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Review Article

Research progress and applications of transcritical carbon dioxide heat pumps: A review

Shengong Mei, Zhongyi Liu*, Xia Liu

Shanghai Research Center for Energy & Power, Shanghai 201306, China

*** Corresponding author:** Zhongyi Liu, Hueyleo@foxmail.com

Abstract: Heat pump technology is an energy-saving technology that can efficiently utilize low-grade energy. It has broad application prospects in building heating, industrial waste heat utilization, new energy, and other fields. However, the refrigerants used in traditional heat pump systems have serious negative impacts on the environment, and there is an urgent need to find a safe, environmentally friendly, and efficient alternative refrigerant. As a natural refrigerant, CO_2 has good physical and chemical properties and is very suitable as a working fluid in transcritical cycles, showing great advantages in the field of heat pump technology. At present, research on CO_2 heat pumps has made certain progress, but there are few reviews of the research status and development trends of CO_2 heat pumps in different applications. Therefore, in this article, the latest research results of transcritical CO_2 heat pumps in different application fields are systematically summarized, pointing out the difficulties such as high pressure and low operating efficiency in system design and operation. The latest optimization research works on system components, cycle structure, mixed refrigerants, and control strategies are also summarized. The results showed that each optimization method can significantly improve system performance, among which mixed refrigerant is the simplest optimization method. Finally, the outlook for CO_2 heat pump technology is put forward. With policy support and technological advancement, a more comprehensive, energy-saving, and intelligent CO_2 heat pump technology will continue to be developed and innovated.

Keywords: transcritical; CO_2 refrigerant; heat pump; application status; review

1. Introduction

In recent years, some new synthetic hydrofluorocarbon (HFC) refrigerants have gradually appeared, such as R32, R134A, R125, R215a, and R410A. They are extremely powerful greenhouse gases with a global warming potential (GWP) of approximately tens of thousands of times that of CO_2, and they have a long lifespan in the atmosphere. If the production and consumption of HFC refrigerants are not controlled, the emissions of HFCs will lead to a global temperature increase of 0.3 °C–0.5 °C by the end of the 21st century[1]. The natural working fluid of CO_2 has an ozone depletion potential (ODP) of 0, a GWP of 1, and a safety level of A1. It has the advantages of being non-toxic and non-flammable and having high density, low viscosity, small flow loss, and low cost. Therefore, using CO_2 as a refrigerant can be one of the ultimate solutions to refrigerant environmental problems.

Heat pumps use less energy consumption to transport heat energy from low-temperature locations to high-temperature locations, and their advantages in performance, economy, and stability have been recognized by industries[2]. At present, heat pumps can meet almost all building heating needs and 40% of industrial process heating needs. Existing industrial heat pumps can provide temperatures up to 168 °C and a heating capacity of up to 18 MW, which also makes heat pumps have a wide range of application scenarios. As shown in **Figure 1**, heat pumps can be used in household and industrial heating, automotive air conditioning, drying, and other fields, and can also be combined with clean energy in various ways. In future scenarios, with a high proportion

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of renewable electricity, heat pumps can reduce nearly 2 billion tons of CO_2 emissions, accounting for nearly 20% of China's total carbon emissions in 2019[3].

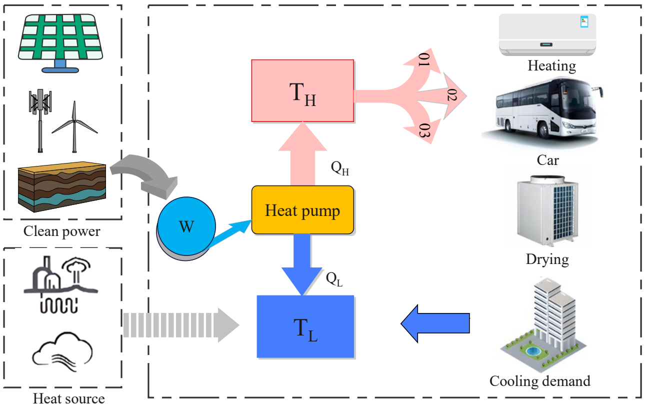


Figure 1. Diverse application scenarios of heat pumps.

The development history of CO_2 refrigerant is shown in **Figure 2**. CO_2 heat pumps can be traced back to the 19th century[4]. However, at that time, the subcritical cycle efficiency of CO_2 was low and it was gradually replaced by synthetic working fluids with excellent performance[5]. It was not until the 1990s that G. Lorentzen, the former president of the International Association of Refrigeration, developed the CO_2 transcritical cycle[6], which allowed CO_2 to absorb heat in the subcritical state and release heat in the supercritical state, which gave it a higher temperature slide and can release a large amount of heat energy. This led to the rapid development of CO_2 heat pumps, and subsequently the world's first heat pump water heaters and commercial vehicles equipped with CO_2 air conditioners appeared one after another[7,8]. To this day, CO_2 is widely used in various fields. According to the International Energy Agency (IEA), CO_2 heat pumps will account for 22.1% of the overall heat pump market share by 2030. It is foreseeable that the use of CO_2 as a heat pump will be a hot spot in future research on new environmentally friendly and low-carbon technologies.

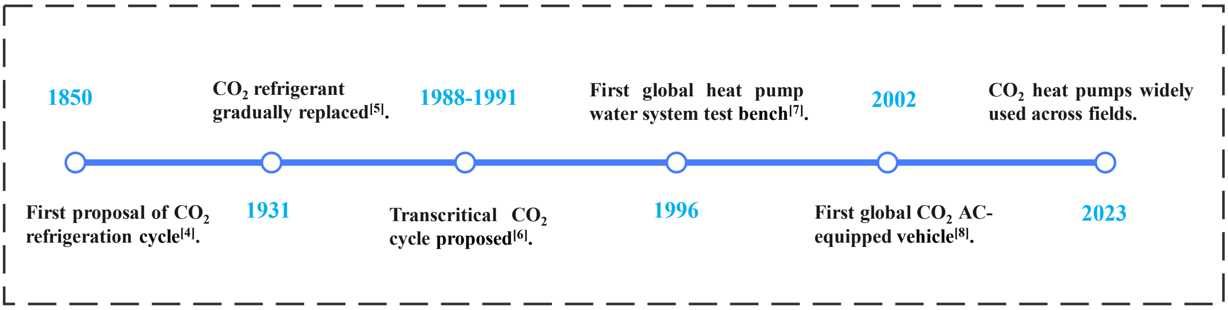


Figure 2. Development history of CO_2 heat pumps.

As can be seen from **Figure 3**, since Lorentzen and Pettersen[9] and Pettersen[10] from the Norwegian SINTEF Institute first proposed the possibility of CO_2 application in fields such as automotive air conditioners and heat pumps in 1992, it has attracted widespread attention and research from many countries and regions around the world. Among them, countries such as Denmark, the United States, Germany, and Japan have achieved remarkable results in theoretical analysis, experimental verification, component design, and system optimization of CO_2 heat pumps and have applied CO_2 heat pumps to commercial and military applications. For example, Saikawa et al.[11] from Japan's Central Research Institute of Electric Power Industry (CRIEPD) began basic research on CO_2 heat pumps in 1995, Denmark's Holst[12] established a CO_2 transcritical automotive air conditioning test bench at Danfoss to study the regulation of the system components, Koehler[13] from Kassel University in Germany carried out research on the application of CO_2 working fluid automotive air conditioners and heat pumps, Schmidt et al.[14] from Germany conducted the feasibility analysis of transcritical CO_2 heat pump drying for the first time, and McEnaney et al. from the University of Illinois Urbana-Champaign (UIUC) in the United States also established an automotive air conditioning test bench[15].

China's research on CO_2 heat pumps started late but has made some progress in recent years. Universities, such as Shanghai Jiao Tong University, Tianjin University, Xi'an Jiaotong University, and Central South University, and companies have conducted theoretical and experimental research on the cycle characteristics, key components, and system control of CO_2 heat pumps. For example, in 2003, Shanghai Jiao Tong University and Santana Company developed China's first CO_2 automotive air conditioning system, and in 2013, Haier announced the launch of China's first CO_2 air-source water heater[16], laying the foundation for the marketization of CO_2 heat pumps in China.

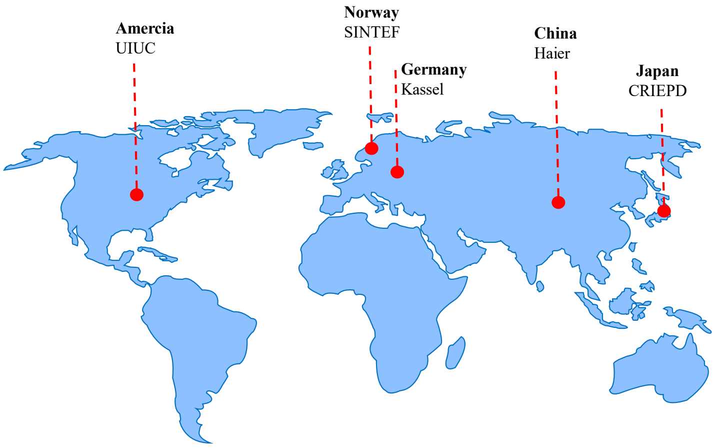


Figure 3. Research on CO_2 heat pumps in different countries.

In this paper, the application of transcritical CO_2 heat pumps in different fields and their development trend are systematically described. The working principle, potential advantages, and technical challenges of supercritical CO_2 heat pumps are firstly introduced, and then the latest research progress of CO_2 heat pumps in the fields of heating, automobile air conditioning, and drying are highlighted. Aiming at the problems existing in current CO_2 heat pumps, optimization measures and development directions have been proposed in terms of system components, system structure, and refrigerant mixing and control strategy, with a view to providing valuable references for the research and promotion of CO_2 heat pump technology in the future. The framework of the paper is shown in **Figure 4**.

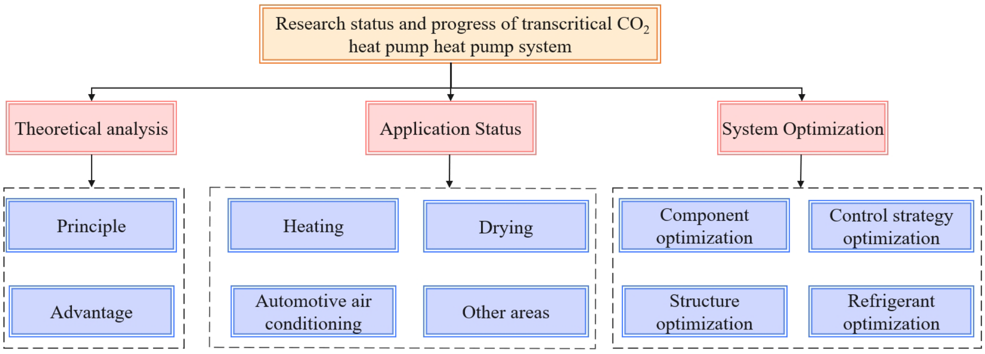


Figure 4. Structure of transcritical CO_2 heat pump system overview.

2. Principles and advantages of transcritical CO_2 heat pump

2.1. Transcritical CO_2 heat pump working principle

A heat pump is a device that can transfer heat energy from a low-temperature heat source to a high-temperature heat source. It can use a small amount of electrical energy or other forms of high-grade energy to achieve this process. Its basic working principle and pressure-enthalpy diagram are shown in **Figure 5**, where 1-2-3-4 is the transcritical process. The gaseous refrigerant enters the compressor suction port from Point 1 and is compressed to reach a high-temperature and high-pressure state at Point 2, and then it passes through the heat released by the air cooler reaches Point 3. The high-pressure refrigerant is depressurized from the throttle valve to a low-temperature and low-pressure state at Point 4 and enters the evaporator. It absorbs heat in the evaporator and reaches Point 1, completing the entire system cycle.

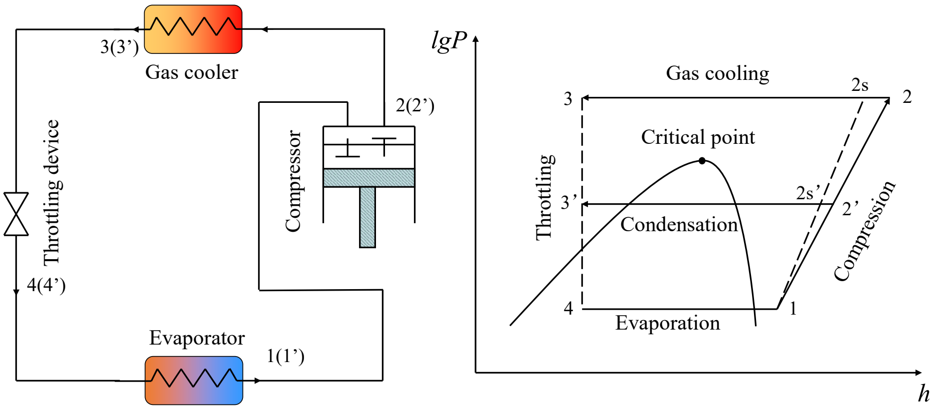


Figure 5. Trans/subcritical CO_2 heat pump system cycle schematic diagram and *lgP-h* diagram.

2.2. Characteristics of CO_2 transcritical state

A lower critical temperature (31.1 °C) determines that the exothermic process in CO_2 heat pump systems usually occurs in a supercritical state. As can be seen from the pressure-enthalpy diagram in **Figure 5**, compared with the conventional refrigerant subcritical cycle (1'-2'-3'-4'), no condensation process occurs in the high-pressure side of the CO_2 transcritical cycle (1-2-3-4), and so no condenser is required, and instead the heat is dissipated by a gas cooler. In a gas cooler, the mass only undergoes sensible cooling without phase change processes and the temperature of the CO_2 fluid is continuously reduced, which is why the heating medium can be heated continuously to very high temperatures. In addition, the pressure difference between the high-pressure and low-pressure sides in the transcritical CO_2 cycle is much larger, but the pressure ratio is relatively small compared with conventional refrigerants.

A full understanding and mastery of the heat transfer mechanism of supercritical carbon dioxide (sCO_2) is essential for the design and safe and stable operation of heat exchanger units. **Figure 6** depicts the variation of thermophysical properties of CO_2 fluid with temperature at 8.0 MPa of pressure. It can be seen from **Figure 5** that the density (ρ), constant-pressure specific heat (C_p), thermal conductivity (λ), and viscosity (μ) of CO_2 change drastically in the temperature interval close to the proposed critical point. This makes supercritical CO_2 have special properties, such as high density, low viscosity, high solubility, high heat transfer coefficient, etc. According to Banuti[17], the drastic change in thermophysical properties is similar to the typical subcritical evaporation behavior, and a detailed theoretical description of this change is based on the concept of "boiling-like". It has been shown that higher operating temperatures can be achieved by utilizing CO_2 as the working fluid within a heat exchanger and that operating at supercritical conditions improves heat transfer efficiency. In addition, CO_2 has a large latent heat of evaporation, a small kinematic viscosity, a large cooling capacity per unit volume, and outstanding flow and heat transfer properties. As a result, the sizing cycle of compressors, piping, and related components in transcritical CO_2 can be significantly reduced, and the volume and size of the CO_2 heat exchanger are significantly reduced compared with those of other heat exchangers. However, CO_2 systems have some shortcomings, such as higher operating pressures, insufficient efficiency, and high compressor discharge temperatures. These deficiencies should be addressed in order to expand the application areas.

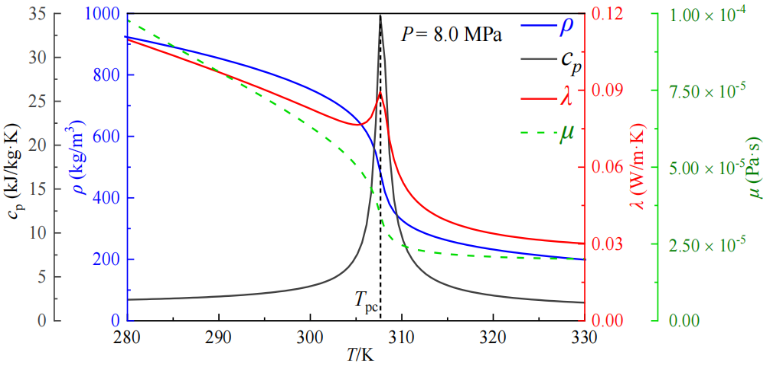


Figure 6. CO_2 physical property diagram with pressure of 8 MPa[18].

3. Current status of research on transcritical CO_2 heat pump applications

The special properties of CO_2 heat pumps have attracted many scholars to conduct in-depth research. At present, the main application fields of CO_2 heat pumps include CO_2 heat pump heating, CO_2 car air conditioning, CO_2 heat pump drying, and some other fields.

3.1. CO_2 heat pump heating

CO_2 heat pump heating is a high-efficiency heating technology based on the transcritical cycle of CO_2, with a large temperature slip in the exothermic process, which is just suitable for adapting to the temperature change of fluids such as water. The CO_2 heat pump cycle is a special Lorentz cycle with a heat transfer curve as shown in **Figure 7**. Compared with subcritical cycles, CO_2 heat pump heating cycles have higher circulation efficiency and heat transfer performance, making them ideal for use in heat pump water heating applications. Japan is the most rapidly developing market for CO_2 heat pump water heaters. Since 2001, Mitsubishi's heat pump water heater Eco-Cute has been marketed as an energy-saving and environmentally friendly product in Japan and has rapidly gained popularity[19]. Compared with conventional combustion equipment, Eco-Cute achieves 30% energy savings, 40% less CO_2 emissions than instantaneous city gas hot water supply equipment, and 30% lower primary energy consumption.

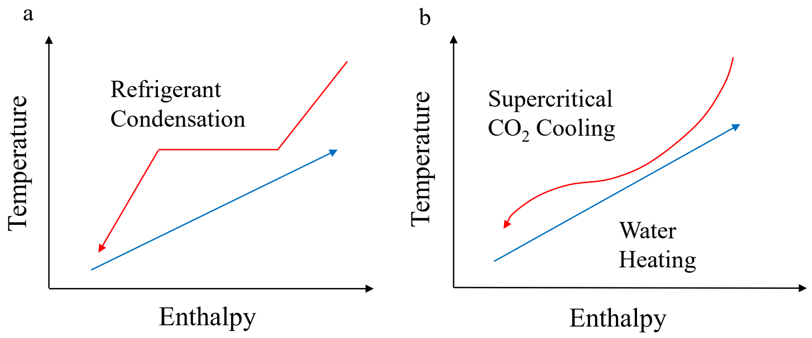


Figure 7. Heat transfer curve: **(a)** subcritical condensation process and **(b)** supercritical gas cooling process.

The research in this field was pioneered by Nekså et al.[20] from the SINTEF Institute in Norway, who theoretically and experimentally proved that CO_2 transcritical circulation heat pumps not only have high heating coefficients but also have a compact system that produces hot water with a high temperature of up to 70 °C or more, which has considerable potential for development in both industrial and civil applications. Nawaz et al.[21] also compared CO_2 and R134a heat pump water heaters and found that CO_2 heat pumps were able to operate more efficiently and perform better at lower ambient temperatures. Moreover, CO_2 heat pump water heaters have high operational efficiency and can reduce energy consumption by 75% compared with those of electric heating and gas water heaters[22]. Therefore, there is a great need to study the CO_2 heat pump heating system.

3.1.1. Operational characterization studies

The operating characteristics of a CO_2 heat pump heating system reflect the performance of the system under different working conditions, which can reveal the influencing factors of system performance and provide theoretical guidance and experimental basis for the optimal design of the system. In a CO_2 heat pump system, small changes in exhaust pressure may lead to a significant decrease in cycle efficiency[23]. The study by Nekså[24] suggested that a system not operating optimally may contribute to more than 20% of the system's energy efficiency loss. As the system pressure increases, the heat production and compression work of the system tends to increase, and so there exists an optimal exhaust pressure that maximizes the COP of the system[25]. As shown in **Figure 8**, the main reason for this phenomenon is that at a certain outlet temperature of the air cooler, the rate of change of the compressor's power consumption with the increase in exhaust pressure (Δh2) is almost unchanged, while in the system, the rate of increase in the amount of heat production (Δh1) is greater than the rate of increase in the compressor's power consumption. Currently, the method of determining the optimal high pressure in CO_2 transcritical cycles has become a hot issue in this field.

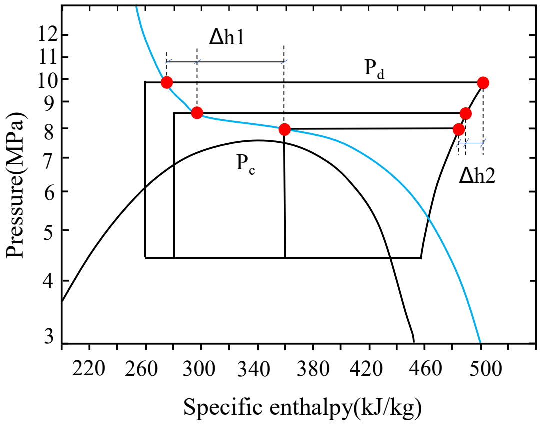


Figure 8. Reasons for formation of optimal high pressure.

In order to determine the optimal high pressure of a transcritical CO_2 refrigeration system and a heat pump water heater system, researchers have analyzed the key factors affecting the optimal high pressure through theoretical calculations and simulations and established corresponding mathematical models. Liang et al.[26] analyzed the optimal high pressure of a transcritical CO_2 refrigeration system and a heat pump water heater system by the response surface method. It was found that the outlet temperature of the gas cooler had the greatest influence on the optimum high pressure of the system, accounting for 96.38%. In addition, Liu et al.[27], Wang et al.[28], and Ye et al.[29] explored the effects of parameters of evaporation temperature, ambient temperature, and discharge temperature on the optimal high pressure of heat pump water heaters, respectively.

Therefore, determining the optimal high pressure is an important task. A large number of scholars have begun to explore optimal high-pressure correlations, and **Table 1** summarizes several major correlations in the literature. In this table, P_{opt} is the optimum high pressure, t_{air} is the ambient outlet temperature, $t_{gc,out}$ is the gas cooler outlet temperature, T_e is the evaporation temperature, and $t_{w,in}$ and $t_{w,out}$ are the inlet and outlet water temperatures, respectively. Qin et al.[30] derived a dimensionless optimal exhaust pressure correlation equation based on the Buckingham PI theorem and verified its applicability under different operating conditions, and its errors with experimental data were less than 3%. Cecchinato et al.[31] proposed a more real-time and efficient algorithm to determine optimal pressure. Shao et al.[32] proposed a constrained optimization method to obtain a constrained optimal high-pressure correlation formula for the CO_2 transcritical cycle.

Table 1. Summary of optimal high-pressure correlations for CO_2 heat pumps.

Authors	Correlation	Applicable condition
Kauf	$P_{\text{opt},Kauf} = 2.6t_{air} \approx 2.6t_{gc,out} + 7.54$	$30\ ℃ \le t_{air} \le 50\ ℃$
Liao	$P_{\text{opt},Liao} = (2.778 - 0.0157t_e)t_{gc,out} + 0.381t_e - 9.34$	$-10\ ℃ \le t_e \le 20\ ℃$
		$30\ ℃ \le t_{gc,out} \le 60\ ℃$
Sarkar et al.	$P_{\text{opt},Sarkar} = 4.9 + 2.256t_{gc,out} - 0.17t_e + 0.002t_{gc,out}^2$	$-10\ ℃ \le t_e \le 10\ ℃$
		$30\ ℃ \le t_{gc,out} \le 50\ ℃$
Sarkar et al.	$P_{\text{opt},Sarkar} = 8.545 + 0.774t_{w,in}$	$20\ ℃ \le t_{w,in} \le 40\ ℃$
Chen and Gu	$P_{\text{opt,Chen}} = 2.68t_{air} + 0.975 = 2.68t_{gc,out} - 6.797$	$30\ ℃ \le t_{air} \le 50\ ℃$
Qi et al.	$P_{\text{opt,Qi}} = 13.23 - 0.84t_{gc,out} + 0.03t_{gc,out}^2 - 2.77 \times 10^{-4}t_{gc,out}^3$	$20\ ℃ \le t_{gc,out} \le 45\ ℃$
Wang et al.	$P_{\text{opt,w}} = 1.09 + 0.106t_{w,out} + 0.101t_{air} - 0.001t_{air}^2$	$5\ ℃ \le t_{air} \le 35\ ℃$
	$P_{\text{opt,w}} = 2.47 + 0.122t_{w,out} - 0.0004t_{w,out}^2 + 0.016t_{air}$	$-15\ ℃ \le t_{air} \le 5\ ℃$

However, a large number of empirical correlation methods still cannot solve the problem of generality. In order to accurately control the optimal pressure, many scholars have studied different control strategies. Zhao et al.[33] compared the effects of eight different exhaust pressure control strategies on the performance of CO_2 heat pump water heater systems and gave some optimized control strategies suitable for different working conditions and component degradation situations. As a model-free control strategy without complex algorithms, extreme seeking control (ESC) experimental verification has always been a topic of greatest concern to relevant practitioners. Cui et al.[34] used multivariable ESC to optimize the exhaust pressure of a transcritical CO_2 heat pump water heater. It was found that the ESC controller increased system COP by 7.62% and 8.81% under fixed design conditions and non-design conditions, respectively. In addition, there is a relatively mature control algorithm called model predictive control (MPC), which can be used as an effective optimization method in thermodynamic cycles. Wang et al.[35] used MPC to optimize the exhaust pressure of CO_2 air-source heat pump water heaters and found that MPC can search for the optimal operating state in nearly 3 min, with a relative error of no more than 1%. Although there are still problems, such as high computational cost and complex controllers, the development trend of optimization methods in transcritical CO_2 applications has gradually changed from offline correlation to online real-time algorithms.

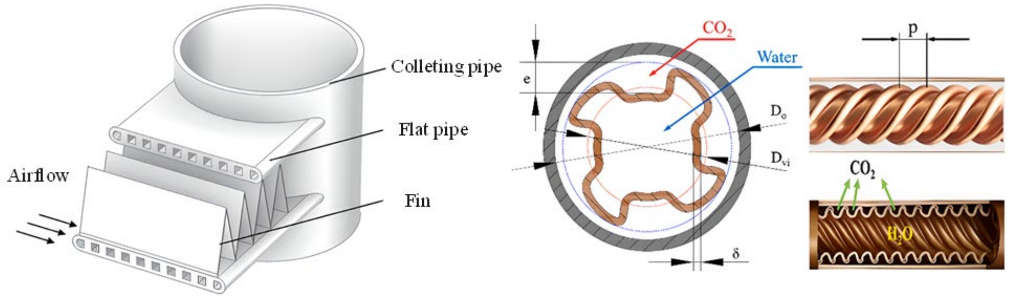
On the other hand, the refrigerant charge in a CO_2 heat pump system is also an important factor and has a great impact on the performance of the system. In a small heat pump system, there is an optimal refrigerant charge that enables the system to achieve the optimal COP[36]. Also, a heat pump system with an optimal refrigerant charge can minimize refrigerant leakage[37]. Wang et al.[38] proposed a thermodynamic model based on a small CO_2 water-source heat pump water heater to predict the optimal combination of capillary geometry and refrigerant charge. Experimental data showed that a 3.7% reduction in refrigerant charge led to a reduction in the system heating coefficient of performance (COP_h) of approximately 3.1%, and a 3.7% increase in refrigerant charge reduced COP_h by approximately 0.346%. Wang et al.[39] used an air-source heat pump water heater as the experimental object and found that at the optimal filling amount, the peak COP of the system increased by 16.27%, and the annual operating cost and CO_2 emissions were reduced by 1.8413 million yuan and 378.01 tons, respectively. Therefore, it is particularly important to accurately predict the refrigerant charge.

3.1.2. System component research

The special heat transfer characteristics and high operating pressure characteristics of the CO_2 transcritical cycle are also a challenge to system components. Gas coolers and evaporators are the two main heat exchange equipment in CO_2 heat pump systems. The development of efficient, compact, safe, and reliable heat exchangers is crucial to improving the efficiency and economy of the entire system.

Heat exchange

The heat transfer enhancement mechanism of heat exchangers refers to changing the structure, material, and surface characteristics of the heat exchanger or applying external fields to increase the heat transfer coefficient or heat transfer area of the heat exchanger, thereby improving heat transfer performance. A large number of scholars have conducted structural research on heat exchangers based on different heat exchange mechanisms. In recent years, microchannel heat exchangers have been widely used in the transcritical CO_2 field due to their efficient heat transfer performance. Pettersen et al.[40] proposed the concept of CO_2 “parallel flow” or “microchannel” gas cooler. The structural diagram is shown in **Figure 9(a)**, which consists of a collecting tube, a porous flat tube, and folded fins between the flat tubes. The smaller the size of the channel, the larger the heat transfer area per unit volume and the higher the heat transfer coefficient. Wang et al.[41] found that microchannel heat exchangers are more suitable for transcritical CO_2 heat pumps than traditional finned tube heat exchangers. They not only have better performance, but are also more energy-saving, environmentally friendly, and cost-effective. Wang et al.[42] used the numerical simulation theory to study the flow and heat transfer characteristics of a transcritical CO_2 spiral groove tube gas cooler. They also enhanced heat transfer by increasing the heat transfer area. Its structure is shown in **Figure 9(b)**. The simulation results showed that the spiral groove structure can significantly improve the heat transfer performance on the CO_2 side, proving that the spiral groove gas cooler is an effective way to improve the operating performance of the transcritical CO_2 system. In addition, Yang et al.[43] studied the performance of multi-twisted tube heat exchangers as air coolers and found that the number of inner tubes had a significant impact on the outlet water temperature of the water heater and the pressure drop of the air cooler. Li et al.[44] proposed a new bionic honeycomb heat exchanger. Through numerical simulations, they proved that the heat transfer coefficient and comprehensive coefficient were 144.6% and 40.7% higher than those of the printed circuit board heat exchanger, respectively. A comprehensive coefficient is a comprehensive index of heat transfer performance, which reflects the heat transfer capacity and heat transfer resistance of the heat exchanger. Sakakibara et al.[45] developed and analyzed a “capillary” heat exchanger. The results showed that the setting mode of the heat exchanger water tube and the inner diameter of the CO_2 tube were key factors affecting heat transfer performance.



(a) (b)

Figure 9. Different heat exchanger geometries: **(a)** microchannel heat exchanger geometry and **(b)** spiral groove tube geometry.

Defrost

When an air-source heat pump operates in a cold climate with an ambient temperature of −7 °C–5 °C and a relative humidity greater than 65%, frost will inevitably form on the evaporator[46], which greatly affects the performance of the system. In order to solve this problem, many scholars have studied different defrosting methods. Currently, reverse-cycle defrost (RCD) and hot-gas bypass defrost (HGBD) are the most commonly used defrost methods in CO_2 heat pumps, and their schematic diagram is shown in **Figure 10**[47]. When a system is operating in the RCD mode, the three-way valve switches to the opposite direction, and the compressor exhaust first flows into the evaporator for defrosting. RCD can effectively reduce defrosting time and energy consumption and improve the stability of the system[48]. In the HGBD mode, the defrost solenoid valve (DSV) is opened and the electronic expansion valve (EEV) is closed. The gas discharged from the compressor does not enter the gas cooler but flows into the evaporator through the DSV to release heat for defrosting. Hu et al.[49] designed a CO_2 air-source heat pump water heater using HGBD and evaluated its performance and energy analysis in different environments. The results showed that the typical efficiency of HGBD was 30%–40%. Ye et al.[47] found that the power consumption of the RCD method was only 17.5% that of the HGBD method and the COP was 4.61% higher than that of the HGBD method. Although the RCD method is superior to HGBD, the reliability and control logic of the RCD method need further verification and improvement.

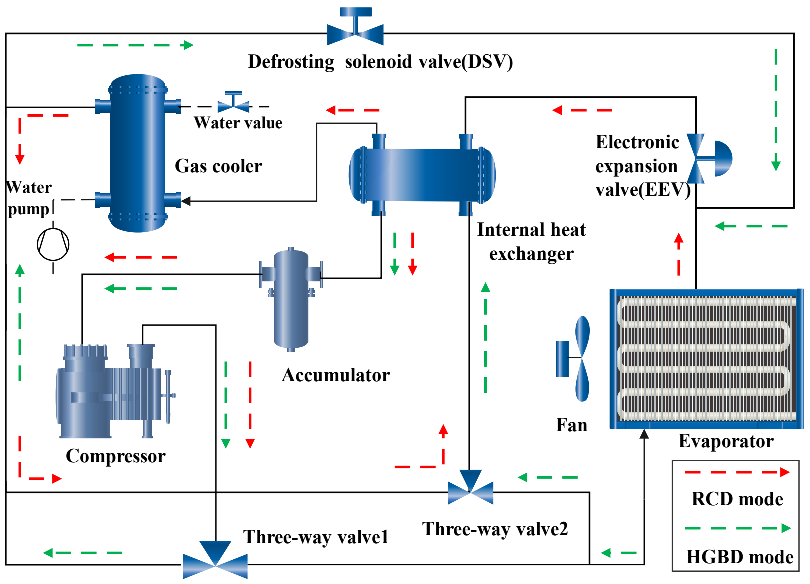


Figure 10. Schematic representation of RCD and HGBD methods in transcritical CO_2 systems.

Throttle

From the analysis in the previous section, it can be seen that the CO_2 heat pump system operates at a much higher pressure than heat pumps using conventional refrigerants, with a large pressure difference between high and low pressures and serious throttling losses, which is the main reason for the relatively low circulation efficiency of the system. In order to improve the performance of transcritical cycle systems, at present, there are three main methods to reduce throttling loss, as follows:

1) Use an expander instead of a throttle valve: An expander uses the expansion of fluid to perform work to recover part of the energy consumed by the compressor. Under normal working conditions, the system COP can be increased by 20%–40%. Research by Qin et al.[50] showed that the heating efficiency of the transcritical CO_2 cycle with an expander was 4.6% higher than that of the R134a cycle and 16.17% higher than that of the cycle with a throttle valve. Moreover, the higher the isentropic efficiency of the CO_2 expander, the better the cooling efficiency of the system and the greater the heating efficiency.
2) Use an ejector instead of a throttle valve: An ejector is a device that uses the expansion energy of high-pressure working fluid to entrain low-pressure working fluid and increase its pressure. It usually consists of a nozzle, an absorption chamber, a mixing section, and a diffusion section. Its structural diagram and physical diagram are shown in **Figure 11**. In an ejector, the high-temperature and high-pressure working flow passes through the main nozzle to reduce pressure and increase speed, thereby converting potential energy into kinetic energy. After the mixed fluid enters the expansion section, the kinetic energy is converted into pressure potential energy. The ejector can effectively increase the compressor suction temperature and reduce the pressure ratio. The maximum refrigeration coefficient was found to be about 22% higher than that of the throttle valve, and the system COP can be increased by about 10%[51]. Elbel and Hrnjak[52] also conducted experimental studies on ejectors in a CO_2 transcritical cycle system, and the results showed that refrigeration capacity and COP increased by 8% and 7%, respectively.

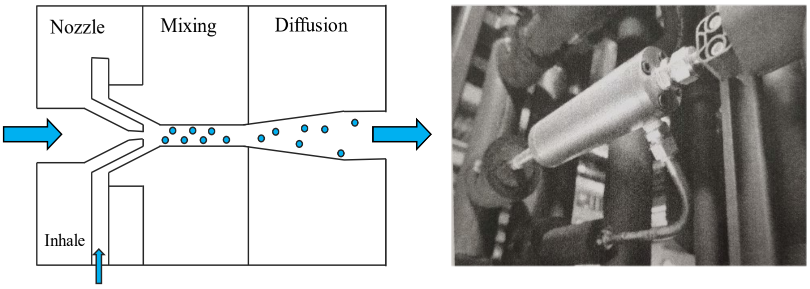


Figure 11. Structure and physical diagram of ejector.

3) Use a regenerator: A regenerator is a device that increases the subcooling and compressor suction superheat and can also prevent liquid slugging. It has a low cost and is suitable for domestic hot water heat pumps with a small capacity and a low gas cooler outlet temperature. However, the regenerator can only improve system performance to a limited extent. Research shows that only when the outlet temperature of the CO_2 side of the air cooler is higher than the critical value, the regenerator can improve the performance coefficient[53] and the COP of the circulation system can be increased by about 10%.

Therefore, from cost considerations, a throttle valve or capillary tube should be used in a small CO_2 transcritical cycle. In a larger system, using an ejector or expander instead of a throttle valve can significantly improve cycle efficiency.

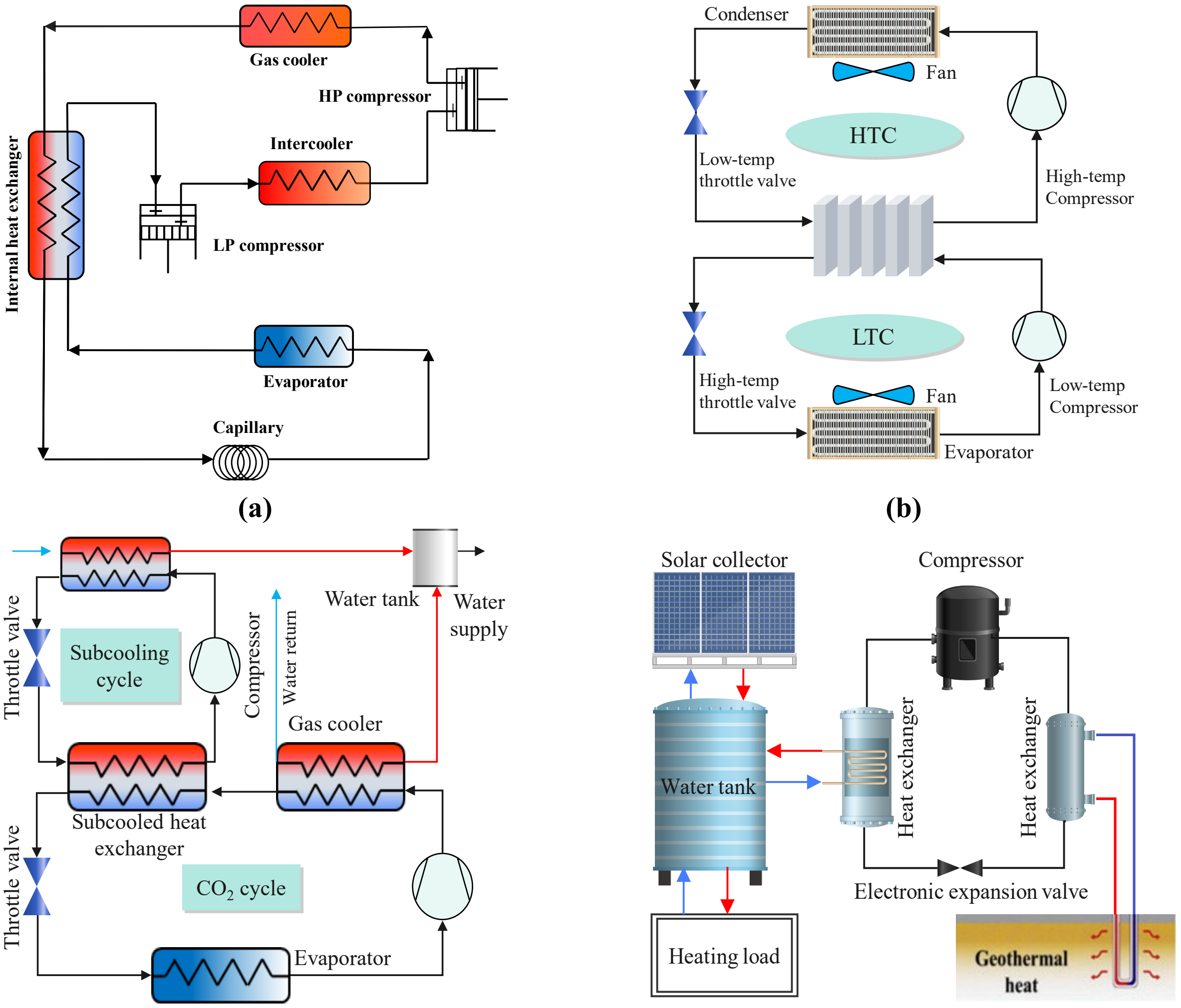
3.1.3. Loop structure research

Using a two-stage cycle with intermediate cooling between the two stages instead of a single-stage cycle can effectively solve the problem of relatively low efficiency in a CO_2 system. The schematic diagram of the two-stage cycle is shown in **Figure 12(a)**[54]. Pitarch et al.[55] established mathematical models of CO_2 two-stage and single-stage compression cycles and simulated and compared their performance in heat pump water heaters. The results showed that when producing 80 ℃ of hot water, the COP of the two-stage compression cycle was approximately 15% higher than that of the single-stage cycle. Zhang et al.[56] also found that a two-stage cycle using an intercooler can steadily increase the COP of the basic cycle by 14%–21%.

The CO_2 cascade cycle is another effective research method for cycle structure optimization. It is formed by using two single-machine cycles of CO_2 and another working fluid to share a condensing evaporator. Its schematic diagram is shown in **Figure 12(b)**[57]. Compared with transcritical CO_2 heat pumps, CO_2 cascade heat pumps can heat water to a higher temperature and have superior heating performance. In the research of R134a/CO_2 cascade air-source heat pump, Luo[58] conducted a trial production and an experimental analysis of the unit he designed. The results showed that when the ambient temperature was as low as −25 ℃, the unit COP still reached 1.6. Xu et al.[59] conducted tests on a cascade air-source heat pump system at hot water temperatures of 55 ℃ and 75 ℃ and an ambient temperature of ±21 ℃. The results showed an upward trend of the COP with the increase in ambient temperature.

CO_2 heat pump mechanical subcooling technology is currently one of the more promising technologies for improving system energy efficiency. It is a technology that uses auxiliary circulation equipment to cool the CO_2 fluid at the outlet of the gas cooler to reduce irreversible throttling losses and improve system circulation performance. The schematic diagram is shown in **Figure 12(c)**[60]. Although introducing a mechanical subcooler will increase energy consumption because the subcooler requires additional energy to operate, the increased performance of heat pumps can lead to greater energy savings, resulting in greater energy efficiency. At present, this technology has been applied in actual production and can significantly improve system efficiency. Some studies have shown that the use of mechanical subcooling technology can increase the COP of the CO_2 system by up to 20.0%[61]. Dai et al.[62] proposed a mechanical subcooling heat pump system for residential space heating and found that the system COP was related to the exhaust pressure and subcooling degree, and the COP increased by 24.4%.

In addition, there are some CO_2 heat pump coupling circulation systems, which use a technology that couples an air-source heat pump with a water-source heat pump, ground-source heat pump, solar collector, and other systems to achieve efficient heating under low-temperature conditions. The principle is shown in **Figure 12(d)**[63]. At present, what is more commonly used is coupling with a solar collector system, giving priority to solar heating and using air-source heat pumps when the solar energy is insufficient to achieve the complementary advantages of the two. Although this technology has a relatively complex structure and high initial investment, it has a high average annual comprehensive energy efficiency and significant energy-saving effects. It has broad application prospects in areas rich in solar energy resources.



(a) (b)

(c) (d)

Figure 12. Schematic diagram of different cycle structures of CO_2: **(a)** CO_2 two-stage compression cycle, **(b)** CO_2 cascade cycle, **(c)** transcritical CO_2 mechanical subcooling system, and **(d)** solar-geothermal-CO_2 coupled heat pump system.

3.1.4. Research on CO_2-based mixed refrigerants

In order to further reduce system pressure and improve system performance, one of the simplest and most effective methods is to use a CO_2-based mixed refrigerant instead of a pure CO_2 refrigerant. In recent years, some non-azeotropic mixed refrigerants based on CO_2 have been widely studied, such as CO_2/R32, CO_2/R290, CO_2/R600, CO_2/R600a, CO_2/R1270, etc. Research results showed that these mixed refrigerants can significantly improve the heating and cooling performance of water-water heat pumps, reduce compressor exhaust pressure, and extend compressor life[64–66]. Among them, CO_2/R290 is considered the most suitable alternative because it has the lowest critical pressure[66].

However, the mass transfer resistance of non-azeotropic mixtures during a high-temperature slip and nucleate boiling makes their heat transfer coefficients lower than pure refrigerants and azeotropic refrigerants[67]. Moreover, the components of non-azeotropic mixed refrigerants are prone to migrate during leakage or charging, which affects practical applications[68]. Therefore, azeotropic mixtures are attracting more and more attention as refrigerants. Compared with systems using non-azeotropic mixtures of refrigerants, systems using azeotropic mixtures of refrigerants have higher coefficients of performance, indicating better performance, high cooling capacity, and lower energy consumption[69].

Currently, only two CO_2-based azeotropic refrigerants, CO_2/R170 and CO_2/R41, have been reported and analyzed in the literature. Studies have shown that these two mixed refrigerants can significantly improve the performance of heat pump water heater systems, reduce the discharge temperature and compression ratio of the compressor, and extend the service life of the compressor[70–72]. Among them, the COP and exergy efficiency of the CO_2/R170 cycle were found to be 31.3% and 30.6% higher than those of the R134a cycle, respectively[70], while the COP of the CO_2/R170 cycle exceeded 50% when the evaporation temperature was above 0 °C and the operating cost is greatly reduced[72]. The CO_2/R41 cycle also has the advantages of low optimal high pressure, small compression ratio, low discharge temperature, large unit cooling capacity, and unit heat capacity, and is an ideal choice to replace pure CO_2[71].

3.2. CO_2 car air conditioner

The global new-energy vehicle market is experiencing exponential growth. According to the International Energy Agency (IEA), global sales of new-energy vehicles exceeded 10 million units in 2022, with a market penetration rate of 14%, a significant increase from 9% in 2021 and less than 5% in 2020, which shows broad prospects for development.

New-energy vehicles' mainstream heating methods are heat pump heating and PTC (positive temperature coefficient) electric heater heating. The most commonly used refrigerants in heat pumps are R134a and R407C, and these two refrigerants are weaker than the CO_2 heat pump system in terms of GWP and system performance. Dong et al.[73] in 2021 experimentally compared the performance of two refrigerants, CO_2 and R134a, in electric vehicle applications with different heat pump (HP) configurations and found that the CO_2 system outperformed the R134a heat pump in heat production, especially in very cold weather. Song et al.[74] compared the performance demonstrated by CO_2 and R407C heat pumps in new-energy vehicles and electric buses and found that CO_2 systems have great potential to replace existing R407C systems. On the other hand, the use of PTC heating makes the range of new-energy vehicles decay seriously in winter. Lee et al.[75] found that the range of a pure electric vehicle with PTC material heating at a full load was reduced by almost 50%. Therefore, the transcritical CO_2 cycle has become one of the alternatives to heat pump air conditioning in the field of automotive air conditioning due to its excellent heating characteristics and environmental protection features. The technology was first initiated by Lorentzen and Pettersen[9] and Pettersen[10] from the Norwegian SINTEF Institute, who discussed both theoretically and experimentally the possibilities and advantages of CO_2 for use in areas such as automotive air conditioning and heat pumps. Currently, CO_2 heat pumps have been commercialized in some new-energy vehicles, such as Tesla Model 3, Toyota Mirai, and Volkswagen ID.4. Among them, the Volkswagen ID.4 equipped with UCO_2 heat pump air conditioning can improve the range by up to 30% and, in the testing process, in the environment of −15 °C, the CO_2 heat pump can improve working efficiency by 25% compared with that of the ordinary heat pump.

3.2.1. CO_2 system performance studies

In the study of the performance of CO_2 automotive air conditioning systems, Song et al.[76] thermodynamically analyzed the causes of inefficiency of ideal and actual CO_2-cycled automobiles in high-temperature environments. The results showed that the ideal efficiency reached 25.3 under 35 °C of outdoor conditions, which was much higher than the actual efficiency currently available. Chen et al.[77] experimentally investigated the performance of a CO_2 heat pump for electric buses to produce 10.5 kW of heat with a COP of 1.24 under the operating conditions of −25 °C of outdoor temperature and 20 °C of indoor temperature. Li et al.[78] experimentally investigated the effect of valve opening on the performance of an environmentally friendly CO_2 automotive heat pump system and components, as well as the performance of the oil cycle, and found that adjusting the valve opening improved the efficiency of the compressor but the effect on the refrigerant charge may be different. Wang et al.[79] evaluated a CO_2 electric vehicle battery and in-vehicle parallel cooling thermal management system. It was found that the maximum COP increased by 8.38% as the evaporation temperature decreased from 17 °C to 5.8 °C. In addition, the optimal cell cooling evaporation temperature range was 10.2 °C–11 °C when the cell heating power was 0.4 kW. These studies analyzed the influencing factors from different perspectives and demonstrated the prospects and advantages of transcritical CO_2 in automotive heat pump systems.

Similar to CO_2 heat pump heating, where the high pressure and charge of the system have a significant impact on system performance, the same phenomenon exists in mobile air conditioning (MAC). In terms of optimal high pressure, Wang et al.[80] investigated the performance and optimal pressure of a novel CO_2 heat pump system under extreme conditions. It was found that at −15 °C of ambient temperature, the heat production reached 5.07 kW with a COP of 1.78. Wang et al.[81] investigated the cycling characteristics of a CO_2 electric vehicle heat pump in different operating modes and conditions and found that the pseudo-optimal exhaust pressure increased with the increase of ambient temperature, inlet air temperature, and supply air temperature. In terms of charge, Yin et al.[82] investigated the effect of refrigerant charge on the system performance of CO_2 automotive air-conditioning systems and suggested that the optimal standardized charge range for supercritical CO_2 air-conditioning systems should be set between 0.111 and 0.321. Song et al.[83] studied the application of the supercritical CO_2 cycle in buses based on a GT-Suite simulation platform and analyzed the effect of the optimal CO_2 charge and refrigerant distribution on system performance. The performance variations of the bus system's COP (1.2–2.2) and cooling capacity (9.5–18 kW) were obtained for different charging volumes (3–8 kg).

3.2.2. CO_2 system component studies

In order to improve the performance of CO_2 compressors for electric vehicles, Zheng et al.[84] numerically simulated the flow field of a CO_2 screw compressor for electric vehicles and analyzed the development characteristics of the tangential leakage flow and the field volume distribution in different scenarios. The results showed different interactions between the tangential leakage flow and the main flow, with different characteristics of the tangential leakage flow in the suction and compression chambers. Heat exchangers are the key component of CO_2 automobile air conditioning, and microchannel parallel-flow heat exchangers have the advantages of a compact structure, high efficiency, and so on compared with the traditional finned tube heat exchangers, which are widely used in the automobile air conditioning industry. Ma et al.[85] theoretically discussed the design of CO_2 automotive air conditioning using compact microchannel heat exchangers and predicted that microchannel heat exchangers would have a good application prospect in automotive air conditioning. Lei et al.[86] utilized a technique to improve the performance of a supercritical CO_2 automotive air conditioning system by utilizing an idle heater core to increase the heat transfer area of an evaporator. In addition to microchannel heat exchangers and heated core technology, there are many other heat transfer enhancement methods, such as the use of different shapes of tubing to improve heat transfer in heat exchangers, which are categorized as shown in **Figure 13**[87].

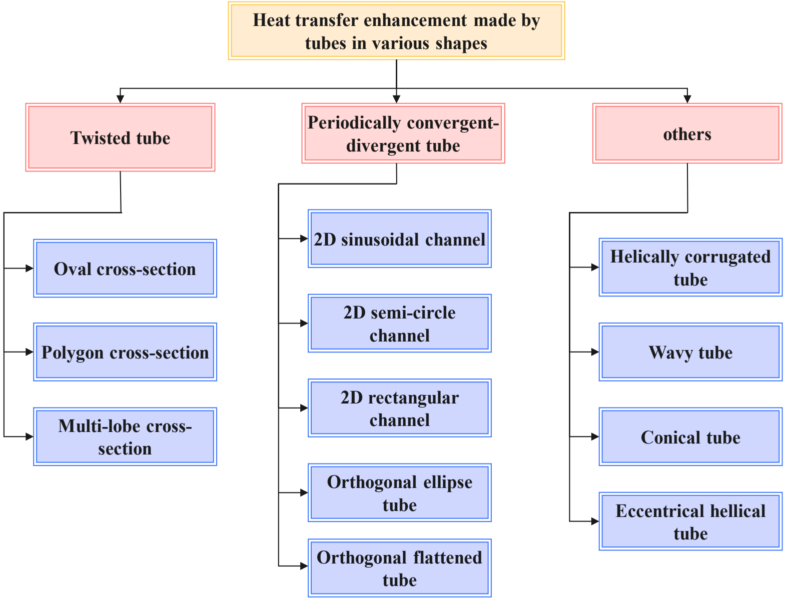


Figure 13. Classification of heat transfer enhancement methods based on various shapes of pipes.

In addition to compressors and heat exchangers, throttling devices are also a hot research topic in CO_2 automotive air conditioning research. Lee et al.[88] designed and developed a two-phase injector for a CO_2 heat pump system that considered the non-equilibrium state to replace the expansion device in the system. The authors carried out performance tests with variations in the structural dimensions of the injector (nozzle diameter, cross-section diameter, etc.). The test results showed that optimum design parameters existed for all test conditions and that the coefficient of performance of the system with the injector was improved by about 15% over that of the conventional system. Yang et al.[89] constructed a vapor-injection supercritical CO_2 heat pump system with a flash tank for electric vehicles. The heating performance of the vapor injection system was found to be significantly improved compared with that of the basic system without injection, and the improvement was greater the lower the outdoor temperature.

3.2.3. CO_2 control strategy research

A system control strategy is an important factor affecting the performance of CO_2 heat pump air conditioning systems for electric vehicles, which needs to be optimized according to different working conditions and objectives. Chen et al.[90] proposed a COP-optimal control strategy based on COP optimization for an intercooled two-stage CO_2 heat pump system for electric vehicle heating. This strategy resulted in a significant increase in heat production and COP with decreasing ambient temperature, with COP increased by 18.9%–61.9%. Zhang et al.[91] used a model predictive control strategy to optimize the operation of a supercritical CO_2 air-conditioning system in railroad vehicles, which resulted in an average COP increase of 7.4% compared with that of the PID control strategy. Wang et al.[92] designed a novel model predictive controller for a supercritical CO_2 cabin thermal management system for electric vehicles, which reduced energy consumption by 13.33%–20.27% compared with that of the PI controller. Wang et al.[93] proposed a novel frost-free control strategy for solving the problem of performance degradation due to the frosting of heat pumps in electric vehicles and found that the frost-free control strategy was optimal when the operation time exceeded 60 min. Yin et al.[94] investigated a new evaporative cooling system based on a supercritical CO_2 cycle and proposed a simple control strategy, which can better solve the problem of overheating and difficult to control the cell, while having a higher COP. From the above study, it can be seen that a control strategy has a significant effect on system performance, and therefore it is necessary to study the control strategy of a CO_2 heat pump air conditioning system for electric vehicles.

According to the authors, in recent years, global automobile manufacturers, scientific research institutions, colleges, and universities are actively researching automotive integrated transcritical CO_2 systems. CO_2 automotive air conditioning will always develop in the direction of green efficiency, functional integration, modular structure, and intelligent control. It is foreseeable that the automotive thermal management industry will become the largest application market for CO_2 technology, and more research on automotive integrated thermal management systems will appear in the future. At the same time, more comprehensive, complex, and intelligent control logics and optimization methods continue to evolve and be innovated.

3.3. CO_2 heat pump drying

Drying is a key step in industrial and agricultural production and is widely used in the processing of various products, including grain, vegetables, tea, wood, pharmaceuticals, and so on. However, the drying process is often accompanied by a large amount of energy consumption, and in developed countries, the energy consumption of drying occupies 7%–15% of industrial energy consumption[95]. Therefore, finding a more efficient and energy-saving drying technology has become an important research direction.

A CO_2 transcritical heat pump drying system has the advantages of high heating temperature (maximum heating temperature of about 110 °C), fast system response, high energy efficiency, and low operating cost[96]. **Figure 14** illustrates the system principle of a transcritical CO_2 heat pump dryer, where the air is heated through a gas cooler and the heated air is then passed into a drying chamber for drying. As early as the end of the last century, researchers at the University of Essen in Germany found that CO_2 was more energy efficient than R134a in drying clothes in a laundry room, with a COP of 5.5 and energy savings of up to 55%[97]. Sian et al.[98] also confirmed that a CO_2 dryer had higher drum outlet air and clothing temperatures than those of the R134a dryer, improved specific humidity extraction and COP, and reduced drying time by 15%. In addition, Li et al.[99] also found that a two-stage drying system had a higher specific humidity extraction rate than that of the single-stage drying CO_2 system and a higher energy utilization efficiency than that of the power dryer.

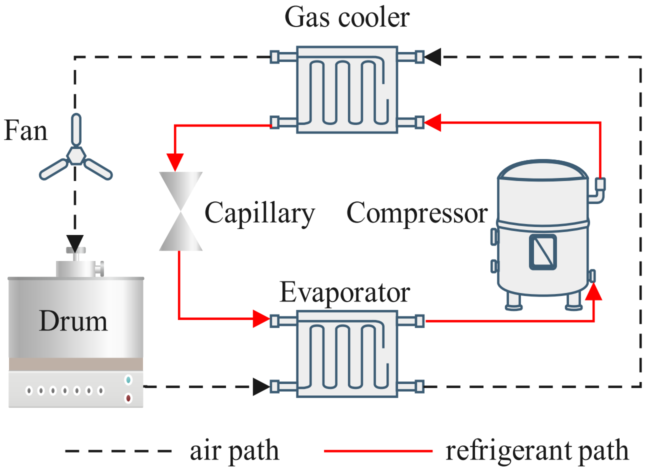


Figure 14. System schematic diagram of transcritical CO_2 heat pump dryer.

CO_2 heat pump transcritical cycle technology has shown great potential in the field of drying. Many scholars have studied its application in different scenarios. Zhou et al.[96] studied its performance in tea drying technology and found that the technology can substantially reduce the load and peak load ratio of tea drying, while still ensuring the quality of tea leaves. Zhang et al.[100] investigated a CO_2 heat pump shrimp scalding system, which was found to significantly reduce energy consumption and operating costs compared with those of the traditional fuel shrimp scalding system, while also increasing the economic value of the shrimps. On the other hand, Xia et al.[101] designed a CO_2 heat pump drying device applicable to the drying requirements of Chinese herbs, which is not only environmentally friendly, energy efficient, and applicable to a wide range of applications but also meets the special requirements for drying of Chinese herbs and preserves their active ingredients and medicinal effects.

In terms of simulation studies, Sarkar et al.[102] carried out a simulation study of a CO_2 heat pump dryer and explored the effect of various parameters on the system performance. The results showed that the parameters of drying efficiency, recirculation air ratio, ambient temperature, and air mass flow rate had a significant effect on the system performance, whereas the bypass air ratio and ambient relative humidity had a lesser effect. Erdem et al.[103] developed a theoretical model of a CO_2 heat pump drum dryer based on MATLAB software and analyzed the effects of different operating parameters on system performance. The results showed that CO_2 as the work mass had good physical and environmental characteristics, and the drying time and energy consumption can be significantly reduced by optimizing the parameters. Jokiel et al.[104] established a dynamic heat pump drying model based on Modelica software, and the results showed that the heat pump drying system not only significantly reduced the energy consumption and increased the humidity extraction rate compared with those of the traditional open-circuit drying system but it also increased the drying time.

From the above studies, it can be seen that CO_2 heat pumps have excellent performance in various drying scenarios. However, the current application of this technology in the drying industry is not widespread enough, and the research on transcritical CO_2 heat pump drying systems mainly focused on theoretical analysis and simulation, while experimental research and system optimization still need to be strengthened. In the future, the experimental validation of transcritical CO_2 heat pump drying should be strengthened, and the combination with other energy sources and drying/dehumidification methods should be explored, such as solar energy assistance and rotor dehumidification. With technological progress and the increase in environmental protection demand, it is expected that transcritical CO_2 technology will soon be integrated and industrialized in the drying field.

3.4. Potential applications in other areas

In addition to the applications mentioned above, there are many potential applications for CO_2 heat pumps. For example, low-temperature waste heat from industrial processes can be utilized to improve energy efficiency and reduce energy consumption and carbon emissions, and CO_2 heat pump technology can also provide stable temperature conditions for agricultural greenhouses, animal husbandry, aquaculture, etc., to ensure the growth and health of agricultural products and animals, and increase agricultural benefits. It can also be combined with solar, geothermal, biomass, and other renewable energy sources to build a multi-energy complementary integrated energy system and realize a clean, renewable, and sustainable energy supply, etc. CO_2 heat pump technology is a comprehensive technology integrating energy saving, environmental protection, and new energy, which has a broad application prospect and potential value. CO_2 heat pumps are also utilized in refrigeration applications. For instance, during the 2022 Beijing Winter Olympic Games, a CO_2 heat pump with direct cooling ice technology was employed. This system featured two-stage compression and full apparent heat recovery, achieving more than 50% energy savings. Additionally, it maintained the ice surface temperature difference within a narrow range of 0.3 ℃ to 0.4 ℃. Both the energy efficiency and the control of ice surface temperature reached an internationally advanced level.

In summary, research in the CO_2 heat pump heating field mainly focused on improving the adaptability to the outdoor temperature in cold areas and the water outlet temperature to realize heating and domestic hot water supply. The key technical challenge is how to maintain a high heating coefficient and increase the outlet water temperature under the large temperature difference between the supply and return water. The research field of CO_2 heat pumps for automotive air conditioning focused mainly on how to achieve efficient heat conversion and regulation in automotive air conditioning systems. The key scientific issue and technical challenge is how to realize the integration and intelligence of automotive air conditioning systems. The CO_2 heat pump drying field is mostly applied to the drying of agricultural and sideline products, rapid drying of clothes, and other scenarios. The main focus is on how to efficiently produce higher-temperature heat from the hot, humid air being exhausted.

4. Transcritical CO_2 heat pump limitations and optimization

4.1. Transcritical CO_2 heat pump limitations

From the study of the above application areas, it is not difficult to find that CO_2 heat pump technology has a wide range of application prospects. Compared with traditional heat pumps, it has unique advantages, but it also faces the following aspects of technical difficulties and challenges:

1) The pressure and temperature on the high-pressure side of a CO_2 heat pump system are much higher than those of a refrigeration system with conventional refrigerants (e.g., R134a), which puts higher performance and reliability requirements on the system's components, such as the compressor, lubricating oil, piping, and valves. At present, the types, specifications, and performance of CO_2 heat pump compressors are not rich and perfect enough and need to be further developed and optimized.
2) The large pressure difference (6–10 MPa) between the front and rear of the expansion device of a transcritical CO_2 heat pump system leads to large irreversible losses in the throttling process, which affects the efficiency and stability of the system.
3) The higher average temperature of CO_2 in the gas cooler in the transcritical CO_2 cycle results in higher heat loss during cooling and a lower COP of the system.
4) The optimal thermodynamic parameters of a CO_2 heat pump system change greatly with working conditions. Determining how to accurately control these parameters and realize the real-time monitoring and adjustment of each component and parameter of a CO_2 heat pump system presents higher demands for the intelligence, precision, and flexibility of the system's control technology. At present, the system control technology of CO_2 heat pumps still has some problems, such as unreasonable control strategy, non-optimized control algorithm, and incompatible controllers, which need to be further improved and upgraded.

4.2. Optimization of CO_2 heat pump systems

Over the past few years, the ways to enhance the performance of transcritical CO_2 heat pumps in various application scenarios have become the focus of research in this field. From the abovementioned studies, it is known that a large number of scholars have conducted in-depth studies on different ways of optimizing CO_2 heat pump systems. Currently, the main system optimization approaches that have been proposed in the literature include the optimization of system components, optimization of the cycle structure, optimization of the cycle mass, and optimization of the control strategy. **Table 2** summarizes the advantages and disadvantages of these optimization approaches, all of which can effectively improve the performance of CO_2 heat pump systems. However, different optimization methods also have different application scenarios and economics.

Therefore, it is necessary to choose the appropriate optimization method according to the specific application requirements and cost-effectiveness.

Table 2. Comparison of different optimization methods.

Issue	**Optimization methods**	**Pros**	**Cons**
Higher throttling losses	Expansion machine[50]	Part of expansion work is recovered and power consumption of compressor is reduced	Not applicable to small heat pump units, considering economic cost
	Heat exchanger[53]	Equipment is simple and more widely used, with significant efficiency gains	Causes compressor discharge temperature to rise
	Ejector[51]	Compact construction reduces throttling losses and compressor power consumption	Operational stability is poor and system is not as efficient as when using expander
Higher exhaust gas temperatures	Two-stage cycle[54]	Better realization of gradient heat release, so that supply and demand of energy are more matched, reducing energy consumption.	System structure is more complex and not conducive to promotion
Higher system pressures	CO_2-based mixed refrigerant[64]	No need to change system structure and has small economic cost	Some flammable refrigerant needs to be added
Real-time variation of optimal thermodynamic parameters	Optimization of control strategies[90]	Precise control can effectively reduce system losses and improve efficiency	High technical difficulty and high investment in hardware and software

5. Summary and outlook

5.1. Summary

In this article, the principles, application research status, and development obstacles of CO_2 heat pump technology were reviewed and the research status and challenges of CO_2 heat pump technology in heating, automotive air conditioning, drying, and other fields were discussed in detail, while the current development direction and promotion obstacles of CO_2 heat pumps were summarized. A summary of the main conclusion obtained is as follows:

1) Due to the thermodynamic characteristics of supercritical CO_2, such as high density and low viscosity, CO_2 heat pumps can usually be smaller in size, giving them a wider range of applications and market potential. At present, CO_2 heat pumps can achieve heat sink temperatures of 90 °C–120 °C in transcritical cycles, covering almost all civil, commercial, and industrial use scenarios, and are expected to replace traditional fossil fuels. CO_2 as a natural refrigerant is non-toxic, harmless, safe, and stable, and it shows great application potential in the context of global dual-carbon development.
2) At present, CO_2 heat pump technology has been gradually applied in the fields of heating, automobile air conditioning, and drying. The transcritical CO_2 cycle is very suitable for use in the heating field due to its large temperature slip during the heat release process. CO_2 heat pump technology has significant energy-saving and environmental protection advantages and is expected to become the mainstream heating method in the future. With the exponential growth of the global new-energy vehicle market, CO_2 heat pumps can adapt to different climate conditions and vehicle needs with their energy-saving capabilities for efficient heating and have a broad market. CO_2 heat pumps also have the characteristics of high-temperature water production and efficient dehumidification in

drying and can be used in the drying process in food, wood, textile, and other industries to improve drying quality and efficiency.

5.2. Outlook

Although CO_2 heat pumps have shown unique advantages, they still face some technological development obstacles. For example, the high-pressure and high-temperature problems of supercritical CO_2 systems have put forward higher performance and reliability requirements for components, such as compressors, lubricants, pipelines, and valves. They also face problems such as large fluctuations in thermodynamic parameters, large heat losses, and low efficiency. In order to promote the development and application of CO_2 heat pump technology, in-depth research and innovation can be carried out from the following aspects in the future:

1) The CO_2 cycle structure can be optimized and improved, the design and manufacturing of high-performance core components (such as compressors and heat exchangers) can be improved, and customized designs for transcritical CO_2 systems can be carried out to achieve efficient heat conversion and give full play to this technology's energy-saving potential.
2) In the technical transition stage, the selection and application of CO_2-based mixed working fluids can be carried out, taking into account efficiency and environmental protection characteristics. As the technology matures, it will gradually transition to a separate CO_2 working fluid cycle. The combination of CO_2 heat pump technology and digital technology to achieve intelligent control and real-time optimization of the circulation process should also be strengthened. In addition, CO_2 heat pump technology, renewable energy technology, and energy storage technology can be collaboratively developed and renewable energy sources, such as solar energy and wind energy, can be used as heat sources or driving sources to maximize the energy saving of CO_2 heat pumps and combine them with energy storage devices. This not only solves the instability of renewable energy but also improves the quality and efficiency of heat, and it is expected to become a new generation of distributed energy technology and is an important development direction of CO_2 heat pump technology.
3) Today, CO_2 heat pumps still face difficulties in market promotion due to problems such as high production costs, few demonstration projects, and low public awareness, and they cannot achieve a beneficial positive cycle of "technology develops the economy, and the economy drives technology". We can strengthen policy guidance, obtain support from management departments, actively introduce economic subsidy policies to support the application of CO_2 heat pumps, promote related industries to adopt CO_2 heat pumps for green upgrades, and increase user awareness of CO_2 heat pump technology through technical publicity and other means. Acceptance of the development of this emerging energy-saving technology will be conducive to the promotion of CO_2 heat pump technology and solve the problem of "difficulty in starting".

Conflict of interest

The authors declare no conflict of interest.

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