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Review Article

Advances in Subcooling Techniques for Transcritical CO_2 Refrigeration Systems: A Comprehensive Review

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ABSTRACT

Transcritical CO_2 refrigeration systems are increasingly adopted as low-GWP alternatives; however, their performance deteriorates due to high gas cooler pressures and large throttling losses. Subcooling the refrigerant before expansion is a key thermodynamic solution to mitigate these losses, yet a comprehensive and updated synthesis that directly compares the performance and applicability of diverse subcooling techniques within a unified framework is lacking. This review addresses that gap by providing a structured, critical analysis of both internal and external subcooling methods, including internal heat exchangers (IHX), ejector- and expander-assisted systems, and mechanical and thermoelectric subcoolers. The consolidated findings indicate that for high-ambient conditions, mechanical subcooling consistently emerges as the most effective approach, offering substantial COP improvements (20-40%) and in the case of DMS, significant discharge pressure reduction. This review further examines integration challenges, advanced control strategies, and emerging hybrid and renewable-assisted systems, offering valuable insights for researchers and designers aiming to enhance the sustainability and performance of next-generation CO_2 refrigeration technologies.

1. Introduction

The refrigeration and air-conditioning industry is gradually shifting toward environmentally benign refrigerants in response to tightening regulations on greenhouse gas emissions. Among the available alternatives, carbon dioxide (CO_2, R744) has gained significant attention as a natural refrigerant due to its near-zero global warming potential, its non-flammable and non-toxic nature, and widespread availability. As a result, many researchers have turned their attention to natural refrigerants, with carbon dioxide (CO_2) being actively explored as a viable alternative to hydrofluorocarbons (HFCs) in refrigeration and air-conditioning applications [1–5].

1.1. Cycle Description

In a typical transcritical CO_2 system, the cycle consists of compression, gas cooling (instead of condensation), expansion, and evaporation. The gas cooler replaces the condenser, where heat is removed from the supercritical CO_2 without a phase change.

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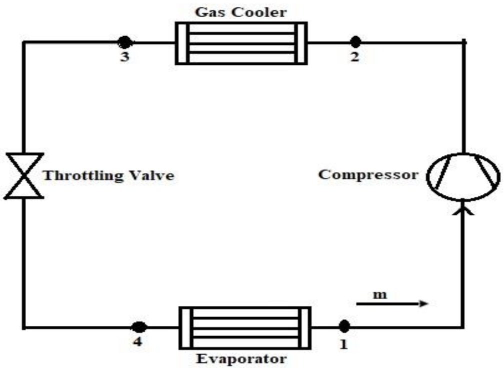
In this cycle, a significant portion of heat is rejected while CO_2 operates in the supercritical region, which exists beyond its critical point. Unlike subcritical systems, this region does not exhibit saturation conditions, and pressure becomes largely independent of temperature. As a result, the conventional condenser is replaced by a gas cooler that performs heat rejection under supercritical conditions. Meanwhile, the process of heat absorption continues through the evaporation of the refrigerant at low pressure, closely resembling the behavior observed in traditional subcritical vapor compression cycles. Figure 1 presents the schematic layout of a typical transcritical CO_2 refrigeration system, accompanied by its corresponding pressure–enthalpy (P-h) diagram.



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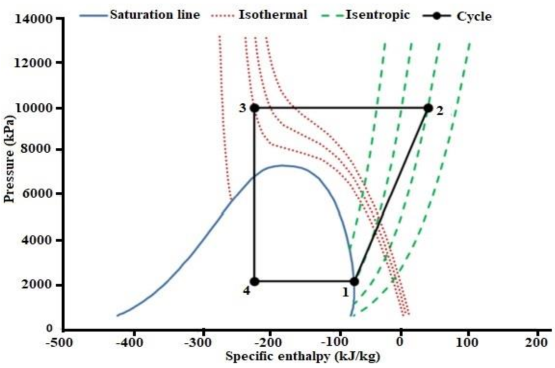

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Fig. 1. Transcritical CO_2 refrigeration system (a) configuration; (b) p-h diagram [6]

1.2. Transcritical CO_2 Refrigeration Systems: Challenges and the Role of Subcooling

Despite of favourable conditions for using CO_2, its practical adoption in refrigeration is challenged by the performance of transcritical cycles, especially in warm climates. The core issue lies in the thermodynamic process itself. In a transcritical CO_2 cycle, heat rejection occurs in a gas cooler above the critical point (31.1°C, 73.8 bar), where no condensation takes place. This results in a high-temperature, high-pressure fluid entering the expansion device. The subsequent isenthalpic expansion across the throttle valve results in significant throttling losses, characterized by a large irreversibility that significantly reduces the refrigerating effect. Therefore, enhancing the performance of transcritical CO_2 systems fundamentally requires strategies to mitigate these expansion losses. Subcooling (lowering the refrigerant temperature before the expansion device) emerges as a critical thermodynamic solution. By increasing the specific enthalpy difference across the evaporator, subcooling directly counteracts throttling losses, improves cooling capacity, and can allow operation at a lower optimal discharge pressure, thereby enhancing overall system COP.

Interest in transcritical CO_2 refrigeration systems has increased steadily in response to the global shift toward low-GWP refrigerants and advances in high-pressure system technology. This growing research activity is reflected in the rising number of scientific publications. Figure 2 presents the publication trend from 1998 to 2025 based on data extracted from the Scopus database.

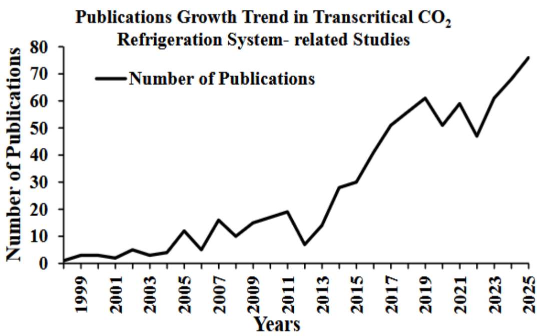


Fig. 2. Growth in the number of publications on transcritical CO_2 refrigeration systems (1998-2025) based on Scopus data

1.3. Scope, Objectives, and Novelty of the Present Review

To overcome the limitations of transcritical CO_2 refrigeration systems, this review focuses on subcooling-oriented performance enhancement strategies as a primary focus, given their strong potential to improve the efficiency of transcritical CO_2 refrigeration systems under high-ambient conditions. Different subcooling concepts, including internal heat exchangers, mechanically driven auxiliary cycles, dedicated subcooling loops, and thermoelectric modules, have been investigated through experimental, numerical, and theoretical studies. The influential review by Llopis et al. [7] systematically summarized the subcooling concepts developed up to that time and provided valuable thermodynamic insights into their performance. While this work established a solid foundation, the field has evolved considerably since then. In recent years, research has increasingly focused on system optimization, hybrid configurations combining subcooling with ejectors or expanders, and experimental validation under realistic operating conditions. In addition, more attention is now being paid to operational aspects such as discharge pressure reduction, compressor thermal limits, annual energy performance, and system controllability, which are critical for commercial applications.

Despite the growing body of literature published after 2018, many recent review studies address only specific enhancement technologies or individual system components. A comprehensive and updated review that focuses exclusively on subcooling techniques and compares their performance, complexity, and applicability within a unified framework is still lacking. Addressing this gap, this review provides a structured, critical synthesis of subcooling strategies for transcritical CO_2 refrigeration systems, with emphasis on recent developments. Its novelty lies in the use of unified comparison tables that consolidate study focus, performance metrics, and key findings, enabling direct cross-comparison of subcooling approaches. Furthermore, the review examines integration challenges, advanced control strategies, and emerging hybrid and renewable-assisted systems, highlighting their practical potential for advancing sustainable CO_2 refrigeration.

2. Subcooling Technique in Transcritical CO_2 Refrigeration Systems

Subcooling in this system can be achieved by internal subcooling methods and dedicated Subcooling Methods. These methods enable lowering the refrigerant temperature before expansion, which increases the refrigerating effect and improves system efficiency.

2.1. Internal Subcooling Methods

Internal subcooling methods in transcritical CO_2 refrigeration systems use the system components to further cool the CO_2, resulting in it exiting the gas cooler at a lower temperature. This is typically achieved by employing an internal heat exchanger (IHX) and integrated mechanical subcooling.

2.1.1. Internal Heat Exchanger

In a transcritical CO_2 refrigeration system, incorporating an internal heat exchanger is a well-established method for performance enhancement, primarily by subcooling the high-pressure refrigerant and superheating the suction gas. The integration of an internal heat exchanger in this system can be categorized into cases, such as frequently adopted configurations, IHX with ejector, IHX with expander, etc. The general schematic layout of this system is shown in Figure 3.

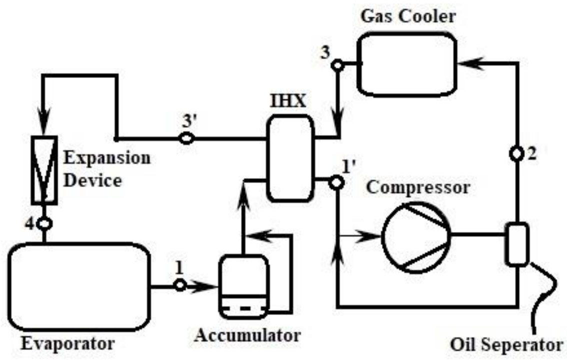


Fig. 3. General Layout of IHX integrated Transcritical CO_2 refrigeration system [8]

(i) Frequently adopted configurations

The internal heat exchanger is typically placed in the section connecting the gas cooler outlet and the evaporator exit. In certain configurations, it may also be placed between the evaporator outlets and downstream of the expansion device. Additionally, some systems employ a dual heat exchanger arrangement to further enhance system performance.

Application of Frequently Adopted Configuration of Internal Heat Exchangers for Subcooling in Transcritical CO_2 Refrigeration Systems: A Study of Reported Research

Rather than simply listing previous studies, this section brings their findings together to explain how conventional IHX layouts perform, what performance compromises are involved, which factors matter most, and how designs are being optimized. The benefit of incorporating an internal heat exchanger lies in its combined effect on both the refrigeration effect and the operating conditions of the compressor. By enhancing liquid subcooling while simultaneously increasing suction superheat, the IHX modifies the thermodynamic balance of the transcritical CO_2 cycle consistently shifting the optimum gas cooler pressure to lower values [8, 9]. This reduction in optimal pressure is particularly advantageous in transcritical operation, as compressor power consumption is strongly pressure dependent. As a result, improvements in the coefficient of performance reported in the literature commonly range from 5% to 25%, with the magnitude of the benefit highly sensitive to operating conditions. The largest gains are repeatedly observed under high ambient temperatures and low evaporating temperatures, where the reference cycle operates far from optimal conditions and the scope for pressure reduction is greatest [10, 11]. These performance gains, however, are accompanied by an important constraint. The increased suction superheat caused by the IHX leads to a noticeable rise in compressor discharge temperature, frequently reported in the range of 10-20 °C [9, 10]. This imposes practical limits on IHX effectiveness and necessitates careful compressor and system design to avoid reliability issues, particularly in systems with limited cooling capabilities. The location of the IHX within the refrigeration circuit further influences its overall impact. Most studies identify the configuration linking the gas cooler outlet with the evaporator outlet (suction line) as the most effective arrangement, offering a favourable balance between subcooling and system integration (Figure 4). Alternative placements, such as downstream of the liquid receiver (Figure 5), generally yield smaller efficiency improvements. Notably, a dual-IHX configuration (Figure 6) has been demonstrated to maximize COP improvements (up to 13%), but at the expense of further escalating discharge temperatures and system complexity, raising questions about its cost-benefit ratio in commercial applications. Furthermore, the IHX influences optimal control parameters. Beyond simple implementation, IHX design plays a decisive role in determining net performance gains. Excessive heat exchanger length or effectiveness can increase suction-side pressure losses, offsetting improvements from enhanced subcooling. Experimental and numerical investigations, therefore, point to the existence of an optimal IHX size. For example, Cao et al. [12] identified an optimal length of approximately 2.5 m for a transcritical CO_2 heat pump, which maximized COP while keeping discharge temperatures within acceptable limits. More recent studies have extended the role of the IHX by integrating it with CO_2-based refrigerant mixtures, such as blends with R32 or R1234yf. These mixtures further lower optimal operating pressures, and when combined with IHX application, COP improvements exceeding 22% relative to pure CO_2 systems have been reported, suggesting a promising hybrid strategy for future system development [13]. Additionally, transient analyses reveal that the IHX's effectiveness can be highly variable during startup, with COP penalties observed during this period due to shifting thermophysical properties, highlighting a consideration for applications with frequent cycling [14]. Advanced analyses, including exergy and exergoeconomic approaches, point to the compressor and gas cooler as the dominant sources of irreversibility, suggesting that while the IHX improves energy efficiency, the focus for major exergy savings should remain on these primary components [15, 16].

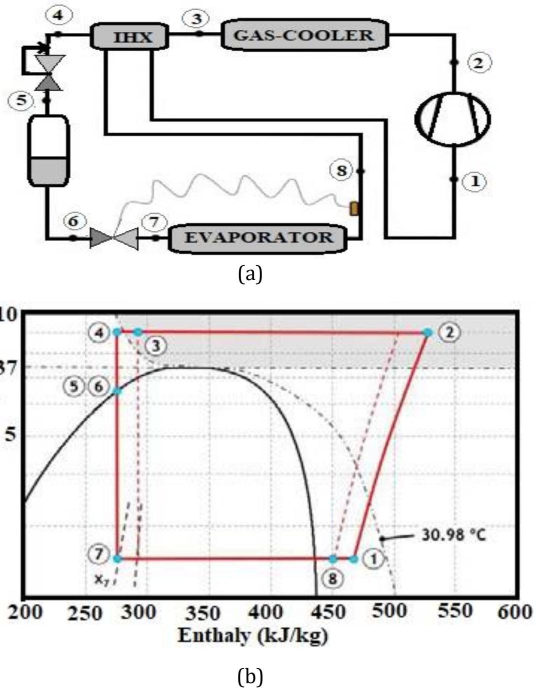


Fig. 4. Internal heat exchanger positioned at the gas cooler exit (left) and corresponding pressure-enthalpy (P-h) diagram (right) for a transcritical CO_2 refrigeration system [9]

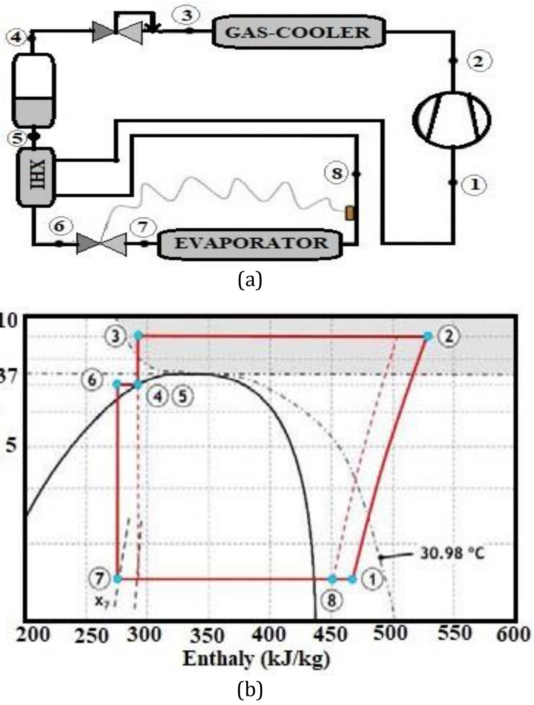
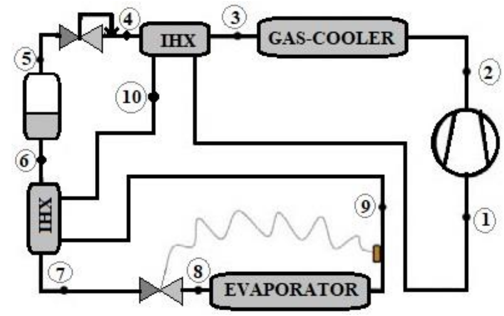


Fig. 5. Internal heat exchanger positioned at liquid receiver outlet (left) and corresponding pressure-enthalpy (P-h) diagram (right) for a transcritical CO_2 refrigeration system [9]



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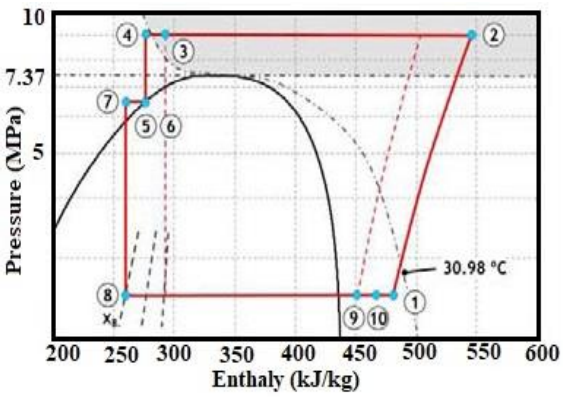

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Fig. 6. Configuration of dual internal heat exchangers (left) and corresponding pressure-enthalpy (P-h) diagram (right) for a transcritical CO_2 refrigeration system [9]

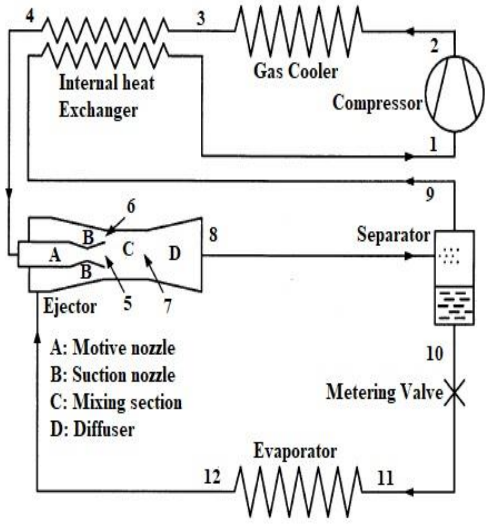
(ii) Internal heat exchanger with ejector

Subcooling in transcritical CO_2 refrigeration systems can be effectively achieved using internal heat exchangers paired with ejectors. This integration aids in reducing throttling losses while improving the refrigerant quality before expansion. However, research indicates that this combination does not always yield significant performance gains and may involve significant trade-offs depending on system design and operating conditions.

Application of Internal Heat Exchangers with Ejector for Subcooling in Transcritical CO_2 Refrigeration Systems: A Study of Reported Research

Numerous experimental, theoretical, and simulation-based studies have been conducted to evaluate the performance benefits of integrating an IHX with the ejector for subcooling in a transcritical CO_2 refrigeration system.

Elbel and Hrnjak [17] conducted a validated simulation study of transcritical CO_2 ejector systems, comparing their performance to conventional systems. Figure 7 (a) illustrates the configuration of the most complex ejector-based system examined, while figure 7 (b) presents the corresponding P-h diagram under typical operating conditions for this arrangement.



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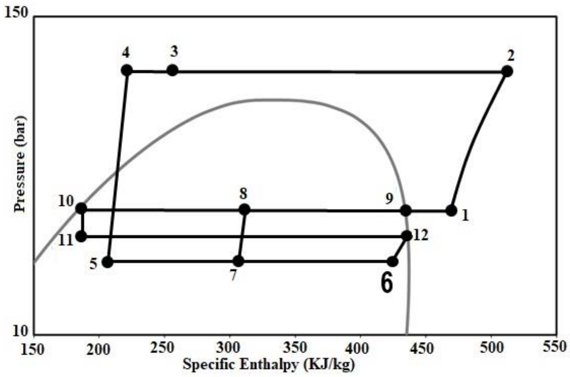

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Fig. 7. (a) Schematic of the IHX with ejector-based transcritical CO_2 refrigeration system; (b) Corresponding P-h diagram [17]

The IHX typically enhances subcooling and increases the primary flow rate through the ejector, but it often reduces the ejector's pressure lift and work recovery potential [18]. This occurs because the IHX elevates the motive stream temperature entering the ejector, thereby diminishing the entrainment ratio and overall ejector efficiency. Consequently, although the IHX may improve the coefficient of performance (COP) under specific conditions, its integration can weaken the ejector's contribution to cycle efficiency, particularly in heating applications or at higher gas cooler outlet temperatures [18, 19].

The effectiveness of the IHX-ejector configuration is highly sensitive to operational parameters. For instance, Nakagawa et al. [20] demonstrated that longer IHXs could increase COP by up to 27%, emphasizing the importance of geometric optimization. Conversely, other analyses suggest that in dual-ejector systems or at low temperatures, the inclusion of an IHX may offer negligible or even negative performance benefits, questioning its utility in such layouts [21]. Furthermore, the optimal performance of these hybrid systems is closely tied to the isentropic efficiency of the ejector and the temperature at the gas cooler and evaporator [19].

A critical synthesis of the literature underscores that the role of an IHX in ejector cycles diverges markedly from its function in conventional throttle-valve systems. In standard cycles, the IHX consistently provides COP improvements by mitigating expansion losses. In contrast, within ejector-assisted systems, its impact is conditional and can sometimes detract from the ejector's efficiency benefits [17]. This highlights the need for a system-level design approach that carefully balances the IHX's subcooling advantages against potential degradations in ejector performance, rather than assuming additive benefits. Large-scale supermarket refrigeration systems integrating internal heat exchangers and ejector-based subcooling have demonstrated measurable improvements in seasonal energy efficiency and reduced discharge pressure, especially under high ambient temperature conditions. Future designs should focus on customized integration, where the internal heat exchanger is carefully matched to the specific ejector and its operating conditions. This will help capture potential benefits while ensuring the ejector's performance is not negatively affected.

(iii) Internal heat exchanger with Expander

Subcooling in transcritical CO_2 systems can be enhanced by using an internal heat exchanger paired with an expander, aiming to recover work and reduce throttling losses. This configuration improves system efficiency by lowering the refrigerant temperature before expansion while utilizing the expander for additional power recovery. It offers a practical pathway to boost COP in sustainable refrigeration applications.

Application of Internal Heat Exchangers with Expander for Subcooling in Transcritical CO_2 Refrigeration Systems: A Study of Reported Research

Early cycle-level analyses, as shown in Figure 8, demonstrated that replacing the throttling valve with an expander significantly reduces irreversibility by converting part of the pressure energy into useful work, which can be utilized to assist compression or generate auxiliary power [22]. However, when an IHX is added upstream of the expander, the thermodynamic interaction becomes more complex. While the IHX increases the degree of subcooling and the specific refrigeration effect, it also alters the inlet state of the expander, which can reduce recoverable work under certain conditions [23].

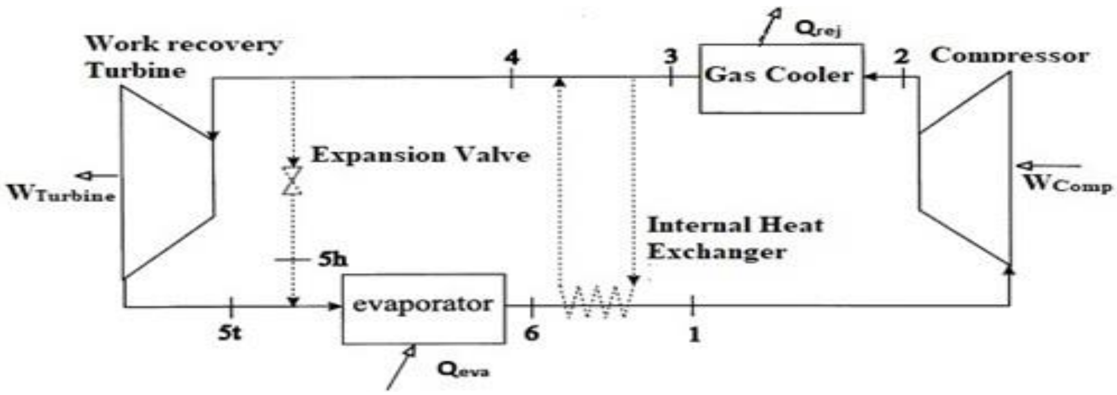
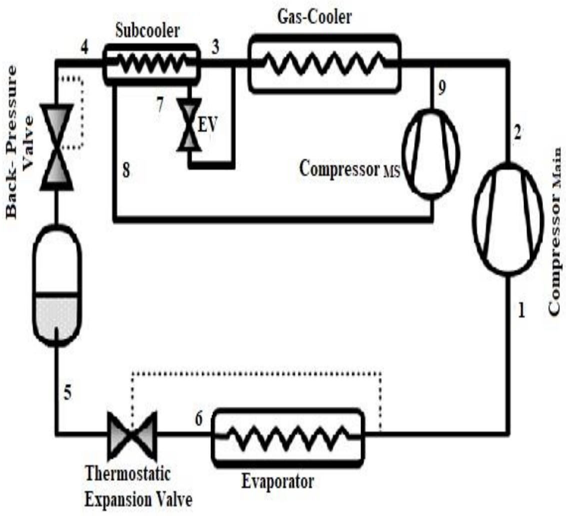


Fig. 8. Schematic of the carbon dioxide cycle with and without IHX and expander [22]

Subsequent comparative energy and exergy analyses consistently indicate that the presence of an IHX in expander-based cycles does not universally improve the coefficient of performance (COP). Shariatzadeh et al. [24] showed that, although IHX integration improves performance in valve-based expansion cycles, it may reduce both COP and exergy efficiency when combined with an expander, primarily due to diminished expander power output. Similar conclusions were reported by Li et al. [25] for cascade CO_2 systems, where high-temperature IHX operation decreased expander recovery work despite lowering the optimal high-side pressure. More recent studies suggest that the effectiveness of the IHX-expander combination depends strongly on expander isentropic efficiency, gas cooler outlet temperature, and system complexity. Zhang et al. [23] demonstrated that COP improvements are achievable only when the expander efficiency exceeds a threshold, and when the gas cooler outlet temperature is sufficiently high. In contrast, under moderate ambient conditions or low expander efficiencies, the additional pressure drop and thermal coupling introduced by the IHX can outweigh its subcooling benefit. Advanced cycle configurations indicate that the limitations of simple IHX-expander integration can be partially mitigated through multi-stage compression or optimized control strategies. Shi et al. [26] proposed and evaluated a transcritical CO_2 refrigeration system integrating an internal heat exchanger, expander, and two-stage compression to enhance system performance. Their study demonstrated that adjusting cycle conditions and IHX effectiveness can lower power consumption and exergy losses while improving COP. These findings suggest that IHX-expander systems are better suited to advanced or hybrid architectures rather than simple single-stage transcritical cycles. Overall, the literature indicates that IHX integration in expander-based transcritical CO_2 systems is not inherently beneficial and should not be treated as a direct extension of throttling-based IHX strategies. Its performance advantage is highly application-specific and depends on expander efficiency, operating temperature range, and system integration level. Future research should therefore focus on optimization of IHX effectiveness, expander design, and pressure control, rather than isolated component improvements, to fully exploit the potential of work-recovery-assisted subcooling in CO_2 refrigeration systems.

2.1.2. *Integrated Mechanical Subcooling*

Integrated mechanical subcooling can provide significant subcooling at the gas cooler outlet by splitting the CO_2 stream and using an auxiliary loop with an expansion valve and compressor to subcool the main flow. Unlike economized cycles, this setup allows a higher evaporation level in the subcooler, enabling the auxiliary compressor to operate at lower compression ratios with improved efficiency. The general schematic and P-h diagram of integrated mechanical subcooling for the Transcritical CO_2 refrigeration system are shown in figure 9.



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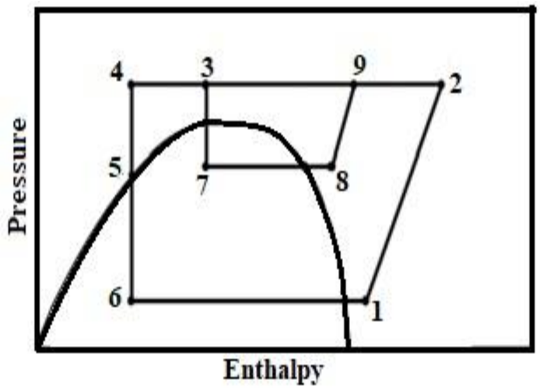


(b)

Fig. 9. Schematic layout of the integrated mechanical subcooling configuration (a) and pressure-enthalpy (P-h) diagram (b); for a transcritical CO_2 refrigeration system [27]

Application of Integrated Mechanical Subcooling for Subcooling in Transcritical CO_2 Refrigeration Systems: A Study of Reported Research

Cecchinato et al. [28] conduct a thermodynamic evaluation of this system, including split and phase separation configurations. Their study analyzes the impact of internal heat transfer and intermediate cooling on performance while optimizing upper and intermediate pressures for each cycle. Their results provide a clear guidance on achieving optimal energy performance, highlighting the potential of advanced two-stage configurations to improve CO_2 system efficiency. Thermodynamic and experimental investigations further reveal that the theoretical advantages of integrated mechanical subcooling are frequently constrained by practical design limitations. Optimal subcooling levels and gas cooler pressures can substantially improve system efficiency, but achieving these conditions often pushes auxiliary compressors beyond their standard operating envelopes, highlighting the need for dedicated compressor design and careful selection of the subcooling extraction point [27, 29, 30]. These findings emphasize that configuration choice affects not only efficiency but also cooling capacity, component sizing, and operational reliability. Beyond hardware configuration, recent work highlights the growing importance of control strategies and working-fluid selection. Advanced real-time optimization methods enhance system adaptability under variable operating conditions, reducing convergence time and improving overall performance [31]. In parallel, the introduction of refrigerant mixtures into integrated subcooling cycles demonstrates additional efficiency gains and enables the system to operate under more favorable thermodynamic conditions. However, this also comes with drawbacks, such as lower volumetric capacity and greater sensitivity to the exact mixture composition [32].

Table 1 below summarizes major studies on internal subcooling methods in transcritical CO_2 systems, including internal heat exchangers (IHX), IHX coupled with ejectors, expander-based cycles, and integrated mechanical subcooling (IMS). These reviewed studies show that these approaches can noticeably improve COP and overall system efficiency by reducing throttling losses and better utilizing available heat. However, the actual performance gains depend strongly on system layout, component efficiency, and operating conditions. In general, IHX and IMS provide more stable improvements, while ejectors and expanders require careful system matching, as their benefits can decrease if the design is not well optimized.

Table 1. Key studies on IHX, ejector-IHX, expander-IHX, and IMS subcooling approaches in Transcritical CO_2 systems

Author(s) & Year	Study Focus	Performance Metrics Examined	Key Findings / Improvements
Boewe et al. (2001) [33]	Coaxial IHX in mobile AC system	COP, Cooling capacity, pressure drop, IHX effectiveness	-Up to 25% efficiency gain -50% material reduction with 10% higher effectiveness.
Chen & Gu (2005) [8]	Impact of discharge pressure and IHX effectiveness	COP, optimal pressure correlation, IHX effectiveness	-IHX reduces system sensitivity to refrigerant quality -high-accuracy pressure correlation provided
Kim et al. (2005) [34]	IHX integration for hot water production	COP, heating capacity, model validation	-Longer IHX improves COP but slightly reduces capacity - model deviation <4%
Cho et al. (2007) [35]	Variable-speed CO_2 cycle with IHX	COP, cooling capacity, discharge pressure	-IHX increases COP by 7.1-9.1% and capacity by 6.2-11.9% -Reduces optimal pressure by 0.5 MPa.
Aprea & Maiorino (2008) [36]	Residential split-system with IHX	COP, energy performance	-IHX improves COP, supports CO_2 viability as low-GWP refrigerant.
Rigola et al. (2010) [37]	Small-capacity system with semi-hermetic compressor	COP, cooling capacity, experimental validation	-IHX enhances COP and capacity, especially at higher ambient temperatures
Tao et al. (2010) [38]	Residential AC with IHX, throttling loss analysis	COP, throttling losses, capacity loss	-IHX reduces throttling losses -COP impacted by 20% due to residual capacity loss
Torrella et al. (2011) [10]	Experimental IHX evaluation across evaporating levels	Cooling capacity, COP, discharge temperature	-Capacity/COP improvements up to 12% -Discharge temp rises by 10°C at low evaporation
Wang et al. (2013) [39]	Dual expansion valve system with IHX	COP, compressor power, pressure fluctuation	-IHX lowers power at high pressures -Dual expansion reduces pressure fluctuations
Karampour & Sawalha (2014) [40]	Booster system with IHX and heat recovery	Cooling COP, total COP, heat recovery potential	-IHX alone offers minimal COP gain, up to 12% improvement with heat recovery
Kim et al. (2014) [41]	Real-time optimal control with IHX	COP, control accuracy, error sources	-COP increased at a constant load, with valve opening reduced from 11.6% to 10.95% -The system achieved about 93-96% of the maximum COP
Sánchez et al. (2014) [9]	Dual IHX placement	COP, cooling capacity, discharge temperature	-Double IHX gives up to 13% COP increase -Discharge temp rises up to 20°C
Ituna-Yudonago et al. (2017) [14]	Transient start up analysis using CFD	COP, IHX effectiveness, heat transfer rate	-COP drops 12% during startup -Effectiveness varies with inlet conditions
Wang et al. (2018) [42]	Dual throttling with IHX and bypass valves	COP, efficiency, pressure control	-Formula for optimal high pressure developed -Efficiency gains under sub-optimal conditions
Cao et al. (2019) [12]	IHX length impact on heat pump performance	COP, discharge pressure/temperature	-Optimal IHX length 2.5 m, balances efficiency and safe discharge temps

Ye et al. (2020) [43]	Pinch point and IHX effects in heat pump water heaters	COP, gas cooler outlet temperature, optimal pressure	-IHX reduces outlet temp by 4.9°C and improves COP by 26.3% at low water temperatures
Liu et al. (2021) [11]	IHX positioning in booster systems for warm climates	COP, annual power consumption, performance factor	-Optimal IHX placement improves COP >6%, reduces annual power use
Fang et al. (2021) [15]	IHX effectiveness in mobile AC systems	COP, exergy destruction	-COP improves 14.5-18.5% -Compressor and gas cooler are main loss sources
Hou et al. (2023) [44]	Closed-loop heat pump drying with IHX	COP, moisture extraction rate, system efficiency	-IHX improves COP and drying efficiency for medical equipment
He et al. (2023) [45]	IHX role with compressor limitations	COP, cooling capacity, application-specific gains	-IHX benefits vary -Notable gains in automotive AC, potential in heat pumps
Sánchez et al. (2024) [13]	CO_2 blends with IHX (R32, R1270, R1234yf)	COP, blend performance	-Blends improve COP up to 22.2% with IHX vs. pure CO_2
Zendehboudi (2025) [16]	CO_2 mixtures in heat pumps with IHX	COP, exergy destruction cost, discharge pressure	-CO_2/R41 blend improves COP by 17.1% -IHX enhances performance further
Elbel & Hrnjak (2004) [17]	Internal heat exchanger (IHX) on transcritical CO_2 systems with ejector	COP, Cooling Capacity (kW)	-Ejector use increases COP by 10% and capacity by 15% compared to conventional systems with IHX.
Nakagawa et al. (2011) [20]	IHX in transcritical CO_2 refrigeration cycle with two-phase ejector	COP, Ejector Efficiency Entrainment Ratio, Pressure Recovery	-IHX significantly improves COP in ejector systems (up to 27% vs. conventional system with similar IHX). -Longer IHX (60 cm) yields higher COP improvement. -Ejector efficiency and entrainment ratio are more critical to performance than pressure recovery.
Xu et al. (2011) [18]	Comparison of transcritical CO_2 ejector system with and without internal heat exchanger (IHX) under varying cooling water conditions	COP, Heating Capacity, Entrainment Ratio, Pressure Lift , Actual Ejector Work Recovery Compression Ratios	- IHX improves system COP and capacity but weakens the ejector's contribution to performance recovery. -IHX increases primary flow rate but reduces pressure lift and actual ejector work recovery. -Compression ratio reduction with ejector alone is 10.0-12.1%, with IHX, reduction is only 5.6–6.7%.
Zhang et al. (2013) [19]	Theoretical evaluation of internal heat exchanger (IHE) effect on ejector expansion transcritical CO_2 refrigeration cycle	COP, Entrainment Ratio, Ejector Efficiency	- IHE does not always improve COP in ejector cycles; benefit depends on ejector isentropic efficiency. - IHE increases entrainment ratio and ejector efficiency but decreases pressure recovery. - IHE is only beneficial when ejector isentropic efficiency is low (< 0.4) or at higher gas cooler/evaporator temperatures.
Zeng et al. (2022) [21]	Effect of internal heat exchanger placement in dual-ejector transcritical CO_2 refrigeration cycle	(COP, Exergy Efficiency, Exergy Destruction Rate, Total Cost	- Dual-ejector cycle COP is 42% higher than conventional two-stage CO_2 cycle. - Dual-ejector system has better exergy efficiency -Exergy destruction rate is 58% lower and total cost 19% lower than conventional cycle. -IHX addition has minimal impact on total system cost.
Robinson and Groll (1998) [22]	IHX added transcritical CO_2 refrigeration cycles with and without an expansion turbine	- Irreversibility analysis (component-level) - COP	-CO_2 cycles with expansion turbine (60% isentropic efficiency) reduce irreversibility by 33% compared to valve cycles. -Internal heat exchange improves COP in valve cycles (up to +7%) but reduces COP in turbine cycles (up to –8%).

Zhang et al. (2014) [23]	First and second laws analysis of Internal Heat Exchanger (IHE) added transcritical CO_2 refrigeration cycles with an expander	- Coefficient of Performance (COP) - Exergy efficiency - Component exergy losses	-For throttle valve cycles, IHE improves COP by 5.6% - 17%. -For ideal expander cycles, IHE reduces COP by 12.3% - 16.1%. -IHE is only beneficial for expander cycles at lower expander efficiencies (η_{exp} < 0.35-0.6) or higher gas cooler exit temperatures. -IHE reduces exergy loss in expansion by 30% but increases losses in other components.
Shariatzadeh et al., 2016 [24]	Energy and exergy comparison of four transcritical CO_2 refrigeration cycles: with/without expander and with/without Internal Heat Exchanger (IHE).	- Coefficient of Performance (COP) - Exergy efficiency - Optimum heat rejection pressure - Component exergy loss percentages	-Adding an IHE reduces COP and exergy efficiency in expander cycles but increases them in throttling valve cycles. -Optimum heat rejection pressure is higher for throttling valve cycles than for expander cycles and decreases with increasing evaporator temperature. -Major exergy losses occur in the evaporator and gas cooler for all cycles. -The expander cycle (without IHE) shows 34% higher exergy efficiency on average than the throttling valve cycle.
Li et al. (2020) [25]	Internal heat exchanger (IHX) and expander on a CO_2 trans-critical cascade refrigeration system (CRS).	COP - Exergy efficiency - Exergy destruction and component exergy destruction ratios	-COP increases with evaporation temperature -The gas cooler is the largest source of exergy destruction (29-40%), while the evaporator has the least.
Shi et al. (2023) [26]	Internal Heat Exchanger (IHX) on a two-stage compression trans-critical CO_2 refrigeration cycle combined with an expander and intercooling.	- Coefficient of Performance (COP) - Exergy efficiency - System power consumption	- In single-stage compression with expander, IHX reduces COP and exergy efficiency (max COP decreases 12.04%, exergy efficiency decreases16.38%). -The two-stage system with IHX and expander reduces power consumption by 2-15.7% and increases max COP by 2.93-6.93% compared to single-stage expander cycle.
Cecchinato et al. (2009) [28]	Thermodynamic analysis/optimization of five two-stage transcritical CO_2 cycles (IMS)	COP, Optimal High & Intermediate Pressures, Mass Flow Ratio	-Split (DTDC_SC) and flash tank (DTDC_OFT) cycles offer highest COP gains (20-70%). -Inter-stage cooling (ICHX) is key for efficiency. IHX enhances ICHX benefits.
Gullo et al. (2015) [46]	Comparing R744 supermarket refrigeration systems in warm climates.	Energy use, TEWI, COP	-Enhanced R744 systems (with subcooling/parallel compression) match cascade system energy use and reduce TEWI by 9-25%.
Nebot-Andrés et al. (2021) [27]	CO_2 -Integrated Mechanical Subcooling (IMS) systems, focusing on compressor operational limits.	COP, Cooling capacity, Compression ratio, Volumetric efficiency , Global efficiency , Suction temperature, Frequency.	-IMS improves COP and capacity over base CO_2 cycles. -Optimum COP conditions require the auxiliary compressor to operate outside its standard range (compression ratio < 1.5, high suction temperature).
Nebot-Andrés et al. (2022) [30]	Comparison of three extraction points (GCO, SCO, TNK) for CO_2 Integrated Mechanical Subcooling (IMS) systems.	COP, Cooling Capacity, Optimum Pressure & Subcooling Degree, Subcooler Effectiveness	-All three IMS configurations achieved very similar COP (2.15–1.58). -Cooling capacity and required subcooler capacity varied: TNK had the highest, GCO the lowest.

2.2. Dedicated Subcooling Methods

Dedicated subcooling methods use a separate heat exchanger or refrigeration circuit to lower the refrigerant temperature below its condensing point before expansion. This approach helps improve system efficiency by increasing the refrigerant's enthalpy difference across the evaporator. Dedicated subcooling is particularly effective in high ambient conditions and for systems requiring stable subcooling without depending on variable condenser conditions.

2.2.1. Dedicated Mechanical Subcooling in CO_2 Refrigeration System

Dedicated Mechanical Subcooling (DMS) improves the performance of transcritical CO_2 systems by using an auxiliary vapor compression cycle specifically to subcool the main CO_2 stream after the gas cooler. This additional cooling lowers the refrigerant enthalpy before expansion, increasing the refrigerating effect across the evaporator and reducing throttling losses. While DMS can decrease the optimal discharge pressure and the specific work of the main compressor, the overall system COP depends on the total cooling capacity divided by the combined work of both the main and auxiliary compressors. The effectiveness of DMS therefore relies on a net positive trade-off, where the gains in cooling capacity and reductions in main compressor work outweigh the power consumed by the auxiliary cycle. This approach is particularly beneficial in warm climates, where standard transcritical CO_2 systems operate less efficiently and the benefits of subcooling are greatest. A schematic of a transcritical CO_2 system with dedicated mechanical subcooling is shown in figure 10.

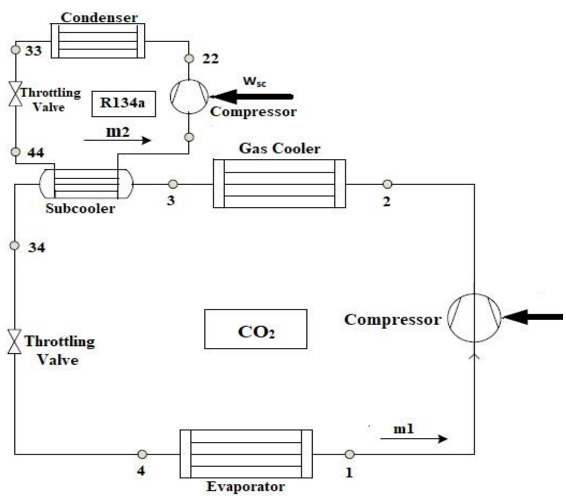


Fig. 10. Transcritical CO_2 refrigeration system with dedicated mechanical subcooling [47]

Application on Dedicated Mechanical subcooling for Subcooling in Transcritical CO_2 Refrigeration Systems: A Study of Reported Research

Experimental and theoretical studies consistently confirm that DMS can significantly boost the net system COP and total cooling capacity, provided the auxiliary cycle is optimally integrated and controlled. Llopis et al. [48] reported potential COP improvements of up to 20% and cooling capacity increases of nearly 29%, particularly at higher evaporating temperatures. However, a critical insight from Bush et al. [49] highlights the context-dependent nature of DMS benefits. Their analysis, considering the total work of both cycles, reveals a law of diminishing returns, the relative COP improvement from subcooling decreases as the base CO_2 cycle's own efficiency improves. This underscores that the net benefit of adding an auxiliary compressor is not absolute but must be evaluated against the performance of the standalone main cycle. The choice of refrigerant in the auxiliary subcooling loop appears to have a secondary effect on overall system performance compared to the implementation of subcooling itself. Llopis et al. [48] found minimal impact from the subcooling refrigerant choice, while in figure 11 Dai et al. [50] demonstrated that zeotropic mixtures could be tailored to offer marginal COP gains. It also shows that the maximum COP decreases with increasing ambient temperature for all refrigerants, due to more difficult heat rejection. In particular, R32/R290, R32/R1234yf, and R32/R152a exhibit superior performance, highlighting the importance of refrigerant selection for improving efficiency under warm conditions. In terms of configuration, comparisons by Catalan-Gil et al. [51] between dedicated and integrated mechanical subcooling in booster systems showed DMS to offer energy savings ranging from 1.3% to 4.0%, varying significantly with climate. The efficacy of DMS is profoundly influenced by operating conditions. It is most advantageous in warm to hot climates where baseline transcritical CO_2 efficiency suffers. For large-scale applications like supermarkets, integrating DMS with parallel compression has been shown to improve the Seasonal Energy Efficiency Ratio (SEER) by 6.8% and reduce overall energy use [52]. Furthermore, Dai et al. [53] demonstrated through thermodynamic modeling that multi-stage DMS configurations could achieve COP improvements up to 28.8% over baseline systems across diverse Chinese climates, highlighting its scalability and adaptability. Practical implementation studies introduce crucial real-world constraints. Cortella et al. [54] emphasized that optimal DMS sizing-typically between 35% and 45% of total cooling capacity-is critical for maximizing energy savings in hot climates, with aggressive control strategies being more beneficial in mild-warm regions. Furthermore, advanced optimization approaches, such as the machine-learning-assisted multi-objective analysis by Dai et al. [55], are being employed to balance the enhanced performance of hydrocarbon-mixture DMS cycles against initial cost increments.

When compared directly with internal heat exchanger (IHX) techniques, DMS generally provides superior performance, as noted by Sánchez et al. [56]. However, combining DMS with other enhancements presents complex trade-offs. For instance, while Zheng et al. [57] found that replacing the throttling valve in the subcooling loop with an expander (MCES) could increase COP by around 10%, it also resulted in slightly lower cooling capacity, illustrating the nuanced compromises between efficiency, cost, and complexity in hybrid system design.

Although many studies report performance improvements, several common limitations are evident across both integrated and dedicated mechanical subcooling systems. The net efficiency gain strongly depends on whether the added cooling benefit outweighs the extra power required by the auxiliary compressor, so improvements are not guaranteed under all conditions. Optimal subcooling often pushes auxiliary compressors beyond standard operating ranges, raising concerns about reliability and practical implementation. Moreover, the benefits are highly sensitive to ambient conditions and base-cycle efficiency, with diminishing returns as the main system becomes more optimized. Mechanical subcooling also increases system complexity, creating challenges in sizing, control, cost, and real-world integration.

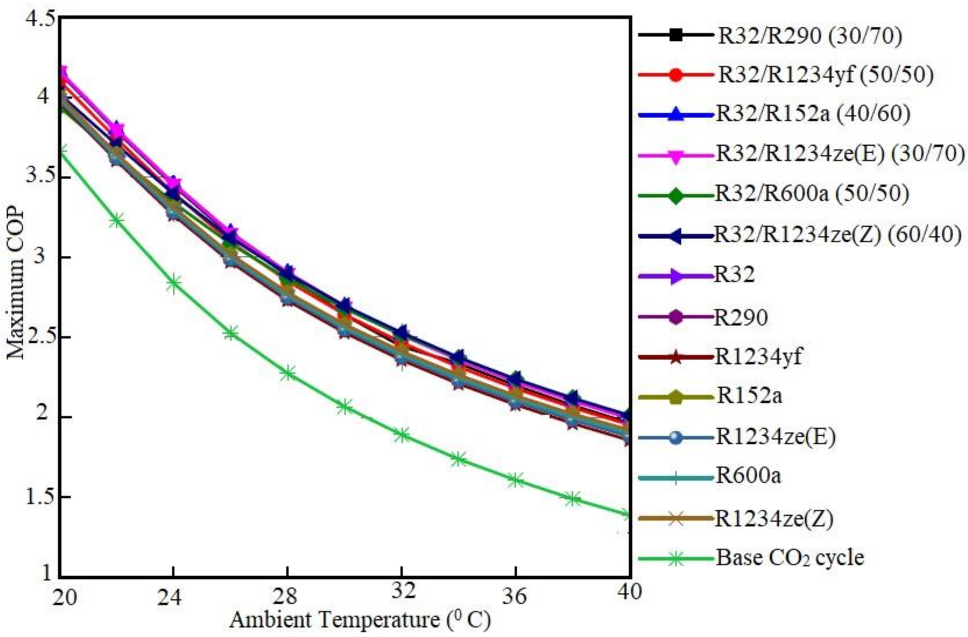


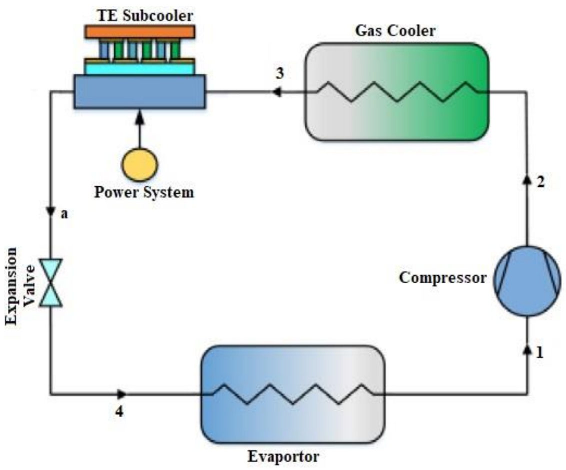
Fig. 11. Variation of maximum COP with ambient temperature for a base transcritical CO_2 cycle and different refrigerants and refrigerant blends [50]

2.2.2. Thermoelectric Based Subcooling

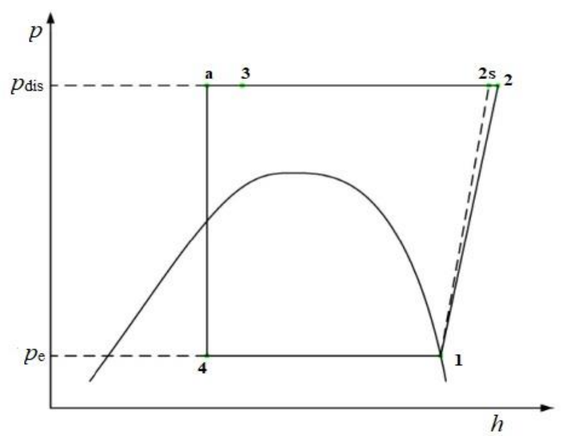
Use of Thermoelectric in Transcritical CO_2 refrigeration system is dedicated methods of subcooling which offers a compact and efficient method to enhance the performance of systems, particularly under high ambient temperatures where system efficiency typically declines. As shown in figure 12 (a) TES is incorporated after Gas cooler, also the figure 12 (b) indicate its p-h diagram. By using thermoelectric modules, which operate on the Peltier effect, additional subcooling of the refrigerant can be achieved without the need for complex mechanical systems, making it well-suited for applications with space constraints such as automotive and small-scale refrigeration.

Application on Thermoelectric Subcooling in Transcritical CO_2 Refrigeration Systems: A Study of Reported Research

Research into thermoelectric subcooling (TES) for transcritical CO_2 systems has employed a range of methodologies, from theoretical simulations to experimental validations, with the consistent aim of mitigating performance losses in high ambient conditions. The collective findings underscore TES as a viable method for enhancing system capacity and efficiency, though its net benefit is heavily dependent on optimal integration and control. Integrating a TES unit after the gas cooler has been shown to improve COP and cooling capacity (Fig. 13). Reported COP improvements typically range from 3.3% to over 25%, while capacity enhancements can reach up to 26% [59–63]. A key mechanism for this improvement is the reduction in optimal gas cooler discharge pressure facilitated by subcooling, which lowers compressor work [59,64]. However, a critical trade-off identified across multiple studies is the parasitic power consumption of the thermoelectric modules (TEMs). Research indicates that an optimal voltage or current supply exists to maximize COP, beyond which increased power draw to the TEMs negates system gains [59,60,63]. Furthermore, the placement and thermal design of the TES heat exchanger are crucial; optimizing cold-side heat transfer is essential to realize the theoretical potential of the TEMs, as excessive thermal resistance can significantly dampen performance [61,65].

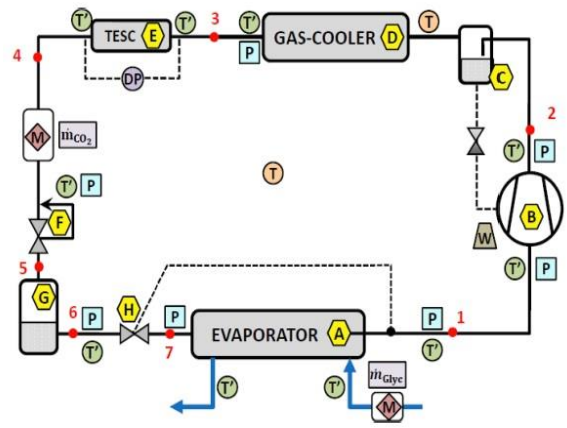


(a)

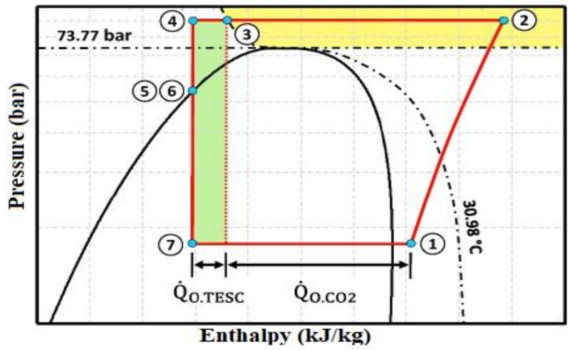


(b)

Fig. 12. Thermoelectric subcooling cycle: (a) schematic representation of the system; (b) Corresponding pressure–enthalpy (P–h) diagram [58]



(a)



(b)

Fig. 13. (a) Schematic diagram of the refrigeration setup; (b) P-h diagram of the system [60]

A distinct advantage of TES emphasized in the literature is its controllability and suitability for small-to-medium capacity systems. Unlike fixed geometry components, the subcooling effect of a TES can be modulated in real-time by adjusting the electrical input, allowing for dynamic optimization under varying load or ambient conditions [63,66]. This feature makes TES particularly attractive for applications with fluctuating demands or space constraints, such as mobile air conditioning or commercial refrigeration units [65,66].

Despite promising results the practical implementation of TE modules in transcritical CO_2 refrigeration is strongly constrained by their relatively low efficiency. Most existing studies are limited to laboratory demonstrations or low-capacity experimental systems, where modest temperature reductions are obtained at the cost of significant electrical input. When the auxiliary power demand is considered, the net system-level performance benefit is often marginal. In addition, the scalability of TE subcooling to commercial refrigeration capacities is challenged by heat dissipation requirements, thermal management issues, and economic considerations. Consequently, TE subcooling is currently better viewed as a complementary or niche solution rather than a stand-alone commercial technology.

Its long-term relevance will depend on future improvements in thermoelectric materials, module design, and hybrid system integration.

To provide a concise overview of recent progress, Table 2 summarizes key experimental and theoretical studies on subcooling-assisted transcritical CO_2 systems, including dedicated mechanical subcooling (DMS) and thermoelectric subcooling (TES). The table highlights the main study objectives, performance indicators, and reported improvements, allowing a clear comparison of how different subcooling strategies influence system efficiency, capacity, and operating characteristics under various conditions.

Figure 14 presents a comparative visualization of COP improvement as a function of ambient temperature for internal heat exchangers (IHX), integrated mechanical subcooling (IMS), and dedicated mechanical subcooling (DMS). The trends indicate that mechanical subcooling approaches exhibit a strong positive correlation with ambient temperature, with both IMS and DMS showing steadily increasing performance gains under warmer conditions. In contrast, the benefit of IHX remains relatively modest and weakly dependent on ambient temperature, suggesting limited effectiveness in high-temperature environments. These results highlight that while IHX offers simplicity and low implementation cost, mechanically driven subcooling becomes increasingly advantageous in hot climates, where reducing gas-cooler outlet temperature and optimal discharge pressure has a greater impact on system performance.

Table 2. Studies on dedicated mechanical subcooling (DMS) and Thermoelectric subcooling in transcritical CO_2 systems

Author(s) & Year	**Study Focus**	**Performance Metrics Examined**	**Key Findings / Improvements**
Llopis et al. (2015) [48]	DMS using propane in CO_2 transcritical cycle.	COP, Cooling Capacity	-Potential COP improvement up to 20% and cooling capacity increase of nearly 29% at higher evaporating temperatures. -Refrigerant choice in subcooling loop had minimal impact.
Bush et al. (2017) [49]	Mechanical subcooling in transcritical CO_2 booster systems for hot climates.	Capacity, COP, Model Accuracy	-DMS improved capacity and COP across all tested conditions. -A steady-state model matched experimental results within 3%.
Nebot-Andres et al. (2017) [67]	Performance comparison of MS and cascade CO_2 systems.	Energy Efficiency	-Mechanical subcooling offered consistently high energy efficiency across various operating conditions.
Dai et al. (2018) [50]	Mechanical subcooling using zeotropic mixtures in transcritical CO_2 systems.	COP, Discharge Pressure	-Selecting appropriate zeotropic mixtures improved COP by 4.91% and reduced discharge pressure by 0.11 MPa, under specific conditions (-5°C evaporation, 35°C ambient).
Fu et al. (2019) [68]	Ejector-assisted transcritical CO_2 system with DMS (R32/R1234ze(Z))	COP, Exergy Efficiency	-Achieved up to 10.27% improvement in COP and 15.56% in exergy efficiency compared to thermoelectric subcooling systems.
Sun et al. (2019) [69]	R744/R744 cascade system with expanders and mechanical subcooling.	COP	-The CESH configuration achieved an average 13.8% COP improvement over conventional R744/R717 systems.
Sanchez et al. (2020) [70]	R600a mechanical subcooling in transcritical CO_2 systems (experimental).	Cooling Capacity, COP	-Mechanical subcooling effectively enhanced cooling capacity and COP. -Validated model predicted optimal subcooling and identified R290 and R152a as promising auxiliary refrigerants.

Wang et al. (2020) [52]	Subcooling in parallel-compressed transcritical CO_2 supermarket systems.	SEER, Energy Consumption	-Achieved a 6.8% increase in Seasonal Energy Efficiency Ratio (SEER) and a 7.1% reduction in overall energy consumption in a hot climate (Haikou).
Hazarika et al. (2021) [71]	Dedicated mechanical subcooling using an R744 auxiliary cycle.	System Performance	-Subcooling at the gas cooler exit significantly improved system performance compared to conventional cycles and IHX-based systems, especially under high heat sink temperatures.
Cortella et al. (2021) [54]	Thermo-economic study of DMS sizing and control in CO_2 refrigeration.	Energy Savings, Optimal Size, Costs	-DMS sizing significantly impacts savings in hot climates, with optimal size between 35% and 45% of total cooling capacity. -Aggressive subcooling control is more beneficial in mild-warm climates.
Dai et al. (2022) [53]	Multi-stage DMS in CO_2 booster supermarket systems.	COP, Annual Performance	-Using genetic algorithm optimization, a three-stage DMS system achieved up to 28.8% higher COP than baseline systems across various ambient conditions.
Na et al. (2022) [72]	Space-constrained mechanical subcooling for CO_2 automotive air-conditioning.	COP, Heat Exchanger Design	-While larger heat exchangers and fans enhance COP, the improvement rate decreases. -Highlighting the need to balance fan power consumption and heat exchanger sizing.
Dai et al. (2024) [55]	Combined heating-cooling transcritical CO_2 system with DMS using hydrocarbon mixtures	COP, Carbon Emissions, Costs	-Through ANN and NSGA-II optimization, the system showed notable COP and carbon emission improvements compared to traditional systems, despite a moderate initial cost increase.
Illan-Gomez et al. (2023) [73]	IHX and DMS subcooling in transcritical CO_2 water-source heat pumps.	Efficiency, Heating Capacity, Optimal Pressure	-A specific coupled DMS configuration (Conf. F) improved efficiency by 26% and heating capacity by 160%, while reducing optimal gas cooler pressure by 12% compared to IHX alone.
Caliskan and Ersoy (2024) [74]	Transcritical CO_2 supermarket systems with DMS across Turkish climates.	Annual Energy Savings, TEWI	-CO_2 systems with DMS showed up to 11% annual energy savings and a 58.4% reduction in Total Equivalent Warming Impact (TEWI) compared to conventional R404A systems.
Zheng et al. (2025) [57]	Comparison of MCVS and MCES mechanical subcooling CO_2 systems	COP, Exergy Efficiency, Cooling Capacity, Economics	-The MCES system showed slightly lower capacity but significantly reduced power consumption, increasing COP by around 10% with notable exergy efficiency gains and favorable economics.
Sarkar (2013) [59]	Theoretical optimization of a transcritical CO_2 cycle with a thermoelectric subcooler (TES).	COP, discharge pressure, compressor discharge temperature.	-Achieved up to 25.6% COP improvement and 15.4% reduction in discharge pressure through optimal current supply.
Schoenfield et al. (2012) [61]	Experimental integration of a TES with a transcritical CO_2 system.	COP, cooling capacity.	-Reported a 3.3% COP increase with a 7.9% capacity gain. -Increasing current to 10A boosted capacity by 18.7% at similar COP, highlighting the importance of cold-side thermal resistance.
Yazawa et al. (2015) [75]	Optimization of TES-based CO_2 chiller for data centers.	Cooling performance, COP, operating pressure.	-TES enabled lower operating pressures, yielding a 12-13% improvement in maximum cooling performance with current TE materials (ZT =1.5).
Jamali et al. (2017) [76]	Two-stage TEG and TEC integration in CO_2 subcooling cycle.	COP, operating pressure.	-The hybrid system achieved a 19% COP improvement over a baseline CO_2 cycle while reducing optimal operating pressure.

Astrain et al. (2019) [62]	TESC development and assessment in small/medium CO_2 systems.	COP, cooling capacity.	-The TESC provided a 20% COP improvement and a 25.6% increase in cooling capacity vs. the base cycle, and outperformed an IHX system.
Sanchez et al. (2020) [63]	Experimental evaluation of a TES in a transcritical CO_2 plant.	COP, cooling capacity.	-Achieved up to 9.9% COP improvement and 16% capacity enhancement at optimal voltage, demonstrating good capacity control via voltage adjustment.
Aranguren et al. (2021) [60]	Experimental assessment of a TES placed after the gas cooler.	COP, cooling capacity, subcooling degree.	-At optimized voltages, the system achieved an 11.3% COP increase and a 15.3% rise in cooling capacity with 5.6 K of subcooling.
Hu et al. (2025) [77]	Performance of an air-source heat pump with a portable TES.	Heating COP, heating capacity.	-The TES-ASHP system showed a 10% COP improvement and an 8.7-24% capacity increase in cold climates, with TE module COP between 1.51-2.07.

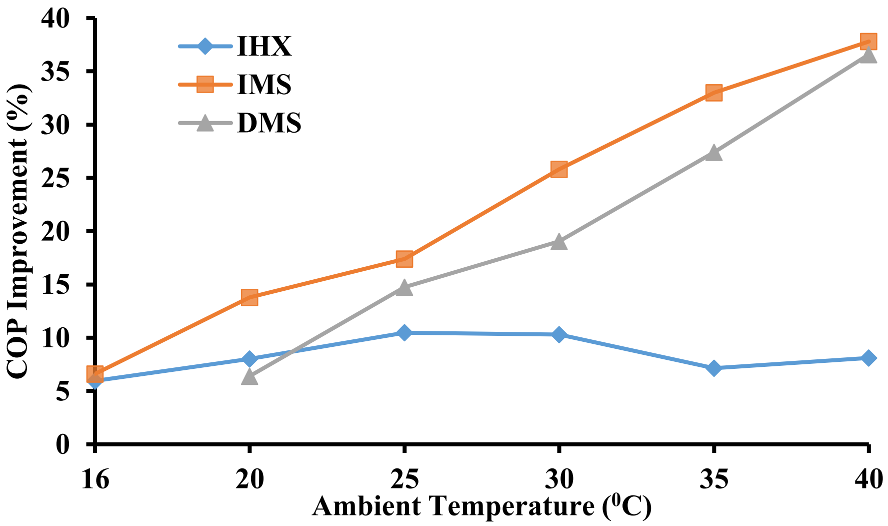


Fig. 14. COP improvement versus ambient temperature for IHX, IMS, and DMS subcooling approaches

3. Advanced Hybrid and Integrated Subcooling System Designs

Building upon the fundamental subcooling methods reviewed in previous sections, significant research efforts are now directed toward hybrid configurations that combine subcooling with other performance-enhancement technologies. Techniques such as ejector-based integrated or dedicated mechanical subcooling, ejector-assisted thermoelectric subcooling, ejector cascade arrangements, and ejector-enhanced two-stage compression improve COP while managing high-side pressures effectively. These integrated system designs aim to mitigate individual limitations and unlock synergistic efficiency gains, particularly for demanding commercial applications.

- **Early Investigations on Component Interaction:** Initial studies began quantifying how subcooling interacts with other cycle modifications. Choudhary et al. [78] demonstrated that in ejector-based systems, both the Suction Nozzle Pressure Drop (SNPD) and the degree of subcooling are critical parameters, with optimized values leading to COP improvements of up to 4.95%.
- **Research progressed to integrating ejectors with mechanical subcooling:** Liu et al. [79] showed that a CO_2 supermarket system combining multi-ejectors and DMS could achieve a 42.7% increase in Seasonal Energy Efficiency Ratio (SEER) in hot climates compared to conventional booster systems. Somasundaram et al. [80] proposes an ejector-based CO_2 transcritical

refrigeration system with integrated mechanical subcooling for dairy applications, enabling simultaneous milk chilling and water heating. Their parametric analysis shows the system can heat water up to 80°C while chilling milk to 4°C, achieving a COP of 4.15 at 40°C ambient. Their study highlights the system's potential as an energy-efficient and sustainable alternative for the dairy industry.

- **Thermoelectric Integration with other Components:** Early research established the potential of integrating thermoelectric modules into CO_2 cycles through simulation. Liu et al. [58] proposed a transcritical CO_2 cycle integrated with a thermoelectric subcooler and ejector (TES+EJE), reporting a 39.34% COP improvement and 8.01% reduction in optimum discharge pressure. These results were observed at an evaporation temperature of 5 °C and a gas cooler outlet temperature of 40 °C. Their study systematically compares TES+EJE with BASE, TES, and EJE configurations under varying subcooling temperatures and pressures, providing detailed energy and exergy analyses. Concurrently, advanced exergy analyses of systems combining thermoelectric subcoolers (TES) with ejectors revealed that most exergy destruction was endogenous, with the compressor being a key component for optimization [81]. Dai et al. [64] proposed transcritical CO_2 refrigeration cycles integrating a thermoelectric subcooler with an expander (TES+EXPHM and TES+EXPML) to enhance system efficiency. The TES+EXPML configuration achieved the highest COP and lowest discharge pressure, particularly under high gas cooler outlet or low evaporation temperatures, making it suitable for hot climates. Their results showed that placing the expander between the liquid receiver and evaporator yielded the most significant COP improvements. Their study underscores the potential of combined TE subcooling and expansion work recovery for improving CO_2 system performance. Kwan et al. [65] examined a thermoelectric device and an internal heat exchanger (TED-IHX) within a transcritical CO_2 cycle, using a 1D finite element model. Their results showed that operating TED-IHX as a TEG improved COP by up to 5% for water heating and 0.8% for refrigeration, but was less effective than a basic IHX due to TED's thermal resistance. Although TEC operation reduced compressor power needs, its high power consumption offset COP gains. Their study highlights TED-IHX's limited refrigeration benefits but potential in water heating applications. The focus on thermoelectric subcooling intensified, with studies optimizing its integration. Casi et al. [66] experimentally compared an Internal Heat Exchanger (IHX) and a Thermoelectric Subcooler (TESC), noting TESC's superior controllability for small systems. Further work by the same group [82] showed that optimizing TESC heat exchanger design could increase COP improvement from 11.96% to 14.75%. They also demonstrated that a combined IHX+TESC system could achieve a 22.4% COP increase [83].
- **Cascade and Magnetic system enhanced with Subcooling:** Hybrid concepts expanded to other domains. Chi et al. [84] integrated ejector subcooling into an NH_3/CO_2 cascade system, reporting 5% improvements in COP and exergy efficiency. In a novel approach, Nebot-Andrés et al. [85] explored using a magnetic refrigeration cycle for subcooling, which could improve the overall COP of a transcritical CO_2 cycle by up to 9%.
- **Advanced Multi-Component Cycles for Specific Applications:** Recent work targets complex, high-performance cycles for specific industries. For large supermarkets, Li et al. [86] proposed a two-stage cycle with both an ejector and a subcooler, reporting COP and exergy efficiency gains over 14%. Similarly, Zou et al. [87] found an ejector-enhanced two-stage compression cycle with a subcooler improved COP by up to 11% for supermarket refrigeration. Studies also investigated vapor-injection cycles enhanced with ejectors and subcoolers [88], and self-heat recuperation systems using compressor waste heat to drive ejector subcooling, with COP gains up to 19.8% [89].

4. Integration with Renewable Energy and Sustainable Heat Sources

A prominent emerging trend is the decoupling of subcooling energy input from the electrical grid by leveraging renewable or waste energy sources. This approach aims to reduce the carbon footprint and operational energy cost of subcooling by harnessing solar thermal or electrical energy.

- **Solar-Assisted Absorption Subcooling:** Syngounas et al. [90] presents a solar-assisted subcooling approach using a LiBr–H_2O absorption chiller integrated into a CO_2 booster system for supermarket refrigeration. Through energetic, exergetic, and financial analyses, they identify an optimal setup with a 100 m^2 solar collector and 60 kW chiller. Their system configuration yields 8.12% energy savings annually, proving its potential for efficient retrofitting or new installations.

- **Solar-Driven Ejector Subcooling Systems:** Recent research has focused on directly using solar energy to enhance ejector subcooling cycles. Ran et al. [91] propose a supermarket CO_2 refrigeration system with ejector subcooling powered by solar energy to improve performance in warm climates. A detailed thermodynamic model and parametric analysis reveal optimal discharge pressure and subcooling degree for maximizing COP while reducing collector area. Their study reveals that even at reduced COP, the system requires much less solar collector area and still achieves a 15-20% performance improvement over conventional systems. Their study offers valuable insights for optimizing hybrid CO_2 refrigeration systems in high-temperature regions. Yin et al. [92] introduce a solar-driven ejector subcooling CO_2 transcritical system to enhance energy efficiency in solar air conditioning while addressing emission reduction goals. Through multi-objective optimization using NSGA-II, their study balances system COP and solar collector area for improved economic feasibility. Their findings demonstrate a trade-off between maximum COP and system economics, offering a practical pathway for environmentally friendly and cost-effective SESRS systems. Their work provides clear insights for optimizing solar-assisted CO_2 refrigeration systems in building applications.
- **Solar-Powered Thermoelectric Subcooling:** The convergence of solar PV and thermoelectric technology has been explored. Tarawneh and Melhem [93] presents an innovative approach to improve transcritical CO_2 refrigeration efficiency by integrating a thermoelectric subcooler powered by solar PV under Jordanian conditions. Their study demonstrates notable improvements in COP and energy savings, with up to 45.3% reduction in energy use and strong alignment between simulation and experimental results. Their work offers a practical pathway for sustainable and efficient CO_2-based cooling systems in warm climates
- **Waste Heat and Resource-Efficient Subcooling:** Beyond solar, other sustainable integrations have been studied. Singha et al. [94] examine how integrated and dedicated mechanical subcooling, along with evaporative cooling, can improve the COP of transcritical CO_2 systems for milk processing in hot climates. Using Pune’s climatic data, their study finds that combining subcooling with parallel compression significantly enhances system performance. Notably, evaporative cooling with parallel compression improves COP by 62.3% over a conventional flash gas bypass system. They also report a water consumption reduction of up to 45.6% compared to indirect evaporative systems, highlighting a balanced pathway for efficiency and resource conservation in hot climates. Syngounas et al. [95] explores a transcritical CO_2 vapor ejector-based refrigeration system tailored for marine provision plants as a sustainable alternative to high-GWP refrigerants. Their study demonstrates a COP improvement of up to 13.2% over conventional R407F systems, with advanced exergy analysis revealing substantial opportunities to reduce irreversibilities. Notably, their work highlights that around one-third of total exergy destruction is avoidable, emphasizing the potential for further system optimization under varying seawater temperatures.

To facilitate a practical comparison of subcooling strategies, Table 3 summarizes key performance indicators reported in the literature, including COP improvement, discharge pressure reduction, estimated energy savings, and system complexity. Unlike earlier reviews that primarily focused on maximum efficiency gains, this multi-metric assessment highlights the trade-offs between performance enhancement and implementation challenges. The comparison shows that while internal subcooling offers limited gains with minimal system modification, dedicated mechanical and hybrid subcooling systems achieve significantly higher performance improvements, but with noticeably higher pressure effects and increased system and control complexity.

Table 3. Comprehensive comparison between different subcooling techniques

Technique	COP Improvement (%)	Pressure Decrement (MPa)	Energy saving (%)	System complexity
Internal Heat Exchanger (IHX)	5-15	0.05-0.15	3-12	Low
Integrated Mechanical Subcooling (IMS)	7-37	0.10-0.30	10-20	Medium
Dedicated Mechanical Subcooling (DMS)	4-35	0.20-0.50	20-35	High
Thermoelectric Subcooling (TES)	10-25	0.10-0.25	8-20	Medium
Hybrid subcooling	5-40	0.30-0.60	30-45	Very high

5. Conclusions and Future Development

This review comprehensively examined various subcooling techniques employed to enhance the performance of transcritical CO_2 refrigeration systems, with a particular focus on internal and external subcooling approaches.

When considering internal subcooling methods, the use of an internal heat exchanger (IHX) is particularly beneficial in transcritical CO_2 systems. COP improvements of up to 20% have been reported, although the inclusion of an IHX may lead to higher discharge temperatures. Moreover, when IHXs are combined with energy recovery devices such as ejectors or expanders, the overall benefit can be diminished due to adverse interactions. The mechanically integrated subcooling units have achieved improvements up to 17.5%.

In context to external subcooling techniques, such as dedicated mechanical subcoolers utilizing a secondary vapor compression cycle with another refrigerant, have been extensively studied. Theoretically, these systems have shown potential COP improvements up to 28.8%, and even up to 67.7% when used alongside expansion devices. However, these projections are often based on idealized assumptions. Experimental studies suggest that practical COP enhancements are closer to 40%. Although it has been suggested that subcooling can help reduce the size of CO_2 systems, this aspect remains underexplored in the literature.

Thermoelectric subcooling systems have also emerged as a potential enhancement technique, offering estimated COP gains ranging from 20% to 25.6%. When coupled with energy recovery components like expanders or thermoelectric generators, the improvement may rise to nearly 37.8%.

Advanced subcooling and hybrid CO_2 refrigeration strategies have demonstrated substantial performance gains, with COP improvements ranging from 4.95% to over 62%, and energy savings up to 45.3% depending on system configuration and application. Ejector-based systems, thermoelectric subcoolers, and solar-assisted designs proved especially effective in hot climates and commercial settings. These developments not only boost efficiency but also reduce emissions, offering a practical path toward sustainable refrigeration solutions.

The comparative analysis presented in this review underscores the importance of selecting the appropriate subcooling strategy to balance performance gains with system constraints.

For future development one can research on Advanced control and real-time optimization strategies, Integration of subcooling with geothermal energy sources, as current renewable-assisted studies are largely limited to solar-based approaches, Use of compact and high-performance heat exchangers, System-level optimization considering energy, exergy, economic, and environmental perspectives.

Nomenclature

ANN	Artificial neural network
ASHP	Air source heat pump
CESH	Cascade refrigeration with high temperature expander subcooling
CFC	Chlorofluorocarbons
COP	Coefficient of performance
CTSH	Cascade refrigeration with high temperature subcooling
CO_2	Carbon dioxide
CRS	Cascade refrigeration systems
DMS	Dedicated mechanical subcooling
DS	Dedicated subcooling
DTDC_SC	Double-Throttling, Double-Compression, Split Cycle

DTDC_OFT	Double-Throttling, Double-Compression, Open Flash Tank
ESC	Extreme seeking control
EJE	Ejector
EXP	Expander
GCO	Gas cooler outlet
GWP	Global warming potential
HFC	Hydrofluorocarbon
HM	From high pressure to middle pressure
H_2O	Water
IHE	Internal heat exchanger
IHX	Internal heat exchanger
IMS	Integrated mechanical subcooling
LiBr	Lithium bromide
ML	From middle pressure to low pressure
MS	Mechanical subcooling
MCES	Mechanical subcooling CO_2 transcritical systems using expander
MCVS	Mechanical subcooling CO_2 transcritical systems using a throttling valve
NSGA-II	Non-dominated sorting genetic algorithm-II
SCO	Subcooler outlet
SEER	Seasonal energy efficiency ratio
SESRS	Solar-drive ejector subcooling CO_2 transcritical refrigeration system
SNPD	Suction nozzle pressure drop
TEC	Thermoelectric cooler
TED	Thermoelectric device
TEG	Thermoelectric generator
TES	Thermal electricy subcooler
TESC	Thermal electricy subcooler system
TNK	Tank
TEWI	Total Equivalent Warming Impact
VCRS	Vapour compression refrigeration system
1D	One dimensional

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Authors Contribution Statement

Saif Nawaz Ahmad: Conceptualization; Data Curation; Formal Analysis; Investigation; Methodology; Visualization; Writing – Original Draft; Writing – Review & Editing.

Nitin Kumar: Data Curation; Writing – Review & Editing.

Rajnish Kumar: Formal Analysis, Writing – Review & Editing.

Adil Nawaz Ahmad: Methodology, Writing – Review & Editing.

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