Review Article

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

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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, CO₂ 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 CO₂ heat pumps has made certain progress, but there are few reviews of the research status and development trends of CO₂ heat pumps in different applications. Therefore, this article systematically summarizes the latest research results of transcritical CO₂ heat pumps in different application fields, pointing out the difficulties such as high pressure and low operating efficiency in system design and operation. It also summarizes the latest optimization research on system components, cycle structure, mixed refrigerants and control strategies. The results show that each optimization method can significantly improve system performance, among which mixed refrigerant is the simplest optimization method. Finally, the outlook for CO₂ heat pump technology is put forward. With policy support and technological advancement, more comprehensive, energy-saving, and intelligent CO₂ heat pump technology will continue to develop and innovate.

Keywords: transcritical; CO₂ 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 to tens of thousands of times that of CO₂, and they have a long lifespan in the atmosphere. If the production and consumption of HFCs refrigerants are not controlled for a long time, the emissions of HFCs will lead to a global temperature increase of 0.3–0.5 ℃ by the end of the 21st century[1]. The natural working fluid CO₂ has an ODP = 0, a GWP = 1, and a safety level of A1. It has the advantages of non-toxic, non-flammable, high density, low viscosity, small flow loss, and low cost. Therefore, using CO₂ 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 the industry[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 ℃ and heating capacity 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 of renewable electricity, heat pumps can reduce nearly 2 billion tons of CO₂ emissions, accounting for nearly 20% of China’s total carbon emissions in 2019[3].
The development history of CO₂ is shown in Figure 2. The CO₂ heat pump can be traced back to the 19th century[4]. However, at that time, the subcritical cycle efficiency of CO₂ 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 CO₂ transcritical cycle[6], which allowed CO₂ 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 CO₂ heat pumps, and subsequently the world’s first heat pump water heaters and commercial vehicles equipped with CO₂ air conditioners appeared one after another[7,8]. To this day CO₂ is widely used in various fields. According to the International Energy Agency (IEA), CO₂ heat pumps will account for 22.1% of the overall heat pump market share by 2030. It is foreseeable that the use of CO₂ as a heat pump will be a hot spot in the future research on new environmentally friendly and low-carbon technologies.

As can be seen from Figure 3, since Lorentzen and Pettersen[9,10] of the Norwegian SINTEF Institute first proposed the possibility of its 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 CO₂ heat pumps, and have applied CO₂ heat pumps to commercial and military applications. For example, in 1995, Saikawa et al.[11] of Japan’s Central Research Institute of Electric Power Industry (CRIEPD) began basic research on CO₂ heat pumps; Denmark’s Holst[12] established a CO₂ transcritical automotive air conditioning test bench at Danfoss to study the regulation of the system components; Kohler[13] of Kassel University in Germany carried out research on the application of CO₂ working fluid automotive air conditioners and heat pumps; Schmidt et al.[14] of Germany conducted the feasibility analysis of transcritical CO₂ heat pump drying for the first time;
the University of Illinois (UIUC) in the United States also established an automotive air conditioning test bench\cite{15}.

China’s research on CO$_2$ heat pumps started late, but has made some progress in recent years. Universities and units such as Shanghai Jiao Tong University, Tianjin University, Xi’an Jiaotong University, and Central South University 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; in 2013, Haier announced the launch of China’s first CO$_2$ air source water heater\cite{16}, laying the foundation for the marketization of CO$_2$ heat pumps in China.

This paper systematically describes the application of transcritical CO$_2$ heat pumps in different fields and its development trend. 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 the current CO$_2$ heat pump, optimization measures and development directions are proposed in terms of system components, structure, 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.
2. Principles and advantages of transcritical CO\textsubscript{2} heat pump

2.1. Transcritical CO\textsubscript{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 high temperature and high-pressure state 2, and then 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\textsubscript{2} heat pump system cycle schematic diagram and lgP-h diagram.

2.2. Characteristics of CO\textsubscript{2} transcritical state

The lower critical temperature (31.1 °C) determines that the exothermic process in CO\textsubscript{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\textsubscript{2} transcritical cycle (1-2-3-4), 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\textsubscript{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\textsubscript{2} cycle is much larger, but the pressure ratio is relatively small compared to conventional refrigerants.

A full understanding and mastery of the sCO\textsubscript{2} heat transfer mechanism is essential for the design and safe and stable operation of heat exchanger units. Figure 6 depicts the variation of thermophysical properties of CO\textsubscript{2} fluid with temperature at 8.0 MPa pressure. It can be seen from Figure 5 that the density $\rho$, constant-pressure specific heat $C_p$, thermal conductivity $\lambda$ and viscosity $\mu$ of CO\textsubscript{2} change drastically in the temperature interval close to the proposed critical point. This makes supercritical CO\textsubscript{2} have special properties such as high density, low viscosity, high solubility, high heat transfer coefficient, etc. According to Banuti\cite{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\textsubscript{2} as the working fluid within the heat exchanger, and that operating at supercritical conditions improves heat transfer efficiency. In addition, CO\textsubscript{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 CO₂ can be significantly reduced, and the volume and size of the CO₂ heat exchanger is significantly reduced compared to other heat exchangers. However, CO₂ 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 their application areas.

3. Current status of research on transcritical CO₂ heat pump applications

The special properties of CO₂ heat pump have attracted many scholars to conduct in-depth research. At present, the main application fields of CO₂ heat pump include: CO₂ heat pump heating, CO₂ car air conditioning, CO₂ heat pump drying and some other fields.

3.1. CO₂ heat pump heating

CO₂ heat pump heating is a high-efficiency heating technology based on the transcritical cycle of CO₂, 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 CO₂ heat pump cycle is a special Lorentz cycle with a heat transfer curve as shown in Figure 7. Compared to subcritical cycles, CO₂ 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 country for CO₂ heat pump water heaters. Since 2001, the Eco-Cute has been marketed as an energy-saving and environmentally friendly product in Japan and has rapidly gained popularity[19]. Compared to conventional combustion equipment, Eco-Cute achieves 30% energy savings, 40% less CO₂ emissions than instantaneous city gas hot water supply equipment, and 30% lower primary energy consumption.

![Figure 6. CO₂ physical property diagram with a pressure of 8 MPa[18].](image)

Figure 7. Heat transfer curve: (a) subcritical condensation process; (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 CO₂ 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 a considerable potential for development in both industrial and civil applications. Nawaz et al.[21] also compared CO₂ and R134a heat pump water heaters and found that CO₂ heat pumps were able to operate more efficiently and perform better at lower ambient temperatures. Moreover, CO₂ heat pump water heaters have high operational efficiency and can reduce energy consumption by 75% compared to electric heating as well as gas water heaters[22]. Therefore, there is a great need to study the CO₂ heat pump heating system.

3.1.1. Operational characterization studies

The operating characteristics of CO₂ heat pump heating system reflect the performance of the system under different working conditions, which can reveal the influencing factors of the system performance and provide theoretical guidance and experimental basis for the optimal design of the system. In CO₂ heat pump systems, small changes in exhaust pressure may lead to a significant decrease in cycle efficiency[23]. The literature by Nekså[24] suggests that whether a system is operating optimally or not 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, 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 because when the outlet temperature of the air cooler is certain, 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 CO₂ transcritical cycles has become a hot issue in this field.

![Figure 8. Reasons for the formation of optimal high pressure.](image)

In order to determine the optimal high pressure of transcritical CO₂ refrigeration system and heat pump water heater system, the researchers analyzed the key factors affecting the optimal high pressure through theoretical calculations and simulations, and established the corresponding mathematical models. Liang et al.[26] analyzed the optimal high pressure of transcritical CO₂ refrigeration system and heat pump water heater system by 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 such as 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, $P_{\text{opt}}$ is the optimum high pressure, $t_{\text{air}}$ and $t_{\text{gc, out}}$ are the ambient and gas cooler outlet temperatures, $T_{e}$ is the evaporation temperature, and $t_{\text{w, in}}$ and $t_{\text{w, out}}$ are the inlet and outlet water temperatures, respectively. Besides, Qin et al.\cite{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.\cite{31} proposed a more real-time and efficient algorithm to determine the optimal pressure. Similarly, Shao et al.\cite{32} proposed a constrained optimization method to obtain a constrained optimal high-pressure correlation formula for CO$_2$ transcritical cycle.

Table 1. Summary of optimal high-pressure correlations for CO$_2$ heat pumps.

<table>
<thead>
<tr>
<th>Author</th>
<th>Correlation</th>
<th>Applicable conditions</th>
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<tr>
<td>Kauf</td>
<td>$P_{\text{opt, Kauf}} = 2.6t_{\text{air}} + 7.54$</td>
<td>$30 , ^\circ \text{C} \leq t_{\text{air}} \leq 50 , ^\circ \text{C}$</td>
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<tr>
<td>Liao</td>
<td>$P_{\text{opt, Liao}} = (2.778 - 0.0157t_{e})t_{\text{gc, out}} + 0.381t_{e} - 9.34$</td>
<td>$-10 , ^\circ \text{C} \leq t_{e} \leq 20 , ^\circ \text{C}$</td>
</tr>
<tr>
<td>Sarkar et al.</td>
<td>$P_{\text{opt, Sarkar}} = 4.9 + 2.256t_{\text{gc, out}} - 0.17t_{e} + 0.002t_{e}^2$</td>
<td>$-10 , ^\circ \text{C} \leq t_{e} \leq 10 , ^\circ \text{C}$</td>
</tr>
<tr>
<td>Sarkar et al.</td>
<td>$P_{\text{opt, Sarkar}} = 8.545 + 0.774t_{\text{w, in}}$</td>
<td>$20 , ^\circ \text{C} \leq t_{\text{w, in}} \leq 50 , ^\circ \text{C}$</td>
</tr>
<tr>
<td>Chen and Gu</td>
<td>$P_{\text{opt, Chen}} = 2.68t_{\text{air}} + 0.975 = 2.68t_{\text{gc, out}} - 6.797$</td>
<td>$30 , ^\circ \text{C} \leq t_{\text{air}} \leq 50 , ^\circ \text{C}$</td>
</tr>
<tr>
<td>Qi et al.</td>
<td>$P_{\text{opt, Qi}} = 13.23 - 0.04t_{\text{gc, out}} + 0.03t_{\text{gc, out}}^2 - 2.77 \times 10^{-4}t_{\text{gc, out}}^3$</td>
<td>$20 , ^\circ \text{C} \leq t_{\text{gc, out}} \leq 45 , ^\circ \text{C}$</td>
</tr>
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<td>Wang et al.</td>
<td>$P_{\text{opt, w}} = 1.09 + 0.106t_{\text{w, out}} + 0.101t_{\text{air}} - 0.001t_{\text{air}}^2$</td>
<td>$5 , ^\circ \text{C} \leq t_{\text{air}} \leq 35 , ^\circ \text{C}$</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{opt, w}} = 2.47 + 0.122t_{\text{w, out}} - 0.0004t_{\text{w, out}}^2 + 0.016t_{\text{air}}$</td>
<td>$-15 , ^\circ \text{C} \leq t_{\text{air}} \leq 5 , ^\circ \text{C}$</td>
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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.\cite{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’s (ESC) experimental verification has always been a topic of greatest concern to relevant practitioners. Cui et al.\cite{34} used a multivariable ESC to optimize the exhaust pressure of a transcritical CO$_2$ heat pump water heater. It was found that the ESC controller increased the 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.\cite{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 the 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\cite{36}. Also, a heat pump system with an optimal refrigerant charge can minimize refrigerant leakage\cite{37}. Wang et al.\cite{38} proposed a thermodynamic model based on a small CO$_2$ water source heat pump water heater, predicting the optimal combination of capillary geometry and refrigerant charge. Experimental data shows that a 3.7% reduction in refrigerant charge can lead to a
reduction in system heating coefficient of performance (COP$_h$) of approximately 3.1%, and a 3.7% increase in refrigerant charge can reduce 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, t 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 the heat exchanger refers to changing the structure, material, 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 the heat transfer performance of the heat exchanger. 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 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 show 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 has 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 simulation, they proved that the heat transfer coefficient and comprehensive coefficient are 144.6% and 40.7% higher than those of the printed circuit board heat exchanger, respectively. The 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 are key factors affecting the heat transfer performance.
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 the system is operating in 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 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 show that the typical efficiency of HGBD is 30%–40%. Ye et al.\[^{47}\] found that the power consumption of the RCD method was only 17.5% of the HGBD method, and the COP was 4.61% higher than 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.
Throttle

From the analysis in the previous section, it can be seen that the CO₂ heat pump system operates at a much higher pressure than 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 system, at present, there are three main methods to reduce the throttling loss as follows:

1) Use an expander instead of a throttle valve. The 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.\cite{50} showed that the heating efficiency of the transcritical CO₂ cycle with an expander is 4.6% higher than the R134a cycle and 16.17% higher than the cycle with a throttle valve. Moreover, the higher the isentropic efficiency of the CO₂ expander, the better the cooling efficiency of the system, and the greater the heating efficiency.

2) Use an ejector instead of a throttle valve. The 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 the 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 is about 22% higher than that of the throttle valve, and the system COP can be increased by about 10%\cite{51}. Elbel and Hrnjak\cite{52} also conducted experimental studies on ejectors in CO₂ transcritical cycle system, and the results showed that the refrigeration capacity and COP increased by 8% and 7%, respectively.

3) Use a regenerator. The 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 small capacity and 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 CO₂ side of the air cooler is higher than the critical value, the regenerator can improve the performance coefficient\cite{53}, and the COP of the circulation system can be increased by about 10%.

![Figure 11. Structure and physical diagram of the ejector.](image)
Therefore, from cost considerations, a throttle valve or capillary tube should be used in a small CO₂ 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 the CO₂ system. The schematic diagram of the two-stage cycle is shown in Figure 12(a)[54]. Pitarch et al.[55] established mathematical models of CO₂ two-stage compression cycle and single-stage compression cycle respectively, and simulated and compared their performance in heat pump water heaters. The results showed that when producing 80 °C hot water, the two-stage compression cycle, the COP of the cycle is 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 CO₂ cascade cycle is another effective research method for cycle structure optimization. It is formed by using two single-machine cycles of CO₂ and another working fluid to share a condensing evaporator. Its schematic diagram is shown in Figure 12(b)[57]. Compared with transcritical CO₂ heat pumps, CO₂ cascade heat pumps can heat water to a higher temperature and have superior heating performance. In the research of R134a/CO₂ cascade air source heat pump, Luo[58] conducted trial production and experimental analysis of the unit he designed. The results showed that when the ambient temperature was as low as −25 °C, 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 °C and ambient temperatures of ±21 °C. The results show that COP shows an upward trend with the increase of ambient temperature.

CO₂ 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 CO₂ 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. However, 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 the efficiency of the system. Some studies have shown that the use of mechanical subcooling technology can increase the COP of the CO₂ 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 CO₂ heat pump coupling circulation systems, which are a technology that couples air source heat pumps with water source heat pumps, ground source heat pumps, solar collectors 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 solar systems, giving priority to solar heating, and using air source heat pumps when 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 in northern my country.
3.1.4. Research on CO₂ mixed refrigerants

In order to further reduce system pressure and improve system performance, one of the simplest and most effective methods is to use CO₂ mixed refrigerant instead of pure CO₂ refrigerant. In recent years, some non-azeotropic mixed refrigerants based on CO₂ have been widely studied, such as CO₂/R32, CO₂/R290, CO₂/R600, CO₂/R600a, CO₂/R1270, etc. Research results show 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, CO₂/R290 is considered the most suitable candidate alternative because it has the lowest critical pressure[66].

However, the mass transfer resistance of non-azeotropic mixtures during high temperature slip and nucleate boiling makes their heat transfer coefficients lower than pure refrigerants and azeotropic refrigerants[67]. Moreover, 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 (COP) and 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 are 31.3% and 30.6% higher than those of the R134a cycle, respectively$^{[70]}$, and the COP of the CO$_2$/R170 cycle exceeds 50% when the evaporation temperature is above 0 ℃, 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%, which is a significant increase from 9% in 2021 and less than 5% in 2020, and 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 outperforms 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 full load will be 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$^{[9]}$ and Pettersen$^{[10]}$ of 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 $-15$ ℃, the CO$_2$ heat pump can improve the working efficiency by 25% compared with 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 show that the ideal efficiency reaches 25.3 at 35 ℃ outdoor conditions, which is 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 $-25$ ℃ outdoor temperature and 20 ℃ 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 improves the efficiency of the compressor, but the effect on the refrigerant charge
may be different. Wang et al.\cite{79} have 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 was decreased from 17 $^\circ$C to 5.8 $^\circ$C. In addition, the optimal cell cooling evaporation temperature range is 10.2 $^\circ$C–11 $^\circ$C when the cell heating power is 0.4 kW. These studies analyzed the influencing factors of the system 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 MAC. In terms of optimal high pressure, Wang et al.\cite{80} investigated the performance and optimal pressure of a novel CO$_2$ heat pump system under extreme conditions. It was found that at $-15$ $^\circ$C ambient temperature, the heat production reached 5.07 kW with a COP of 1.78. Wang et al.\cite{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.\cite{82} investigated the effect of refrigerant charge on system performance for 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.\cite{83} studied the application of supercritical CO$_2$ cycle in buses based on GT-Suite simulation platform and analyzed the effect of optimal CO$_2$ charge and refrigerant distribution on the system performance. The performance variations of bus system COP (1.2–2.2), 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 the CO$_2$ compressor for electric vehicles, Zheng et al.\cite{84} numerically simulated the flow field of the CO$_2$ screw compressor for electric vehicles, and analyzed the development characteristics of the tangential leakage flow and the field volume distribution in different studies. The results show 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 exchanger are the key component of CO$_2$ automobile air conditioning, and the microchannel parallel flow heat exchanger has the advantages of compact structure, high efficiency and so on compared with the traditional finned tube heat exchanger, which is widely used in the automobile air conditioning industry. Ma et al.\cite{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.\cite{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 the evaporator. In addition to the microchannel heat exchanger 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\cite{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 CO₂ automotive air conditioning systems. Lee et al.\cite{88} designed and developed a two-phase injector for CO₂ heat pump system considering non-equilibrium state to replace the expansion device in the system. On this basis, 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 the 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 the conventional system. Yang et al.\cite{89} constructed a vapor-injection supercritical CO₂ 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 to the basic system without injection, and the improvement was greater the lower the outdoor temperature.

3.2.3. CO₂ control strategy research

The system control strategy is an important factor affecting the performance of CO₂ heat pump air conditioning systems for electric vehicles, which needs to be optimized according to different working conditions and objectives. Chen et al.\cite{90} proposed a COP-optimal control strategy based on COP optimization for an intercooled two-stage CO₂ 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 increasing by 18.9%–61.9%. Zhang et al.\cite{91} used a model predictive control strategy to optimize the operation of a supercritical CO₂ air-conditioning system in railroad vehicles, which resulted in an average COP increase of 7.4% compared to the PID control strategy. Wang et al.\cite{92} designed a novel model predictive controller for supercritical CO₂ cabin thermal management system for electric vehicles, which reduced energy consumption by 13.33%–20.27% compared to the PI controller. Wang et al.\cite{93} proposed a novel frost-free control strategy for solving the problem of performance degradation due to frosting of heat pumps in electric vehicles, and found that the frost-free control strategy is optimal when the operation time exceeds 60 min. Yin et al.\cite{94} investigated a new evaporative cooling system based on a supercritical CO₂ 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 the control strategy has a significant effect on the
system performance, therefore, it is necessary to study the control strategy of CO₂ 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 CO₂ system. CO₂ 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 CO₂ technology, and more research results 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 innovate.

3.3. CO₂ 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.

The CO₂ 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 CO₂ 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 CO₂ was more energy efficient than R134a in drying clothes in the laundry room, with a COP of 5.5 and energy savings of up to 55%[97]. Sian et al.[98] also confirmed that the CO₂ dryer had higher drum outlet air and clothing temperatures than the R134a dryer, and that it had improved specific humidity extraction and COP, and reduced drying time by 15%. In addition, Li et al.[99] also found that the two-stage drying system had a higher specific humidity extraction rate than the single-stage drying CO₂ system and a higher energy utilization efficiency than the power dryer.

![Figure 14. System schematic diagram of transcritical CO₂ heat pump dryer.](image)

CO₂ heat pump transcritical cycle technology has shown great potential in the field of drying. Many scholars have studied its application in different occasions. 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 the CO₂ heat pump shrimp scalding
system, which can significantly reduce energy consumption and operating costs compared to the traditional fuel shrimp scalding system, while also increasing the economic value of shrimp. On the other hand, Xia et al.\textsuperscript{[101]} designed a CO\textsubscript{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 ensures their active ingredients and medicinal effects.

In terms of simulation studies, Sarkar et al.\textsuperscript{[102]} carried out a simulation study of a CO\textsubscript{2} heat pump dryer and explored the effect of various parameters on the system performance. The results showed that the parameters such as 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.\textsuperscript{[103]} developed a theoretical model of a CO\textsubscript{2} heat pump drum dryer based on MATLAB software and analyzed the effects of different operating parameters on the system performance. The results showed that CO\textsubscript{2} as a work mass has good physical and environmental characteristics, and the drying time and energy consumption can be significantly reduced by optimizing the parameters. Jokiel et al.\textsuperscript{[104]} established a dynamic heat pump drying model based on Modelica software, and the results showed that the heat pump drying system can significantly reduce the energy consumption and increase the humidity extraction rate compared with the traditional open-circuit drying system, but it also increases the drying time.

From the above studies, it can be seen that CO\textsubscript{2} heat pump has excellent performance in various drying occasions. However, the current application of this technology in the drying industry is not widespread enough, and the research on transcritical CO\textsubscript{2} heat pump drying system mainly focuses on theoretical analysis and simulation, while the experimental research and system optimization still need to be strengthened. In the future, the experimental validation of transcritical CO\textsubscript{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 the technological progress and the increase of environmental protection demand, it is expected that transcritical CO\textsubscript{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\textsubscript{2} heat pumps. For example, low-temperature waste heat from industrial processes is utilized to improve energy efficiency and reduce energy consumption and carbon emissions; it 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 combine with solar energy, geothermal energy, biomass energy and other renewable energy sources to build a multi-energy complementary integrated energy system and realize clean, renewable and sustainable energy supply, etc. CO\textsubscript{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\textsubscript{2} heat pumps are also utilized in refrigeration applications. For instance, during the 2022 Beijing Winter Olympic Games, a CO\textsubscript{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 have reached an internationally advanced level.

In summary, the CO\textsubscript{2} heat pump heating field mainly focuses 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 supply and return water. The field of CO₂ heat pumps for automotive air conditioning focuses 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 CO₂ 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 CO₂ heat pump limitations and optimization

4.1. Transcritical CO₂ heat pump limitations

From the study of the above application areas, it is not difficult to find that CO₂ heat pump technology has a wide range of application prospects. Compared with traditional heat pumps, it has unique advantages, but it is also facing the following aspects of the technical difficulties and challenges:

1) The pressure and temperature on the high pressure side of a CO₂ heat pump system is much higher than that 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 CO₂ 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 the transcritical CO₂ 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 CO₂ in the gas cooler in the transcritical CO₂ cycle results in higher heat loss during cooling and lower COP of the system.

4) The optimal thermodynamic parameters of CO₂ heat pump system change greatly with working conditions. Determining how to accurately control these parameters and realize real-time monitoring and adjustment of each component and parameter of the CO₂ 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 CO₂ heat pump still has some problems, such as unreasonable control strategy, non-optimized control algorithm, incompatible controllers, which need to be further improved and upgraded.

4.2. Optimization of CO₂ heat pump systems

Over the past few years, ways to enhance the performance of transcritical CO₂ heat pumps in various application scenarios have become the focus of research in this field. From the above it is known that a large number of scholars have conducted in-depth studies on different ways of optimizing CO₂ heat pump systems. Currently, the main system optimization approaches that have been proposed in the literature include: 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 CO₂ 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.

<table>
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<tr>
<th>Issues</th>
<th>Optimization methods</th>
<th>Pros</th>
<th>Cons</th>
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<tr>
<td>Higher throttling losses</td>
<td>Expansion machine[50]</td>
<td>Part of the expansion work is recovered, reducing the power consumption of the compressor.</td>
<td>Not applicable to small heat pump units considering the economic cost.</td>
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<td>Heat exchanger[53]</td>
<td>The equipment is simple and more widely used, with significant efficiency gains.</td>
<td>Causes the compressor discharge temperature to rise.</td>
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<tr>
<td></td>
<td>Ejector[51]</td>
<td>Compact construction reduces throttling losses and compressor power consumption.</td>
<td>Operational stability is poor and the system is not as efficient as an expander.</td>
</tr>
<tr>
<td>Higher exhaust gas temperatures</td>
<td>Two-stage cycle[54]</td>
<td>Better realization of gradient heat release, so that the supply and demand of energy is more matched, reducing energy consumption.</td>
<td>The system structure is more complex and not conducive to promotion.</td>
</tr>
<tr>
<td>Higher system pressures</td>
<td>CO₂ mixed refrigerant[64]</td>
<td>No need to change the system structure, small economic cost.</td>
<td>Some flammable refrigerant needs to be added.</td>
</tr>
<tr>
<td>Real-time variation of</td>
<td>Optimization of control strategies[90]</td>
<td>Precise control can effectively reduce system losses and improve efficiency.</td>
<td>High technical difficulty and high investment in hardware and software.</td>
</tr>
<tr>
<td>thermodynamic parameters</td>
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5. Summary and outlook

5.1. Summary

This article reviews the principles, application research status and development obstacles of CO₂ heat pump technology, discusses in detail the research status and challenges of CO₂ heat pump technology in heating, automotive air conditioning, drying and other fields, and summarizes the current development direction and promotion obstacles of CO₂ heat pumps. The main conclusions obtained are as follows:

1) Due to the thermodynamic characteristics of supercritical CO₂ such as high density and low viscosity, CO₂ heat pumps can usually be smaller in size, giving them a wider range of applications and market potential. At present, CO₂ 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. At the same time, CO₂, as a natural refrigerant, is non-toxic, harmless, safe and stable, and shows great application potential in the context of global dual-carbon development.

2) At present, CO₂ heat pump technology has been gradually applied in the fields of heating, automobile air conditioning and drying: The transcritical CO₂ cycle is very suitable for use in the heating field due to its large temperature slip during the heat release process. It 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, CO₂ heat pumps can adapt to different climate conditions and vehicle needs with their energy-saving capabilities for efficient heating, and have a broad market; CO₂ heat pump has the characteristics of high-temperature water production and efficient dehumidification in drying. It can be used in the drying process of food, wood, textile and other industries to improve drying quality and efficiency.

5.2. Outlook

Although CO₂ heat pumps have shown unique advantages, they still face some technological development obstacles. For example, the high-pressure and high-temperature problems of supercritical CO₂ 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\textsubscript{2} heat pump technology, in-depth research and innovation can be carried out from the following aspects in the future:

1) Optimize and improve the CO\textsubscript{2} cycle structure, improve the design and manufacturing of high-performance core components (such as compressors and heat exchangers), carry out customized design for transcritical CO\textsubscript{2} systems, achieve efficient heat conversion, and give full play to this technology energy-saving potential.

2) In the technical transition stage, the selection and application of CO\textsubscript{2} mixed working fluid can be carried out, taking into account efficiency and environmental protection characteristics. As the technology matures, it will gradually transition to a separate CO\textsubscript{2} working fluid cycle; strengthen the combination of CO\textsubscript{2} heat pump technology and digital technology to achieve intelligent control and real-time optimization of the circulation process; collaboratively develop CO\textsubscript{2} heat pump technology, renewable energy technology, and energy storage technology, and use renewable energy sources such as solar energy and wind energy as heat sources or driving sources to maximize the energy saving of CO\textsubscript{2} heat pumps and combine them with energy storage devices. It not only solves the instability of renewable energy, but also improves the quality and efficiency of heat. It is expected to become a new generation of distributed energy technology and is an important development direction of CO\textsubscript{2} heat pump technology.

3) Today, CO\textsubscript{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 cannot achieve a beneficial positive cycle of “technology develops the economy, and the economy drives technology”. For example, we can strengthen policy guidance, obtain support from management departments, actively introduce economic subsidy policies to support the application of CO\textsubscript{2} heat pumps, promote related industries to adopt CO\textsubscript{2} heat pumps for green upgrades, and increase user awareness of CO\textsubscript{2} heat pump technology through technical publicity and other means. Accepting the development of this emerging energy-saving technology will be conducive to the promotion of CO\textsubscript{2} heat pump technology and solve the problem of “difficulty in starting”.

**Conflict of interest**

The authors declare no conflict of interest.

**References**


