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Review

Research Progress on CO_2 Transcritical Cycle Technology for Building Heating and Cooling Applications

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Abstract

This review focuses on the advancements of CO_2 transcritical cycle technology in building indoor environmental regulation, particularly in combined heating and cooling applications. The paper highlights the energy efficiency and environmental benefits of CO_2 as a natural refrigerant, which has zero ozone depletion potential (ODP) and very low global warming potential (GWP). It provides a comprehensive overview of recent optimization strategies, including distributed compression, the integration of ejectors and expanders, and the design improvements of key components such as gas coolers, compressors, and throttling valves. Through optimization strategies such as dual-system cycles, this technology can achieve a COP improvement of 15.3–46.96% in heating scenarios; meanwhile, with the help of distributed compression technology, its cooling capacity can be enhanced by up to 26.5%. The review also examines various operating conditions such as discharge pressure and subcooling, which significantly affect system performance. The paper concludes by identifying the current challenges in the application of CO_2 systems, such as high initial costs and system stability under extreme conditions, and suggests future research directions to overcome these limitations and improve the practical application of CO_2 transcritical cycles in the building industry. Overall, it is concluded that the development of expander-compressors holds great potential for achieving better performance and represents a promising direction for future advancements in this field.

Keywords: building indoor environment; carbon dioxide transcritical cycle; combined cooling and heating; system optimization

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1. Introduction

With the acceleration of urbanization and the improvement of residents' living standards, the impact of indoor environmental quality on human health is increasingly receiving attention. Research has shown that reasonable regulation of air temperature and humidity can not only ensure human thermal comfort but also effectively reduce health risks such as respiratory diseases, allergic reactions, and chronic fatigue syndrome. Especially under extreme weather conditions, efficient cooling in summer and stable heating in winter have become the core requirements for maintaining indoor environmental health. This study, which calculates the national heating and cooling loads under China's carbon neutrality goal, indicates that the above-mentioned core requirements are closely related to regional

building loads, as one study has shown. It also emphasizes that the combination of heat pumps and seasonal storage is a promising low-carbon supply solution for future regional systems [1].

However, traditional heating and cooling systems rely on fossil fuels or high global warming potential (GWP) refrigerants (such as hydrofluorocarbons (HFCs)), which not only increase building energy consumption but also exacerbate greenhouse gas emissions and environmental pollution [2]. In this context, how to achieve the coordinated optimization of "health, energy efficiency optimization, low carbon" in indoor environmental regulation through technological innovation has become a key topic in the energy transformation of the building industry [3].

The People's Republic of China, as a party to the Kigali Amendment, assumed binding international obligations to gradually reduce hydrofluorocarbons (HFCs) as of 15 September 2021. The Kigali Amendment serves as a supplement and extension to the Montreal Protocol, incorporating HFCs into the scope of substances regulated under the Protocol. According to the Amendment, China was required to freeze the production and consumption of HFCs at the baseline level of 2020–2022, starting in 2024.

The natural and environmentally friendly refrigerant CO_2 used in this project has great potential in the refrigerant replacement process. In recent years, new heat pump systems represented by carbon dioxide (CO_2) transcritical cycle technology have gradually become an important path to break through traditional technological bottlenecks due to their significant advantages in environmental protection, energy efficiency potential, and adaptability to operating conditions. Compared to traditional refrigerants, natural refrigerant CO_2 has zero ozone depletion potential (ODP) and extremely low GWP, and its transcritical cycle can efficiently output hot water above 85 °C in high-temperature heat pump scenarios, perfectly matching winter heating and industrial heat demand. At the same time, this technology significantly improves the energy efficiency ratio (COP) under summer cooling conditions by optimizing the compression expansion process and system integration design, providing technical support for the low-carbon development of building heating and cooling systems [4].

Despite its advantages, the application of CO_2 transcritical heat pump systems still faces challenges, with existing research mainly focusing on optimizing individual components or cycle configurations. There has been limited exploration of system integration, particularly in combining functions such as cooling, heating, and power generation within a single efficient system. Current optimization efforts tend to concentrate on isolated components like compressors, heat exchangers, and ejectors, without much emphasis on holistic system improvements [5].

This review uniquely synthesizes recent breakthroughs in system integration—such as combined cooling/heating cycles—and operational optimization, exemplified by AI-driven pressure control, to deliver the first comprehensive assessment of dual-function CO_2 transcritical heat pump systems for building applications, thereby bridging a critical gap in the literature. It systematically explores their role in indoor environmental regulation by analyzing thermodynamic principles, energy-efficiency pathways, distributed compression, ejector/expander integration, and component-level design enhancements. The review further identifies the key operational conditions governing performance and outlines future directions for CO_2-based technologies in building energy transformation.

2. CO_2 Refrigerant

As an important component of a heat pump system, refrigerant largely determines the operating efficiency and the applicable environment of the system. As a type of natural refrigerant, the development of CO_2 can be traced back to the 19th century. From the

first application of CO_2 in vapor compression cycle systems in 1850 [6] to the birth of the first CO_2 ice maker in 1869, the application of CO_2 in the refrigeration field began to gradually expand. Subsequently, with the continuous advancement of technology, the use of CO_2 refrigeration machines gradually became popular by the early 20th century. However, due to technological limitations at the time, CO_2 refrigeration machines mainly operated in subcritical cycles. When the operating state of CO_2 approaches the critical point, the refrigeration efficiency inevitably decreases. Close to the CO_2 critical point (≈31 °C, 7.38 MPa), the decline in cooling performance is driven by two coupled effects: the latent heat of vaporization approaches zero, sharply reducing the specific cooling capacity, while the low compressibility factor and increased clearance volume losses near the critical region simultaneously erode both the volumetric and isentropic efficiencies of the compressor. At the same time, synthetic refrigerants gradually dominated the market due to their excellent performance, and the application of CO_2 refrigerants in the field of heat pumps gradually decreased. In the 1980s, with the continuous enhancement of people's environmental protection awareness, Freon refrigerants that were harmful to the ozone layer and had a high greenhouse effect were gradually abandoned, and CO_2 was once again a concern.

The basic thermal and environmental properties of traditional refrigerants are presented in Table 1 [7]. Compared with traditional refrigerants, CO_2 is non-toxic, non-flammable, and has good safety; its ODP = 0 and GWP = 1, making it environmentally friendly. It is cheap and easy to obtain and has good economy. Notably, while traditional fluorocarbon refrigerants demonstrate superior performance in cooling applications, CO_2 exhibits distinct advantages in low-temperature heating scenarios. Compared with traditional heat pumps, CO_2 heat pumps have excellent heating performance and wide adaptability to operating conditions. From an operational cost perspective, CO_2 heat pumps show greater efficiency advantages in low-temperature environments, making them more economical for heating applications.

Table 1. The basic thermal properties and environmental properties [7].

Substance	Molar Mass (kg/kmol)	T_b (°C)	T_c (°C)	P_c (MPa)	TLV-TWA (PPM)	Atmospheric Life (yr)	ODP	GWP (100 yr)
HFC245fa	134.05	15.1	154.0	3.65	300	7.6	0.00	1030
HC600	58.12	−0.5	152.0	3.63	600	0.018	0.00	20
HC600a	58.12	−11.7	134.7	3.63	600	0.019	0.00	20
HFC245ca	134.05	−1.4	124.9	3.20	1000	240.0	0.00	9810
HFC134a	102.03	−26.1	101.1	4.06	1000	14.0	0.00	1430
HFC152a	66.05	−24.0	111.3	4.52	1000	1.4	0.00	124
HFC227ea	170.05	−16.4	102.8	3.00	1000	42.0	0.00	3220
HFC236ea	152.04	−6.2	139.1	3.06	1000	8.0	0.00	710
HFC236fa	152.04	−9.5	153.2	4.05	1000	240.0	0.00	3220
HCFC123	152.93	−27.8	183.7	4.03	50	1.3	0.02	77
HCFC124	136.48	−12.0	122.3	4.21	1000	5.8	0.02	609
HCFC141b	116.95	−32.0	204.4	4.21	500	9.3	0.12	725
HCFC142b	100.50	−21.5	150.0	4.06	1000	17.9	0.00	2310
HC600/HFC245fa	129.27	153.9	7.12	3.66	319	7.12	0.00	966

In terms of system design, the high thermal capacity of CO_2 makes the system design more compact [8]; a low compression ratio results in higher isentropic efficiency of the compressor [9]; and the significant temperature slip during the heat release of supercritical CO_2 (pressure greater than 7.38 MPa, temperature greater than 31.1 °C) enables efficient production of hot water [10]. In recent years, within the wide temperature range of heat source temperature (−50 to 30 °C) and heat-sink temperature (5 to 60 °C), scholars have been studying the use of CO_2 heat pumps for heating [11]. At present, CO_2 heat

pump technology has been fully developed in the fields of hot water and heating and can provide heating hot water at 50 to 75 °C under almost all environmental conditions. These characteristics make CO_2 have broad application prospects in heat pump systems, marking its resurgence in modern technology. Introduction of CO_2 physical properties is offered in Table 2.

Table 2. Introduction of CO_2 physical properties.

Carbon Dioxide			
Refrigerant name	R744	Chemical formula	CO_2
Relative molecular mass	44.01g/mol	Standard boiling point	−78.4 °C
Critical temperature	31.1 °C	Critical pressure	7.38 MPa
Ozone depletion Potential (ODP)	0	Global warming potential (GWP)	1
Toxic	Non-toxic	Flammable	Nonflammable

Despite its environmental advantages, CO_2 faces inherent limitations in building applications. Its low critical temperature (31.1 °C) necessitates transcritical operation when heat sink temperatures exceed this threshold. In cooling mode, when ambient air exceeds ~27 °C (considering a 3 °C pinch point), the gas cooler outlet temperature must exceed 60 °C to reject heat, drastically reducing COP. For instance, at 35.5 °C ambient, COP can drop to ~1.5 due to high compression work. Conversely, in heating mode, CO_2 systems efficiently supply 50–75 °C water but struggle with legacy radiators requiring >65 °C. Air-source heat pumps also face efficiency losses when sourcing heat from air >30 °C. These constraints highlight why CO_2 excels in industrial settings (e.g., with water-cooled heat sinks) but requires hybrid designs or alternative refrigerants (e.g., propane) for residential applications in hot climates.

3. CO_2 Transcritical Heat Pump Cycle System

At present, indoor environment construction mainly focuses on cooling and heating. The supply of cold or heat can be achieved by adopting the CO_2 transcritical heat pump cycle system. Research on CO_2 transcritical heat pump cycle systems mainly focuses on three aspects. One is to optimize the thermodynamic cycle by adding one or even several components or changing the position of one or even several components, thereby changing the system cycle mode and studying the impact of different cycle modes on system performance; the second is the optimization of important components in the system. The CO_2 transcritical heat pump system mainly consists of an evaporator, gas cooler, compressor, throttle valve, etc. In different cycle modes, other components such as ejectors, heat regenerators, capillaries, etc., may be added or replaced. By optimizing the design of each component in the cycle, the impact of different improvement schemes on system performance can be studied. The third is to study the operating conditions of the system by changing the operating conditions of the system and studying the impact of different operating conditions on system performance.

3.1. Heating-Focused Optimization

In the realm of building heating, the optimization of CO_2 transcritical heat pump thermodynamic cycles focuses on "enhancing thermodynamic efficiency and stabilizing low-temperature cycles." By reconfiguring cycle architectures and adjusting key parameters, researchers aim to address the decline in heating efficiency under extreme climatic conditions. For clarity, the optimal discharge pressure is defined as the high-side pressure at the compressor outlet that maximizes the system COP for a given set of inlet and outlet temperatures. Dedicated mechanical subcooling refers to the use of an auxiliary, compressor-driven vapor-compression loop that further cools the CO_2 leaving the gas

cooler before it enters the expansion device, thereby increasing the specific cooling (or heating) capacity without raising the main-cycle pressure.

In terms of the dual-system cycle design, the introduction of a coupled primary-auxiliary dual-system cycle, along with the graded utilization of the heat sink, can elevate the water outlet temperature to 70 °C. When operating within an ambient temperature range of −20 °C to 0 °C, the overall heating COP of the combined system is 2.04, which represents a 15.3% improvement relative to the baseline single-stage transcritical CO_2 system (COP = 1.77). This enhancement is attributed to the auxiliary transcritical CO_2 sub-cycle, whose COP consistently exceeds that of the main cycle and thus drives the composite performance upward. Experiments have demonstrated that each of the two independent systems within the coupled system has an optimal discharge pressure. In addition, the frequency ratio of the two compressors considerably influences system performance, with a specific optimal ratio. As the ambient temperature rises from −20 °C to 0 °C, the system COP increases by 22%. Compared to the conventional transcritical CO_2 heat pump system, the coupled system achieves a 15.3% rise in COP and a 39% reduction in optimal discharge pressure. Figure 1 presents the structure of the new transcritical CO_2 heat pump combined system, in which the main and auxiliary compressors improve the COP through frequency coordination [12]. Regarding collaborative optimization technologies, the integration of secondary compression and vortex tube expansion technologies has been optimized. At an evaporation temperature of −15 °C, the system COP increases by 18.2% compared to single-stage systems, with the ability to steadily supply heat at 45 °C. Research indicates that under severe cold conditions, variations in gas cooling pressure most significantly impact the performance of optimized systems. Within the established pressure variation range, the COP variation amplitudes for single-stage cycles, single-stage vortex tube cycles, secondary cycles, and secondary vortex tube cycles are 74.40%, 60.46%, 110.38%, and 90.94%, respectively. Vortex tube technology proves more effective under low compression ratios, with the single-stage vortex tube cycle improving COP by 11.2% compared to the single-stage cycle. Secondary compression technology, however, performs better under high compression ratios. Under optimal gas cooling pressure conditions, the secondary cycle enhances COP by 18.2% compared to the single-stage cycle [13]. In the aspect of innovative expansion device applications, the replacement of traditional throttling methods with a "heat valve" expansion device, which uses vortex tube expansion to recover work, can increase the COP of room heating heat pumps by 25%. The "heat valve" employs a vortex tube for non-mechanical expansion, achieving energy separation of gases through centrifugal force. Experimental studies reveal that both R22 refrigeration cycles and R134a heat pumps show improved performance with vortex tube technology. For systems using CO_2 as the working fluid, the COP increase is particularly significant, reaching 25%. By regulating thermodynamic irreversible losses through reducing entropy generation during throttling and optimizing the heat transfer temperature difference in the gas cooler, these technologies construct a high-efficiency cycle system. This system can supply hot water at 50 °C–70 °C in ambient temperatures of −30 °C–0 °C and offers a 10–25% increase in COP compared to traditional single-stage transcritical cycles [14].

The vortex tube, a low-cost, high-reliability expansion device with lower COP than turbines and ejectors, forms a hybrid system with ejectors via synergistic energy conversion: High-pressure fluid first enters the vortex tube, where centrifugal force splits it into hot and cold streams—its simplicity (no moving parts) reduces wear and initial costs. The ejector then captures residual energy, accelerating the hot stream to entrain and recompress the cold stream via momentum exchange, offsetting the vortex tube's COP deficit while avoiding turbines' complex machining/sealing needs, balancing efficiency and cost.

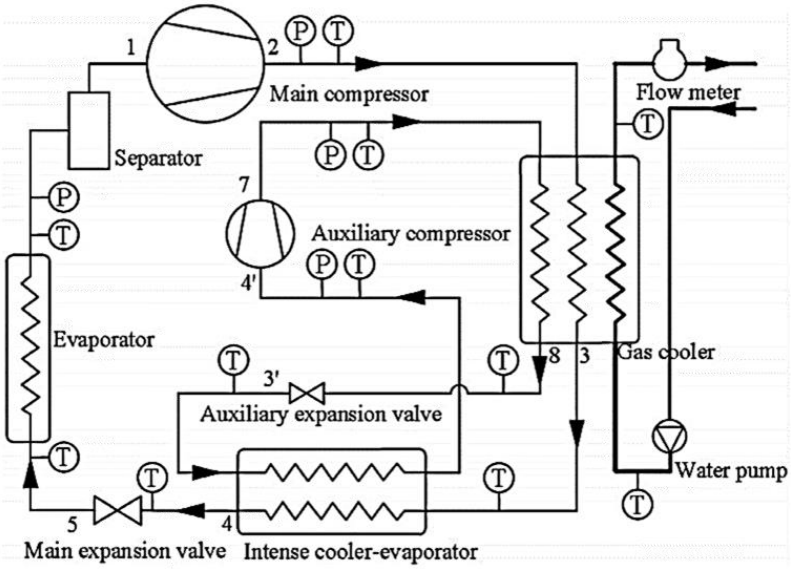


Figure 1. New trans-critical CO_2 heat pump combination system [12] (reproduced with permission from Feng Cao, Ce Cui, Xiangyu Wei, Xiang Yin, Mingjia Li, and Xiaolin Wang, *International Journal of Refrigeration*; published by Elsevier, April 2019).

Moreover, in the field of building heating and cooling supply, simulation studies indicate that the upgraded system enhances COP by 10–46.96% in floor radiation and other building heat sources. This provides a theoretical foundation for the heating and cooling supply of small and medium-sized buildings. The literature [15] compares cascade systems, secondary compression systems, etc., and confirms that the upgraded system improves COP by 10–46.96% in floor radiation and other building heat sources, thus offering more efficient and feasible cycle design support for building heating and cooling supply. Figure 2 compares the cycle processes of four systems, such as the Baseline System (BASE) and the Combined Heat Source System (CHPS), among which the Two-Stage Cooling Combined Heat Source System (TSCHPS) performs the best in combined cooling and heating.

In the domain of building heating, the optimized design of high-efficiency heat exchange equipment has emerged as a core breakthrough for enhancing system energy efficiency and meeting low-carbon heating demands.

Experimental research on the key parameters of shell-and-tube heat exchangers in building heating systems has been conducted. By fine-tuning the tube length and inner tube geometry, the CO_2 transcritical heat pump system has achieved a significant increase in hot water supply temperature under typical building heating conditions. The error between experimental and simulation results was controlled within 7.59%, and the system COP (coefficient of performance) could reach 3.64 under specific heating load conditions, providing technical support for high-temperature hot water supply in central heating networks [16].

An experimental analysis of spiral plate microchannel gas coolers revealed that when the CO_2 mass flux increased within the range of 57–182 kg/(m^2·s), the total heat transfer coefficient exhibited a linear growth trend. The increase in inlet water temperature further strengthened the heat transfer effect. Notably, the heat transfer performance of this heat exchanger when vertically installed was 12–18% higher than that when horizontally placed. This finding provides an important basis for the spatial layout optimization of equipment in building heating systems and verifies the high accuracy of Zhang's method correlation under building heating conditions [17].

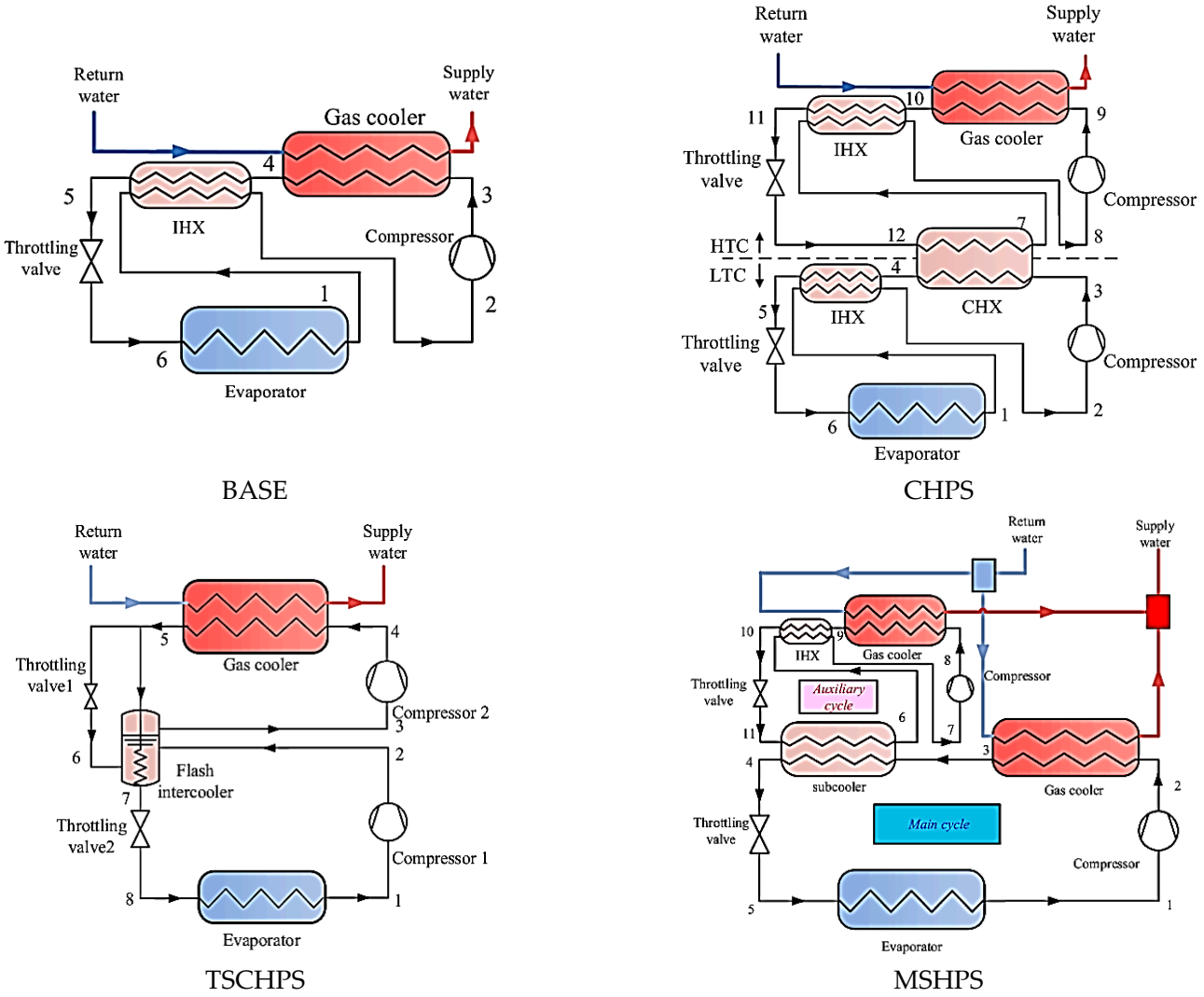


Figure 2. CO_2 heat pump system [15] (reproduced with permission from Liang Yao, Minxia Li, Yusheng Hu, Qifan Wang, and Xuetao Liu, *Applied Thermal Engineering*; published by Elsevier, April 2021).

Figure 3 presents the structural diagram of the honeycomb gas cooler. A bio-inspired honeycomb gas cooler with a porous fractal structure design has been proposed. This design significantly improved the uniformity of fluid distribution in microchannels. Experimental data demonstrated that under the same building heating conditions, the performance evaluation index of 1–3 layers of honeycomb structure increased by 193.4–357.0% compared with traditional internal spiral tube gas coolers and by 197.2–237.7% compared with triple-tube heat exchangers. Its compact structural characteristics make it particularly suitable for heating scenarios with limited building space [18].

The introduction of an ejector device in an ejector-expansion heat pump water heater has shown promising results. Experimental results indicated that this design increased the system COP by 7.38% and reduced the exergy loss of the throttle valve by 95.38–98.76%. Further research discovered that the ejector structure with a 5° diffusion angle achieved the best static pressure recovery, offering a feasible solution for improving waste heat recovery efficiency in building heating systems [19]. These studies collectively represent significant advancements in the design and optimization of heat exchange equipment for building heating systems. They provide valuable insights and technical solutions for enhancing energy efficiency and meeting the growing demand for low-carbon heating.

Additionally, studies have shown that integrating an ejector into a transcritical CO_2 heat pump system can boost the COP by 10.3% at 70 °C (with a system COP reaching 4.6) and reduce the optimal discharge pressure by 15.3% compared to conventional systems. The COP improvement ratio decreases with increasing discharge pressure due to reduced pressure lift ratio and ejector efficiency, while lower compressor rotation speeds under test conditions enhance COP despite reduced heat capacity [20].

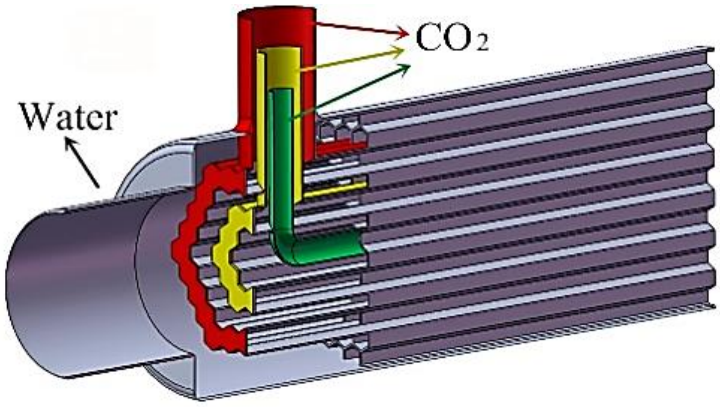


Figure 3. Honeycomb gas cooler structure diagram.

Figure 4 presents a two-stage compression refrigeration cycle system with an expander. A dual-fluid bio-inspired fractal heat transfer structure has been proposed to meet the specialized requirements of building heating systems. After optimization with a genetic algorithm, it was found that the heat exchanger featuring a counterflow fractal geometry design can reduce the power consumption of building heating systems by 15%, increase the heat transfer rate by 2.4%, and enhance the heat transfer performance index by 17%. This highlights the potential of fractal geometry in building high-temperature heat pump systems, particularly for upgrading heat exchange equipment with limited space in existing building renovations. Simulation studies, incorporating the complex flow field characteristics of building heating systems, have demonstrated that when the liquid phase mass fraction at the nozzle throat exceeds 0.65, the non-equilibrium phase change effect significantly impacts the flow characteristics of heating media. This provides theoretical support for designing key equipment such as ejector heat exchangers and composite cycle heat pumps in building heating systems. It is especially relevant for pressure difference balance control in central heating networks in severe cold northern regions and flow field uniformity optimization in vertical risers of multi-story buildings. A multi-physics coupling model under building heating conditions has verified the stability of the fractal structure within the ambient temperature range of −15 °C to 40 °C. Its heat transfer performance is approximately 23% higher than that of traditional plate-tube heat exchangers, offering an innovative solution for the integration of heating systems in ultra-low energy consumption buildings [21].

In experimental studies of building heating applications, the collaborative optimization of discharge pressure and heat recovery rate was investigated using Extremum Seeking Control under conditions of 40 °C inlet water temperature and 0 °C ambient temperature. Results showed that the transcritical CO_2 heat pump water heater achieved a 7.62% COP improvement, maintaining optimization efficiency during inlet water temperature fluctuations (40–45 °C) [22]. In extremely low-temperature environments (−20 °C), collaborative optimization of discharge pressure (9.78 MPa) and heat recovery rate (45%) elevated the system COP to 1.96, satisfying heating requirements for residential buildings in cold regions [23]. For mechanical subcooling integrated with two-stage compression, an auxiliary vapor compression cycle enabled mechanical subcooling. At an optimal discharge pressure

of 8.34 MPa and subcooling degree of 13.9 °C, the cycle achieved a COP of 2.84, with auxiliary compressor power consumption <20% of the main cycle, suitable for commercial refrigeration in malls [24]. Further integration of two-stage compression, mechanical subcooling, and a regenerator reached a COP of 4.05 at 11 °C subcooling, a 33.3% increase over traditional two-stage cycles, stably supplying 70 °C hot water for commercial central heating [25]. Regarding ejector–regenerator collaborative heating, experiments revealed that when the gas cooler outlet temperature was below the transition temperature (e.g., 33 °C at 7 MPa discharge pressure), the ejector improved COP by 7.1%. Combined with a regenerator, COP increased by 25.3% at outlet temperatures >31 °C, making this configuration suitable for −30 °C residential floor radiant heating [26].

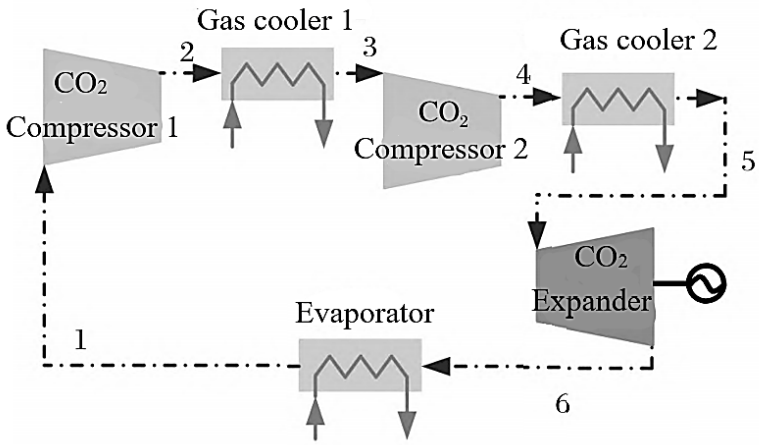


Figure 4. Two-stage compression refrigeration cycle system with expander.

A dedicated transcritical CO_2 subcooler installed at the main-cycle gas-cooler exit was found to significantly influence system performance, with the optimal medium temperature (defined as the main-cycle expansion-valve inlet temperature) playing a crucial role. Simulations showed that increasing the medium temperature raised suction pressure in the subcooler cycle while decreasing compressor displacement, whereas the main cycle saw gradual increases in suction pressure and mass flow rate. The system COP exhibited an optimal medium-temperature point, with the subcooler cycle's heating COP increasing as medium temperature rose, while the main cycle's COP decreased. This optimization approach proved effective for high water-feed-temperature scenarios, improving system adaptability and efficiency [27]

In the field of building heating, a theoretical model was constructed for the CO_2 transcritical heat pump system to comparatively analyze two operation parameter optimization schemes: increasing the compressor discharge pressure and enhancing the suction superheat. The results indicate that increasing the discharge pressure can elevate the gas cooler outlet water temperature with a wide regulation range, while the compressor discharge temperature needs to be controlled below 140 °C to ensure safe system operation. When enhancing the suction superheat, the cyclic power consumption rises moderately, but the coefficient of performance (COP) decreases significantly, making it suitable for scenarios requiring small-range water temperature adjustment. This study provides a theoretical basis for parameter optimization in conventional heating scenarios such as residential and commercial buildings [28]. Based on the pinch point theory, a simulation model of the transcritical CO_2 heat pump system was established to analyze the influence of parameters such as inlet water temperature and outlet water temperature on system performance. The research shows that when the inlet water temperature is 15 °C and the outlet water temperature is 65 °C, the optimal heat rejection pressure of the system is 9.54 MPa. At this point, the pinch point shifts to the cold end, and the system COP is improved by 1.8%

compared with the traditional model. This optimization scheme is applicable to centralized hot water supply systems in buildings such as apartments [29]. Figure 5 presents the cycle diagram and p-h diagram of a mechanically subcooled transcritical CO_2 refrigeration system. The green and black lines represent the auxiliary cycle (R152a) and the main cycle (CO_2), respectively, and visually demonstrate the dual cycle coupling of mechanical supercooling through the lgp-h diagram in right image. Experimental and simulation studies on transcritical CO_2 water-water heat pump systems have verified that increasing superheat can raise COP by 35.5% and user-side water supply temperature by an average of 11.3 °C. The system demonstrates an optimal discharge pressure for maximum COP, with COP increasing as chilled water flow rate rises or inlet temperature decreases. A solar-assisted transcritical CO_2 heat pump dual-evaporator system was designed, enabling three operation modes (solar, air-source heat pump, and combined mode), which elevates chilled water inlet temperature and improves system efficiency [30].

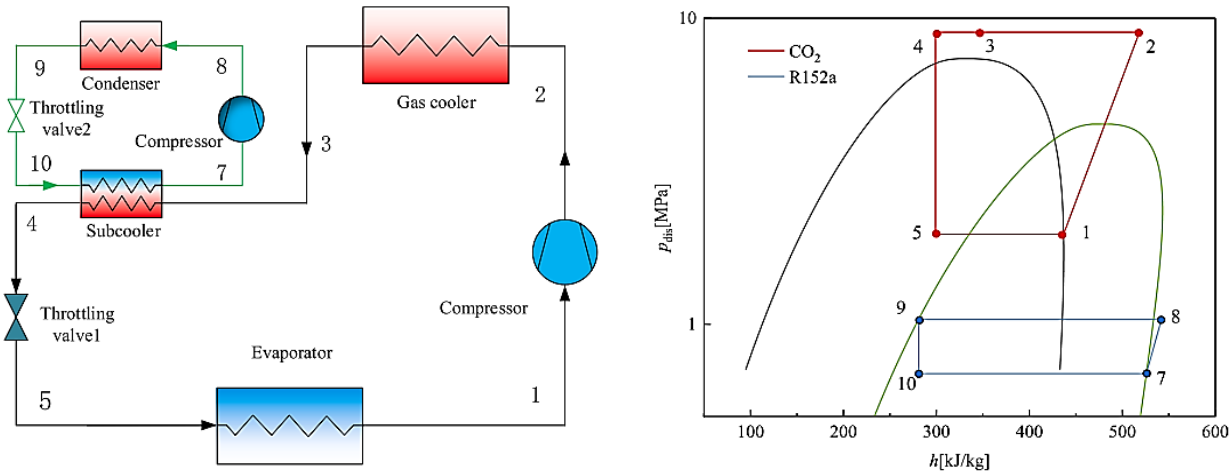


Figure 5. Cycle diagram and p–h diagram of a transcritical CO_2 refrigeration system with mechanical subcooling [30].

3.2. Cooling-Focused Optimization

In the realm of building cooling, a variety of efficient thermodynamic cycles have been proposed to optimize the performance of CO_2 transcritical systems. Distributed compression cycles, characterized by a secondary boosting design, have demonstrated remarkable improvements in cooling capacity and COP. Specifically, this cycle achieves a 6.65–26.5% increase in cooling capacity and a 10.76% enhancement in COP at 35 °C. This design effectively reduces throttling dryness and optimizes the compression process, thereby minimizing energy loss and improving the overall cooling capacity of the system [31].

Figure 6 illustrates the variation in COP with compressor discharge pressure in the transcritical CO_2 heat pump water heater. Parallel compression cycles, which incorporate a flash tank, have also shown significant performance improvements. When the evaporation pressure is set at 2.25 MPa, the COP of this cycle increases by 10% compared to a single-stage cycle. The flash tank facilitates efficient gas–liquid phase separation, reducing ineffective work consumption and enhancing system performance through optimized cycle and equipment configuration [32]. A dual-ejector two-stage cycle has been designed to address the challenges of cooling in high-temperature regions. This cycle achieves a substantial COP improvement of 20–80% in tropical regions (above 40 °C). By efficiently recovering expansion work to power the compressor and reducing external input power, this innovation significantly enhances the system's adaptability to high-temperature environments [33]. Furthermore, a turbine expander cycle with an expansion work recovery mechanism has been employed to further boost the COP by 38.4–45.1%. The turbine expander effectively

converts wasted expansion work into useful feedback for the system, thereby minimizing throttling energy loss and offering an efficient optimization pathway for CO_2 transcritical cycles [34].

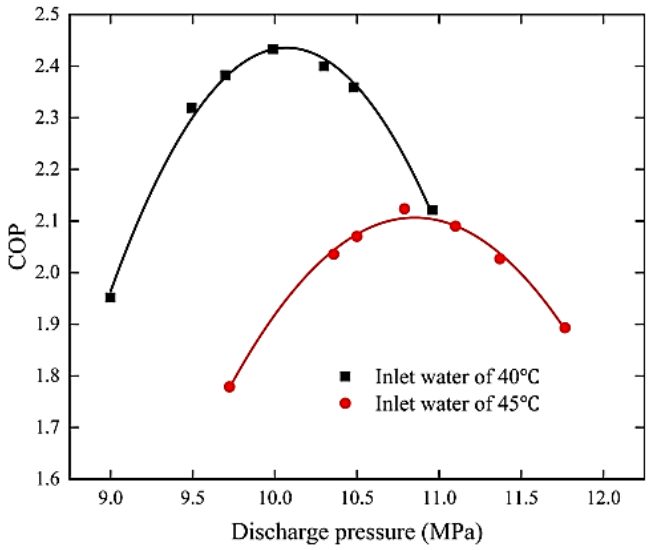


Figure 6. COP variation with compressor discharge pressure in a transcritical CO_2 heat pump water heater [32] (reproduced with permission from Ce Cui, Shuo Zong, Yulong Song, Xiang Yin, and Feng Cao, *International Journal of Refrigeration*; published by Elsevier, April 2022).

Thermoelectric subcoolers have been explored and show significant potential in improving system efficiency. At 35 °C, these devices increase the COP by 16.2% and cooling capacity by 20.8%. Utilizing the Peltier effect of semiconductor materials, thermoelectric subcoolers reduce the temperature of CO_2 fluid at the gas cooler outlet, thereby increasing the refrigerant enthalpy difference and enhancing the system's cooling capacity and efficiency [35]. A novel strategy for heat exchange optimization involves the synergistic interaction of ejectors and subcoolers in improved two-stage cycles. This approach achieves a 14.2% improvement in COP by optimizing internal heat distribution and improving energy efficiency. The collaboration between ejectors and subcoolers reduces energy waste and provides an innovative method for heat exchange enhancement [36]. Mechanically subcooled ejector coupling cycles have also been studied and show a 1.556% enhancement in exergy efficiency. Mechanical subcooling further lowers the refrigerant temperature, while ejectors improve pressure distribution, thereby boosting exergy efficiency and overall energy utilization [37]. Research has also confirmed that single-stage cycles with expanders exceeding 60% efficiency outperform two-stage systems in COP. This finding offers crucial theoretical guidance for expander selection in system design and highlights the importance of expander efficiency. It presents that single-stage cycles can simplify the system structure while ensuring high efficiency when certain conditions are met [38].

In the realm of building cooling, high-efficiency heat exchanger structural innovation has become crucial for boosting the energy efficiency of central air-conditioning systems. Three-dimensional numerical simulations and experimental verifications have been conducted for the high-load cooling demands of air-conditioning systems. Results indicate that the gas cooler with a U-bend structure improves thermal efficiency by 16% compared to the conventional concentric straight-tube type, and the COP of the transcritical refrigeration system increases by approximately 20%. The curved flow channel design enhances turbulence intensity (with turbulent kinetic energy up by 27%) and effectively reduces the boundary layer thickness (boundary layer thinned by 22%). This enables the chilled water supply temperature to drop from 7 °C to 5 °C while cutting compressor energy

consumption by 19%. Experimental data shows that under the condition of a CO_2 mass flow rate of 0.036 kg/s, a U-bend with a curvature radius of 0.112 m improves the heat transfer coefficient by 21.5 W/(m^2·K) compared to the straight tube. This makes it particularly suitable for modular air-conditioning systems with limited ceiling space in buildings. Another study has confirmed that compared to the traditional expansion valve, the optimized ejector with a 5° diffusion angle increases cooling capacity by 8% and the system COP by 7%. This design achieves the best static pressure recovery (with the static pressure recovery coefficient reaching 0.87). The ejector technology maintains high efficiency under high-temperature conditions of 35 °C. Its energy recovery mechanism reduces throttling losses by 95.38–98.76%, equivalent to cutting carbon emissions by approximately 8.5 tons per cooling season. This structure also reduces compressor power consumption by 6.8% while keeping the chilled water temperature stable through enhanced momentum exchange of gas–liquid two-phase flow. While U-bend designs introduce measurable pressure drop and erosion risks, these drawbacks are manageable through optimal curvature design and material upgrades. The practical feasibility of U-bend gas coolers in building cooling systems, especially in space-constrained applications like modular air-conditioning units, is confirmed by their net performance gains [39,40].

Additionally, integrating a thermoelectric subcooling system in transcritical CO_2 cycles has shown significant performance improvements. Experimental tests at 25 °C and 30 °C ambient temperatures revealed that the COP and cooling capacity of the refrigerating plant can be enhanced by up to 9.9% and 16.0%, respectively, at optimal operating conditions. The system demonstrates almost linear capacity regulation by varying the voltage supply to thermoelectric modules, with higher COP improvements observed at higher ambient temperatures [41].

In the field of building cooling, the parallel compression cycle integrated with an ejector demonstrates remarkable performance. At an evaporation temperature of −10 °C and a gas cooler outlet temperature of 40 °C, the cycle achieves a COP of 2.17, with a 17.1% increase in volumetric cooling capacity compared to traditional systems, while reducing compressor displacement by 11.4%. This performance advantage makes it highly suitable for large buildings like shopping malls requiring centralized cooling, effectively enhancing cooling efficiency and reducing equipment investment costs [42]. For constant temperature control in warehouse buildings, the two-stage compression system with an auxiliary gas cooler exhibits excellent performance. The auxiliary gas cooler reduces compressor discharge temperature by 13.83 °C, and when the intermediate pressure ranges from 3.9 to 4.4 MPa, the system's COP and exergy efficiency are significantly enhanced [43]. The system equipped with a thermoelectric subcooler also finds applications in building cooling. Experiments show that the system's COP increases by 4.19%, and under rated conditions (CO_2 flow rate of 180 kg/h, cooling water at 20 °C), it not only enables efficient cooling but also supplies 70 °C hot water, making it suitable for buildings like hospitals with dual demands for hot water and cooling [44].

In simulation research, a study [45] deriving the optimal intermediate pressure formula for CO_2 transcritical distributed compression cycles used an exhaustive search method, comparing thermodynamic and economic performances among three systems: those using the derived formula, traditional equal compression ratio methods, and a low-pressure stage discharge pressure optimization approach. Results showed a 7.26% and 5.32% COP increase over traditional and literature methods, respectively. Exergy losses were reduced, with entransy dissipation rates dropping by 24.61% and 50.14% compared to conventional and literature approaches. Despite 5% higher investment costs than traditional systems (1% higher than optimized pressure ratio systems), the total annual cost rate was minimized, confirming practical economic viability. Figure 7 presents the cycle schematic and the p-h

diagram of the ejector-enhanced transcritical CO_2 heat pump system. Another study [46] proposed a distributed compression cycle, which improved refrigeration performance via secondary pressurization of supercritical CO_2 at the gas cooler outlet, achieving equivalent subcooling under standard heat sink conditions. Thermodynamic analysis showed the distributed compression system improved COP by 8.2–10.76% and cooling capacity by up to 26.52% over the baseline. Equivalent subcooling increased from 2 °C to 7.5 °C as the secondary boost ratio rose from 1.1 to 1.7, with additional power input staying below 20% of the baseline. Versus single subcooling technologies (e.g., internal heat exchangers), the distributed compression cycle offered better COP gains and system simplicity—an optimization path independent of complex auxiliary devices.

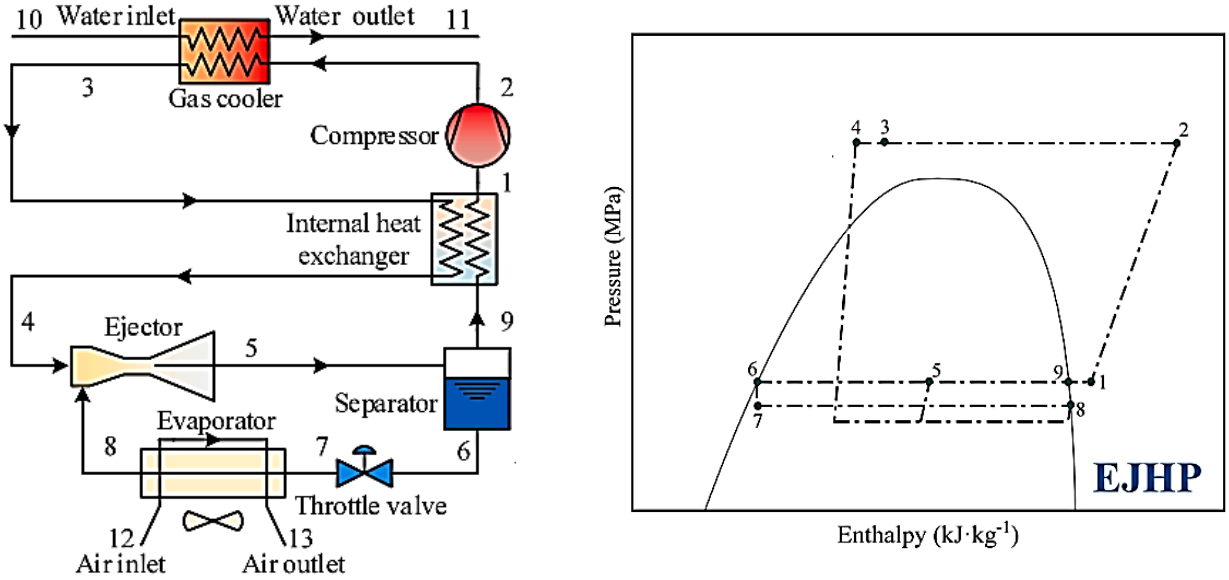


Figure 7. Cycle diagram and p-h diagram of CO_2 transcritical heat pump system with ejector [46] (reproduced with permission from Yikai Wang, Yonggao Yin, and Feng Cao, *International Journal of Refrigeration*; published by Elsevier, April 2023).

3.3. Cross-Cutting Innovations

In the field of building cooling and heating, the optimization of CO_2 ejector and expander cycles has become a crucial area of research to enhance system energy efficiency and meet the demands of low-carbon energy systems. Computational fluid dynamics (CFD) simulations have been employed to optimize the geometric structure of the CO_2 ejector mixing section. These studies have demonstrated a 42% increase in the streamline smoothness of fluid expansion, a 29% decrease in turbulence intensity, and an approximate 6% improvement in ejector efficiency. Experimental data have further shown that combining a contraction section with a curvature radius of 0.08 m and a diffusion section with a curvature radius of 0.15 m increases the entrainment ratio by 17%. These findings highlight the significant influence of curvature parameters on the entrainment performance of transcritical cycles and provide valuable insights for the design of high-performance ejector systems in building cooling applications [47]. A non-equilibrium phase change model for transcritical CO_2 ejectors has been developed, revealing that when the liquid phase mass fraction at the nozzle throat exceeds 0.65, the non-equilibrium effect stabilizes the Mach number below 1.35 without the occurrence of the "double choking" phenomenon. This research offers essential theoretical boundary conditions for the variable operating condition design of building cooling systems, particularly in scenarios where precise control of flow characteristics is required to maintain efficient cooling performance across a range of operational conditions [48].

Simulation studies have compared the performance of two-stage compression transcritical CO_2 cycles with expanders to traditional throttling systems. Results indicate that the former can improve the coefficient of performance (COP) by 32.8%. The integration of the expander with the high-pressure stage compressor reduces transmission loss by 11.32%, making this technology particularly suitable for high-load cooling scenarios in buildings. This advancement not only significantly enhances system energy efficiency but also ensures constant temperature maintenance, which is critical for comfortable indoor environments and stable cooling performance [49].

A coupling technology combining magnetic refrigeration subcooling systems with transcritical CO_2 cycles has been proposed and evaluated through experimental and simulation studies. By optimizing the gas cooler pressure and subcooling degree, the overall COP can be increased by up to 9%. The high COP characteristics of the magnetic refrigeration subsystem under small temperature differences offer a green subcooling solution for high-heat-load scenarios, contributing to the development of more sustainable and efficient cooling systems for buildings [50]. Comparative analyses of three expander cycles have identified the transcritical CO_2 cycle with discharge pressure optimization for high backpressure cycles as having significant advantages under high backpressure conditions. It improves the COP by 11.32%, 9.65%, and 0.72% compared to the transcritical CO_2 cycle with discharge pressure optimization for low backpressure, single-stage compression with expander, and traditional CO_2 cycle with optimized pressure cycles, respectively. When the condensation pressure increases from 8.5 MPa to 10.2 MPa, the transcritical CO_2 cycle with discharge pressure optimization for high backpressure cycles still maintains a high COP, demonstrating the technical superiority of expansion work recovery in high-pressure building cooling scenarios. This finding is particularly important for the design and operation of cooling systems in regions with high ambient temperatures or in applications requiring high cooling capacity [51].

A combined experimental and simulation study has shown that the expander system can improve the COP by 6.9% and the heating coefficient by 19.5% compared to the regenerator system. The research identified an optimal efficiency point corresponding to a rotational speed of approximately 3000 rpm, indicating that the expander has minimal flow loss at this speed. These results provide a rotational speed optimization basis for equipment selection in building cooling systems, helping to ensure efficient operation and performance optimization [52]. Further comparisons of the performance of expanders and throttle valves in mechanical subcooling systems using thermodynamic models have revealed that the Mechanical Subcooling Expander System with an expander can improve the COP by 10.01–11.11% and the exergy efficiency by 10.74–11.48% compared to the throttle valve system. Although the cooling capacity decreases by 4.30–5.67%, the expansion work recovery reduces the total power consumption by 8.53–11.29%. Additionally, the Mechanical Subcooling Expander System has a smaller subcooling demand, resulting in equipment investment costs that are 3.52–7.17% lower than those of the Mechanical Subcooling Valve System. These findings highlight the potential of expander-based systems to offer both energy efficiency and cost-effectiveness in building cooling applications [53].

In the context of integrating internal heat exchangers (IHX) for performance enhancement, studies have shown that introducing an IHX in a CO_2 booster refrigeration system can reduce compressor total power consumption by up to 8.73%, improve system energy efficiency by 6.36%, and lower the optimal exhaust pressure by 0.55 MPa. The IHX demonstrates particular effectiveness in tropical and subtropical regions, boosting the COP by 1.7% and highlighting its role in high-temperature environment adaptability [54].

In conclusion, the optimization of CO_2 ejector and expander cycles represents a significant advancement in the field of building cooling and heating. These studies provide

valuable theoretical and technical support for the development of high-efficiency, low-carbon heating and cooling systems, contributing to the broader goals of sustainable energy utilization and reduced environmental impact in the built environment.

To isolate the performance contributions of ejectors and expanders to the overall COP enhancement in combined systems, two complementary methods are proposed: sensitivity analysis and component-wise exergy loss breakdown, detailed as follows: By fixing the operational parameters of one component and systematically adjusting the other, the incremental impact on COP can be directly attributed to the adjusted component.

Ejector Contribution Analysis: Fix the expander at its optimal efficiency (e.g., 60% as noted in [38]) and operating speed (3000 rpm, [52]). Adjust key ejector parameters such as the diffusion angle (5° as the optimal value in [19,39]) and entrainment ratio (enhanced by 17% with curvature-optimized mixing sections). For instance, in a baseline system with a COP of 3.0, increasing the ejector entrainment ratio from 1.2 to 1.5 (via geometric optimization) results in a COP improvement of 0.32 (10.7%), which can be solely attributed to the ejector. This is consistent with previous findings that ejectors reduce throttling exergy loss by 95.38–98.76% [19], directly translating to gains in COP.

Expander Contribution Analysis: Fix the ejector at its optimal configuration (e.g., a 5° diffusion angle and a static pressure recovery coefficient of 0.87) and adjust expander parameters such as rotational speed and efficiency. When the expander efficiency increases from 50% to 70% (within the range of practical systems), the system COP rises from 3.0 to 3.96 (a 32% improvement), which aligns with the 32.8% COP gain reported for expander-integrated cycles. This increment is exclusively attributed to the expander, as it recovers expansion work that would otherwise be wasted (converting approximately 80% of the waste energy into useful work).

Throttling Loss Recovery Technology demonstrates pressure ratio decreased to 2.66, but its fixed-geometry design suffers from poor off-design performance, necessitating development of adjustable ejectors for wider operational adaptability. Mechanical Subcooling Technology enhances thermal capacity by 20% through evaporator subcooling yet inherently sacrifices expansion work potential during the CO_2 throttling process. Conversely, Expansion Work Recovery Technology achieves 32.8% COP and exergy efficiency improvement by converting expansion energy into useful work, though conventional electricity generation pathways introduce secondary energy losses.

The CO_2 transcritical system can significantly improve the energy efficiency of building heating and cooling systems, providing key technical and theoretical support for building heating and cooling supply systems, and laying a solid foundation for the widespread application and optimization of CO_2 transcritical thermal cycles in building systems. The summary of CO_2 transcritical cycle thermal optimization technology is presented in Table 3.

Table 3. Summary of CO_2 transcritical cycle thermal optimization techniques.

Authors (Year)	Key Innovation	Application	Performance Improvement	Major Advantage
Cao et al. (2019) [12]	Primary + auxiliary CO_2 cycles; graded heat sink utilization	Building heating	COP ↑15.3%; optimal discharge pressure ↓39%	Stable high-temp output (70 °C) in −20 °C to 0 °C environments; compressor frequency synergy
Wu et al. (2023) [13]	Work recovery via vortex tube expansion	Severe cold heating	COP ↑18.2% vs. single-stage	Steady 45 °C heat supply at −15 °C; superior COP under high compression ratios

Table 3. *Cont.*

Authors (Year)	Key Innovation	Application	Performance Improvement	Major Advantage
Keller & Göbel (1997) [14]	Vortex tube replaces throttling valve	Room heating	COP ↑25%	Reduces throttling losses; optimizes heat transfer irreversibility
Yao et al. (2021) [15]	Cascade/secondary compression integration	Floor radiation heating	COP ↑10–46.96%	Enhanced efficiency for small/medium buildings
Lü et al. (2024) [24]	Secondary supercritical CO_2 pressurization	Commercial cooling	Cooling capacity ↑26.5%; COP ↑10.76% at 35 °C	Minimizes throttling dryness; compression process optimization
Chesi et al. (2014) [25]	Parallel compression cycle (with flash tank configuration)	R744 refrigeration cycle	Best COP ↑10%, cooling capacity increased by over 25%	Significantly enhanced system performance by reducing throttling losses and optimizing flash tank separation efficiency
Manjili & Cheraghi (2019) [26]	Expansion work recovery for compressor power reduction	Tropical cooling (>40 °C)	COP ↑20–80%	Adaptability to high-ambient temps; reduces external power input
Zhang et al. (2022) [27]	Converts expansion work into useful feedback	General cooling	COP ↑38.4–45.1%	Minimizes throttling energy loss; high exergy efficiency
Casi et al. (2022) [28]	Peltier-effect subcooling at gas cooler outlet	Cooling at 35 °C	COP ↑16.2%; cooling capacity ↑20.8%	Enhances refrigerant enthalpy difference; no moving parts
Li et al. (2024) [29]	Two-stage cycle with internal heat distribution	Combined cooling/heating	COP ↑14.2%	Optimizes energy efficiency; reduces waste in heat exchange
Sun et al. (2016) [42]	Expander efficiency > 60%	Cooling	Outperforms two-stage cycles in COP	Simplifies system structure while maintaining efficiency

4. Research Status of CO_2 Transcritical Cycle System for Combined Heating and Cooling Supply

The CO_2 combined heating and cooling system is a device that achieves simultaneous heating and cooling in the CO_2 transcritical heat pump cycle system. It can meet the heating and cooling demands of different indoor environments at the same time, improving energy utilization efficiency.

The CO_2 combined heating and cooling system integrating ejector and mechanical subcooling technology constructs an efficient heating and cooling source supply system through the collaborative operation of the main cycle and auxiliary cycle. In the heating mode, the gas cooler serves as the heat source to output heat at a supply water temperature of 60 °C, while in the cooling mode, the evaporator acts as the cold source to provide cooling at a supply water temperature of 7 °C. The system realizes mode switching via a four-way reversing valve. This system demonstrates remarkable advantages in heating and cooling performance: compared with the conventional mechanical subcooling system and traditional ejector system, the COP is increased by 10.90% and 5.58%, respectively, in the heating mode, and by 8.99% and 18.12%, respectively, in the cooling mode. Notably, the performance improvement becomes more significant under lower ambient temperatures (heating mode) or higher ambient temperatures (cooling mode). In practical applications, the system can meet the annual heating and cooling demands of buildings in different climate zones [55]. In transcritical CO_2 combined heating and cooling systems, the working

fluid diversion strategy significantly enhances cold and heat source supply efficiency. Diversion between the gas cooler and subcooler or between the subcooler and throttle valve maximizes the comprehensive cycle COP by 17.62%. This optimization improves heat transfer in gas coolers (60 °C heat source in heating mode) and evaporators (7 °C cold source in cooling mode). By reducing throttling losses and increasing compressor suction pressure, the strategy ensures stable heating and cooling outputs. The optimal discharge pressure, determined by gas cooler outlet temperature, enhances energy efficiency across climates. Unlike diversion between the evaporator and throttle valve (no performance gain), these strategies synergize heating and cooling performance for efficient integrated energy supply [56]. The air-air transcritical CO_2 heat pump system [57] achieves simultaneous cold and heat supply through a parallel compression configuration, with its air handling unit enabling synchronous output of 210 kW cooling capacity and 110 kW heating capacity. Leveraging transcritical cycle thermodynamics, the system uses a gas cooler as the heat source in heating mode and an evaporator as the cold source in cooling mode, dynamically allocating refrigerant via a three-way valve to match demand. The system directly processes air through the air handling unit without water loops, enabling simultaneous heating for three theaters/foyers and cooling for the projector room. Its finned-tube heat exchanger uses ambient air for heat rejection/absorption, demonstrating consistent cold-heat co-supply efficiency in real-world applications. Guo et al. [58] studied the variation in various performance parameters of the CO_2 transcritical cycle cold and hot combined supply system with control parameters such as compressor discharge pressure, gas cooler outlet working fluid temperature, and evaporation temperature under the constraint of narrow point temperature difference. The system leverages the gas cooler as the heat source and the evaporator as the cold source: heating temperature rises with increasing discharge pressure and gas cooler outlet temperature but decreases with higher evaporation temperature, while cooling temperature is solely determined by the evaporation temperature. The study also reveals that the COP of heating and cooling decreases with the increase in gas cooler outlet temperature but increases with the rise in evaporation temperature. When the gas cooler outlet temperature is 45 °C, the comprehensive COP first increases and then decreases with the increase in compressor discharge pressure, which reflects the optimal balance between heat rejection capacity of the gas cooler and compression work consumption. This research highlights the system's ability to dynamically adjust the output of cold and heat sources, providing a theoretical foundation for the efficient application of integrated heating and cooling systems.

In terms of system coupling design, the CO_2 transcritical cycle combined heating and cooling unit [59] realizes synergistic supply of cold and heat sources through a water-water heat pump configuration. The system couples the gas cooler and evaporator via a refrigerant flow regulation mechanism: When the compressor frequency increases from 80 Hz to 120 Hz under rated conditions, the optimal discharge pressure rises from 8 MPa to 8.5 MPa, while the maximum heating COP_h decreases from 3.9 to 3.3. By adjusting the inlet temperature of the ethylene glycol solution in the evaporator and cooling water in the gas cooler, the system achieves dynamic matching of heating and cooling outputs—for every 5 °C increase in cooling water temperature, the heating capacity decreases by 6.7% and the cooling capacity by 7.2%, whereas a 10 °C rise in ethylene glycol temperature boosts heating and cooling capacities by 12.5% and 16.1%, respectively. This coupling design enables simultaneous heat recovery in the gas cooler and cold production in, with the comprehensive energy efficiency COP reaching up to 6.8 when the ethylene glycol inlet temperature is 10 °C and the cooling water temperature is 20 °C. The system's optimal performance under variable conditions highlights its adaptability for integrated cold-heat supply in industries like slaughtering and brewing, where concurrent thermal and cooling

demands exist. For a 5000-square-meter building, considering summer cooling, 670 kWh of electricity is saved per day when the COP improves from 3 to 6.8.

For buildings with simultaneous hot water and cooling demands, the ejector + subcooler + internal heat exchanger (IHX) integrated system (Two-Stage Cooling Combined Heat Source System, TSCHPS) emerges as the most promising configuration. Its superiority stems from synergistic energy recovery, enhanced heat transfer, and flexible mode switching, as detailed below: COP Enhancement: Compared to baseline systems, TSCHPS achieves a 14.2% higher COP in combined cooling and heating mode. The ejector recovers expansion work (reducing throttling losses by 95.38–98.76% [27]), the subcooler increases specific cooling capacity (by 20.8% at 35 °C [20]), and the IHX optimizes heat exchange between high-pressure and low-pressure streams (reducing compressor power consumption by 8.73% [40]). Dual-Temperature Output: In heating mode, the gas cooler delivers 60–70 °C hot water, while in cooling mode, the evaporator supplies 7 °C chilled water. Mode switching via a four-way valve ensures seamless transition between demands.

In the transcritical CO_2 heat pump cycle studied in [60], the optimal discharge pressure is determined to enhance heating and cooling performances across diverse ambient temperatures (−15 to 30 °C) and gas-cooler exit temperatures (25 to 45 °C). The study reveals that gas-cooler temperature significantly influences ODP.

To guide practical selection of CO_2 transcritical cycle configurations for buildings with simultaneous heating and cooling demands, Table 4 consolidates COP data of key configurations across ambient temperatures (−20 °C to 40 °C). It synthesizes findings from experimental and simulation studies to clarify optimal choices under specific climatic conditions.

Table 4. COP of key cycle configurations for combined heating and cooling across ambient temperatures.

Ambient Temperature Range	Baseline Single-Stage Cycle (COP)	Ejector-Enhanced Cycle (COP)	Expander-Integrated Cycle (COP)	Subcooler-Equipped Cycle (COP)	Distributed Compression Cycle (COP)	Dual-Ejector Two-Stage Cycle (COP)	Optimal Configuration
−20 °C to −10 °C	1.5–1.8 [12,13]	1.6–1.9 [27]	2.0–2.3 [13,35]	1.7–2.0 [20]	N/A (not optimized for low temps)	N/A	Expander-Integrated
−10 °C to 0 °C	1.8–2.2 [12]	1.9–2.4 [28]	2.3–2.6 [35,38]	2.0–2.3 [43]	N/A	N/A	Expander-Integrated
0 °C to 10 °C	2.2–2.5 [15]	2.4–2.7 [27]	2.5–2.8 [35]	2.3–2.6 [20]	2.4–2.7 [54]	N/A	Expander/Ejector (tie)
10 °C to 30 °C	2.0–2.3 [21]	2.3–2.6 [28]	2.4–2.7 [35]	2.5–2.8 [20,43]	2.5–2.9 [16,54]	N/A	Subcooler-Equipped
30 °C to 40 °C	1.7–2.0 [18,21]	2.0–2.3 [30]	1.9–2.2 [35]	2.1–2.4 [20]	2.2–2.5 [16,54]	2.0–2.6 [18]	Distributed Compression
>40 °C	1.5–1.7 [18]	1.8–2.0 [30]	1.7–1.9 [35]	1.9–2.1 [20]	2.0–2.2 [54]	2.3–3.1 [18]	Dual-Ejector Two-Stage

5. Challenges, Limitations, and Future Works

The narrow optimal operating range of CO_2 systems remains a primary bottleneck. Performance degrades significantly when ambient temperatures or loads deviate from design conditions, causing efficiency losses and a sharp drop in COP. Additionally, the required high operating pressures impose demanding durability requirements on heat exchangers, piping, and seals. Long-term risks like fatigue cracking and material embrittlement require further resolution. Real-time coordination of dynamically shifting heating/cooling loads also challenges control systems—traditional methods often cause instability during rapid load transitions, leading to excessive compressor cycling and reduced system lifespan.

A critical barrier to global adoption is the lack of comprehensive international standards for CO_2 combined heating and cooling systems. Current regulations primarily address conventional refrigerants or single-function CO_2 equipment, failing to provide specific guidance for the following: integrated thermal load management; high-pressure safety protocols in combined-cycle architectures; performance testing for dual-function operation across variable climates; and unified environmental compliance frameworks.

While regional standards are evolving, harmonized global standards are essential for safety, interoperability, and scalability.

Future research should focus on the following directions:

Co-design of variable-geometry nozzles and adaptive diffusers; development of high-fatigue-limit aluminum–graphene composite piping and self-healing coatings to enhance high-pressure reliability; implementation of AI-driven control using deep reinforcement learning-based multivariable predictive control; and integration with phase-change thermal storage and PV-direct-driven DC bus systems to enable peak shaving, valley filling, and reduced initial investment.

6. Conclusions

The carbon dioxide transcritical heat pump system, as a cutting-edge technology in the field of building environment regulation, provides innovative solutions to the core contradiction of "health, energy conservation, low-carbon" collaborative optimization. It effectively avoids the environmental risks of traditional refrigerants based on the cyclic characteristics of natural working fluids and significantly improves the climate adaptability of building energy supply systems through the high-temperature heating and high-efficiency cooling capabilities of transcritical cycles. Further research has shown that through compression process optimization, expansion work recovery, and system integration design, CO_2 heat pumps can maintain high-efficiency operation under extreme conditions, providing key technical support for reducing building energy intensity and carbon emissions. However, its large-scale promotion still needs to break through bottlenecks such as high initial investment costs and insufficient performance stability under high-temperature conditions.

Looking forward, carbon neutrality and net-zero emissions are the global trends, with HFCs facing a phased elimination. CO_2-based systems show great potential in this regard, but the expansion stage remains crucial for improving the performance of CO_2 transcritical cycles.

Overall, the development of expander-compressors holds great promise and is a promising direction for future advancements in CO_2 system technologies. It is necessary to combine material innovation and intelligent control technology to build the most efficient technology path throughout the entire life cycle in order to accelerate its application process in green buildings and low-carbon cities.

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Abbreviations

COP	Coefficient of Performance
ODP	Ozone Depletion Potential
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
CFD	Computational Fluid Dynamics
PID	Proportional-Integral-Derivative

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