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Optimization and Thermodynamic Analysis of CO_2 Refrigeration Cycle for Energy Efficiency and Environmental Control

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ABSTRACT

Supermarket applications are significant contributors to greenhouse gas emissions, necessitating efforts to reduce carbon footprints in the food retail sector. Carbon dioxide (R744) is recognized as a viable long-term refrigerant choice due to its favorable properties, including low Global Warming Potential, non-toxicity, non-flammability, affordability, and widespread availability. However, enhancing the energy efficiency of pure CO_2 systems in basic architecture units, particularly in warm regions like India, remains a challenge. To address this, modern refrigeration systems must prioritize low energy consumption and high coefficient of performance (COP) while meeting environmental standards. This study investigates different operating conditions to determine the optimal parameter range for maximizing COP and improving the efficiency of conventional CO_2 refrigeration configurations. It examines both subcritical and transcritical refrigeration cycles under varying parameters, emphasizing the importance of understanding COP's relationship with factors such as subcooling, superheating, ambient temperature, and evaporator temperature. The study advises against superheating in CO_2 systems but highlights the substantial COP increase with higher degrees of subcooling, leading to enhanced system performance. Additionally, it provides a comprehensive theoretical comparison between advanced pure CO_2 supermarket applications and commonly used hydrofluorocarbons-based systems, offering insights into energy efficiency and environmental impacts for informed decision-making in the industry.

INTRODUCTION

Modern refrigeration systems face multiple demands, including performance, reliability, controllability, compactness, and environmental sustainability. Pollution in compression systems arises mainly from refrigerant leakage and energy consumption for system operation, making it crucial to use an environmentally friendly refrigerant, particularly in mobile applications like automotive air-conditioning (Prabakaran et al. 2022). Carbon dioxide (CO_2) has emerged as a suitable refrigerant that meets these criteria when combined with optimized system components (Yuan et al. 2021).

CO_2 (R744) was widely used as a refrigerant in the 19th century (Ciconkov 2018). However, in the 1930s, it was gradually replaced by newly developed synthetic refrigerants (HCFCs) due to their lower system pressures and simpler technology (Riffat et al. 1997). The shift in refrigerants was driven by the desire for more efficient and easier-to-handle refrigeration systems.

Moulina & Rowland (1974) brought attention to the damaging effects of chlorine emissions on the ozone layer, leading to the introduction of HFCs like R-134a, which are currently used in many refrigeration applications. R-134a, a commonly used refrigerant, does not contribute to ozone depletion as it has an ozone-depleting potential (ODP) of zero. However, it does have a substantial impact on global warming potential (GWP) compared to CO_2. In fact, the GWP of R134a is approximately 1,300 times higher than that of CO_2 (Bolaji & Huan 2013).

The consideration of global warming potential has become increasingly important in recent years, as there is a growing awareness of the environmental impact of greenhouse gas emissions (Shirmohammadi et al. 2018). As a result, there has been a renewed interest in utilizing CO_2 as a refrigerant due to its negligible global warming potential and other favorable thermophysical properties. CO_2 is non-flammable, inexpensive, non-toxic, and readily available, making it an attractive long-term working fluid for refrigeration systems (Lorentzen & Pettersen 1993). The CO_2 (R744) is compared with R-12, R-22, R-134a, and R717 refrigerants in Table 1 (Kim et al. 2004).

Table 1: Comparison of R744 with other refrigerants (Kim et al. 2004).

	R-12	R-22	R-134a	R717	R744
GWP	8500	1700	1300	0	1
ODP	1	0.05	0	0	0
Flammability	No	No	No	Yes	No
Toxicity	No	No	No	Yes	No
Mass [kg.kmol^{-1}]	120.9	86.5	102	17	44
Critical Temperature [℃]	112	96	101.1	133	31.1
Critical Pressure [MPa]	4.11	4.97	4.07	11.42	7.38
Refrigeration Capacity [kJ.m^{-3}]	2734	4356	2868	4382	22545
First commercial use	1931	1936	1990	1859	1869

By transitioning back to CO_2 as a refrigerant, it is possible to significantly reduce the carbon footprint associated with the refrigeration industry. However, further research and development are needed to advance the energy efficiency of pure CO_2 systems, particularly in units with basic architectures operating in warm regions (Kauf 1999). These efforts aim to maximize the performance of CO_2 refrigeration systems and make them even more environmentally friendly alternatives to synthetic refrigerants like R134a.

The resurgence of CO_2 as a refrigerant sheds light on the development of air conditioning and refrigeration systems. Initially, efforts concentrated on enhancing compressors to address cost and efficiency concerns. The introduction of CFCs brought advantages like low-pressure operation, improved thermodynamic efficiency, and enhanced safety. This led to cost reductions, enabling widespread production. As energy prices decreased, the industry focused on the simplified vapor-compression cycle and optimized components to maximize efficiency by utilizing the specific transport properties of the refrigerant (Bose & Saini 2022).

Carbon dioxide serves as the working fluid in a refrigeration system through the thermodynamic CO_2 refrigeration cycle. To produce cooling effects, CO_2 is compressed, condensed (making the gas cooler), expanded, and evaporated. The CO_2 gas is compressed by a compressor during the CO_2 refrigeration cycle, raising its pressure and temperature (Javadpour et al. 2024). The high-pressure CO_2 then travels through a condenser, where it undergoes a phase transition into a liquid and emits heat to the environment. The high-pressure liquid CO_2 then passes through an expansion valve (Ejector), where it rapidly expands, resulting in a decrease in pressure and temperature. The use of an ejector in a transcritical CO_2 cycle has several benefits, including a higher performance coefficient and easier management of the gas cooler pressure (Manjili & Yavari 2012). This is accomplished by adjusting the ejector nozzle's throat region. After entering an evaporator, the low-pressure CO_2 liquid or mixture of liquid and gas absorbs heat from its surroundings, such as a refrigerated area or product. As a result, the CO_2 evaporates and turns back into a gas, completing the cycle.

Brown et al. (2005) investigated the thermodynamic analysis of the transcritical refrigeration system theoretically. It was concluded that CO_2 exhibits promise as a natural refrigerant in refrigeration and air-conditioning, particularly in compact automobile systems with high operating pressures. Unlike R134a, which contributes to global warming, CO_2 is environmentally friendly. However, additional research is necessary to enhance the safety and efficiency of CO_2 systems. While current performance may not be on par with existing systems, CO_2 and similar refrigerants hold potential as realistic alternatives in the future.

Silva et al. (2012) conducted a comparative study between R744 cascade, R404A, and R22 refrigeration systems. Their findings indicated that carbon dioxide cascade systems offer significant advantages in refrigeration applications. These advantages include reduced electric energy consumption (13-24%), increased compressor lifespan due to lower compression ratio, high CO_2 density and pressure in the low-pressure stage, reduced piping diameter, lower refrigerant charge, affordability, improved enthalpy and cooling capacity, lower Global Warming Potential (GWP) and carbon taxes, compact compressors with reduced displacement, streamlined installation with fewer compressors and a compact refrigeration rack, efficient evaporator coils, and reduced installation and maintenance costs.

Getu & Bansal (2008) investigated the thermodynamics of an R744-R717 cascade refrigeration system at -50°C evaporator temperature and 40°C condensing temperature. It observed that increasing superheat decreased COP but increased mass flow ratio while increasing subcooling improved both. Additionally, higher condensing temperatures reduced COP but increased mass flow ratios, whereas higher evaporating temperatures enhanced COP while reducing mass flow ratios.

Kauf (1999) investigated the impact of high pressure in transcritical refrigeration systems on the COP. However, the graphical method was found to be time-consuming for determining the optimal high pressure. Kauf proposed a linear correlation suggesting that the optimal high pressure should be 0.26 times the ambient temperature to achieve maximum COP.

Sun et al. (2020) conducted a comprehensive analysis to evaluate the operational efficacy of the supermarket refrigeration system in varying climate zones across China, employing both R134a and R744 (CO_2) as working fluids. Their study focused on the examination of cascade and double-stage compression configurations. The findings of their investigation unequivocally demonstrated that the CO_2 refrigeration system featuring the cascade and double-stage compression designs exhibited remarkable promise for deployment in supermarket refrigeration applications.

Zhang et al. (2015) conducted an in-depth investigation into the transcritical carbon dioxide refrigeration cycle with double-stage compression, incorporating an expander. The study focused on the analysis of four distinct double-compression CO_2 transcritical refrigeration cycles: the double-compression external intercooler cycle (DCEI), double-compression external intercooler cycle with an expander (DCEIE), double-compression flash intercooler cycle (DCFI), and double-compression flash intercooler cycle with an expander (DCFIE). The key findings of their research concluded that the replacement of the throttle valve with an expander in the DCEI cycle resulted in a decrease in the optimal gas cooler pressure, with minimal variation observed in the optimal intermediate pressure.

Perez-Garcia et al. (2013) conducted simulations on a single-stage transcritical CO_2 refrigeration cycle. The study concluded that the implementation of an internal heat exchanger (IHE) for subcooling the refrigerant exiting the gas cooler proved to be the most effective configuration for enhancing the COP. For gas cooler outlet temperatures below 31 °C, the inclusion of an IHE was not advised as it resulted in slightly lower cycle performance compared to the basic cycle. The degree of superheating in the Dual Expansion Cycle (DEC) and DEC + IHE configurations proved to be beneficial in both cases. However, in the DEC, the influence of this parameter was particularly significant in the first two Celsius degrees, as it led to a noteworthy increase in COP within this range.

Singh et al. (2016) conducted a comparative analysis of various configurations of CO_2 refrigeration cycles specifically designed for warm climate conditions. The study yielded important conclusions, notably that systems incorporating internal heat exchangers demonstrated reduced mass flow rates at elevated ambient temperatures. This finding implies that such systems can operate effectively with lower gas cooler pressures. Additionally, the performance of systems equipped with internal heat exchangers was observed to be comparatively superior under higher ambient temperature conditions. However, for applications involving refrigeration and air cooling, the performance of multi-stage systems was found to be similar to that of the basic system, rendering them less effective. Among the real-time constraints considered, compressor efficiency emerged as the most influential factor affecting the system's COP. Furthermore, the gas cooler capacity exhibited rapid growth with increasing ambient temperature.

One of the primary goals in the design of refrigeration systems is to achieve elevated energy efficiency while minimizing energy consumption. In transcritical CO_2 refrigeration cycles, the system's high pressure and desired cabin temperature exert significant influence on the COP, which directly impacts energy efficiency. This study focuses on calculating the optimal COP under various operating conditions and determining the ideal high pressure based on the ambient temperature. Additionally, the analysis in this study examines the impact of superheating on the system's COP and compressor work. Furthermore, the subcooling effect achieved through the use of an internal heat exchanger to reduce the refrigerant temperature emerging from the gas cooler is analyzed at different ambient and evaporator temperatures.

To optimize the COP of the refrigeration system, careful examination of operating parameters is necessary. By adjusting these parameters, the COP can be maximized, leading to enhanced overall performance and energy efficiency. This study showcases the utilization of CO_2 as a refrigerant in modern refrigeration systems, highlighting the importance of optimized components. Specifically, the study investigates the impact of superheating after the evaporator outlet and subcooling after the gas cooler. In this study, MATLAB simulation is employed to investigate the impact of different operating parameters on both subcritical and transcritical refrigeration cycles, facilitating a thorough examination of system performance.

MATERIALS AND METHODS

CO_2 Refrigeration System

A CO_2 compression cycle comprises several essential components, including the compressor, gas cooler (which replaces the conventional condenser to handle supercritical heat rejection), expansion unit, and evaporator, as depicted in Fig. 1. Ideally, the refrigerant is drawn from the evaporator

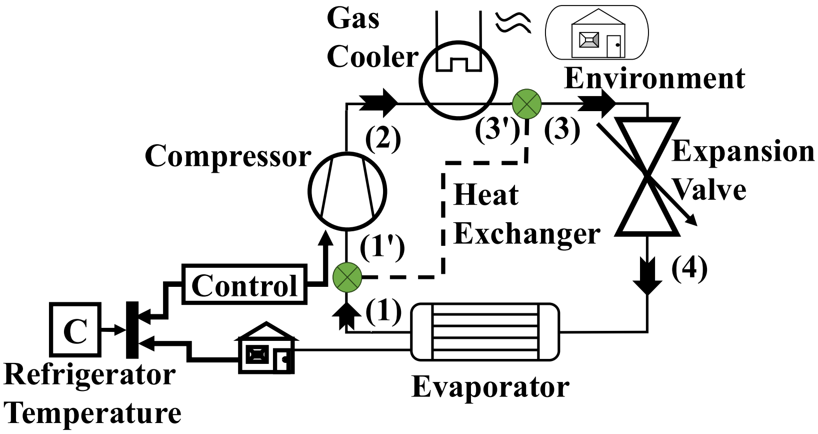


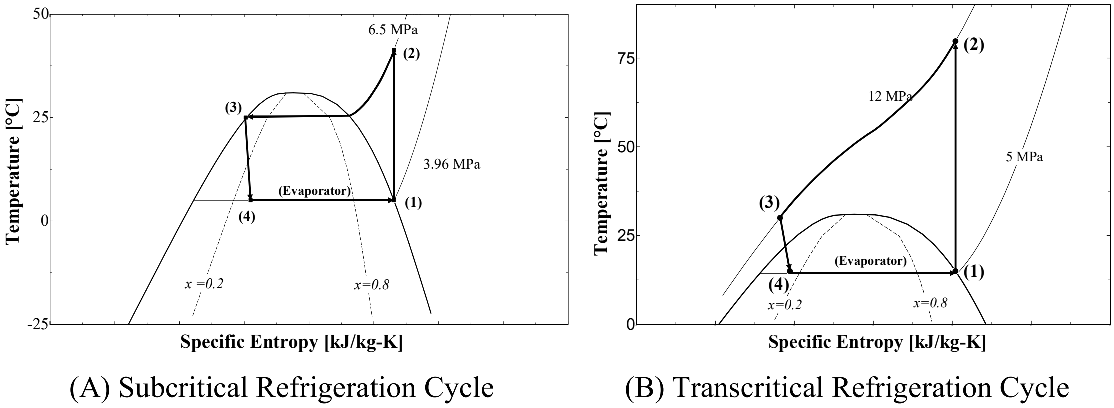
Fig. 1: CO_2 Refrigeration system.

as saturated vapor (point 1) and undergoes an isentropic compression process to reach a higher pressure (point 2). At this higher pressure, the hot CO_2 is cooled in the gas cooler by transferring heat (Q_{amb}) to the surrounding ambient air (point 3). Subsequently, the refrigerant is throttled to a lower pressure (point 4). Within the evaporator, the refrigerant extracts heat (Q_{evap}), also referred to as the refrigerating capacity, from the ambient air, thereby providing a cooling effect.

The subcritical cycle having CO_2 as refrigerant is depicted in Fig. 2(A). Subcritical cycles are a type of refrigeration system where the refrigerant can undergo the condensation process. This implies that the pressure at the discharge of the compressor is maintained at a level below the critical pressure of the refrigerant. In subcritical cycles, the refrigerant transitions from a high-pressure, high-temperature vapor state to a lower-pressure liquid state during the condensation process (Yaakop et al. 2023).

Currently, the management of high system pressures in CO_2 refrigeration cycles has become more manageable through effective regulation. The critical point of CO_2, which occurs at 7.38 bar and 31°C, often necessitates the operation of refrigeration cycles in a transcritical mode. This is particularly prominent in automotive air-conditioning systems and supermarket refrigeration systems that operate in environments with high ambient temperatures. In such systems, the evaporation process occurs at pressures and temperatures below the critical point, referred to as subcritical conditions, while heat rejection takes place at pressures and temperatures above the critical point, known as supercritical conditions. The supercritical (Transcritical) cycle having CO_2 as refrigerant is depicted in Fig. 2(B).

In the subcritical cycle, the refrigerant is evaporated and condensed below the critical point of CO_2, which is 31.1°C and 7.38 MPa. In this cycle, the CO_2 goes through a phase transition from a liquid to a vapor in the evaporator and then condenses back into a liquid form in the condenser. In applications needing moderate cooling temperatures, including commercial refrigeration



(A) Subcritical Refrigeration Cycle (B) Transcritical Refrigeration Cycle

Fig. 2: CO_2 Refrigeration cycles on T-S diagrams.

and air conditioning, the subcritical cycle is frequently employed.

The transcritical cycle, on the other hand, functions at pressures and temperatures higher than the CO_2 critical point. During the heat rejection phase of this cycle, the refrigerant does not change phases. Instead, a supercritical process where the characteristics of a liquid and a gas coexist is used to release the heat. The transcritical cycle is appropriate for operations like heat pumps and some industrial ones that need cooling at higher temperatures.

Superheating after the evaporator occurs when the temperature of the refrigerant exceeds its saturation temperature after completing the evaporation process within the evaporator. Initially, in the refrigeration cycle, the refrigerant enters the evaporator as a saturated mixture of liquid and vapor. As heat is absorbed from the surroundings, the liquid component of the refrigerant evaporates, transforming into a fully saturated vapor state. However, if the refrigerant temperature continues to rise beyond the saturation temperature, it becomes superheated. The presence of superheating is typically desirable in specific applications to prevent any potential for liquid refrigerant entering the compressor, which can result in system damage and reduced efficiency. To visually illustrate the phenomenon of superheating, a schematic representation of the process (1-1') is presented in Fig. 3.

Subcooling in a CO_2 refrigeration system involves an additional reduction in temperature that occurs after the refrigerant has passed through the gas cooler. The gas cooler's main purpose is to lower the refrigerant's temperature, and subcooling builds upon this process by further decreasing the temperature of the refrigerant. To accomplish subcooling, an internal heat exchanger is utilized. This heat exchanger facilitates the transfer of heat from the refrigerant as it exits the evaporator. The heat extracted by the internal heat exchanger is then utilized to superheat the refrigerant that is leaving the evaporator.

Consequently, the temperature of the refrigerant that exits the gas cooler is effectively reduced. The subcooling process plays a vital role in optimizing the performance and efficiency of the refrigeration system. To visually illustrate the phenomenon of subcooling, a representation of the process (3-3') is presented in Fig. 3.

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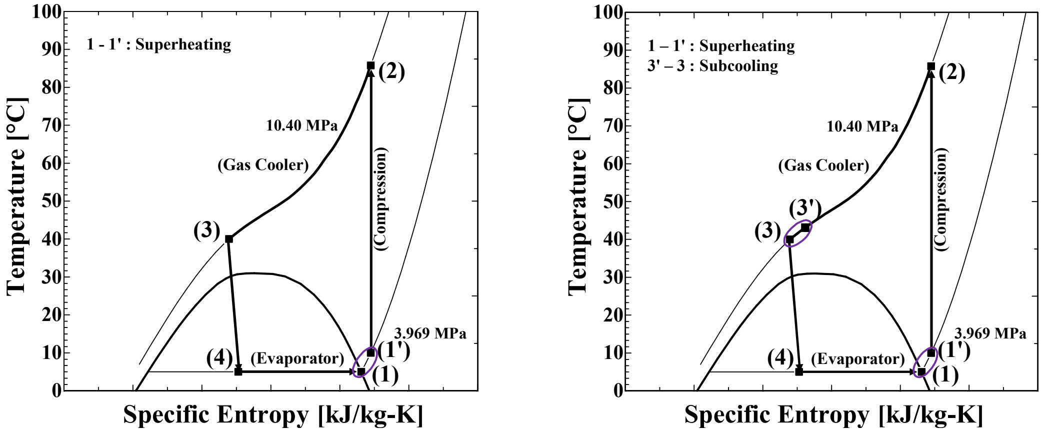
This paper focuses on using carbon dioxide as the refrigerant and examines subcritical and transcritical cycles with subcooling and superheating in great detail. A thorough understanding of these cycles, their performance traits, and their applicability for various applications are the goals of



(A) Transcritical Cycle with superheating (B) Transcritical Cycle with subcooling

Fig. 3: CO_2 Transcritical refrigeration cycles on T-S diagrams.

the analysis. These cycles are used in a range of cooling applications, including small-scale industrial processes and home freezers. The intended temperature range, needed energy efficiency levels, and environmental concerns all play a role in which the cycle is selected.

This study's analysis includes a thorough assessment of the thermodynamic efficiency of subcritical and transcritical cycles with superheating and subcooling using an internal heat exchanger. Considerations are made for variables such as system complexity, cooling capacity, pressure effect, and energy efficiency. When employing CO_2 as the refrigerant, the researchers want to be able to determine the benefits and drawbacks of each cycle.

Data Reduction

This study's major goal was to evaluate the effectiveness of transcritical refrigeration systems with subcooling and superheating. Determining the rate at which heat is removed from the refrigerated room, which is described by equation (1), was a significant component of the investigation. It was supposed that all of the refrigerant that leaves the evaporator is vapor.

$$Q_{evp} = h_1 - h_4 \quad ...(1)$$

The heat exchanger plays a pivotal role in elevating the temperature of the refrigerant after its evaporation process. This augmentation in temperature beyond the point of saturated vapor is commonly referred to as the degree of superheat.

Entropy at the compressor's input and exit is assumed to be constant in this analysis under the assumption that the compressor is isentropic. The analysis and calculations can be made simpler due to this supposition. The compressor work without superheating, a crucial factor in evaluating the performance of the refrigeration system, is calculated using equation (2). The calculation of compressor work following the superheating of the refrigerant is determined utilizing equation (3).

Without superheat $W_c = h_2 - h_1$ . ..(2)

With superheat $W_c = h_2 - h_{1'}$ ...(3)

The quantity of heat rejected by the heat exchanger, sometimes referred to as the gas cooler, is calculated using equation (4).

$$Q_{amb} = h_2 - h_3 \quad ...(4)$$

A refrigeration system's COP is greatly influenced by equation (5). The system's effectiveness at converting energy input into practical cooling output is determined by the COP. Equation (4) can be used to calculate the COP based on the ratio of the intended cooling effect (heat removed from the refrigerated space) to the energy input (compressor effort).

$$COP = Q_{evp} / W_c \quad ...(5)$$

The degree of superheating is calculated using equation (6)

$$Degree\ of\ superheat = T_{1'} - T_1 \quad ...(6)$$

The degree of subcooling is calculated using equation (7)

$$Degree\ of\ subcooling = T_{3'} - T_3 \quad ...(7)$$

In the refrigeration system, the refrigerant is assumed to undergo subcooling by superheating it after the evaporator, resulting in a reduction of its temperature. The heat that is lost by the refrigerant after passing through the gas cooler is then gained by the refrigerant coming out from the evaporator. The degree of subcooling can be determined by utilizing equation (8), which takes into account the degree of superheating. In this equation, $C_{p,H}$ represents the specific heat at higher pressure, while $C_{p,L}$ represents the specific heat at the evaporator pressure, which is the lower pressure in this context. For this analysis, a mass flow rate of 1 (unity) is considered.

$$C_{p,H}(T_{3'} - T_3) = C_{p,L}(T_{1'} - T_1) \quad ...(8)$$

The higher pressure (P_2), which corresponds to the refrigerant pressure after compression, is determined based on the ambient temperature. The optimal value for the higher pressure (MPa) is calculated as 0.26 multiplied by the ambient temperature (T_{amb}) in degrees Celsius (Kauf 1999).

To make the analysis of the refrigeration system simpler, certain assumptions are used in this study. The gas cooler's pressure drop is regarded as insignificant, which reduces how much it affects system performance. The expansion process in the ejector is also thought to be isenthalpic, which implies that there is no enthalpy change. These presumptions make the study simpler by assuming that losses and energy changes during expansion are eliminated.

RESULTS AND DISCUSSION

The study sheds light on how refrigeration systems function under various circumstances by analyzing the performance and behavior of these systems. In particular, it looks into the COP and how different operational factors affect it in subcritical and transcritical refrigeration systems with superheating and subcooling. The study improves our comprehension of system performance by examining the effects of variables like pressure, evaporator temperature, and ambient temperature on COP. The results and discussions offer insightful information for supporting energy conservation, increasing system performance, and enhancing efficiency in transcritical refrigeration systems.

Effect of Evaporator Temperature on COP of Subcritical CO_2 Refrigeration System at Constant Higher Pressure

In Fig. 4, the link between evaporator temperature and COP is shown, highlighting significant results. The findings provide important light on how fluctuations in evaporator temperature affect the energy efficiency of the subcritical refrigeration system. This information helps with system optimization and encourages energy efficiency. By illuminating the system's behavior under various operating circumstances, the research helps us get a greater knowledge of how well it performs. In the research, the compressor's output pressure is referred to as "higher pressure" (P_2).

The main objective of the inquiry is to determine how the COP in a subcritical refrigeration system is impacted by the evaporator temperature. While the evaporator temperature is adjusted between -5°C and 12°C, three constant high pressures, i.e., 6 MPa, 6.5 MPa, and 7 MPa, are taken into consideration. The findings show a clear relationship between evaporator temperature and COP, with higher temperatures translating into greater COP numbers. The greater temperature difference between the evaporator and its surroundings, which improves heat transfer and increases refrigeration capacity, is the likely cause of this link. By requiring less compression work, lower compressor pressures also help increase COP values. Notably, the study finds that the COP increases more significantly at 6 MPa as a result of the interaction between lower compressor pressures and higher evaporator temperatures. The diminishing returns and limited gains in heat transfer at higher pressures, on the other hand, may be the cause of the COP increment being less noticeable at 7 MPa.

A greater COP is related to a higher evaporator temperature in a refrigeration system. This is because there is less temperature disparity, which lowers heat transfer losses and boosts system effectiveness. A higher COP is also the result of higher evaporator temperatures because they necessitate less compression effort and permit greater refrigeration capacity. To maximize system effectiveness and achieve a higher COP, evaporator temperature optimization is essential.

Effect of Superheating after Evaporator and Subcooling after Gas Cooler on COP

The objective is to examine the impact of the degree of superheat on the COP in a transcritical refrigeration system with a fixed high pressure. By investigating this relationship, the research aims to gain a better understanding of how varying degrees of superheat influence the system's energy efficiency. The determination of the optimal high pressure after the compressor is investigated by Kauf (Kauf 1999), providing insight into the appropriate operating conditions for the system. In Fig. 5(A), the link between the degree of superheating and COP is shown, highlighting significant results. The findings provide important light on how variations in the degree of superheat affect the energy efficiency of the transcritical CO_2 refrigeration system. The subcooling is not considered for this analysis in Fig. 5(A). This information helps with system optimization and energy efficiency while using the system with superheating. By illuminating the system's behavior under various operating circumstances, the research would help to get a greater knowledge of how well it performs.

Fig. 5(B) presents a comparison between the degree of superheating and subcooling and their respective impacts on the COP. These findings contribute valuable insights into the influence of variations in the degree of superheat on the energy efficiency of transcritical CO_2 refrigeration

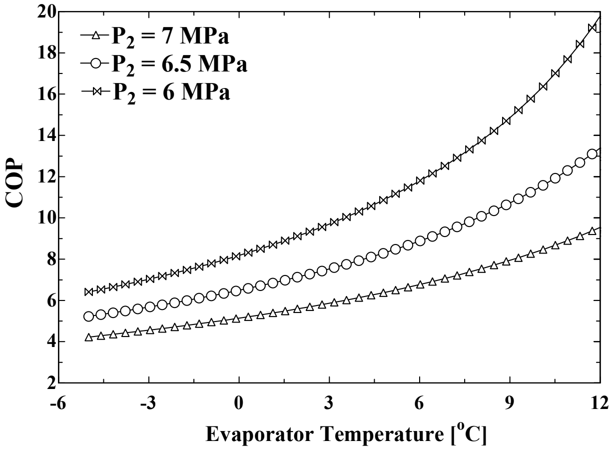
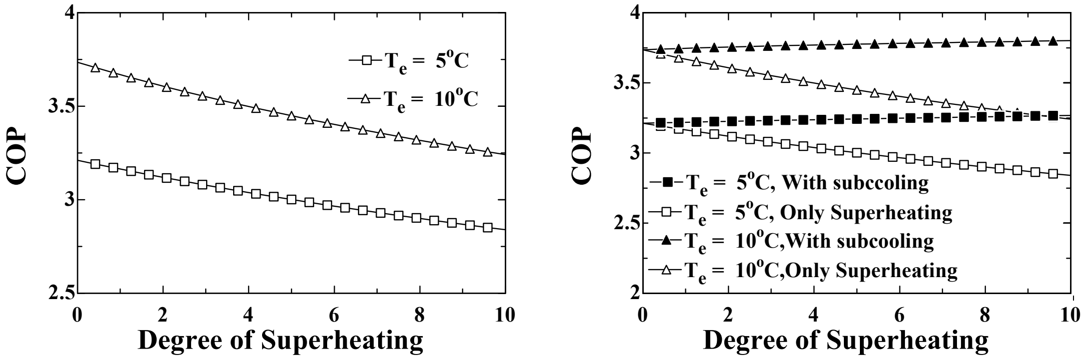


Fig. 4: Effect of evaporator temperature on COP of subcritical CO_2 refrigeration system.



(A) Effect of Superheating (B) Effect of Subcooling

Fig. 5: Effect of superheating and subcooling on COP and compressor work.

systems, particularly in relation to the subcooling process. By examining the system's behavior under different subcooling and superheating conditions, this research enhances our understanding of its performance characteristics.

The primary aim of this investigation is to assess the impact of evaporator temperature resulting from superheating on the COP in a transcritical refrigeration system. By gradually increasing the evaporator temperature after reaching saturated vapor, the effects on COP are examined. The evaporator temperature is adjusted at two specific values, namely 5°C and 10°C, to obtain the corresponding results. To investigate the relationship between superheating and COP, the degree of superheating after the evaporator temperature is varied from 0 to 10. Additionally, the higher pressure maintained throughout this simulation is 10.4 MPa, while the ambient temperature remains constant at 40°C.

The results reveal a distinct correlation between the degree of superheat and the coefficient of performance (COP), indicating that higher temperatures lead to lower COP values. Particularly noteworthy is the finding that the COP experiences a more pronounced reduction with an increase in the degree of superheat. Comparing identical boundary conditions, the COP is higher at a 10°C evaporator temperature than at a 5°C evaporator temperature. Fig. 5(A) further illustrates that superheating is not recommended for use in CO_2 refrigeration systems.

Fig. 5(B) displays the impact of subcooling in the CO_2 refrigeration system. Subcooling significantly affects the coefficient of performance of the system, with COP increasing as the degree of subcooling increases. The degree of subcooling also influences the degree of superheating. Greater subcooling results in higher degrees of superheating. The heat released during subcooling is subsequently absorbed by the refrigerant during superheating.

The findings in Fig. 5(B) indicate that the COP increases with an increase in superheating at both 5°C and 10°C of subcooling. However, it is important to note that superheating is only advisable when used in conjunction with subcooling of the refrigerant. This relationship between subcooling and superheating plays a crucial role in optimizing the system's performance and efficiency in CO_2 refrigeration systems.

Gas Cooler Subcooling Effects on Evaporator Inlet Vapor Quality

The degree of subcooling is dependent on the degree of superheating, as illustrated in Fig. 6. Increasing the degree of superheating influences the degree of subcooling, and this relationship is analyzed. The investigation is conducted under a constant ambient temperature of 40°C.

At a constant evaporator temperature of 5°C, when the degree of superheating increases from 0 to 10°C, the degree of subcooling also increases from 0 to 4.284°C, as depicted in Fig. 6. As a result of this increase in subcooling, the vapor quality at the evaporator inlet decreases from 0.4426 to 0.3585. This reduction in vapor quality has a positive impact on the performance of the refrigeration system, as a lower inlet vapor quality leads to a higher refrigeration effect, thus improving the COP.

Similarly, at a constant evaporator temperature of 10°C, an increase in the degree of superheating from 0 to 10°C results in an increase in the degree of subcooling from 0 to 4.781°C, as shown in Fig. 5. Consequently, the vapor quality at the evaporator inlet decreases from 0.4155 to 0.3144. This decline in vapor quality again leads to an improvement in the performance of the refrigeration system, enhancing the COP. Overall, the findings from Fig. 6 demonstrate the interplay between the degree of superheating and subcooling and their effects on the refrigeration system's performance, ultimately positively influencing the COP.

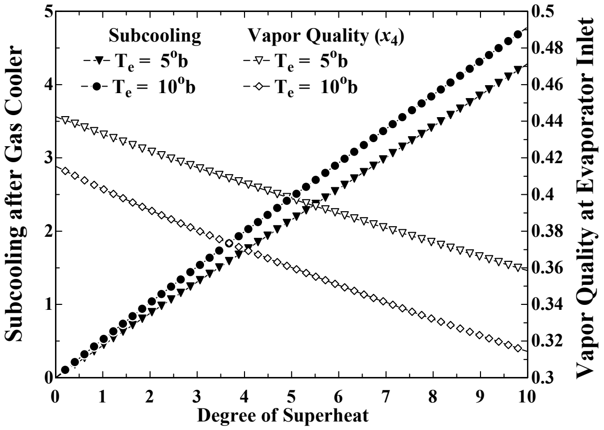
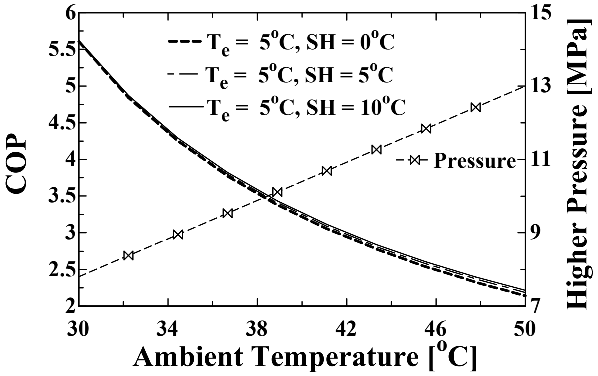


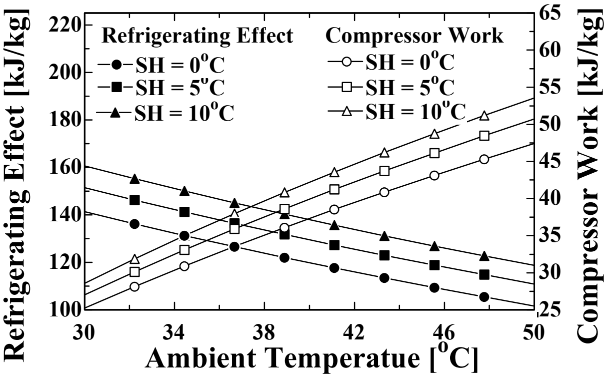
Fig. 6: Effect of subcooling on evaporator inlet and gas cooler temperature.

Effect of Ambient Temperature on the COP of Refrigeration System with Subcooling

Fig. 7 presents an investigation into the combined effect of ambient temperature and degree of subcooling. The ambient temperature is varied from 30 to 50°C to observe its impact. For this analysis, a constant evaporator temperature of 5°C is maintained, and three different degrees of superheating, namely 0°C, 5°C, and 10°C, are considered. The system's optimum pressure is determined based on the ambient temperature. Understanding the relationship between ambient temperature and the coefficient of performance is essential for optimizing energy efficiency and overall system performance in transcritical refrigeration systems.



(A) COP and pressure variation with ambient temperature



(B) COP and compressor work variation with ambient temperature

Fig. 7: Effect of ambient temperature on COP with superheating.

Engineers can make informed decisions regarding energy efficiency improvements and energy consumption reductions based on this understanding. Moreover, the refrigeration system's capability is significantly influenced by the ambient temperature.

In Fig. 7(A), the optimal higher pressure (P_2) is displayed on the secondary y-axis, which is selected based on the surrounding temperature range from 30°C to 50°C. The primary y-axis shows the resulting COP values, providing valuable information on the connection between system performance and ambient temperature.

The results from Fig. 7(A) reveal that the COP of the transcritical refrigeration system decreases as the ambient temperature rises. Without superheating, the COP varies from 5.605 to 2.14 when the ambient temperature is changed from 30°C to 50°C. Concurrently, the compressor work increases from 25.22 to 47.44 kJ.kg^{-1} under the same ambient temperature range. With 5°C of superheating, the COP changes from 5.609 to 2.186 as the ambient temperature varies from 30°C to 50°C. The compressor work increases from 27.01 to 50.71 kJ.kg^{-1} during this temperature change. Similarly, with 10°C of superheating, the COP varies from 5.623 to 2.216 when the ambient temperature is changed from 30°C to 50°C. The compressor work increases from 28.57 to 53.57 kJ.kg^{-1} for the same range of ambient temperatures.

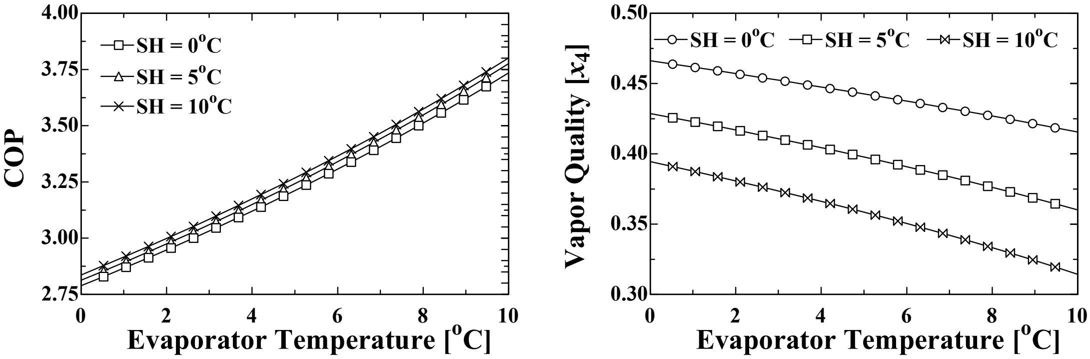
Fig. 7(B) provides an analysis of the refrigerating effect and compressor work in response to changes in ambient temperature. The refrigerating effect varies from 141.4 kJ.kg^{-1} to 101.6 kJ.kg^{-1} when the ambient temperature is varied from 30°C to 50°C without superheating. With 5°C of superheating, the refrigerating effect ranges from 151.5 kJ.kg^{-1} to 110.9 kJ.kg^{-1} for the same variation in ambient temperature. Additionally, with 10°C of superheating, the refrigerating effect varies from 160.6 kJ.kg^{-1} to 118.7 kJ.kg^{-1} as the ambient temperature is changed from 30°C to 50°C. It is important to note that the evaporator temperature for this analysis is maintained at 5°C.

Furthermore, it is observed from Fig. 6 and Fig. 7 that the COP decreases as the ambient temperature increases. However, there is only a minimal increase in COP at 10°C superheating. These findings provide valuable insights into the impact of ambient temperature and superheating on the performance of the refrigeration system. There are many reasons for the decrease in COP with rising ambient temperature observed in Fig. 7. First of all, greater ambient temperatures result in a smaller temperature difference between the condenser and the environment, which reduces heat rejection and lowers system efficiency. As a result, the system is less able to effectively remove heat. Second, greater ambient temperatures put the compressor under more strain, which raises energy costs and lowers COP. Increased system losses and decreased refrigeration capacity may also result from higher ambient temperatures. These elements work together to explain the transcritical refrigeration system's reported decline in COP with rising ambient temperature.

Effect of Evaporator Temperature on COP with Subcooling

Fig. 8 provides an analysis of the effect of evaporator temperature with superheating in a transcritical refrigeration system. The evaporator temperature is varied from 0 to 10°C to observe its impact on the coefficient of performance. Three different degrees of superheating, namely 0°C, 5°C, and 10°C, are considered for this analysis, with the ambient temperature set at 40°C.

Optimizing energy efficiency and overall system performance requires a thorough investigation into how the evaporator temperature affects the COP in a transcritical refrigeration system. Additionally, the refrigeration system's capacity is significantly influenced by the evaporator temperature.



(A) Variation of COP (B) Variation of vapor quality

Fig. 8: Effect of evaporator temperature on COP with subcooling.

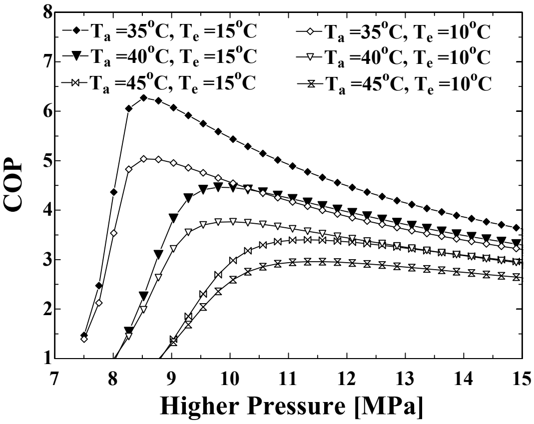
In Fig. 8(A), it is evident that the transcritical refrigeration system's COP increases with an increase in the evaporator temperature. Moreover, the COP shows a consistent rise with the increase in superheating. Notably, at 10°C of superheating, the COP is higher at higher evaporator temperatures. Specifically, the COP varies from 2.789 to 3.735 when the evaporator temperature is changed from 0 to 10°C without superheating. With 5°C of superheating, the COP ranges from 2.814 to 3.776 for the same range of evaporator temperatures. Furthermore, with 10°C of superheating, the COP varies from 2.837 to 3.801 as the evaporator temperature is changed from 0 to 10°C.

In Fig. 8(B), the inlet vapor quality at the evaporator is presented for the variation of evaporator temperature from 0 to 10°C. Without superheating, the inlet vapor quality at the evaporator varies from 0.4662 to 0.4155 as the evaporator temperature changes from 0 to 10°C. With 5°C of superheating, the inlet vapor quality at the evaporator ranges from 0.4287 to 0.3601 for the same range of evaporator temperatures. Similarly, with 10°C of superheating, the inlet vapor quality at the evaporator varies from 0.3944 to 0.3144 as the evaporator temperature is changed from 0 to 10°C.

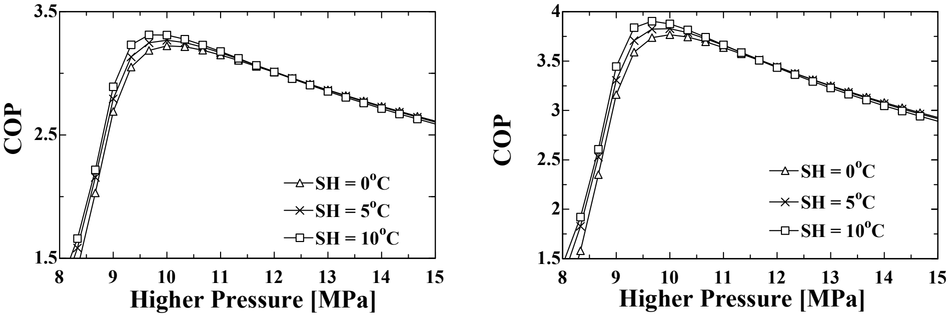
The findings from Fig. 8 indicate that the COP is higher at higher evaporator temperatures and increases with the increase in the degree of superheating. Additionally, the inlet vapor quality at the evaporator is decreased due to subcooling. Increasing the evaporator temperature results in a larger temperature difference between the evaporator and the surroundings, leading to improved heat transfer rates and increased refrigeration capacity. These observations offer valuable insights into the factors affecting the performance and efficiency of the transcritical refrigeration system.

Effect of Higher Pressure on COP of Transcritical Refrigeration System

Fig. 9(A) shows how increased pressure affects a transcritical refrigeration system's COP at constant evaporator temperatures. The study's goal was to evaluate the impact of various higher pressures (P_2) on the system's COP. At constant evaporator temperatures of 10°C and 15°C, the ideal higher pressure of a transcritical refrigeration system is examined. There are three different ambient temperatures: 35°C, 40°C, and 45°C. The ideal higher pressure is determined by the maximal COP at various higher pressures.



(A) Optimum pressure for higher COP



(B) Evaporator temperature =5°C (C) Evaporator Temperature =10°C

Fig. 9: Effect of compressor pressure on COP.

The ideal higher pressure at 35°C ambient temperature is 8.52MPa at both the 10°C and 15°C evaporator temperatures. The ideal higher pressure for both evaporator temperatures is 9.8MPa at 40°C ambient temperature. The ideal higher pressure at both evaporator temperatures is 11.33MPa at 45°C ambient temperature.

An ambient temperature of 35°C produced an ideal higher pressure of 8.52 MPa for both evaporator temperatures. Similar to this, at 40°C and 45°C, respectively, the optimal higher pressure was 9.8 MPa and 11.33 MPa. Lower evaporator temperatures result in decreased heat transfer rates and refrigeration capacity, which lowers COP. The smaller temperature differential has an impact on the system's capacity to extract heat.

Fig. 9 presents the effect of increased pressure on the coefficient of performance of a transcritical refrigeration system with superheating while keeping the evaporator temperatures constant. The primary goal of this study was to assess the influence of various higher pressures (P_2) on the system's COP. For this analysis, constant evaporator temperatures of 5°C and 10°C were considered, with an ambient temperature of 40°C. Three different degrees of superheating, namely 0°C, 5°C, and 10°C, were also taken into account. The ideal higher pressure (P_2) was determined by identifying the maximum COP at various higher pressures.

In Fig. 9(B), the ideal higher pressure values for a 5°C evaporator temperature are 3.233 MPa, 3.249 MPa, and 3.268 MPa for superheating values of 0°C, 5°C, and 10°C, respectively. Similarly, in Fig. 9(C), the ideal higher pressure values for a 10°C evaporator temperature are 3.766 MPa, 3.827 MPa, and 3.904 MPa for the same superheating values.

One important observation from Fig. 9 is that the optimum higher pressure is dependent on ambient temperature. However, evaporator temperature and superheating do not have a significant effect on the optimum higher pressure. Lower evaporator temperatures lead to decreased heat transfer rates and refrigeration capacity, which subsequently lower the COP. The reduced temperature differential affects the system's ability to extract heat effectively. Additionally, the compressor experiences higher stress in lower temperatures, resulting in increased energy consumption and decreased performance. System losses also increase at lower evaporator temperatures, further reducing the COP. These factors collectively explain why the COP decreases with decreasing evaporator temperature.

CONCLUSION

This study provides a comprehensive analysis of subcritical and transcritical refrigeration systems using CO_2 as the refrigerant, with a primary focus on the coefficient of performance and its relationship with various operating parameters. The effects of subcooling and superheating on the COP have been thoroughly investigated. Understanding the interplay between the COP and operating parameters, such as subcooling, superheating, ambient temperature, and evaporator temperature, is critical in optimizing the performance and energy efficiency of CO_2 refrigeration systems.

The findings underscore that superheating is not advisable for CO_2 refrigeration systems. Conversely, the COP experiences a significant increase with greater degrees of subcooling. Subcooling results in a decrease in vapor quality, leading to enhanced system performance and an elevated COP.

Furthermore, as the ambient temperature rises, the COP decreases, with only minimal improvements observed at 10°C superheating. Higher evaporator temperatures correspond to higher COP values, and the COP further increases with increasing degrees of superheating. Additionally, subcooling reduces the inlet vapor quality at the evaporator. The study also highlights that the optimum higher pressure depends on ambient temperature, while evaporator temperature and superheating have negligible effects on the optimal higher pressure.

NOMENCLATURE

Definitions

T	Temperature [°C]
C_p	Specific heat [J.kgK^{-1}]
Q_{amb}	Heat transfer to ambient [kW]
Q_{evap}	Evaporator heat [kW]
W_c	Compressor work [kJ.kg^{-1}]
h	Enthalpy [kJ.kg^{-1}]
P	Pressure [MPa]

Abbreviations

CO_2	Carbon Dioxide
COP	Coefficient of Performance
ODP	Ozone Depleting Potential
GWP	Global Warming Potential
THE	Internal Heat Exchanger
DEC	Dual Expansion Cycle

Subscripts

L	Lower (Evaporator)
H	Higher (Condenser)
c	Compressor
amb	Ambient
evp	Evaporator

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