

**Progress and Prospects for Research and Technology
Development of Supercritical CO₂ Thermal Conversion
Systems for Power, Energy Storage, and Waste Heat
Recovery**

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Progress and Prospects for Research and Technology Development of Supercritical CO₂ Thermal Conversion Systems for Power, Energy Storage, and Waste Heat Recovery

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ABSTRACT

CO₂ is an environmentally friendly heat transfer fluid and has many advantages in thermal energy and power systems due to its peculiar thermal transport and physical properties. Supercritical CO₂ (S-CO₂) thermal energy conversion systems are promising for innovative technology in domestic and industrial applications including heat pump, air-conditioning, power generation, renewable energy systems, energy storage, thermal management, waste heat recovery and others. Both S-CO₂ and transcritical CO₂ thermodynamic cycles have been extensively investigated in order to improve the efficiencies of thermal and power systems and achieve net zero carbon emissions. This paper focuses on the progress and prospects for current research and technology development of S-CO₂ thermal energy conversion systems and their applications including power generation, energy storage and waste heat recovery. First, the CO₂ thermal transport and physical properties and benefits using CO₂ as a heat transfer fluid in thermal energy and power systems are discussed. Then, classification of CO₂ thermodynamic systems is presented. Next, S-CO₂ for power generation, energy storage and waste heat recovery systems are presented. Finally, research needs of subcritical and supercritical CO₂ heat transfer, fluid flow and heat exchangers for the development of various thermal energy and power systems are discussed.



Introduction

Due to global warming, climate change, waste pollution and energy consumption, developments and breakthroughs of scientific theories and innovative technologies for advanced and decarbonized thermal and energy conversion systems are urgently needed in order to achieve net zero emissions [1]. Research and development of thermal management, heat transfer enhancement and process intensification technologies, novel thermal energy and power systems, energy storage and waste heat recovery technologies have been extensively conducted for the purpose of effective utilization of energy, decarbonization and environment protection over the past years [2–4]. As an efficient and environmentally safe working fluid, CO₂ has been considered an alternative to conventional heat transfer fluids in various thermal energy conversion systems such as power generation, thermal energy conversion

and utilization, waste heat recovery, air conditioning, heat pump and refrigeration systems, thermal management for sustainable energy technologies, nuclear energy, high heat flux removal and so on [5–13].

S-CO₂ Brayton thermodynamic cycle is a promising thermal conversion system for power generation to replace the conventional steam Rankine cycle owing to its high thermal efficiency, simple cycle layout, compactness of components and wide operation range [14–17]. S-CO₂ Brayton systems can be used in thermal energy conversion systems using both non-renewable and renewable sources such as nuclear, geo-thermal, solar, thermal power plants, energy storage and waste heat recovery [18–28].

In the heat pump, air-conditioning, and refrigeration systems, natural refrigerants which exist in nature's biological or chemical cycles have been chosen to replace synthetic refrigerants [29]. As a nature refrigerant, CO₂ (also known as R744) has

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Nomenclature

C	compressor	p_2	high pressure, Pa
$CCGT$	combined cycle gas turbine	Q_L	latent heat
DC	data center	Q_S	sensible heat
HE	heat engine	RC	recompressing compressor
HP	heat pump	s	entropy
HT	high temperature	$S-CO_2$	supercritical CO ₂
HTR	high temperature regenerator	ST	stationary CO ₂ source
HXI	heat exchange - ice	T	temperature, K, or turbine
HXW	heat exchange - water	T_{crit}	critical temperature, K
$HydT$	hydraulic turbine	T_{ps}	pseudocritical temperature, K
IHX	internal heat exchanger	$T-CO_2$	transcritical CO ₂
LNG	liquefied natural gas	W	work
LT	low temperature	WHR	waste heat recovery
LTR	low temperature regenerator		
MC	main compressor		
ORC	organic Rankine cycle		
P	pump		
p	pressure, Pa		
p_{ps}	pseudocritical pressure, Pa		
p_{crit}	critical pressure, Pa		
p_1	low pressure, Pa		

Subscripts

<i>cha</i>	charge
<i>crit</i>	critical
<i>dis</i>	discharge
<i>ps</i>	pseudocritical
1	low
2	high

been receiving renewed interest as an efficient and environmentally safe working fluid in mobile air conditioning, heat pump systems and refrigeration systems at low temperatures [30–32]. Due to its low critical temperature T_{crit} of 31.1 °C and high critical pressure p_{crit} of 7.38 MPa, CO₂ is utilized at much higher operating pressures in air-conditioning and heat pump systems. Supercritical CO₂ gas cooling in gas coolers rather than condensation heat transfer in condensers operates in the high-pressure process. Furthermore, CO₂ can be used in electronic cooling, two-phase thermosiphon loop and evaporative CO₂ cooling system for the upgrade of the Compact Muon Solenoid pixel detector etc. [4]. CO₂ thermal systems can be used in geothermal energy utilization, combined heat, cooling and power systems, thermal management, solar energy utilization and recovery of waste heat [33–51].

In order to develop advanced CO₂ thermal and power systems, compressors, and heat exchangers such as evaporators, gas coolers, condensers, internal heat exchangers and recuperators should be properly designed [6–11]. CO₂ heat exchangers with micro-channels and enhanced elements can enhance heat transfer and thus improve the thermal efficiencies of various thermal energy conversion systems [7,8]. Understanding subcritical and supercritical heat transfer and fluid flow is the key to design of various heat transfer components and needs to be specially investigated due to the peculiar heat transfer and fluid flow behaviors for both evaporation and supercritical heat transfer processes. The sharp variations of the thermal transport and physical properties at high reduced

pressures result in quite different heat transfer and fluid flow phenomena in various channels and components [7,11]. Therefore, heat transfer calculation correlations and design methods of heat transfer components have been extensively studied over the past years and technical risks in the design of the components used for various thermal conversion systems are reduced. However, adaptation of the CO₂ thermal and power systems to interface with various heat sources is imperative for its adoption as an industry manufactured technology. Further research on CO₂ heat transfer and fluid flow in emerging enhanced heat transfer tubes and heat exchangers is still needed to provide robust and reliable design correlations and methods for various thermal energy conversion systems.

For understanding the current research and technology development of S-CO₂ thermal and power systems and future research and technology development needs, this paper presents a review on S-CO₂ thermal energy conversion systems and their applications focusing on power generation with conventional and renewable heat sources, energy storage and waste heat recovery. Research of CO₂ heat transfer, fluid flow and heat transfer components and future research needs are also mentioned in this review.

CO₂ thermal transport and physical properties and benefits of using CO₂ as a heat transfer fluid in thermal energy conversion systems

CO₂ is a nontoxic, environmentally friendly and non-flammable heat transfer fluid. It is stable at high

temperature with a large operational temperature range from -73 to 1000 °C at both subcritical and supercritical conditions in thermal energy and power conversion systems [33]. As shown in Figure 1, the critical point of CO_2 is at the pressure of 73.8 bar and the temperature of 31.1 °C [52]. At the supercritical conditions, CO_2 behaves like a gas but with the density of a liquid performing like a single-phase fluid. Due to its particular thermodynamic and physical properties, CO_2 can work at subcritical and supercritical conditions in various thermal and energy conversion systems such as heat pump, air conditioning and refrigeration systems, power generation systems using both conventional and renewable energy sources, energy storage, cooling and heating, thermal management and waste heat recovery.

The thermal transport and physical properties of CO_2 may vary significantly near the critical point and thus can significantly affect the evaporation and supercritical heat transfer and fluid flow behaviors of CO_2 , the heat transfer components, and the thermal and energy systems. Figure 2 [19] shows the thermal transport and physical properties of CO_2 versus temperature at the pressures of 7.5, 8, 9, 10 and 12 MPa, which were obtained from REFPROP 7.0 [53]. For a constant pressure larger than the critical pressure, an important characteristic is that the specific heat reaches a sharp maximum as shown in Figure 2(c). This point is called the pseudocritical point as indicated by the dash line in Figure 2(c) for the pressure of 9 MPa and the corresponding pressure and temperature are the pseudocritical pressure (p_{ps}) and the pseudocritical temperature (T_{ps}). Near the critical pressure, the thermal conductivity also reaches a maximum value. The thermal transport and physical properties of CO_2 change drastically with temperature around the critical point in an isobaric process,

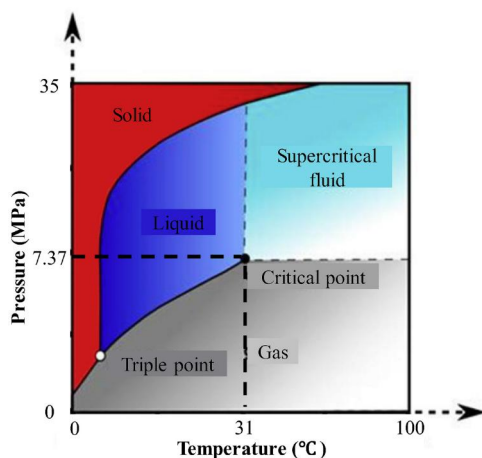


Figure 1. p-T diagram phases to carbon dioxide [52].

especially near the pseudocritical and critical points. However, with increasing the pressure, these changes become less pronounced. The density and dynamic viscosity undergo a significant drop near the critical point, which is almost vertical within a very narrow temperature range while the enthalpy undergoes a sharp increase. The specific heat, thermal conductivity and Prandtl number have peak values near the critical points. The magnitude of these peaks decreases very quickly with increasing pressure.

Due to its high density, a relatively low fluid flow rate is needed for S- CO_2 in thermal and power systems. This significantly reduces the compression work and lead to simple and compact turbines at high temperatures and improvement of the system efficiency [34]. S- CO_2 heat transfer and fluid flow processes are critical to reducing the temperature difference between the metal tubes and CO_2 . Furthermore, CO_2 is used as a natural refrigerant for air-conditioning, heat pump and low temperature refrigeration systems. The physical and transport properties of CO_2 are quite different from those of conventional refrigerants at high reduced pressures. In general, CO_2 has much higher evaporation heat transfer than conventional refrigerants. Microchannels are needed for both evaporators, internal heat exchangers and gas coolers. Microchannel heat exchangers can increase the heat transfer and therefor increase the thermal system efficiencies and make the thermal systems compact.

There are many benefits in using CO_2 as a heat transfer fluid in various thermal energy and power generation systems. For example, combined S- CO_2 heating, cooling and power generation systems are crucial to achieving zero carbon emissions. S- CO_2 thermal conversions systems can be used for energy storage, waste heat recovery and cooling for high heat flux, solar collectors, power generation, cooling for green hydrogen energy systems and so on. When S- CO_2 is used as the heat transfer fluid for solar collectors and power systems, it eliminates a heat exchanger in the systems and thus results in more efficient and less complex units. Despite the benefits of using S- CO_2 , it also presents some challenges which need to be addressed here. Operating near the critical point means high working pressures, so reduced tube diameters are required leading in a reduction in the heat transfer rate in tubular receivers. As well as the possible leaks associated to moving parts and connections. Accordingly, the materials considered for various components of the system must have resistance to corrosion and thermal fatigue caused by high temperature, oxidation, and creep. In the aspects of subcritical and supercritical CO_2 heat

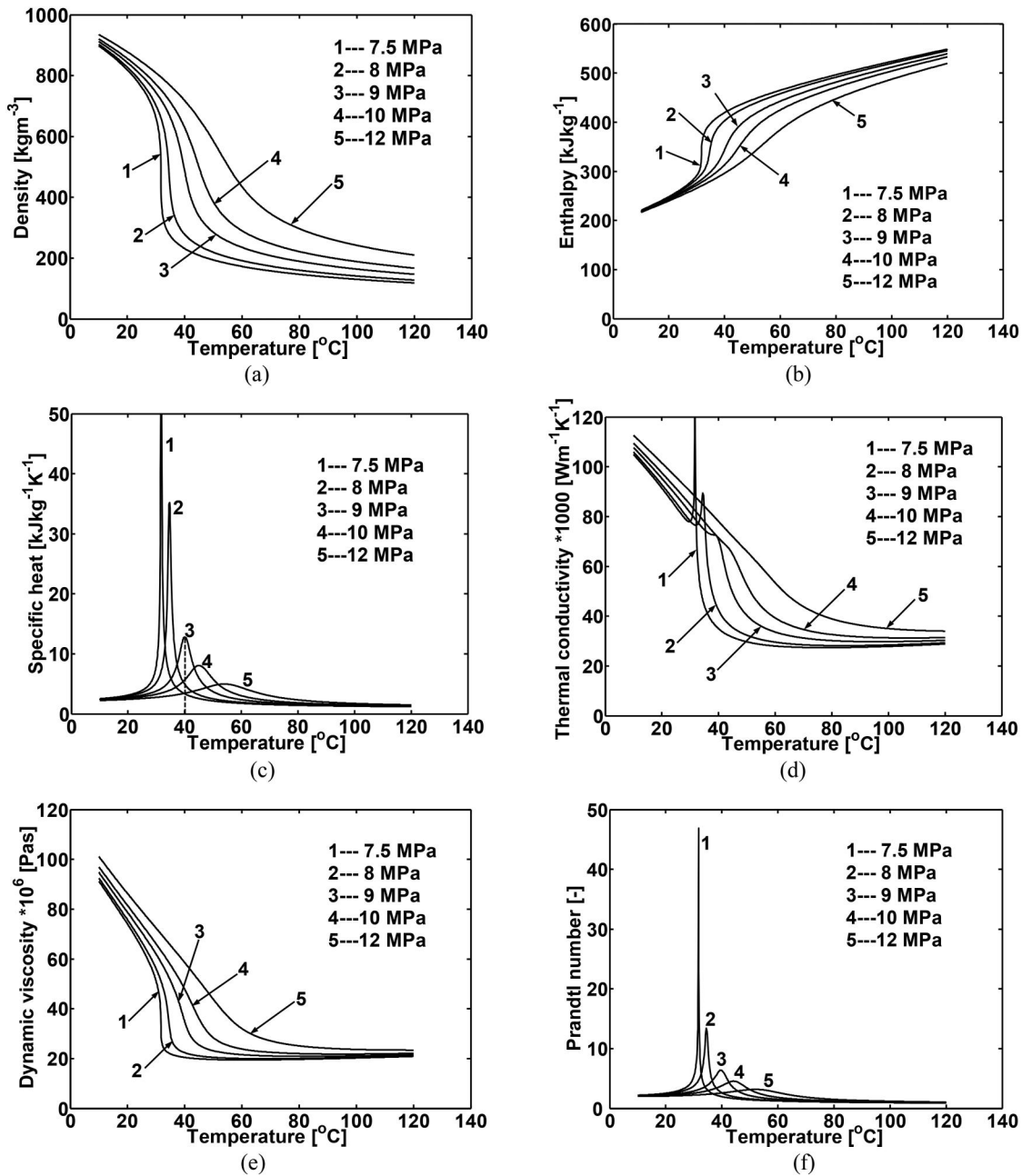


Figure 2. Physical properties of supercritical CO₂ at five different pressures versus temperatures [19]. (a) Density; (b) Enthalpy; (c) Specific heat (the dash line indicates the pseudo-critical point at the pressure of 9 MPa); (d) Thermal conductivity; (e) Dynamic viscosity; and (f) Prandtl number.

transfer, fluid flow and heat exchangers, proper calculations correlations and design methods should be verified and adopted [54–56].

Classification of S-CO₂ thermal energy conversion systems

A thermal energy conversion system generally consists of four basic processes, namely compression, heat addition at high pressure p_2 , expansion, and heat

rejection at low pressure p_1 . Depending on if there is a phase change process in the thermal energy conversion systems, thermal power systems are classified as two types of systems as shown in Figure 3. In the Joule–Brayton cycle, the thermal system remains in the vapor region and in the Rankine system, the heat transfer fluid undergoes phase change process in the heat addition and heat rejection processes [11].

Thermal energy conversion systems are also classified according to their operating pressures below or

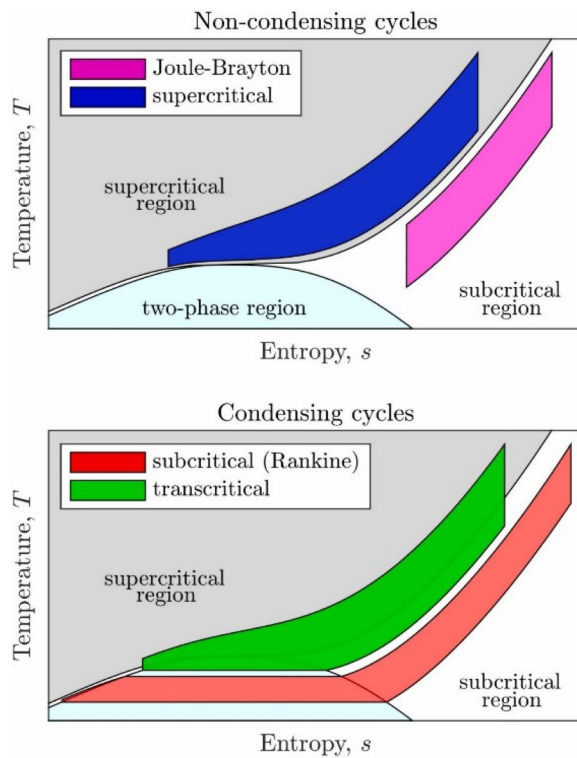


Figure 3. Classification of thermodynamic power cycles (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article) [11].

above the critical pressure of the heat transfer fluid (p_{crit}). There are three classifications: subcritical thermal systems for $p_1 < p_{crit}$ and $p_2 < p_{crit}$, supercritical thermal systems for $p_1 > p_{crit}$ and $p_2 > p_{crit}$, and transcritical thermal systems for $p_1 < p_{crit}$ and $p_2 > p_{crit}$ as shown in Figure 3 [11]. In supercritical systems, the low pressure of the system is also above the critical pressure 73.8 bars, and there is no distinction between the fluid being in a liquid or a vapor state as shown in Figure 1. In transcritical systems, the low pressure of the system is below the critical pressure 73.8 bars, and condensation heat transfer may occur in heat-rejection process. In transcritical systems, the lower the compressor inlet temperature and the closer the compression process is to the saturated liquid line, thus the lower the compression work. Therefore, transcritical systems can improve the thermal efficiencies of the thermal systems.

Figure 4 shows the thermal efficiencies of various thermal power conversion systems and heat sources with respect to the turbine inlet temperature. The heat sources include geothermal energy, solar thermal energy, nuclear energy, coal, waste heat recovery, and liquefied natural gas (LNG). The power conversion systems are organic Rankine cycle (ORC), steam Rankine cycle (steam turbine), air Brayton cycle (gas turbine), combined cycle gas turbine (CCGT), and

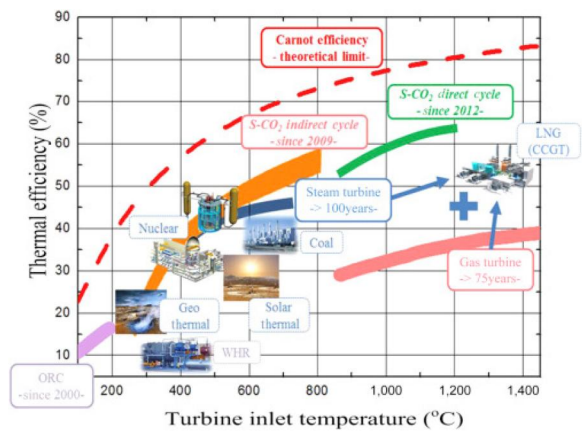


Figure 4. Thermal efficiencies of power conversion systems and applications [13].

S-CO₂ direct and indirect cycles [13]. As indicated in Figure 4, the steam Rankine cycle can achieve high efficiency at low turbine inlet temperatures because liquid water is incompressible and requires less work for compression. However, the gas turbine utilizes air and a large amount of work is consumed in the compression process. Therefore, the thermal efficiencies of the systems with gas turbines are lower than that of the steam Rankine systems although the turbine inlet temperatures are much higher. This is because the compressors consume a large amount of work. Furthermore, there is a big issue with the materials at higher turbine inlet temperatures for the gas turbines.

S-CO₂ thermal systems have higher efficiencies than other thermal systems and are promising systems to replace the existing systems. Figure 5 shows the principles of power conversion systems using steam and S-CO₂. S-CO₂ Brayton cycle is a power conversion system which combines the advantages of both steam Rankine systems and gas turbine systems. CO₂ becomes more incompressible near the critical point [13]. Therefore, S-CO₂ is compressed in the incompressible region and the higher turbine inlet temperature can be utilized with less material issues as compared to the steam Rankine systems.

Progress and prospects for S-CO₂ thermal and power conversion systems

S-CO₂ Brayton systems for power generation

S-CO₂ Brayton power generation systems have high thermal efficiency, simple cycle layout, compactness of component and wide operation range. Figure 6 shows the comparison of power conversion systems using water, air and CO₂ as working fluids [13]. The advantages of S-CO₂ Brayton systems are due to the high

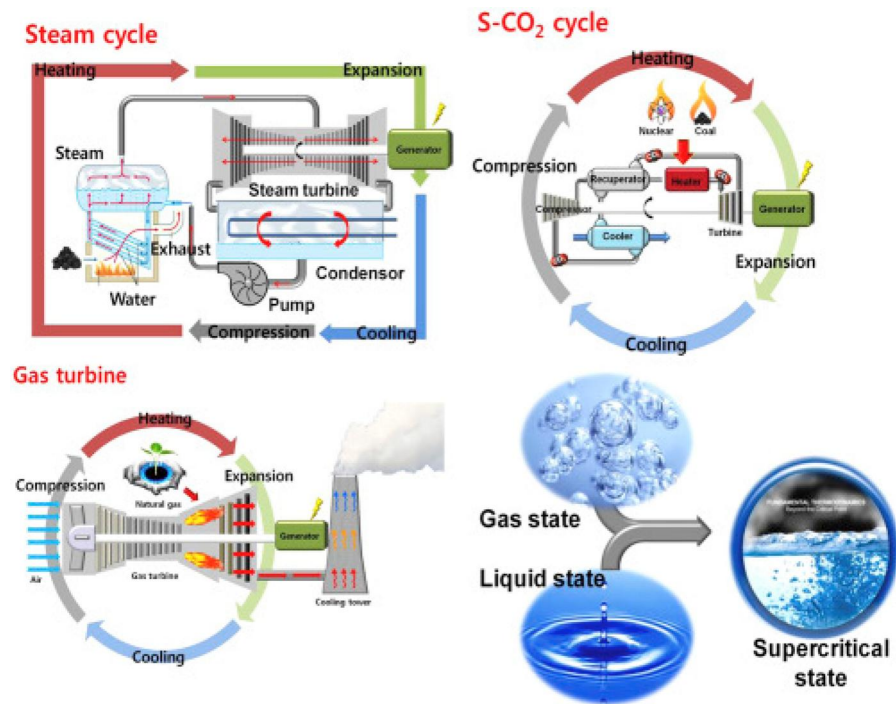


Figure 5. Principles of power conversion system [13].

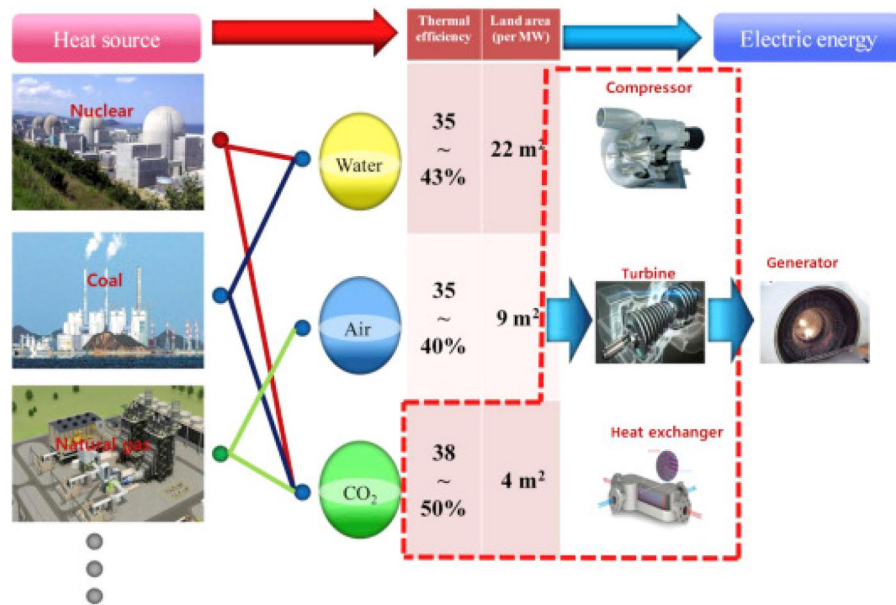


Figure 6. The comparison of steam, air, S-CO₂ power conversion systems [13].

density and low compressibility of CO₂ near its critical point and the wide and rapid variation in the thermodynamic properties as shown in Figure 2. S-CO₂ Brayton systems can be used in nuclear, geothermal, solar and thermal power plants and combined heat, cooling and power systems and others.

Various layouts of S-CO₂ Brayton power generation systems have been investigated over the past years [56–62]. A simple recuperated S-CO₂ Brayton cycle is the basic layout because a recuperator is essential for

the system. Figures 7 and 8 illustrate a typical recompression cycle which consists of a main compressor, a recompression compressor, a turbine, a low temperature recuperator, a high-temperature recuperator, and a precooler [18]. The thermodynamic processes occur at state points in the cycle in Figures 7 and 8. The recuperators minimize the heat which is wasted after the turbine stage. The precooler is set to achieve thermodynamic conditions of the main compressor inlet. This cycle uses a flow split in front of the

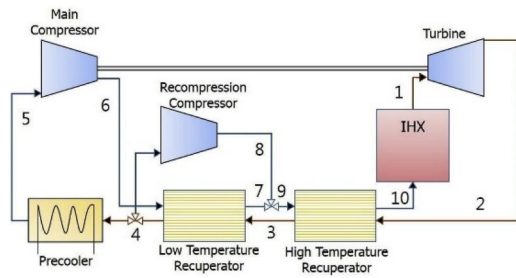


Figure 7. Layout of S-CO₂ Brayton recompression cycle [18].

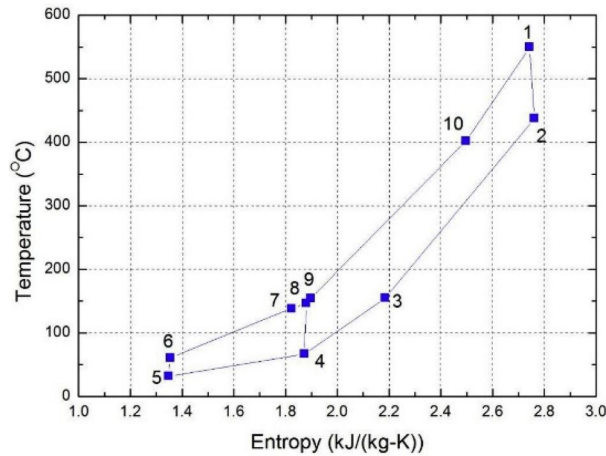


Figure 8. T-s diagram of S-CO₂ Brayton recompression cycle [18].

precooler to allow some of the CO₂ to bypass the cooling process and to be recompressed. The recompression cycle is a typical layout which significantly improves the thermal efficiency of the system by recovering the heat and solving the pinch-point problem in the recuperators. The reheating and intercooling cycles are typical layouts which improve the system performance by increasing the expansion work and reducing the compression work, respectively. Based on the basic S-CO₂ Brayton cycle, research has been investigated to optimize the layouts in order to improve the thermal efficiencies of the thermal energy conversion systems [15,18,26,27,42].

One of the main advantages of the S-CO₂ Brayton systems is the compact turbomachinery. This is mainly because the S-CO₂ Brayton systems operate at the supercritical conditions, the minimum pressure is higher (up to 7.4 MPa) than any existing steam Rankine systems (a few kPa) or gas Brayton systems (up to 100 kPa). Furthermore, S-CO₂ remains dense throughout the whole power generation systems. Therefore, the volumetric flow rate decreases as the S-CO₂ density is higher than that of other working fluids. This results in up to 10 times smaller turbomachinery of the S-CO₂ Brayton systems as compared to

the turbomachinery of a steam Rankine cycle. However, the cycle pressure ratios of the S-CO₂ Brayton systems are much smaller as compared to those of the steam Rankine systems, the turbine outlet temperatures are relatively high. Therefore, a large amount of heat must be recuperated in order to increase the thermal efficiencies of the systems. The recuperation process is needed in the S-CO₂ Brayton systems. The most efficient layout of the S-CO₂ systems is the recompressing layout. This is because the S-CO₂ systems are similar to the steam Rankine systems in terms of the layout while the systems are similar to the gas turbine systems in the aspect of the design of main components. Various layouts are employed for the S-CO₂ power systems depending on their applications [42].

One key feature of the S-CO₂ Brayton systems is that the specific heat of the cold side fluid is two to three times higher than that of the hot side fluid in the recuperators. It is especially important to explain why the recompressing layouts can improve the thermal efficiencies. As shown in Figures 7 and 8, CO₂ flow is split to compensate for the specific heat difference in the low temperature recuperators and to maximize the heat recuperation in the recompressing layouts. Therefore, waste heat can be reduced, and thermal efficiencies can be improved in the recompressing layouts [47].

The operating conditions in the S-CO₂ heat exchangers play a crucial role in improving the thermal efficiencies of the systems. As a large amount of heat is recovered in the recuperators to increase the thermal efficiencies of the systems, high effectiveness is required and therefore the capital cost increases when conventional shell and tube heat exchangers are utilized. However, various compact heat exchangers with high compactness (up to 10 times compared as compared to shell and tube heat exchangers), such as printed circuit heat exchangers have been commercialized and can be applied to the S-CO₂ cycle directly [62].

S-CO₂ Brayton systems can be applied to various heat sources including conventional sources and renewable sources. They are considered as an alternative to the steam Rankine systems, nuclear energy ranging from pressurized water reactors (both large and small modular reactors) to the next generation nuclear reactors and fusion reactor applications as well [42]. The S-CO₂ systems can be utilized as topping systems for fossil fuel powered plants and bottoming systems of gas combined cycle plants. There are also promising heat sources including several

renewable energy sources such as high temperature fuel cells, concentrated solar power and geothermal power which can be integrated with energy storage technology [25,44,46,56,59].

S-CO₂ thermal and power systems for energy storage

In recent years, research, and development of power generation from renewable resources are considerably increasing in order to achieve net zero carbon emission. Due to the stochastic and non-continuous nature of renewable resource availability (wind, solar and others), electrical energy storage is one of the main challenges for large-scale renewable power plants integration into the electric grid. Therefore, energy storage systems at different scales are needed to advance toward electrified systems with a high share of renewables. Depending on the amount of energy to be stored, there are different types of energy storage systems. Different integrations of S-CO₂ systems in energy storage systems have been investigated [28,32,34,35,37,44].

Several options have been considered for storing electricity in thermal systems based on a combination of heat pumps and heat engines systems using CO₂ as the working fluid. These are based on heat pumps, compression or incorporating underground reservoirs, thermal or geological storage [35]. One promising energy storage technology is to use reversible heat pumps based on two closed cycles, indirectly connected by hot and cold thermal storage tanks. Figure 9 [35] shows the conceptual system operation: in periods of excess energy, it is stored by a heat pump which compresses the working fluid. Sequence 1-2-3-4, transforming electrical energy into thermal energy and stores it, transferring/absorbing energy from the high and low-temperature (HT and LT) reservoirs. In periods with net electrical demand, the cycle follows

the sequence 5-6-7-8, in which thermal energy is transformed into electrical energy by the operation of a heat engine. A functional heat transfer integration with heat storage tanks is required to obtain high efficiencies in the operation of the heat pump energy storage system. During charging, the working fluid temperature must be above the storage temperature during the whole heat transfer process. Figure 9(a) illustrates an example of poor integration in the temperature profile of LT storage, where the working fluid changes state (horizontal line denoting evolution at constant temperature) temperature change occurs in storage. Figure 9(b) illustrates an example of good thermal integration with the parallel evolution of the charge-discharge temperature profiles in the heat exchange with the thermal storage, where there is a sensible heat exchange in the HT reservoir and a latent exchange in the LT reservoir.

The integration of an energy storage system and geological storage of CO₂ based on renewable energy within carbon capture and utilization applications is promising. The CO₂ captured in a power plant or industrial facility is used as a working fluid in the proposed thermodynamic cycle to store renewable electrical energy underground. The storage of energy occurs in mechanical (work) and thermal (heat) forms [35]. Figure 10 [35] illustrates the conceptual scheme of a new energy storage system and storage of

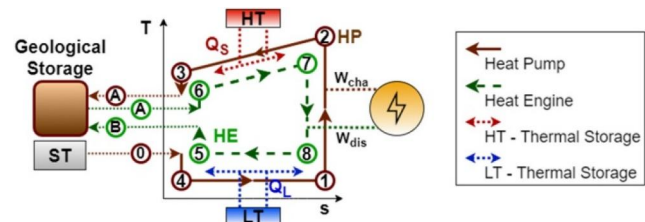


Figure 10. Reversible heat pump energy storage system with well-integrated temperature profiles, including geological storage. Q_s : Sensible heat; Q_L : Latent heat; W : Work; cha: Charge; dis: Discharge; ST: Stationary CO₂ source [35].

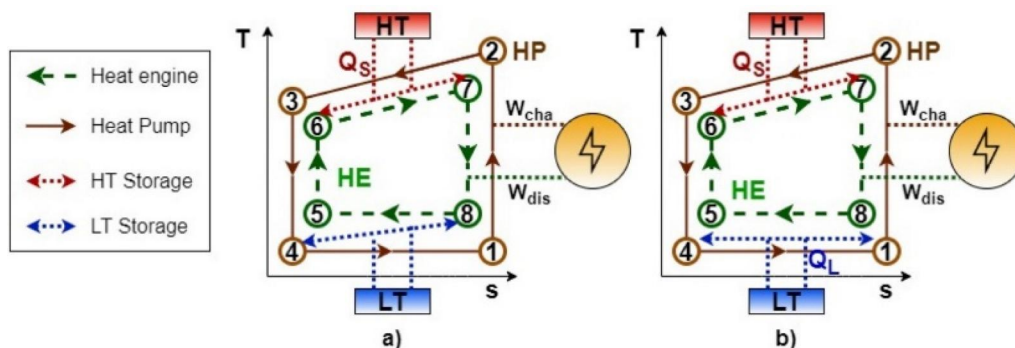


Figure 9. Reversible heat pump energy storage system with: (a) bad-integrated temperature profiles, and (b) well-integrated temperature profiles. Q_s : Sensible heat; Q_L : Latent heat; W : Work; cha: Charge; dis: Discharge [35].

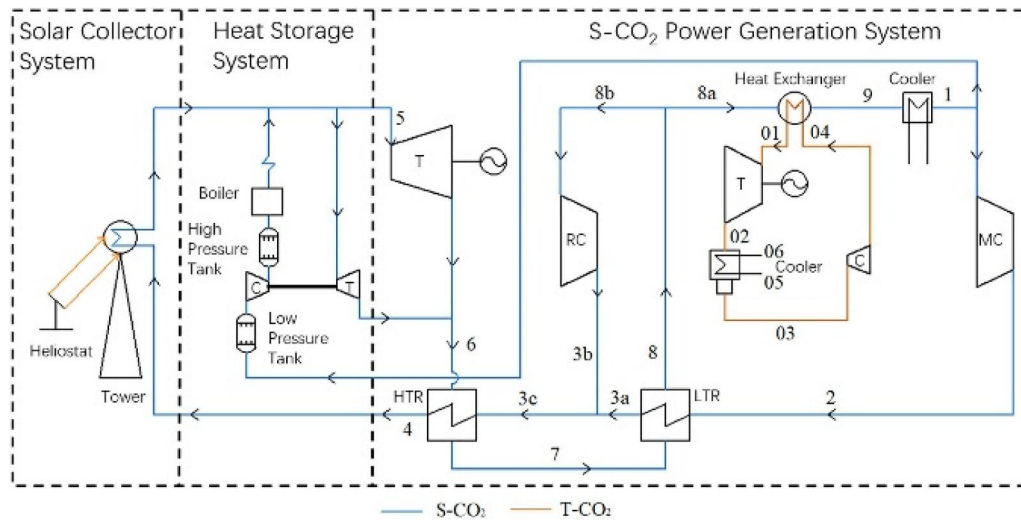


Figure 11. Schematic diagram of the integrated scheme of compressed CO₂ energy storage and auxiliary combustion system [34].

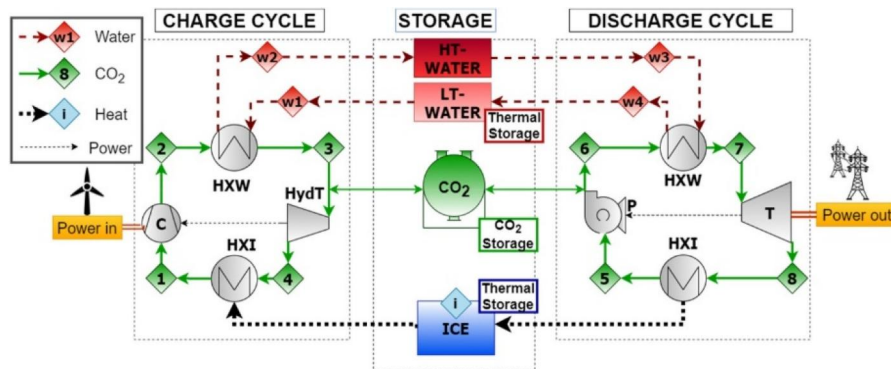


Figure 12. Conceptual layout of the basic electrothermal energy storage system. C: Compressor; HydT: Hydraulic turbine; P: Pump; T: Turbine; HXW: Heat exchange - Water; HXI: Heat exchange - Ice; HT: High temperature; LT: Low temperature [35].

captured CO₂ in a stationary source, consisting of two independent and open CO₂ cycles, connected directly by geological storage and indirectly by thermal storage. As shown in Figure 10, CO₂ captured in a stationary source is used as a working fluid in a heat pump and injected into a geological formation (sequence 0-4-1-2-3-A), performing a charging cycle equivalent to that of the electrothermal system in the high (HT) and low (LT) temperature reservoirs. For the discharge, CO₂ is extracted from the geological formation and used as the working fluid in the reverse cycle, ending with the re-injection of CO₂ into the geological formation (sequence A-6-7-8-5-B).

To avoid the problem occurred in the traditional molten salt heat storage system, such as molten salt solidifying, heat transfer loss between the molten salt and working medium, and heat loss of stored heat, Liu et al. [34] proposed a nonmolten salt heat storage scheme which uses compressed CO₂ energy storage integrated with auxiliary combustion as shown in

Figure 11 [34]. In the cycle, under the energy storage conditions, the working fluid flows through the tower collector to absorb heat, some of the working fluid enters the main turbine to meet the power generation demand while other of the working fluid enters the turbine to drive the coaxial compressor to compress the CO₂ near the critical point in the low-pressure tank and then stores it in the high-pressure tank. Under the energy release condition, supercritical CO₂ flows out of the high-pressure tank, heated by a gas boiler, enters the turbine for work, and then passes through the heat exchanger to heat the bottom circulating working fluid. Then, CO₂ is cooled to near the critical point and stored in a low-pressure tank without compression.

Geological storage in the concept of electrothermal energy storage has been studied in recent years. Carro et al. [35] have proposed an energy storage system using transcritical CO₂ cycles based on the concept of electrothermal energy storage and its integration with geological CO₂ storage. Figure 12 [35] illustrate the

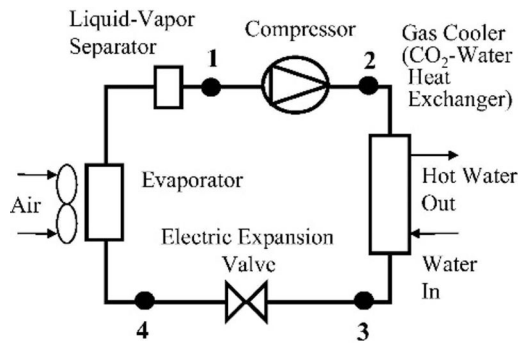


Figure 13. Schematic of the heat pump prototype [56].

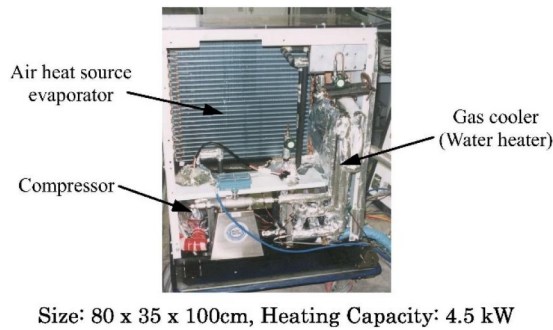


Figure 14. Photograph of the heat pump prototype [56].

proposed conceptual layout of the basic electrothermal energy storage system based on a reversible heat pump. The thermodynamic charging cycle starts at the compressor inlet, where the fluid is compressed, reaching the highest temperature of the whole process. After transferring the heat to the hot water tank, the fluid expands in a hydraulic turbine, in whose output the lowest temperature of the process is reached. Similarly, the discharge cycle begins at the pump inlet, where the working fluid is compressed. After the evaporator, it expands in a gas turbine.

S-CO₂ heat pump systems for heating and waste heat recovery

Due to the advantages of energy-saving, high-efficiency, and cost effectiveness, heat pump systems have been adopted in both residential and industrial sectors. The heat pumps based on the vapor-compression cycle consume a small amount of energy for a single-stage or multiple-stages compression, in order to generate the high-temperature and high-pressure vapor. Thus, the following heat-rejection process can be utilized for various purposes, including water heating, air heating, and steam production. Compared to electric or gas water heaters, the heat pump water heaters can contribute to a significant reduction in energy consumption and is able to provide high-temperature hot

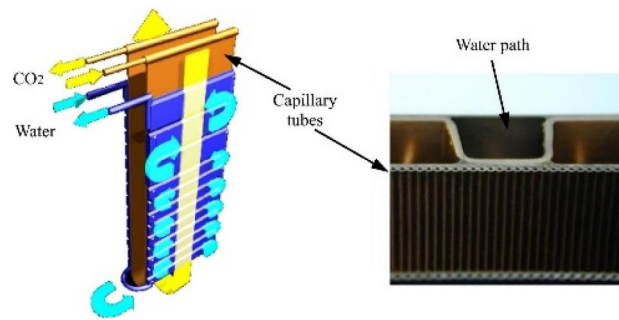


Figure 15. The developed CO₂-water heat exchanger [56].

water with a relatively high coefficient of performance (normally around 3 to heat hot water up to 65 °C). Saikawa and Koyama [56] developed a transcritical CO₂ heat pump prototype as shown in Figures 13 and 14. The CO₂-water heat exchanger of the prototype is a countercurrent type as shown in Figure 15 [56]. Using capillary tubes for CO₂ flow path could achieve high withstand pressure of the heat exchanger and high heat transfer coefficient of CO₂. Also using plate with off-set inner fin for water flow path could achieve high heat transfer coefficient of water. Instead of a tube type, a plate type was selected for preventing the water path clogging. There is a case in which scale is generated when tap water is heated to over 60 °C. With these technologies, small and highly efficient heat exchanger with small temperature difference was developed.

Transcritical CO₂ heat pumps can be used for waste heat recovery in domestic and industrial applications. Just for one typical example of waste of heat recovery of data centers (DCs) using CO₂ heat pumps, the energy consumption of DCs has increased considerably with the rapid development of the information technology industry. DCs use about 3% of the global electricity supply, and the consumption is increasing at an annual rate of 15–20%. Around 40% of the power consumed by DCs is used for the cooling systems. The exergy loss of energy flow in DCs is huge due to the use of electrical energy for cooling DCs. A large amount of waste heat of the cooling is discharged to the external environment. Therefore, DCs may be considered energy producers if large amounts of low grade and medium-grade waste heat are effectively recovered and used for building heating, water heating, refrigeration, and air conditioning. Wang et al. [62] have proposed a prosumer DC waste heat energy recovery system using a CO₂ direct expansion ground source heat pump. Their proposed system is able to efficiently recycle the waste heat from DCs, including waste heat collection, building heating load matching, and non-heating period waste heat

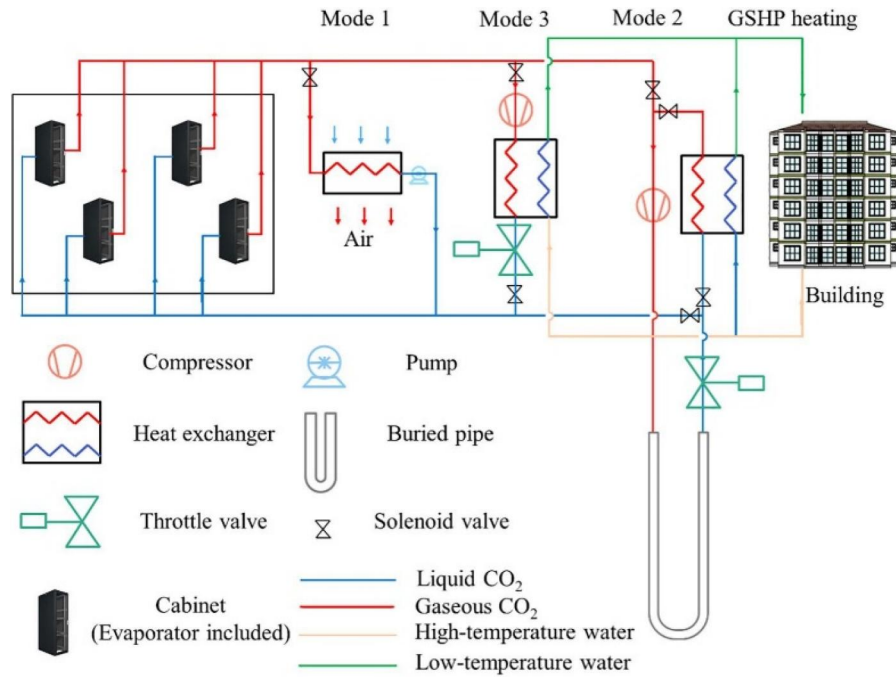


Figure 16. Model of the prosumer DC waste heat energy recovery system [62].

utilization. Figure 16 illustrates the model and components of the prosumer DC waste heat energy recovery system integrated with the CO₂ direct expansion ground source heat pump [62]. The system consists of an evaporator placed in the cabinet, air cooler, working fluid pump, compressor, throttle valve, borehole heat exchanger, and heat exchangers. If the outdoor temperature is lower than the initial operating temperature which is at least 5 °C below the temperature of the working fluid CO₂, the air cooler will operate, and CO₂ exchanges heat with outdoor air. To recycle the waste heat from the DC during the heating period, the temperature of CO₂ from the DC is increased by the compressor, and CO₂ exchanges heat with water that is used for building heating. In the non-heating period, CO₂ is compressed and exchanges heat with the borehole heat exchanger. The heat generated by the DC is stored in the soil and later used for building heating. Different operation modes can be realized by applying different valve switching modes. The system can meet the cooling demands of the DC and recover waste heat for the purpose of building heating.

Research of heat transfer, fluid flow and heat exchangers for CO₂ thermal and power systems

The transport and physical properties of CO₂ strongly affect the heat transfer and pressure drops at both subcritical supercritical conditions. Fundamentals and design correlations of evaporation, vapor liquid two

phase flow, supercritical heat transfer and fluid flow are important in the design of various components such as evaporators, gas coolers, compressors, recuperators in the CO₂ thermal and power systems. In particular, microchannel heat exchangers, compact heat exchangers and printed circuit heat exchangers rather than shell tube heat exchangers have been developed and used in S-CO₂ systems as shown in Figure 15 [56], 17 [63] and 18 [11]. Therefore, a good knowledge of the transport and physical properties and their effects on the calculation methods of CO₂ heat transfer, and pressure drops, and the design methods of the components are needed.

Studies of evaporation heat transfer, two phase flow, supercritical heat transfer and fluid flow behaviors in macro and microchannels, enhanced tubes and various heat exchanges have been extensively conducted over the past decades [64–86]. The heat transfer mechanisms and design correlations have been proposed for the purpose of design of various heat exchangers of CO₂ as well [87–99].

For CO₂ evaporation heat transfer and two-phase flow, the models developed by Cheng et al. [87–90] are the proper methods which have been widely adopted in the design and simulations of CO₂ evaporators [7,10,54,93]. For supercritical CO₂ heat transfer and fluid flow, as most single-phase heat transfer correlations were not developed for supercritical fluids, they cannot necessarily be expected to give accurate results for CO₂ at supercritical conditions. The main reason is that near the supercritical and subcritical

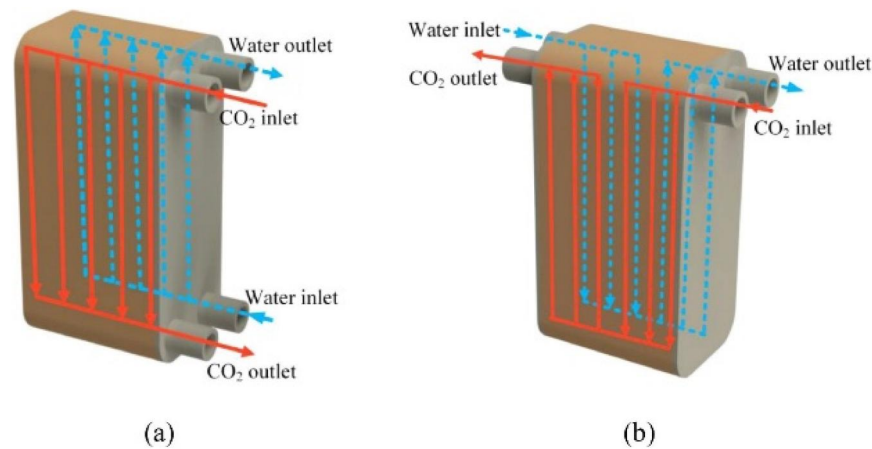


Figure 17. The (a) one-pass and (b) two-pass internal configurations of the brazed plate heat exchangers [63].

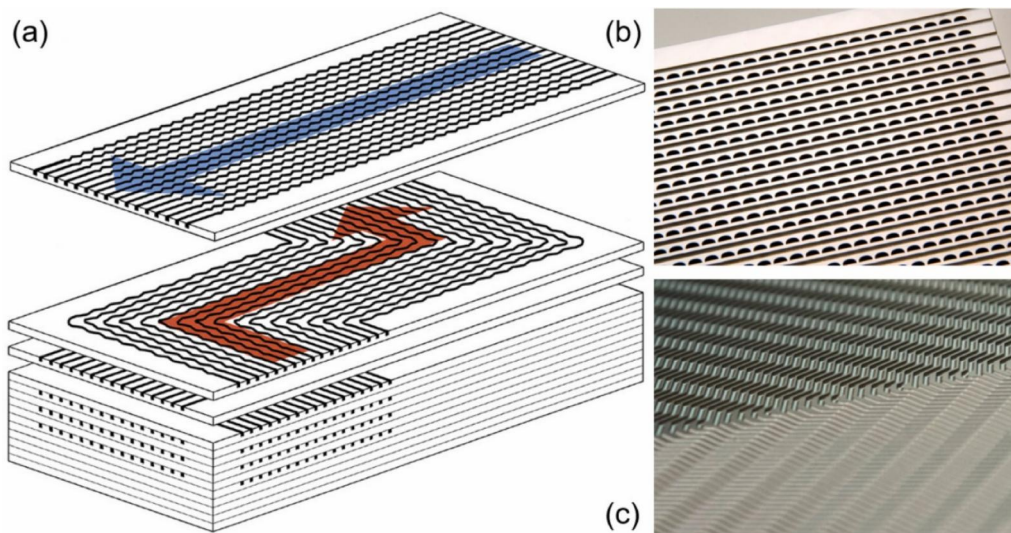


Figure 18. (a) Typical printed circuit heat exchanger, (b) flow paths and details of the diffusion-bonded core, and (c) and of an etched plate [11].

regions, in the case of an isobaric change of state at subcritical pressures, all properties of a single-phase fluid change significantly continuously (sometimes very sharply) with temperature. If a supercritical fluid flow and heat transfer processes pass near the critical region, strong variations of fluid properties take place, and the heat transfer process is largely governed by local conditions [100–102]. In a S-CO₂ gas cooling and heating heat transfer process, the pressure of the heat exchangers during heat transfer is maintained above the critical pressure, so the physical and transport property variations can be severe as shown in Figure 2. Consequently, heat transfer coefficients have to be calculated locally and heat exchangers with small increments [102–108]. In addition, because of the large viscosity changes and gradients near the wall, pressure drop correlations need to be validated for S-CO₂.

Concluding remarks

CO₂ thermal energy conversion systems are promising technology in many applications in power generation with conventional and renewable energy sources, energy storage and waste heat recovery. Both supercritical and transcritical CO₂ thermal systems are efficient energy conversion and utilization technology. The benefits of the S-CO₂ thermal and power systems include (a) The thermal efficiency can be increased up to 5% as compared with the steam Rankine systems; (b) The turbomachinery can be much smaller and the overall system size can be reduced up to ten times as compared to the conventional steam Rankine systems; (c) The positive potential of the air-cooled S-CO₂ cycle can be adopted if the system design becomes more sophisticated; (d) As the minimum pressure is higher than the CO₂ critical pressure, the purification

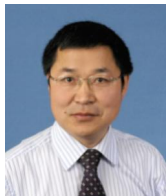
system requirements are lower than those of the steam Rankine systems; (e) CO₂ is relatively cheaper and less harmful than other working fluids when an appropriate ventilation system is installed to prepare for a sudden large release of CO₂ from the power conversion systems.

There are challenges of developing CO₂ thermal systems and applications. Various layouts have been proposed for various applications. However, optimization of the systems is still needed. Development high performance components is needed. Various heat transfer enhancement and process intensification technologies are needed. Both subcritical and supercritical CO₂ heat transfer and fluid flow research is still needed. In particular, for microchannels and printed heat exchangers and emerging structures heat transfer components.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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