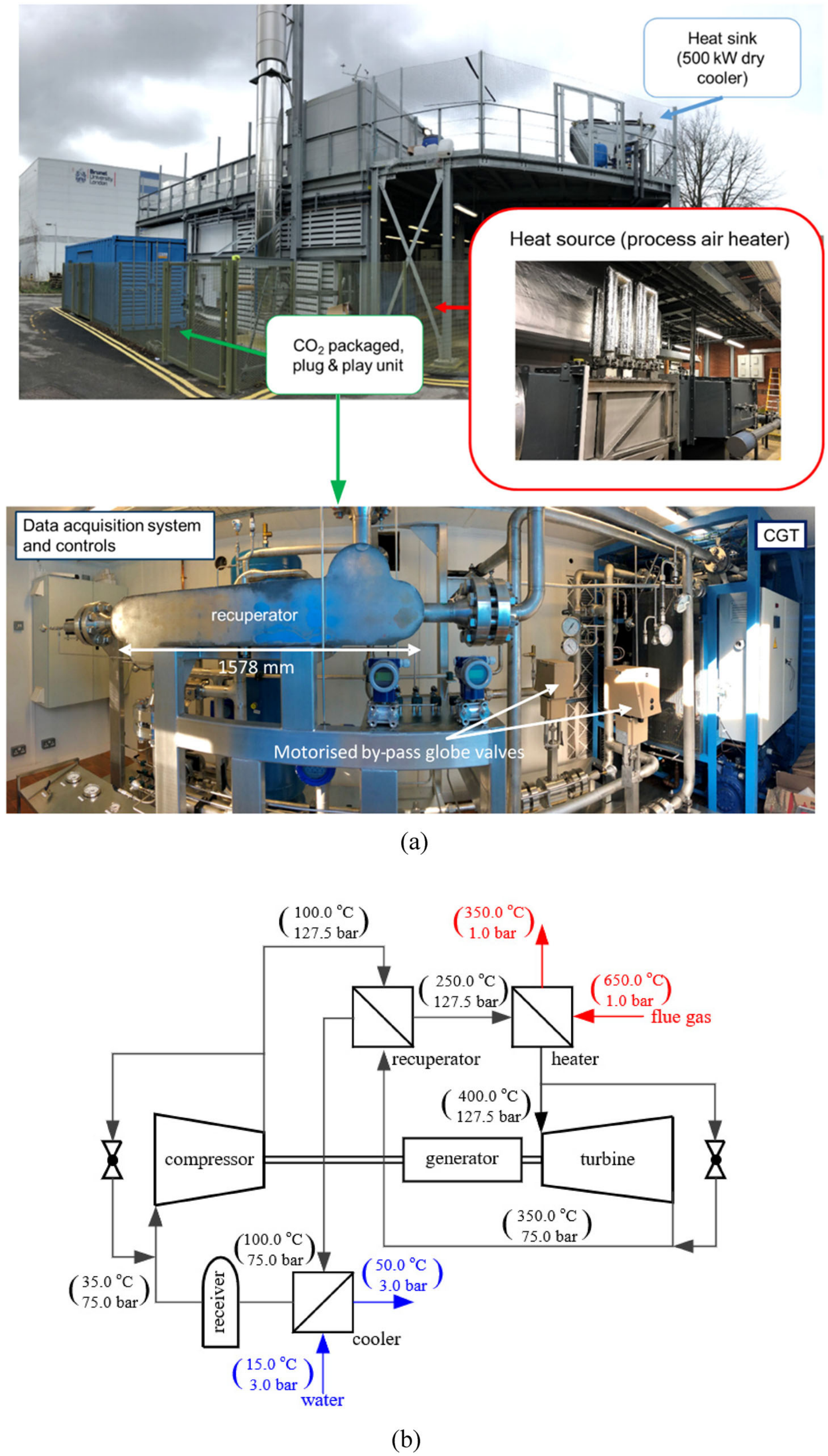
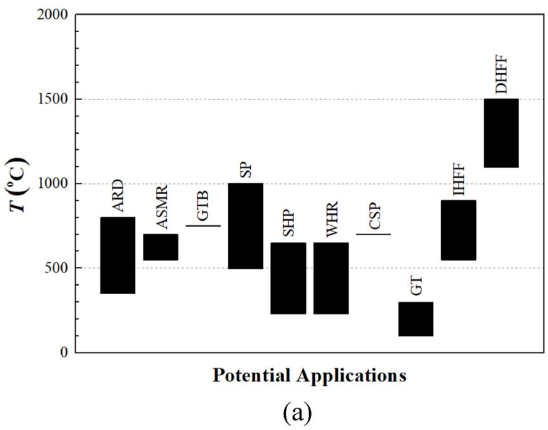


Figure 1. A supercritical CO_2 Brayton cycle developed at Brunel University London, UK. (a) Test facility, and (b) Cycle design conditions.



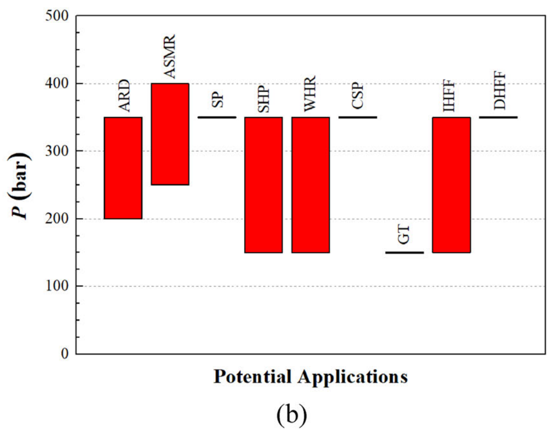


Figure 2. Potential applications relevant to supercritical CO_2 Brayton cycle (a) operating temperature range and (b) required operating pressure range. Source data from Reference [10], ARD (advanced reactor designs), ASMR (advanced small modular reactors), GTB (gas turbine bottoming), SP (shipboard propulsion), SHP (shipboard house power), WHR (waste heat recovery), CSP (concentrated solar power), GT (geothermal), IHFF (indirect heating fossil fuel), DHFF (direct heating fossil fuel).

heat recovery applications [9, 15]. The following discusses key issues from these applications.

Firstly, material performance and code qualifications need to be addressed. The operation environment requires the material to be able to endure the high temperature and high pressure and withstand fast transients at startup, shut down and changes in operating conditions whilst delivering long enough lifetime. These requirements demand heaters to have large enough heat transfer areas, thick enough walls and be corrosion resistant. At heat source temperatures below 600 °C, stainless steel 316/316 L/347 can be employed. At higher temperatures, nickel alloys, such as Alloy 625 or 617, may be feasible. However, not sufficient experimental data exist for supercritical CO_2 heater heat exchangers at high temperatures due to the general lack of high temperature experimental test facilities. The impact of exhaust gas impurities and fabrication approaches on alloy corrosion, strength and durability have also not been well defined as yet. The capital cost of alloys could also hinder their use by industry for the further development of supercritical CO_2 technologies [16].

Procedures for manufacturing and assembly also need to be developed for every expected material combination. After manufacturing and assembly, the material strength and durability could be lower than that reported by the manufacturer from sample tests. A critical issue particularly occurs in the joining between the high strength alloys and other materials [10]. The difference in their ionization tendency can also cause corrosion at the interface. The chromium element in the alloys can significantly affect the welding characteristics. The nickel, manganese and molybdenum elements have some influence on the oxide slag during melting. Other residual elements in stainless steels such as carbon, phosphorus, selenium, and sulfur are also important in welding, although their effect is still uncertain.

Thermohydraulic challenges impose requirements of very high heat flux, and large pressure differential between the heat source and supercritical CO_2. Further, the heat source can be fossil, nuclear, solar or waste heat and the heating fluid can be fuel gas, molten salt, heat transfer oil, even liquid metals. Different heating fluids demonstrate different thermohydraulic performance and impose different constraints on heater design. The heater must be matched to the heat source and provide adequate heat transfer characteristics and low-pressure drop on both heat transfer sides [13]. These requirements increase the cost of manufacture and thus the design of heaters requires a compromise between good thermohydraulic performance and cost without compromising operational, safety and environmental impacts.

The heater must withstand rapid startups and transients during operation, as well as thermal cycling and fatigue. A transient response can result in a quick temperature rise or drop. The operational problems caused by thermal stresses significantly impact the durability of the heater [17]. To ensure reliable, repeatable, and safe cyclic operation, it is necessary to develop procedures of repeated startup and shutdown tests for different heat sources before heaters are deployed in service [1].

Recuperator

Depending on operating conditions and heat exchanger performance, over 60% of the heat addition to the compressor discharge is achieved through recuperation, while the remaining is provided by the heat source [10]. The objectives of recuperator design are to maximize heat transfer efficiency, minimize pressure drop, and ensure even flow distribution. Challenges facing recuperators are the requirements to withstand high temperature and large pressure differentials, flow passage design to improve thermohydraulic performance and reduce pressure drop and need to reduce capital cost.

The erosive and corrosive degradation of materials of recuperators are similar to those in the heater, but at lower temperature and lower pressure differentials between the fluid streams. The employed material should be selected based on operating temperature, operating pressure, fouling and corrosion resistance [18, 19].

Most supercritical CO_2 systems employ the Printed Circuit Heat Exchanger (PCHE) as recuperator, due to the need for compact and high-performance heat exchangers. PCHEs are normally manufactured using diffusion-bonding, and the process employed has much influence on their performance. The surface preparation of the boned plates is critical and difficult, and the boned size is limited by the manufacturing equipment available. In addition, the manufacturing process does not provide easy access to examining the internal channels and the heat exchanger cannot be disassembled for cleaning or maintenance [20].

Key issues remaining to be addressed with PCHE recuperators are high capital cost and uncertainty around mechanical performance and thermal fatigue. To improve the recuperative performance, zigzag channels, S-shaped channels, and channels with airfoil fins have been developed. Such methods do improve the heat transfer performance, but also contribute to larger pressure drop due to the bends present in the flow path. Further, most of the developed empirical correlations of heat transfer and pressure drop are not universal but for specific flow passages. This makes it difficult to further optimize PCHE design and multi-objective optimization research is necessary to achieve this [8].

High thermal stresses can influence the durability of the recuperator that should achieve sufficiently long operating life, typically 90,000 hours of operation and 10,000 cycles. The influence therefore of cyclic operation on burst strength, creep, and fatigue, are areas that merit significantly further investigation [17].

Cooler

Due to lower temperatures and pressures, concerns about material selection and manufacturing of the coolers are much less. Heat exchanges developed and being used in CO_2 refrigeration and heat pump systems are mostly suitable for this application. The biggest concern in the cooler is the CO_2 temperature and pressure close to the critical point, where the pinch point can affect the heat transfer effectiveness and total heat rejected to the cooling fluid as well as how fast the temperature of CO_2 entering the compressor can be controlled [21].

The cooling fluid can be either air or water, and the differing thermophysical properties can also significantly affect the cooler geometry and performance. The air-coupled coolers usually require large heat transfer areas due to the thermophysical properties of air, and some investigators have questioned the practicality of air cooling in supercritical CO_2 systems [22]. Reduction of the surface area can be achieved by reducing coil diameter and tube spacing, while other challenges include heat transfer enhancement on the air side and optimization of the tube circuitry to alleviate pinch point problems and minimize pressure drop and footprint. For water-coupled coolers, the risk of leakage between the two fluids during operation is an important consideration. Corrosion of copper solder or steel plates caused by impurities in the water, including chlorides, sulfites, iron, conductivity, pH value, etc., can cause the corrosion of copper solder or steel plates.

High temperature and pressure compact heat exchangers currently in use

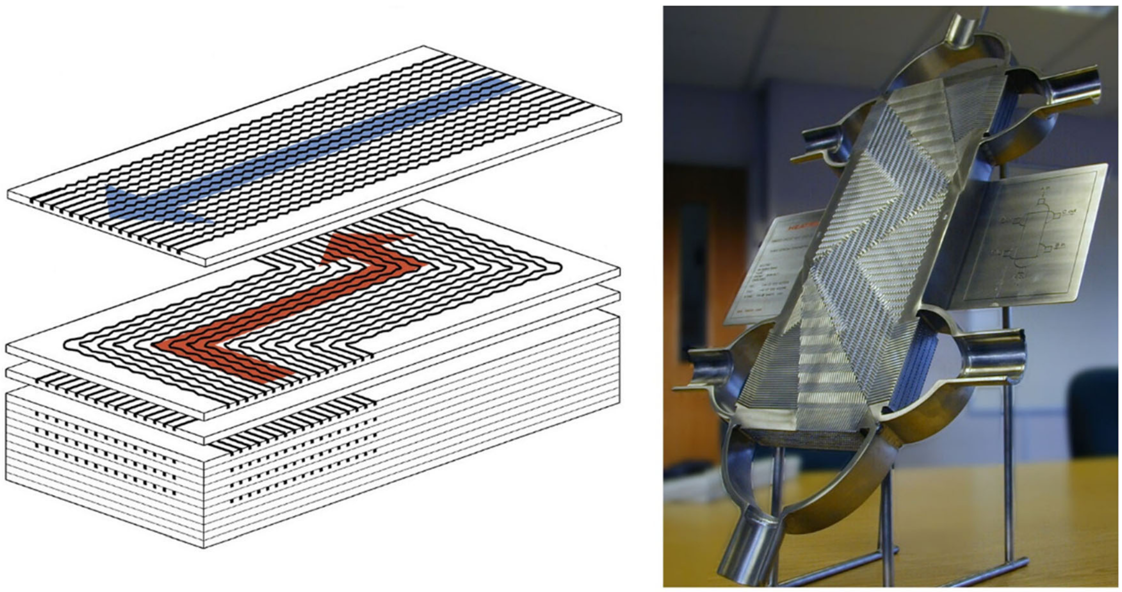
Currently, the most common compact heat exchangers for supercritical CO_2 applications include PCHEs, diffusion-bonded plate-fin heat exchangers, and micro shell and tube or microtube heat exchangers. Table 1 details their principal features, including maximum temperature, maximum pressure, and maximum surface area density.

Printed circuit heat exchanger (PCHE)

PCHE is a diffusion-bonded microchannel heat exchanger that can achieve high heat transfer effectiveness. As shown in Figure 3, a typical PCHE is fabricated from a number of substrate plates where the flow passages are manufactured by photochemical

Table 1. Developed high temperature and pressure heat exchangers for supercritical CO_2 applications.

Type of heat exchanger	Maximum temperature (°C)	Maximum pressure (bars)	Maximum compactness (m^2/m^3)
Printed circuit	900	400	5000
Diffusion-bonded plate-fin	500	200	800
Micro shell and tube or microtube	650	400	2000



(a) (b)

Figure 3. Typical PCHE (a) flow paths and (b) diffusion-bonded core (courtesy of Heatric Meggitt UK).

machining. The plates are stacked together and diffusion-bonded to form compact, very strong, all-metal heat exchanger cores. The authors have reviewed material selection, manufacture, and assembly, thermohydraulic performance and geometric optimization of PCHEs for helium and supercritical CO_2 Brayton cycles in an earlier publication [8]. Therefore, in this paper the focus is on progress since 2019, and in particular on the influence of flow passages: straight channel, zigzag channel, channels with S-shaped fins, and channels with airfoil fins shown in Figure 4, on PCHE performance.

Liu et al. [23, 24] performed experimental investigations on the thermohydraulic performance of a printed circuit cooler, with supercritical CO_2 rejecting heat to water. The PCHE had straight semi-circular channels

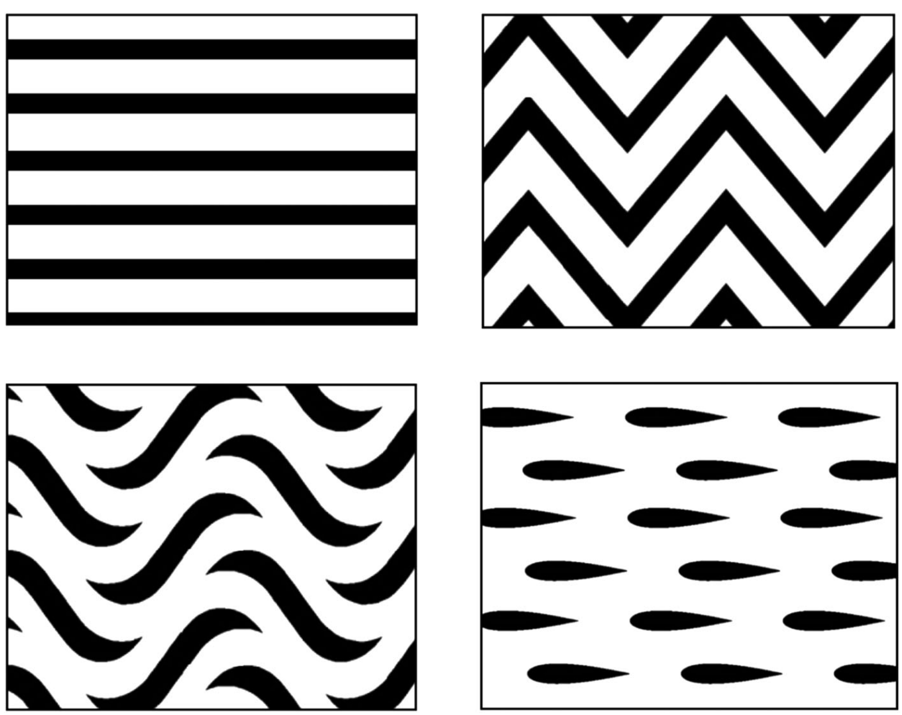


Figure 4. Etched flow paths of PCHEs: (a) straight channel, (b) zigzag (or wavy) channel, (c) channel with S-shaped fins, and (d) channel with airfoil fins.

of diameter 1.87 mm and pitch along the cross section of 2.7 mm. To determine the local heat transfer coefficient, six temperature measurement locations were used along the CO_2 flow direction. The data was used to determine a correlation for the local heat transfer coefficient which was found to predict 92.4% of the data within ± 30% of the error band. Heat transfer enhancement was found to occur when the supercritical CO_2 was cooled from the gas-like zone to the pseudo-critical zone. At this point, the LMTD between the water and CO_2 were found to be minimum. Park et al. [25] investigated the heat transfer and flow characteristics of supercritical CO_2 near the critical point in a printed circuit CO_2-water heat exchanger with straight channels. To account for the significant changes in the properties of CO_2 near the critical point, they developed a discretization method for data reduction and compared the results with the more conventional method of using average inlet and outlet property values. The results showed only a small difference between the two methods at conditions away from the critical point. However, at conditions close to the critical point, the Nusselt number calculated using the discretization method was found to be more than double that calculated with the averaging method. This demonstrates that the discretization method is more appropriate for Nusselt number calculations close to the critical region.

For numerical investigations and theoretical models, Zhang et al. [26] analyzed the effect of buoyancy on the heat transfer characteristics of supercritical CO_2. They found that buoyancy can improve the heat transfer on the top wall but reduce it on the bottom wall on the hot side, while on the cold side the effect is exactly the opposite. The buoyancy effect becomes smaller with increasing CO_2 mass flow rate. Chai and Tassou [27] investigated the thermohydraulic performance of supercritical CO_2 flow in a PCHE. Their numerical model takes into consideration entrance effects, conjugate heat transfer and buoyancy effects. The average heat transfer and friction pressure drop as well as the overall performance of the heat exchanger are discussed. Sarmiento et al. [28] presented a theoretical model to predict the thermohydraulic behavior of PCHEs. It is a one-dimensional steady-state thermal model based on channel geometry parameters and fundamental heat transfer and friction factor equations. Good agreement was found between the test data and the models for both the heat transfer and flow performance.

Torre et al. [29] investigated numerically thermal stresses in PCHEs for different temperature gradients and geometric parameters. A proportional relationship was observed between the thermal stress and the thermal gradient between channels. Chu et al. [30] investigated the thermohydraulic performance of a printed circuit cooler with zigzag channels for heat transfer between supercritical CO_2 and water at pressures ranging from 8.0 to 11.0 MPa on the CO_2 side. The major convective thermal resistance was found on the supercritical CO_2 side. Increasing the operating pressure leads to increased heat transfer coefficient but also pressure drop. Li et al. [31] examined the effect of CO_2 inlet temperature and pressure on the overall heat transfer performance of a CO_2-water pre-cooler. They found that increasing the inlet temperature of CO_2 decreases the overall heat transfer coefficient but increasing the mass flow rate and operating pressure improves it. Cheng et al. [32] analyzed the influence of the inlet temperatures and Reynolds number on the exergy loss and efficiency of a printed circuit recuperator. Lower Reynolds number and higher inlet temperature on the cold side was found to result in a higher exergy efficiency. Zhou et al. [33] investigated the heat transfer effectiveness, pressure drop and heat load of a 100 kW printed circuit recuperator. For numerical investigations and theoretical models, Ren et al. [34] and Saeed et al. [35] respectively investigated the local flow and heat transfer of supercritical CO_2 during cooling near the critical or pseudo-critical point. The thermophysical property variations, mass flux, pitch length, and inclined angles of the zigzag channels can significantly affect the flow and heat transfer. Zhang et al. [36] investigated the effect of bend angle of zigzag channel on the thermo-hydraulic performance as supercritical CO_2 near the critical or pseudo-critical point. The reduction of the zigzag bend angle leads to improvement of heat transfer performance, but larger pressure drop. Bend angles between 110° to 130° were found to produce best performance. Wen et al. [37] investigated the flow and heat transfer characteristics of sinusoidal and zigzag channels. The sinusoidal channel can significantly reduce the pressure drop while keeping almost the same heat transfer performance compared to the zigzag channel. Marchionni et al. [38] employed a one-dimensional dynamic model to investigate the heat transfer processes in a supercritical CO_2 printed circuit recuperator at design and off-design operating conditions. Dynamic simulations under transient operating conditions show that the thermal expansion of the working fluid resulting from the fast-reducing density and increased pressure can be a concern, and careful management of the startup of supercritical power cycles to avoid sudden changes in temperature and thermal stresses are required. Yang et al. [39, 40]

employed a multi-objective evolutionary algorithm for optimization to improve the overall thermohydraulic performance of a printed circuit recuperator. Saeed et al. [41] also undertook a multi-objective optimization study to determine a balance between the size of the PCHE and its performance. Five different fin configurations including straight, zigzag, C-shaped, S-shaped, and airfoil were compared. The C-shaped and zigzag channel geometries resulted in maximum efficiency and minimum size.

Saeed and Kim [42] also employed a response surface methodology combined with a genetic algorithm to optimize the channel geometry of a recuperator with staggered sinusoidal fins. The optimized channel geometry showed much better overall thermohydraulic performance, up to 21% and 16% higher for the cold and hot side respectively compared to the conventional zigzag channel geometry.

Chu et al. [43] investigated the thermohydraulic performance of PCHE with supercritical CO_2 flow in channels with airfoil fins. The airfoil fins resulted in improved heat transfer performance but increased pressure loss than symmetrical fins. Shi et al. [44] studied the flow and heat transfer performance of a supercritical CO_2 and molten salt PCHE with airfoil, zigzag and straight fins. The channels with the airfoil fins showed best overall heat transfer performance. Increasing inlet temperature improved the heat transfer performance of the molten salt but reduced the performance of supercritical CO_2. Wang et al. [45] investigated experimentally the performance of PCHEs with molten salt on the hot side and synthetic oil on the cold side with distributed airfoil fins on the hot side and straight fins on the cold side. Hot side temperature and Reynolds number were varied between 198 °C and 254 °C and between 500 to 1548 respectively. The channels with airfoil fins showed better heat transfer performance than the channels with straight fins.

The results of recent studies on the thermohydraulic characteristics of PCHEs are summarized in Table 2 [23–28, 30–39, 42–44], and a summary of heat transfer and friction factor correlations developed since 2019 is given in Table 3 [23, 24, 30, 32, 34, 35, 44]. It is important to point out that these correlations have been developed for specific flow passages and operating conditions and using thermophysical properties corresponding to the average temperature of channel inlet and outlet. When these correlations are used for heat exchanger design, care should be taken that conditions are similar to those for which the developed correlations were based on.

Diffusion-bonded plate-fin heat exchanger

The diffusion-bonded plate-fin heat exchanger is a type of compact heat exchanger that consists of a stack of alternate flat plates and corrugated fins, and the joining is accomplished by diffusion bonding to form a solid block of metal with flow passages passing through it. The thermal operational limits of the plate fin style cores depend on the type of materials used and are generally more suitable to lower pressure applications up to 200 bars, which are lower than those of printed circuit style cores [46]. Plain, perforated, offset-strip, louvered, wavy

Table 2. Representative studies of thermohydraulic characteristics of supercritical CO_2 in printed circuit heat exchanger.

Reference	Geometry	Type	Methodology	Measurement
Liu et al. [23, 24]	PCHE-SC	Cooler	Experiment	Local temperature, local heat transfer, average friction factor, average heat transfer
Park et al. [25]	PCHE-SC	Cooler	Experiment	Local temperature, local heat transfer, average heat transfer
Zhang et al. [26]	PCHE-SC	Recuperator	CFD	Velocity contour, temperature distribution, local heat transfer, average heat transfer, Buoyancy effects
Chai and Tassou [27]	PCHE-SC	Recuperator	CFD	Local heat transfer, local friction factor, average heat transfer, average friction factor
Sarmiento et al. [28]	PCHE-SC	Recuperator	Theoretical model	Overall heat transfer, average friction factor
Chu et al. [30]	PCHE-ZC	Cooler	Experiment	Average friction factor, average heat transfer
Li et al. [31]	PCHE-ZC	Cooler	Experiment	Overall heat transfer
Cheng et al. [32]	PCHE-ZC	Recuperator	Experiment	Average friction factor, average heat transfer
Zhou et al. [33]	PCHE-ZC	Recuperator	Experiment	Average friction factor, average heat transfer
Ren et al. [34]	PCHE-ZC	Cooler	CFD	Velocity contour, temperature distribution, local heat transfer, average heat transfer, average friction factor
Saeed et al. [35]	PCHE-ZC	Cooler	CFD	Average heat transfer, average friction factor
Zhang et al. [36]	PCHE-ZC	Recuperator	CFD	Velocity contour, temperature distribution, local heat transfer, overall flow and heat transfer
Wen et al. [37]	PCHE-ZC	Recuperator	CFD	Velocity contour, average heat transfer, average friction factor
Marchionni et al. [38]	PCHE-ZC	Recuperator	1D dynamic model	Transit flow and heat transfer
Yang et al. [39]	PCHE-ZC	Recuperator	CFD	Heat flux distribution, average heat transfer, average friction factor
Saeed and Kim [42]	PCHE-SF	Recuperator	CFD	Average heat transfer, average friction factor
Chu et al. [43]	PCHE-AF		CFD	Velocity contour, average heat transfer, average friction factor, overall flow and heat transfer
Shi et al. [44]	PCHE-AF	Heater	CFD	Velocity contour, average heat transfer, average friction factor, overall flow and heat transfer

Table 3. Correlations of friction factor and heat transfer during supercritical CO_2 flowing in PCHEs.

Reference	Geometry	Correlations
Liu et al. [23]	PCHE-SC	$Nu = 0.1229Re^{0.6021}Pr^{0.3}\left(c_{p,w}/c_{p,b}\right)^{0.1310}$ where $3600 < Re < 36500$
Liu et al. [24]	PCHE-SC	$f = \begin{cases} 15.08/Re, & 2100 < Re \\ 6.34 \times 10^{-5}Re^{0.6373}, & 2100 \le Re < 2700 \\ 0.0557Re^{-0.2137}, & 2100 \le Re < 7.1 \times 10^{5} \end{cases}$
Chu et al. [30]	PCHE-ZC	$Nu = 0.0183Re^{0.82}Pr^{0.5}(\rho_b/\rho_w)^{-0.3}\left[\left(c_1 + c_2\left(\frac{Gr}{Re^{c_3}}\right)\right)\right]$ $f = c_4Re^{c_5}$ where $25000 < Re < 70000$, coefficients $c_1 - c_5$ dependent on zigzag angles
Cheng et al. [32]	PCHE-ZC	$Nu = (0.02475 \pm 0.002657)Re^{0.76214 \pm 0.03899}$ $f = (0.7510 \pm 0.09037)Re^{0.2834 \pm 0.08859}$ where $4897 \le Re \le 23888$, $0.765 \le Pr \le 0.784$ $Nu = (0.02063 \pm 0.002562)Re^{0.7678 \pm 0.04928}$ $f = (12.74 \pm 3.815)Re^{0.4806 \pm 0.07792}$ where $3213 \le Re \le 15631$, $1.01 \le Pr \le 1.10$
Ren et al. [34]	PCHE-ZC	$Nu = 6.3943Re^{0.4611}Pr^{0.4759}(\rho_b/\rho_w)^{1.027}(\mu_b/\mu_w)^{-0.3428}\left(\bar{c}_{p,b}/c_{p,b}\right)^{0.7601}(L_p/D_h)^{-0.2121}(\beta \cdot \pi/180)^{0.4735}$ $f = 15.78/Re + 5.366 \times 10^{-4}Re^{0.1182}e^{14.597 \cdot \beta \cdot \pi/180}(L_{c,p}/D_h)^{-3.6154 \cdot \beta \cdot \pi/180}$ where $2.1 \times 10^4 < Re < 4.8 \times 10^4$, $0.9 < Pr < 12$, $25^o < \beta < 40^o$, $6\,mm < L_p < 12mm$, $L_{c,p} = L_p/\cos(\beta \cdot \pi/180)$
Saeed et al. [35]	PCHE-ZC	$Nu = 0.475Re^{0.61}Pr^{0.17}$ $f = 0.13Re^{-0.044}$ where $3000 < Re < 60000$, $2.0 \le Pr \le 13$
Shi et al. [44]	PCHE-AF	$Nu = 0.0986Re^{0.687}Pr^{0.4}(\mu_b/\mu_w)^{0.14}$ $f = 0.513Re^{-0.667}$ where $11671 < Re < 123483$, $0.73 < Pr < 0.75$

fin geometries have been used in the design of plate-fin heat exchangers for heat transfer enhancement. Plate-fin heat exchangers have been applied in power and energy industries, and a growing research activity is under way on the development of diffusion-bonded plate-fin heat exchangers for supercritical CO_2 cycles. The supercritical CO_2 flows through the internal fin-supported passages and distributes and collects at the two ends of the header blocks, while the hot air or flue gas flow crosses between the fins. However, studies on general fin performance and applicable fin selection strategies at high temperature and high pressure are limited.

Sullivan et al. [17] developed an internally supported plate-fin compact heat exchanger as supercritical CO_2 recuperator and investigated its mechanical performance including burst strength, creep, and fatigue. The extrapolated section stress of 67.84 MPa suggested creep life can be up to 1,000,000 hours and the anticipated peak stress of 157.8 MPa suggested fatigue life up to 200,000 cycles. The authors also suggested that the fin thickness and fin density should be selected based on the specified life targets and the heat exchanger operating conditions. Tioual-Demange et al. [47, 48] also designed a supercritical CO_2 plate-fin recuperator and tested its mechanical performance. A bursting test pressure of 800 bars was reached. Sullivan et al. [49] used Alloy 625 for the manufacture of a plate-fin heat exchanger to be used as heater in supercritical CO_2 solar power applications. The heat exchanger was designed to withstand temperatures up to 750 °C and pressures of up to 277 bars based on fatigue and creep considerations. The bursting pressure was found to exceed 800 bars.

Bartel et al. [50] investigated the helium-helium recuperative thermohydraulic performance of an offset strip-fin heat exchanger and PCHEs for advanced nuclear reactors. Results indicate that the offset strip-fin heat exchanger may offer high surface area to volume ratio, high thermal effectiveness, and overall low pressure drop, but as yet do not match the performance PCHEs with zigzag channels. Jiang et al. [51] investigated the thermohydraulic characteristics of helium flowing through plate fin heat exchangers with offset-strip fins. The heat transfer performance was found to deteriorate gradually with the temperature decrease, and the friction factor increased slightly at low temperatures and more sharply at lower Reynold numbers, due to increase in the Prandtl number and decrease in thermal conductivity. They suggested that the Reynold number, fin spacing, and thickness are important parameters in the optimization of plate heat exchangers with offset-strip fins.

Micro shell and tube or microtube heat exchanger

Micro shell and tube heat exchangers are of shell and tube design with micro-tubes. The high-pressure fluid is flowing through the micro-sized tubes and the low-pressure fluid flows through the shell. The advantages of this micro design include high heat transfer efficiency, ease of maintenance, and meeting high temperature and high differential pressure criteria [7].

Thar Energy LLC has developed a counter-current microtube recuperator and a cross flow, counter-current, micro-tube heat exchanger for supercritical CO_2 heater applications. They also built a heat exchanger test loop that can accommodate test pressures up to 275 bars and temperatures up to 700 °C to characterize recuperator and heater heat exchangers [11]. The recuperator has an area density of 4500 m^2/m^3 and is made of Inconel 625. The low-temperature and high-pressure supercritical CO_2 flows inside the microtubes and the high-temperature and low-pressure supercritical CO_2 flows in the shell side. The two supercritical CO_2 flows are also separated by a tube sheet. The heater has an area density of 1800 m^2/m^3 and is made of Inconel 625 and stainless steel 316. The supercritical CO_2 flows inside the microtubes and the air in the shell side. The thermohydraulic performance of the recuperator and the air-to-CO_2 thermohydraulic performance of the heater were tested in the test loop. They suggested that microtube heat exchangers have the potential to replace PCHEs, due to their potential to satisfy the high temperature and high pressure differential criteria but at much lower capital cost. Exergy LLC (www.exergyllc.com) and Tokyo Titanium (http://tokyo-titanium.com) also developed micro shell and tube heat exchangers for CO_2 applications.

Chai and Tassou [52] investigated the recuperative thermohydraulic performance of microtube heat exchangers with and without separator sheets based on modeling using the segmental approach and the ε-*NTU* method. The separator sheets improve the heat transfer coefficient of the shell side and increase the heat transfer area but increase the friction factor. This leads to smaller footprint, but higher pressure drops than microtube heat exchangers without separator sheets for a given heat transfer effectiveness and heat transfer rate.

Cai et al. [53] experimentally investigated the heat transfer and pressure drop characteristics of supercritical CO_2 and water in microtube heat exchangers with and without baffles. The microtube heat exchanger consisted of 37 stainless steel tubes with length of 500 mm, outer diameter of 2 mm and wall thickness 0.2 mm. Baffles on the shell side significantly enhanced the heat transfer on the water side but also led to larger pressure drop. The inlet and outlet pressure drop of supercritical CO_2 in the tube side was found to be much larger than that of conventional shell and tube heat exchangers due to the welding process employed.

A microtube heater, shown in Figure 5 has been developed for Brunel University London by Reaction Engines (https://reactionengines.co.uk) for heat recovery applications. The supercritical CO_2 is designed to

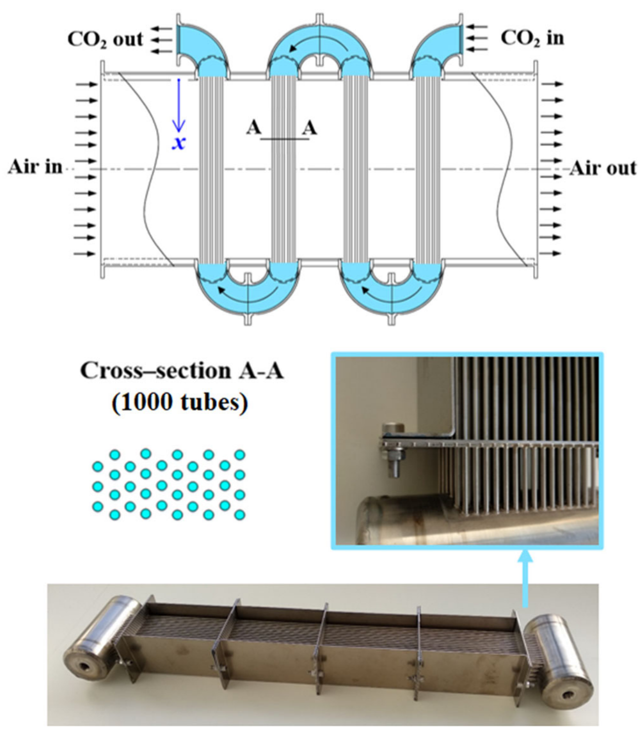


Figure 5. Microtube heater (courtesy of Reaction Engines Ltd).

flow through the micro tubes and the flue gas across the tube bundles. The microtubes have outside diameter of 2 mm, wall thickness of 0.1 mm, and tube length of 0.5 m. The test of its thermohydraulic performance is in progress.

To illustrate the advantages and drawbacks of developed microtube heat exchangers for supercritical CO_2 heat exchangers, a comparative summary is given in Table 4.

Potential heat exchanger designs, materials and fabrication methods

High performance, compact, low cost, large capacity heat exchangers are required by supercritical CO_2 power generation and conversion systems. With these requirements in mind, engineers and scientists have continued to conduct research to identify potential concepts to improve heat exchanger performance, counteract fouling problems, save space, reduce cost, and increase efficiency. Three approaches offering potential to address these challenges are: i) the use of additive manufacturing for the manufacture of 3 D printed heat exchangers; ii) investment casting of metal heat exchangers; iii) manufacture of ceramic heat exchangers by laminated-object or additive manufacturing.

3D printed heat exchanger

Additive manufacturing is the process of joining materials layer upon layer to make objects from 3 D model data [54]. This process is a versatile, flexible, highly customizable fabrication method and can suite most sectors of industrial production. This fabrication method is crucial for developing the next-generation heat exchangers, which has the significant potential to facilitate the development of the high-efficiency heat exchangers due to the complex, geometric freedom this manufacturing technique offers [55, 56]. Different from traditional manufacturing where heat exchangers are made from thin sheets of material that are welded or brazed together, additive manufacturing systems build heat exchangers layer-by-layer with only adding material where needed and can produce lightweight yet complex heat exchangers. The digitally driven process employed in additive manufacturing gives the engineers the design freedom to create heat exchangers with complex structures that would never be possible with traditional machining. Additively manufactured heat exchangers have the potential for less material, reduced volume, increased thermal performance, increased reliability, compared to conventional heat exchangers and the process, to-date, has been used with metals, polymers, and ceramics [57, 58].

Additive manufacturing has been successfully employed for the fabrication of heat sinks from aluminum and copper for electronic cooling applications [59] and many other heat transfer devices from stainless steel, nickel and titanium alloys for thermal energy conversion applications [60]. Despite the impressive progress made to date, the development of additively manufactured heat exchangers for supercritical CO_2 applications, has been slow owing to the very demanding performance requirements. For supercritical CO_2 recuperator application, researchers investigated the manufacture of additively manufactured tubes with internal pin fins [61]. All the tubes were made of 316 stainless steel and had an inner diameter of 7 mm and a wall thickness of 1.2 mm. The tube length was limited to 127 mm due to limitations in the volume chamber.

Table 4. Main advantages and drawbacks of developed heat exchangers for supercritical CO_2 applications.

Type of heat exchanger	Manufacturing techniques	Advantages	Drawbacks
Printed circuit heat exchanger	Photochemical machining; Diffusion bonding.	Compact footprint and reduced weight; Flexible flow passage design; High heat transfer efficiency; Withstand extremely high pressures and temperatures; Wide operating parameters and performance.	Equipment and manufacturing are still quite expensive; Fabricated parts require some post-processing and not installation-ready once complete; Limits of thermal fatigue; High pressure loss; High capital cost.
Diffusion-bonded plate-fin heat exchanger	Diffusion bonding.	Compact footprint and reduced weight; High heat transfer efficiency; High thermal stresses.	Fabricated parts require some post-processing and not installation-ready once complete; Limits of operating pressures and temperatures; Issue occurs in the joining of plate and fin.
Micro shell and tube or microtube heat exchanger	Vacuum brazing; Diffusion bonding.	High heat transfer efficiency; High thermal stresses; Easy maintenance; Meeting the high temperature and high differential pressure criteria.	High pressure loss; Issue occurs in the joining of microtube and header.

For heat transfer enhancement due to swirl flow, the circular or elliptical pins in cross-section were printed at a 30° angle relative to the inner wall and with helical arrangement. The test pressure was up to 207 bars. The pins were found to significantly improve the heat transfer but caused much higher pressure drops. The tubes with pins were estimated to decrease the required heat exchanger material by 13%. A prototype of additively manufactured heat exchanger has also been designed by General Electric (GE) for supercritical CO_2 power generation [62]. GE (https://www.ge.com/) expect the lung-inspired 3 D additively manufactured heat exchanger to play a key role in building a supercritical CO_2 demonstration plant capable of generating 10 megawatts of electrical power.

Despite the recent progress, there are still significant technical challenges to overcome before additive manufactured CO_2 heat exchangers become a commercial reality. During manufacture, the material experiences complex thermal processing cycles which impact the properties of the developed device, like hardness and corrosion resistance and needs to be taken into consideration [63]. Some studies have also found deviation of experimental results of thermal properties of the material from those published by the manufacturers of the materials [64]. The manufacturing process also may lead to parts with internal porosity resulting from shrinkage, gas entrapment during solidification, and adhesion of partially molten particles to surfaces between layers [57]. The porosity greatly influences the thermal conductivity and the tensile and fatigue strength of the fabricated parts [65, 66].

Currently available additive manufacturing systems have relatively small effective building volumes, which limit the capability to integrally manufacture large components [67, 68]. The current processes are also costly and time-consuming and thus are not suitable for large volume production. The qualification and certification of additive manufactured heat exchangers are also challenging as there are no specific standards for assessing the properties of additively manufactured heat exchangers because they depend on many process parameters [60, 69]. Surface roughness and powder removal of additively manufactured heat exchangers are also a challenge that adds to the manufacturing cost and increases pressure drop particularly in the case of mini/microchannel heat exchangers [59, 64, 70, 71].

Casted metal heat exchanger

Investment casting produces patterns using rapid prototyping processes rather than molded wax. The pattern is encased in refractory material, and then burned out to form a mold cavity in the shape of the pattern, and then the mold cavity is filled with molten metal to create the metal part with the similar geometric shapes and size of the patterns [72, 73]. The mold surface can have low roughness and the refractory material can offer ample refractory strength and chemical inertness. The technique can make metal components with complex geometry and accurate dimensions, compared to those manufactured with sand casting. Tolerances as low as 76 μm have been claimed and metal components with sections as narrow as 0.4 mm have been manufactured [74, 75]. The technique can also make metal parts from various metal alloys including carbon and low alloy steels, stainless steels, tool steels, nickel and cobalt alloys, and aluminum and copper alloys, [76]. It has been used for the production of quality components for many applications in the aerospace, power generation, automotive, gas and oil, and energy industries [74, 77].

Most of the metal components produced by investment casting in the power and energy industries are rotors and turbine blades in motors and generators with only very few heat exchangers and heat sinks manufactured to date. Lei et al. [78] fabricated six pin-fin heat sinks for electronics cooling applications and Matz et al. [79] manufactured open-pore metal foams for heat engineering application. For supercritical CO_2 applications, investment casted heat exchangers have the potential to offer greater flexibility in material options and channel geometries, similar or better heat transfer capacity, but lower capital cost than PCHEs. The ability to fabricate large heat exchangers with materials that are difficult to machine such as novel high-performance nickel alloys, is particularly attractive. Sandia National Laboratories has employed investment casting to develop S-shaped fin and airfoil fin surface geometries used in PCHEs [80].

Despite its main advantages, the adoption of investment casting for supercritical CO_2 heat exchanger applications faces crucial technical challenges. Mismatch in the thermal expansion between the pattern and ceramic shell can cause cracks in the shell [81]. It is also difficult to remove the casting core material from the finished block and relatively significant quantities of residual ash may also cause defects in the final castings [82]. The casting of high-temperature metal may induce porosity which can impact the quality of the fabricated components [75]. Investment casting presents some difficulties where holes or cores are involved with the minimum diameter of casted holes being approximately 1.6 mm [75]. Another major challenge are the long cycle times that require the development of cost-effective solutions for low-volume production to facilitate the commercial application of casted metal heat exchangers [83].

Ceramic heat exchanger

Since the specific strength of metallic materials decreases very rapidly with high temperature and pressure, especially at temperatures over 650 °C, the ceramic heat exchanger may be an economical solution for high temperature applications [84, 85]. Ceramic materials offer many benefits for use in heat exchangers, including high temperature thermodynamic stability, high thermal conductivity, high thermal shock resistance, low creep at high temperature, high compressive strength and corrosion and erosion resistance, and ability to operate with high pressure differential between the hot and cold sides [86, 87]. Among the structural ceramic materials, silicon carbide-based ceramics have received the most attention and been thought as the most promising heat exchanger materials. They have high temperature of decomposition of around 2500 °C and about four times the thermal conductivity of steel. They also show excellent thermal shock resistance and maintain their flexural strength at elevated temperatures. Ceramic heat exchangers have found applications in the chemical process, power generation and industrial waste heat recovery industries [85, 87].

Pioneering work on the development of ceramic heat exchangers can be traced back to the 1980s. Coombs et al. [88] fabricated a ceramic finned-plate recuperator for fluidized-bed waste heat recovery, Kleiner et al. [89] designed a highly compact, all-prime surface, internally manifolded, plate-and-fin ceramic recuperator for engine applications, and Luu and Grant [90] designed a ceramic bayonet tube heat exchanger for high temperature waste heat recovery.

Lewinsohn [86] demonstrated the potential of ceramic microchannel heat exchangers to offer higher efficiency over more conventional designs. A stack of silicon carbide heat exchanger plates and a conceptual design of modular, microchannel plate heat exchanger for a macroscale process have been developed. Sommers et al. [87] reviewed ceramics and ceramic matrix composites for new heat exchanger designs for advanced thermal systems. Scheithauer et al. [91] compared two advanced ceramic heat exchanger fabrication methods, additive manufacturing, and laminated-object-manufacturing, and discussed advantages and limitations. Kee et al. [92] fabricated a kilowatt-scale, compact, alumina ceramic microchannel plate heat exchanger and tested its thermohydraulic performance with hot air up to 750 °C. Haunstetter et al. [93] fabricated ceramic heat exchangers with modified offset-strip-fin design and investigated their thermohydraulic performance with hot air up to 800 °C.

So far, ceramic heat exchangers for supercritical CO_2 applications have been tested only under high temperature, but not under both high temperature and high pressure, and little is known regarding the effects of CO_2 and exhaust gas species in heat recovery applications on the ceramics. The challenges in the use of ceramic heat exchangers in supercritical CO_2 systems are discussed below. Firstly, the difficulty of joining of ceramics to metals. The problems making the joining difficult come from the different thermal expansion coefficient, atom bond configuration, and chemical and physical properties between ceramic and metal materials [94]. Using the general joining method of diffusion bounding and fusion welding to join them together is almost impossible, and the molten metal does not generally wet on ceramic surfaces [95]. Secondly, reliable high temperature, high pressure seals between metal pipes and ceramic heat exchangers. The pressure forces under the seal faces must be balanced and tolerance must be allowed for the thermal distortion of the metal pipes. The seals must be efficient under high temperature, high pressure and high-pressure differential operations and must accommodate the mismatched expansion and contraction of ceramic materials and metal pipes [96]. Thirdly, the lack of ductility and inherent brittleness in tension of the materials that can significantly affect the reliability and consistency of material properties [87]. Finally, the manufacturing costs and methods. Suitable fabrication methods for compact ceramic heat exchanger are additive manufacturing and the laminated-object-manufacturing approach [86, 97]. The challenges for additive manufacturing are the molds used for forming ceramic bodies, which are expensive and require a significant number of materials and components to enable the fabrication of dense ceramic parts with optimal properties including density, mechanical strength, surface finish, as well as the production of ceramic components at high volume [90, 97]. In the laminated-object-manufacturing approach, ceramic heat exchanger plates are built by lamination of sheet feedstock, and then cut into the desired shape with a computer-controlled laser or blade. Compared to additive manufacturing, the laminated-object-manufacturing approach affords manufacturing of comparatively large-scale at lower cost and convenient processing speed. The challenge of this method is the surface quality and dimensional accuracy of the produced parts. Removal of the laminated supporting material can be tedious and complex undercuts and hollow structures can be very difficult to produce. The joining of the individual heat transfer plates is also a challenge where the joints must have good mechanical properties to withstand the high pressure at elevated temperatures [86, 98]. To address the above challenges, further research and development is needed to address issues of ductility and brittleness, joining methods to metallic components and demonstration of reliable manufacturing processes for commercial scale heat exchangers.

The advantages and drawbacks of emerging heat exchangers for supercritical heat exchangers are summarized in Table 5.

Conclusions and recommendations

This paper provides a comprehensive review of high temperature and high pressure heat exchangers for supercritical CO_2 applications, covering key issues associated with the design, manufacture, and operation processes. Major conclusions are:

- High-temperature materials and fabrication methods restrict the development of heat exchangers in the supercritical CO_2 Brayton cycles. The material performance and code qualification are required to develop material databases and standards. The manufacturing and assembly procedures are expected to exert less influence on material strength and durability.
- Design strategy and evaluation criteria are required to balance the heat exchanger type, cost, durability, and performance. The thermohydraulic design demands low pressure drop and high effectiveness. The structural design requires the ability to withstand rapid startups and transients during operation as well as endure thermal cycling and fatigue. The capital cost significantly impacts the process of supercritical CO_2 power system development from demonstration to commercialization.
- PCHEs are currently the most widely adopted heat exchangers for recuperation in supercritical CO_2 applications. Their advantages include compactness and structural rigidity and reliable performance under conditions of high pressure and high temperature. So far, most of the research has focused on thermohydraulic design under steady state operating conditions. Performance under off-design conditions (startup, shutdown, and changes in load)

Table 5. Main advantages and drawbacks of potential heat exchangers for supercritical CO_2 applications.

Type of heat exchanger	Manufacturing techniques	Advantages	Drawbacks
3D printed heat exchanger	Additive manufacturing	Versatile, flexible, highly customizable fabrication method; More freedom for design of complex structures; Custom parts are easy to prototype; Less material, reduced volume.	Equipment and raw materials are still quite expensive; Fabricated parts require some post-processing and not installation-ready once complete; Quality of the fabricated parts are difficult to control; Infeasible mass production for most products and components; Issues related to surface roughness and powder removal; Size limitation.
Casted metal heat exchanger	Investment casting	Practically any metal can be investment cast; Many intricate forms with undercuts can be cast; Smooth surface can be obtained with no parting line; Allows high dimensional accuracy; Very thin sections can be produced by this process.	Limited to small casting, and present some difficulties where cores are involved; Quality of the fabricated parts are difficult to control; Difficulty to cast objects requiring large size, or holes and cores; The whole parts cannot be made totally for hollow parts, the finished piece will need no welding or assembling.
Ceramic heat exchanger	Laminated-object-manufacturing; Additive manufacturing	Resistance to high-temperature corrosion and oxidation; Stability at elevated temperature; Good thermal shock resistance; Low coefficient of thermal expansion; Ability to be fabricated in practical geometries; Chemical durability.	Brittleness; Permeability; Unsuitable for fabrication by joining techniques; Difficulty of joining of ceramics to metals; Require reliable high temperature, high pressure seals; Irreparability; Mass production and size limitations.

needs to be further investigated due to its influence on other system components and control as well as the influence of thermal cycling on fatigue of the whole heat exchanger, not just that of a single plate.

- Diffusion-bonded plate-fin heat exchangers are generally suitable for lower pressure applications, below those employing printed circuit style cores. Further research into the fin selection, fabrication and performance is required, also to establish the pressure and temperature limits of these heat exchangers. Their thermohydraulic performance under transient operating conditions should also be investigated further as well as the thermal stresses and reliability of bonded joints.
- Microtube heat exchangers have been developed for both heater and recuperator applications, but more research is required on their performance as well as capital cost. Microtube heaters are usually employed for heating or heat recovery from hot exhaust gas streams. Issues that need further consideration include cleaning of the heat exchangers if they are to be used with "dirty" exhausts and maintenance in the event of tube failure. For recuperative CO_2 to CO_2 heat transfer applications, microtube shell and tube heat exchangers compete with more established PCHEs and further work is required to investigate their comparative heat transfer and pressure drop performance and capital cost.
- The development of additive manufacturing technologies has facilitated the 3D printing of metallic heat exchangers. Advantages include less material use and the ability to manufacture complex and highly efficient designs. The manufacture of large 3D printed heat exchangers is currently hindered by the 3D printing technology available which also reduces the potential for mass production.
- Investment casted heat exchangers have the potential to reduce the number and complexity of fabrication steps required compared to alternative heat exchanger manufacturing techniques. However, there are limitations on the size of the flow passages, the size of the heat exchanger that can be produced in a single casting operation as well as uncertainties on the properties of the final product. These areas need further research and development before casted heat exchangers can find wide applications in supercritical CO_2 heat to power technologies.
- Ceramic heat exchangers can offer many benefits that include high temperature thermodynamic stability, ability to withstand high pressure differentials between the hot and cold sides of the heat exchanger and excellent erosion and corrosion resistance. The main challenges are difficulties of joining of ceramic cores to metals piping, relatively low ductility and inherent brittleness in tension. These challenges need to be addressed before ceramic heat exchangers find wide application in the supercritical CO_2 heat exchanger industry.
- The review has demonstrated that significant progress has been made in recent years in the development of PCHEs and to a lesser extent microtube heat exchangers for supercritical CO_2 power applications. A number of new design concepts and manufacturing methods are emerging aimed at reducing costs and improving performance, but significantly more research and development effort is required for these concepts to become commercially viable alternatives to microtube and PCHE type heat exchangers.

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