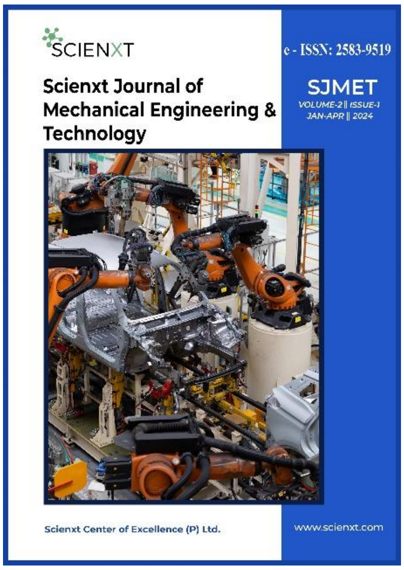

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Comparison of thermodynamic performance in cascade systems utilizing various refrigerant combinations

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Abstract:

In numerous industrial and medical settings, achieving very low temperatures poses a challenge for conventional refrigeration systems due to extremely low evaporator pressures. Consequently, cascading presents itself as a viable solution, wherein two distinct vapor compression plants, each operating with different refrigerants, are interconnected. This arrangement enables the condensation of vapor from the low-temperature stage by utilizing the evaporation of liquid from the high-temperature stage.

The primary objective of this study is to conduct a comparative thermodynamic performance analysis of cascade systems (CCS) tailored for both cooling and heating applications, focusing on various refrigerant pairs. The specific aims are to identify the most suitable refrigerant pair and to investigate the influence of operating parameters on the performance of cascade refrigeration systems (CRSs) across different refrigerant combinations.

Key findings indicate that the highest coefficient of performance (COP) for CCS in cooling applications is achieved with the CO_2-NH_3 refrigerant couple (COP = 1.934), while the lowest COP is observed with the CO_2-R1234yf refrigerant couple (COP = 1.777). Additionally, exergy efficiencies of CCS for cooling applications are reported as follows: 49.89% (CO_2-HFE7000), 49.72% (CO_2-R134a), 50.74% (CO_2-R152a), 49.17% (CO_2-R32), 48.56% (CO_2-R1234yf),

51.19% (CO_2-NH_3), 49.29% (CO_2-Propane), and 49.28% (CO_2-Propylene).

Keyword:

Cascade system, Refrigerant, Coefficient of Performance, and Couple of Refrigerant

1. Introduction:

As a result of environmental problems related to global warming and depletion of the ozone layer caused by the use of synthetic refrigerants (CFC's, HCFC's and HFC's) experienced over the last decades, the return to the use of natural substances for refrigeration purposes appears to be sound practice. It must be a better solution to use naturally existing and environmentally harmless substances as alternatives refrigerants in refrigeration systems.

Amongst the natural refrigerants, Lorentzen and Petterson [1] suggested the use of carbon dioxide (CO_2) and seems to be the most promising one especially as the natural refrigerant [1-6]. The key advantages of CO_2 include the fact that is not explosive, non-toxic, easily available, environmental friendly and has excellent thermo-physical properties. On the other hand, researches in Norway in 1993 showed that the refrigerant leakages coming from the commercial sector were 30% of the annual total [7]. In this research, the use of a cascade system using CO_2 in the low temperature stage and NH_3 in the high temperature stage turned out to be an excellent alternative for cooling applications at very low temperatures [8-10]. Researches from Eggen and Aflekt [11], Pearson and Cable [12] and Van Riessen [13] show practical examples of the use of a cascade system of CO_2/NH_3 for cooling in supermarkets. Eggen and Aflekt [11] developed research based on a prototype of a cooling system built in Norway. Pearson and Cable [12] showed data from a cooling system used in a Scottish supermarket line, (ASDA), and Van Riessen [13] carried out technical energy and economic research of a cooling system used in a Dutch supermarket.

In the same way, different researches about the performance of different cooling systems involving CO_2 have been carried out together with its reuse as a refrigerant fluid. Lorentzen and Petterson [1] evaluated the possibility of the use of a heat exchanger in a CO_2 transcritical system. Hwang et al. [6] showed experimental results and simulation research including expansors and double stage cycles. Groll et al. [14] carried out a numerical analysis of a double stage cycle changing the compression ratio of each compression stage.

Regarding energy shortage problems, much attention has been devoted to the optimization of CRS performance. One of the research topics is the selection of refrigerant couples [3]. A suitable refrigerant couple is able to provide a large temperature lift while improving system performance [2]. The HTC of a CRS can normally be charged as an intermediate-temperature refrigerant with a normal boiling point ranging from 0 °C to -60°C, such as R22 [4], R404A [5], R290, NH_3 (R717), propylene (R1270), R12, R134a, and R410A, whereas the normal boiling points of low-temperature refrigerants such as R23, carbon dioxide (R744) and N2O are usually lower than -70°C. However, there is no definite temperature boundary between.

2. Need of cascade system:

Cascade refrigeration systems utilize two independently operated single-stage refrigeration systems. One system maintains a lower evaporating temperature, generating a refrigeration effect, while the other operates at a higher evaporating temperature. In certain industrial scenarios where achieving moderately low temperatures with significant temperature and pressure differences poses challenges for single-stage vapor-compression refrigeration cycles, cascade systems offer a solution. By employing multiple stages operating in series, cascade refrigeration cycles enable the attainment of high-temperature differentials between the heat source and heat sink. They are particularly suitable for applications requiring temperatures ranging from −70°C to -100°C.

In many industrial and medical fields, extremely low temperatures are essential. For instance, temperatures as low as -80°C are required for tasks like freezing and storing blood, while specialized alloy steels need temperatures as frigid as -90°C for precipitation hardening. Traditional refrigeration systems face significant challenges in achieving such low temperatures due to the exceptionally low pressures in the evaporator. Even with high-pressure refrigerants like R-22, the evaporator pressure remains as low as 0.105 bar at -80°C. For R-12, the pressure is even lower. This low-pressure operation presents difficulties in terms of sealing and high displacement volume. R-13 is one of the few refrigerants suitable for such extreme temperatures, with a saturation pressure of 1.12 bar at -80°C. However, its exceedingly low critical temperature (28.8°C) precludes direct or stage compression up to condensing pressures. Hence, the only viable solution is cascading, which involves employing two distinct vapor compression systems using different refrigerants. These systems are interconnected so that the vapor from the low- temperature stage is condensed by the evaporation of liquid from the high-temperature stage.

3. Cascade refrigeration system:

The cascade system shares similarities with the binary vapor cycle utilized in power plants. In a binary vapor cycle, a mercury condenser serves as a boiler for water. Similarly, in the cascade system, the condenser of the low-temperature cycle functions as the evaporator for the high- temperature cycle. This system employs a series of refrigerants with progressively lower freezing points in a sequence of single-stage units.

The cascade condensing unit comprises two refrigerating systems or cycles, denoted as cycles A and B. Cycle B's condenser, known as the "high stage," is typically fan-cooled, though water cooling may be used in some instances. The evaporator of cycle B cools the condenser of cycle a, known as the "low stage." This unit, comprising cycle A's condenser and cycle B's evaporator, is often termed the "Inter-stage condenser" or "cascade condenser." Thus, a cascade condenser serves as an evaporator for the high-temperature cascade system (cycle A).

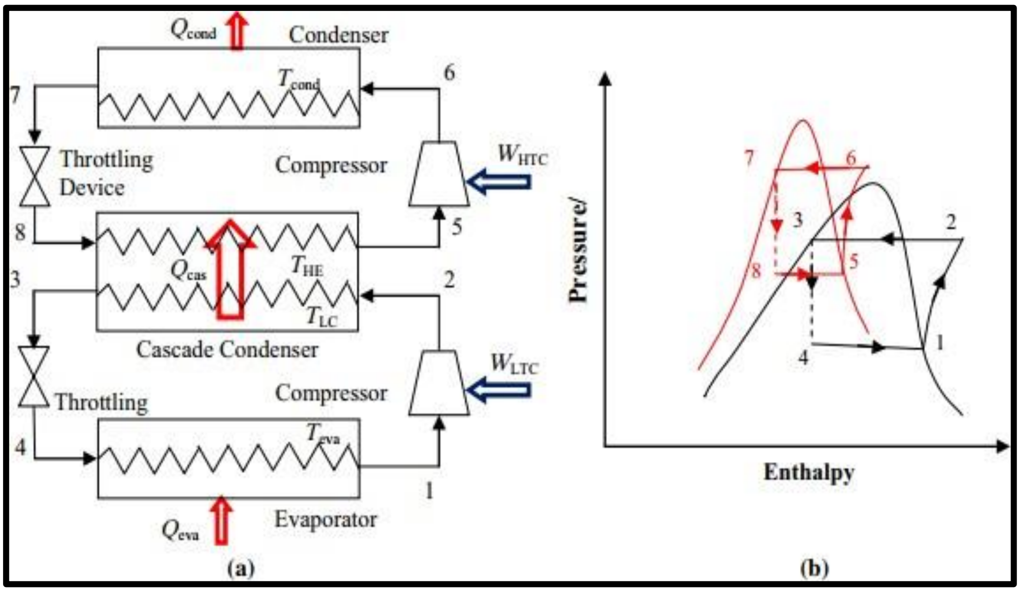

Figure. 1: Two stage cascade refrigeration system and P-H chart

The temperature difference between the low-temperature cascade condenser and the high-temperature cascade evaporator is termed temperature overlap, essential for efficient heat transfer. Cascade systems employ two different refrigerants in each stage because single-stage systems cannot achieve the high compression ratio required for evaporating and condensing temperatures economically.

The high-temperature cascade system employs a refrigerant with a low boiling temperature, such as R-13 or R-13B1. These refrigerants have extremely high pressures, ensuring a smaller compressor displacement in the low-temperature cascade system and a higher coefficient of performance (COP).

4. Assumptions:

1. All components are assumed to be a steady state and steady flow processes. The changes

in the potential and the kinetic energy of the components are negligible.

2. The low circuit compressor is isentropic
3. All throttling devices are isenthalpic.
4. Refrigerants at the cascaded heat exchanger outlet, condenser outlet and evaporator outlet are saturated.
5. Negligible pressure and heat losses or gains in the pipe networks or system components.
6. The dead state is Ta=25°C and Pa=1 atm.

5. Design parameter for two stage cascade system:

The calculation process for the two-stage cascade refrigeration system begins with setting fixed values for the evaporator and condenser temperatures. Saturation pressures, liquid and vapor enthalpies, entropies, and specific heats are then computed using Engineering Equation Solver (EES). The evaporator absorbs heat from the cooling space, with the evaporator temperature (TE) initially assumed at -60°C and subsequently incremented by 5°C with 50°C intervals. The condenser temperature (TC) is set at 50°C and increased by 5°C with 5°C intervals. The condenser temperature for the low-temperature cycle (TcasL) is maintained at 10°C. Optimal condensing temperatures are determined corresponding to each evaporating temperature to minimize energy consumption. The mass flow rates of refrigerant through the cascade condenser (m1) and the main condenser (m2) are computed. Additionally, parameters such as COP, η Exergy, and XTotal loss are evaluated for each operating temperature set.

6. Results and discussion:

This study delves into the exploration of Carbon Capture and Storage (CCS) for both heating and cooling applications through a comprehensive assessment of thermodynamic performance. The thermodynamic characteristics of the individual components comprising CCS are determined utilizing Engineering Equation Solver (EES) software (EES, 2017).

6.1. Evaluation of cascade system performance across different investigated refrigerants:

In order to validate the current model, simulation outcomes were juxtaposed with existing numerical data from literature across various refrigerant pairs. The study's findings were cross- referenced with simulation data previously published by Yilmaz & Selbaş (2019), under identical operating conditions, as outlined in Table. 1. The comparison revealed a satisfactory level of agreement between the two sets of simulation results. Additionally, Table. 1 outlines a comparison of cascade system performances employing the suggested refrigerant candidates.

Table. 1: Performances of cascade system according to the studied working fluids

Parameter	***CO2-HFE7000***	***CO2-R134a***	***CO2-R152a***	***CO2-R32,***	***CO2-R1234yf***	***CO2-NH3***	***CO2-Propane***	***CO2-Propylene***
COP	1.853	1.843	1.906	1.809	1.77	1.934	1.816	1.815
Exergy efficiency	49.89	49.72	50.74	49.17	48.56	51.19	49.29	49.28
Exergy destruction rate, kW	3.38	3.41	3.23	3.94	4.089	3.155	3.49	3.49

The results in Table. 1 show that among all candidates, CO2-NH3 has a highest COP among the all refrigerant couples at evaporator temperature -30°C and condenser temperature of 50°C. With respect to refrigerant couple CO2-NH3 exergy efficiency is maximum among the all refrigerant couples. Exergy destruction rate is minimum in case of refrigerant couple CO2-NH3 among the all refrigerant couples.

6.2. Effect of evaporator temperature on the performance of cascade system:

In the present work thermodynamic model has been developed in Engineering Equation Solver software and results of the analysis have been given in the following sections.

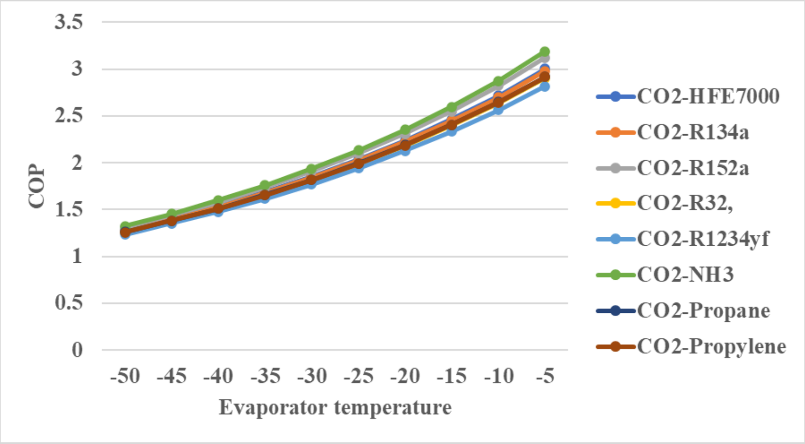

Figure. 2: Variation of COP with different refrigerant couples

Fig. 2 illustrates the impact of varying evaporator temperature on the Coefficient of Performance (COP) of the Carbon Capture and Storage (CCS) system, while maintaining a constant condenser temperature of 50°C. As the evaporator temperature rises from -50 to -5°C, there is a corresponding increase in the COP of the CCS. Notably, the highest COP recorded for the CCS is 3.189, observed with the CO_2/NH_3 refrigerant couple at an evaporator temperature of -5°C and a condenser temperature of 50°C.

The trend depicted in Fig. 2 indicates that as the evaporator temperature increases, the COP of the CCS also rises, suggesting a positive correlation between the two variables. Moreover, the upward trend in evaporator temperature is shown to have a beneficial impact on the overall efficiency of the system.

6.3. Effect of condenser temperature:

In the present work thermodynamic model has been developed using Engineering Equation Solver software and results of the analysis have been given in the following sections.

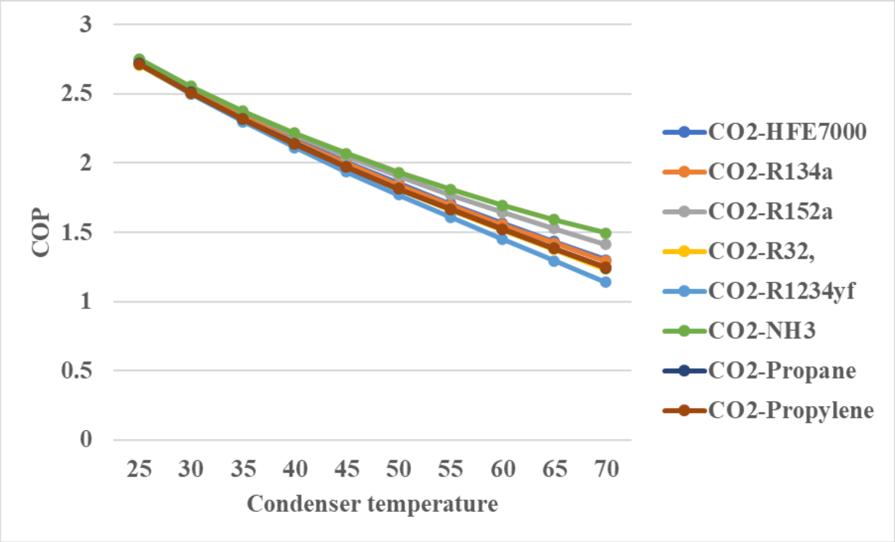

Figure. 3: Variation of COP with different condenser temperature

Fig. 3 depicts the impact of varying condenser temperature on the rate of exergy destruction within the Carbon Capture and Storage (CCS) system, while maintaining a constant evaporator temperature of -50°C. As the condenser temperature increases from 25 to 70°C, there is a corresponding rise in the exergy destruction rate of the CCS. The highest exergy destruction rate recorded for the CCS is 6.006 kW, observed with the CO_2-HFE7000 refrigerant couple at an evaporator temperature of -50°C and a condenser temperature of 50°C.

The trend illustrated in Figure 3 reveals that as the condenser temperature increases, the rate of exergy destruction within the CCS also rises, indicating a positive correlation between the two variables. Furthermore, the upward trend in condenser temperature is shown to have a favorable impact on the rate of exergy destruction.

7. Conclusion:

The current study conducts a comprehensive comparative analysis of the thermodynamic performance of Carbon Capture and Storage (CCS) systems tailored for both cooling and heating applications, employing various refrigerant pairs. This evaluation encompasses the assessment of key performance metrics such as Coefficient of Performance (COP), exergy destruction rate, and exergy efficiencies of the overall system. The analysis is conducted utilizing fundamental thermodynamic equilibrium equations encompassing mass, energy, entropy, and exergy principles, alongside energy and exergy efficiency equations.

Furthermore, a parametric study is undertaken to elucidate the influence of evaporator and condenser temperatures on the energy and exergy efficiencies, as well as the exergy destruction rate of the system. This endeavor aims to facilitate a deeper understanding of how adjustments in operating parameters can enhance the overall efficiency of the process, thereby aiding in the optimization of system design.

The conclusions drawn from the results of this study are summarized as follows:

1. Environmentally friendly refrigerants with low Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) values are recommended.
2. CO2 refrigerant is preferred for Low Temperature Cooling (LTC) applications, particularly for achieving lower temperatures.
3. Among the refrigerant couples investigated, the highest coefficient of performance (COP) for CCS in cooling applications is achieved with the CO2-NH3 pair (COP = 1.934), whereas the lowest COP is observed with the CO2-R1234yf pair (COP = 1.777).
4. Exergy efficiencies for cooling applications vary across different refrigerant pairs, with values ranging from 48.56% to 51.19%, highest being for CO2-HFE7000 and lowest for CO2-R1234yf.
5. The heat exchanger experiences the highest exergy destruction rate among all CCS components, with relatively consistent rates across different refrigerant pairs due to operating within similar temperature ranges.

6. Expansion valves exhibit the lowest exergy destruction rate among CCS components.
7. COP decreases for both cooling and heating applications as condenser temperature increases while evaporator temperature remains constant.
8. Exergy efficiency and COP of CCS demonstrate positive correlation with increasing evaporator temperature.
9. CO_2-NH_3 refrigerant pair emerges as the most favorable choice for the proposed CCS based on exergy efficiency.

Overall, these findings provide valuable insights for optimizing CCS design and operation, emphasizing the importance of refrigerant selection and temperature control in achieving efficient system performance.

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