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Energy and Exergy Analyses of CO_2/HFE7000 Cascade Cooling System

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Abstract: In this study, a new refrigerant HFE7000, has been investigated thermodynamically in the cascade cooling system. Energy (COP) and exergy efficiency of cascade cooling system with CO_2/HFE7000 refrigerants are performed. In this regard, the impacts of various parameters on the COP and exergy efficiency and exergy destruction rate of CCS are studied. Moreover, the CO_2 refrigerant is used in the low-temperature circuit and HFE7000 is used in the high-temperature circuit. The COP and exergy efficiency of cascade cooling system are found as 2.313 and 0.5482, for cooling application. In the last section, comparison with R134a refrigerant is done, which is widely used in cascade cooling system.

CO_2/HFE7000 Kaskad Soğutma Çevriminin Enerji ve Ekserji Analizi

Anahtar Kelimeler
Kaskad soğutma,
CO_2,
HFE7000,
Enerji,
Ekserji

Özet: Bu çalışmada yeni bir akışkan türü olan HFE7000 soğutucu akışkanın kaskad soğutma çevriminde termodinamik yönden incelenmiştir. Karbondioksit/HFE7000 akışkanın kaskad soğutma sisteminde enerji (COP) ve ekserji verimleri araştırılmıştır. Bu anlamda, farklı parametrelerin COP, ekserji verimleri ve ekserji yıkım oranları üzerine etkisi incelenmiştir. Yapılan çalışmada; CO_2 düşük sıcaklık bölgesinde HFE7000 akışkanı ise yüksek sıcaklık bölgesinde kullanılmıştır. Kaskad soğutma çevriminin soğutma uygulaması için genel COP ve ekserji verimleri 2.313 ve 0.5482 olarak hesaplanmıştır. Son kısımda, kaskad soğutma sistemlerinde yaygın olarak kullanılan R134a akışkanı ile kıyaslanmıştır.

1. Introduction

Extensive use of conventional energy sources has led to serious environmental concerns especially global warming and ozone depletion. In this view, the importance of energy saving measures and methods have considerably increased and the efficient use of energy have gained tremendous attention in all forms of energy utilization for domestic applications as well as industrial applications. Recent report on climate change has reported that stringent actions need to be deployed to environment problems such as carbon dioxide emissions, global warming, ozone depletion etc. [1]. Currently, the usage of an integrated system has been considered as a solution to efficient use of energy for industrial applications such as energy conversion, air conditioning and refrigeration systems.

The single-stage vapour compression cooling (SVCC) system is unsuitable for engineering applications that are required below -40 ^oC and 27 ^oC temperature ranges [2]. SVCC system require a very high compression ratio in the compressor to achieve under these temperature values. As the compression ratio increases, compressor energy consumption increases and it leads to reducing the efficiency of the SVCC system. Therefore, cascade-cooling system (CCS) is used to avoid such inconveniences in engineering applications that requiring a lower temperature.

A CCS consists of two refrigeration circuits that are thermally unified an internal cascade heat exchanger. The heat exchanger serves as a condenser in the low-temperature circuit while the works as an evaporator in the high-temperature circuit. Generally, carbon dioxide (CO_2) is used as a working fluid in the low-temperature circuit of CCS because, the use of synthetic refrigerants causes environmental problems such as ozone depletion, global warming etc. In addition, the use of some synthetic refrigerants is prohibited because of the global warming potential (GWP) value and ozone depletion potential (ODP) value. However, CO_2 has zero ODP value and low

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direct GWP value and colorless, odorless, natural and environmentally refrigerant [3].
In the literature, several investigators have presented many studies related to CCS. Sarkar et al, [4], have presented a transcritical heat pump system for cooling and heating applications. Mosaffa et al. [5], have studied an exergoeconomic and environment analyses of CO_2/ammonia (NH_3) cascade refrigeration system. They have investigated two system and the annual cost rates for system 1 and 2 founded as lower than 11.25% and 11.9%. Lee at al. [6], have evaluated a thermodynamically analyses of cascade refrigeration system, which used CO_2 and NH_3 as working fluids. They have found that the optimal condenser temperature and performance co-efficient (COP) of system are -15 ^oC and 1.15. Kilicarslan and Hosoz [7], have investigated an energy and irreversibility analyses of cascade refrigeration system for different refrigerants. They selected fluids as R152a–R23, R290–R23, R507–R23, R234a–R23, R717–R23 and R404a–R23. The highest COP value has been seen in an R717-R23 refrigerant couple. Yilmaz et al. [8], have proposed a performance analysis of CO_2/ Nitrous oxide (N_2O) cascade refrigeration system. They have founded COP and exergy efficiency of the system as 2.1 and 36%. Sun et al. [9], studied a comparative analyses of cascade cooling system with R41/R404A and R23/R404A refrigerants. They have investigated as theoretical whether R41 is a suitable substitute for R23 according to thermodynamically performance. In particularly, there are many studies presented based on CO_2 refrigerant in CCS [10-13].

The main objective of this study is evaluating a thermodynamic performance assessment of a CCS by using energy and exergy efficiencies methods. The CO_2 and HFE700 refrigerants have been used in the low-temperature circuit and high temperature circuit, respectively. In addition, the variation of COP and exergy efficiency of CCS have been examined and the effect of a new refrigerant HFE7000 on performance of a CCS is investigated.

2. Cascade Cooling System

The schematic diagram of CCS is illustrated in Figure 1. The system made up of two circuits; a low-temperature circuit with CO_2 as working fluid and a high-temperature circuit with HFE7000 as working fluid.

In the system, these circuits are connected to each other by a heat exchanger. The heat exchanger works as a condenser in low-temperature circuit whereas serves as an evaporator in the high-temperature circuit. The superheated steam CO_2 existing from the low-temperature circuit compressor and enters in the heat exchanger. In the heat exchanger, while the CO_2 refrigerant condenses to a statured liquid, the HFE 7000 refrigerant evaporates to a statured vapor. Then, HFE-7000 refrigerant enters to compressor of the high-temperature circuit. The schematic pressure- enthalpy (P-h) diagram of CCS system displayed in Figure 2.

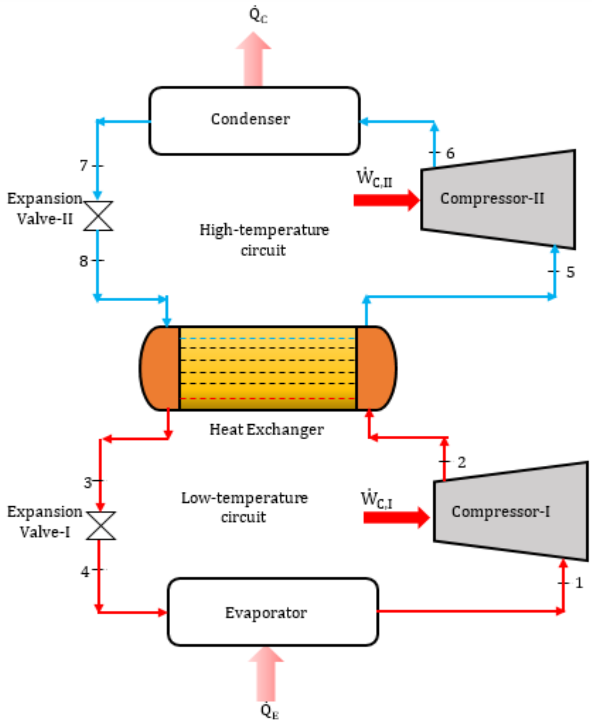

Figure 1. A Schematic diagram of proposed CCS

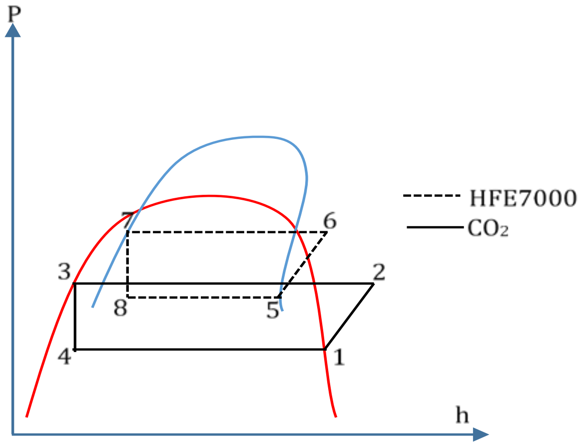

Figure 2 A schematic P-h diagram of CCS system

The thermodynamic and environmental datas of CO_2, HFE7000 and R134a refrigerants are given Table 1. It can be seen clearly that, the GWP value of HFE700 refrigerant lower than R134a refrigerant. In addition, the HFE700 has low toxicity and zero flammability.

Table 1. CO_2, HFE7000 and R134a refrigerants thermodynamic and environmental datas [14, 15]

Property	CO_2	HFE7000	R134a
Critical Pressure (kPa)	7377	3800	4000
Critical Temperature (^oC)	30.98	165	101.1
Boling Point (^oC)	-56.56	34	-26.1
Molecular Weight (g/mol)	44,01	200	102.0
GWP	1	530	1300
ODP	0	0	0

2. 1. Thermodynamic performance analysis

The thermodynamic performance analysis based on energy and exergy analyses are defined. Thermodynamic analysis is usually given by using four balance equations, such as a-) mass balance equation, b-) energy balance equation, c-) entropy balance equation, and d-) exergy balance equation [16, 17]

The general mass balance equations for the steady state process can be explained by below;

$$\Sigma\dot{m}_{in}=\Sigma\dot{m}_{out} \tag{1}$$

Where, "in" and "out" subscripts stands for input and output rates of mass. The general energy balance equation for steady state process can be written as Equation 2;

$$\Sigma\dot{m}_{in}h_{in}+\Sigma\dot{Q}_{in}+\Sigma\dot{W}_{in}=\Sigma\dot{m}_{out}h_{out}+\Sigma\dot{Q}_{out}+\Sigma\dot{W}_{out} \tag{2}$$

where h is specific enthalpy, $\dot{W}$ is work rate and $\dot{Q}$ is heat transfer rate. For the steady state process, the general entropy balance equation given in Equation 3;

$$\Sigma\dot{m}_{in}s_{in}+\Sigma(\frac{\dot{Q}}{T})_{in}+\dot{S}_{gen}=\Sigma\dot{m}_{out}s_{out}+\Sigma(\frac{\dot{Q}}{T})_{out} \tag{3}$$

where, s is specific entropy, $\dot{S}_{gen}$ is entropy generation rate, and T is the temperature at which heat fluxes cross the process boundary.

The general exergy balance equation can be descripted as;

$$\Sigma\dot{m}_{in}ex_{in}+\dot{Ex}^{Q}_{in}+\dot{Ex}^{W}_{in}=\Sigma\dot{m}_{out}ex_{out}+\dot{Ex}^{Q}_{out}+\dot{Ex}^{W}_{out}+\dot{Ex}_{D} \tag{4}$$

In Equation 4, ex is specific exergy, $\dot{Ex}^{Q}$ is the heat of exergy rate, $\dot{Ex}^{W}$ is the work of exergy rate and $\dot{Ex}_{D}$ is exergy destruction rate.

$$ex=ex_{ph}+ex_{pt}+ex_{ch}+ex_{kn} \tag{5}$$

where, ex_{ph}, ex_{pt}, ex_{ch}, and ex_{kn} stands for physical , potential, chemical and kinetic exergy rates. For this study, potential, chemical and kinetic exergy rates are neglected. The physical exergy (ex_{ph}) can be written below as [18];

$$ex_{ph}=(h-h_0)-T_0(s-s_0) \tag{6}$$

The balance equations for the CCC components are described below;

For the Compressor-I;

The mass, energy, entropy and exergy balance equations for the steady state process, which is compressor-I can be explained as;

$$\text{Mass; } \dot{m}_1=\dot{m}_2 \tag{7}$$

$$\text{Energy; } \dot{m}_1h_1+\dot{W}_{C,I}=\Sigma\dot{m}_2h_2 \tag{8}$$

$$\text{Entropy; } \dot{m}_1s_1+\dot{S}_{geni\ C,I}=\dot{m}_2s_2 \tag{9}$$

$$\text{Exergy; } \dot{m}_1ex_1+\dot{W}_{C,I}=\dot{m}_2ex_2+\dot{Ex}_{D,C,I} \tag{10}$$

For the heat exchanger;

The mass, energy, entropy and exergy balance equations of the steady state process for heat exchanger can be defined as;

$$\text{Mass; } \dot{m}_2=\dot{m}_3;\ \dot{m}_8=\dot{m}_5 \tag{11}$$

$$\text{Energy; } \dot{m}_2h_2+\dot{m}_8h_8=\dot{m}_3h_3+\dot{m}_5h_5 \tag{12}$$

$$\text{Entropy; } \dot{m}_2s_2+\dot{m}_8s_8+\dot{S}_{geni\ hex}=\dot{m}_3s_3+\dot{m}_5s_5 \tag{13}$$

$$\text{Exergy; } \dot{m}_2ex_2+\dot{m}_8ex_8=\dot{m}_3ex_3+\dot{m}_5ex_5+\dot{Ex}_{D,hex} \tag{14}$$

For the expansion valve-I;

The mass, energy, entropy and exergy balance equations of the steady state process for expansion valve-I can be defined as;

$$\text{Mass; } \dot{m}_3=\dot{m}_4 \tag{15}$$

$$\text{Energy; } \dot{m}_3h_3=\dot{m}_4h_4 \tag{16}$$

$$\text{Entropy; } \dot{m}_3s_3+\dot{S}_{gen,ex-v,I}=\dot{m}_4s_4 \tag{17}$$

$$\text{Exergy; } \dot{m}_3ex_3=\dot{m}_4ex_4+\dot{Ex}_{D,ex-v,I} \tag{18}$$

For the evaporator;

The mass, energy, entropy and exergy balance equations of the steady state process for evaporator can be defined as;

$$\text{Mass; } \dot{m}_4=\dot{m}_1 \tag{19}$$

$$\text{Energy; } \dot{m}_4h_4+\dot{Q}_E=\dot{m}_1h_1 \tag{20}$$

$$\text{Entropy; } \dot{m}_4s_4+\dot{S}_{gen,E}=\dot{m}_1s_1 \tag{21}$$

$$\text{Exergy; } \dot{m}_4ex_4+\dot{Q}_E(1-\frac{T_0}{T_E})=\dot{m}_1ex_1+\dot{Ex}_{D,E} \tag{22}$$

For the compressor-II;

The mass, energy, entropy and exergy balance equations for the steady state process, which is compressor-II can be explained as;

$$\text{Mass; } \dot{m}_5=\dot{m}_6 \tag{23}$$

$$\text{Energy; } \dot{m}_5h_5 + \dot{W}_{C,II} = \Sigma\dot{m}_6h_6 \quad (24)$$

$$\text{Entropy; } \dot{m}_5s_5 + \dot{S}_{geni\ C,II} = \dot{m}_6s_6 \quad (25)$$

$$\text{Exergy; } \dot{m}_5ex_5 + \dot{W}_{C,II} = \dot{m}_6ex_6 + \dot{E}x_{D,C,II} \quad (26)$$

For the condenser;

The mass, energy, entropy and exergy balance equations of the steady state process for condenser can be defined as;

$$\text{Mass; } \dot{m}_6 = \dot{m}_7 \quad (27)$$

$$\text{Energy; } \dot{m}_6h_6 = \dot{m}_7h_7 + \dot{Q}_C \quad (28)$$

$$\text{Entropy; } \dot{m}_6s_6 + \dot{S}_{gen,C} = \dot{m}_7s_7 \quad (29)$$

$$\text{Exergy; } \dot{m}_6ex_6 = \dot{m}_7ex_7 + +\dot{Q}_C\left(1-\frac{T_0}{T_C}\right) + \dot{E}x_{D,C} \quad (30)$$

For the expansion valve-II;

The mass, energy, entropy and exergy balance equations of the steady state process for expansion valve-II can be defined as;

$$\text{Mass; } \dot{m}_7 = \dot{m}_8 \quad (31)$$

$$\text{Energy; } \dot{m}_7h_7 = \dot{m}_8h_8 \quad (32)$$

$$\text{Entropy; } \dot{m}_7s_7 + \dot{S}_{gen,ex-v,II} = \dot{m}_8s_8 \quad (33)$$

$$\text{Exergy; } \dot{m}_7ex_7 = \dot{m}_8ex_8 + \dot{E}x_{D,ex-v,II} \quad (34)$$

The overall energy (COP) and exergy efficiency of CCS for cooling application can be written as below;

$$COP = \frac{\dot{Q}_E}{\dot{W}_{C,I} + \dot{W}_{C,II}} \quad (35)$$

$$\psi_{sys} = \frac{\dot{E}x_E^Q}{\dot{W}_{C,I} + \dot{W}_{C,II}} \quad (36)$$

3. Results and Discussion

In this study, energy and exergy efficiencies of a CCS were studied theoretically to determine ideal process parameters. The high-temperature circuit in CCS was selected as a new refrigerant HFE700. The engineering equation solver (EES) software program has been used for the modelling of CCS. The following assumptions have been made for thermodynamic calculations;

- The refrigerant is saturated at the evaporator outlet of the low-temperature circuit and at the condenser outlet of the high-temperature circuit
- The kinetic and potential energies neglected.
- The isentropic efficiency of compressor assumed as 80%.
- Pressure and heat losses in the piping have been neglected in the CCS system.
- The reference temperature (T_0) and reference pressure (P_0) assumed as 21 °C and 100 kPa.

Figure 3 illustrates the effect of condenser temperature on COP with different evaporator temperatures. It can be seen that, while the condenser temperature increases from 30 °C to 40 °C, COP of CCS decreases at constant evaporator temperature. The COP of CCS is calculated as 2.972, the condenser and evaporator temperatures are constant 40 °C and -10 °C. Also, the effect of condenser temperature on exergy efficiency of CCS at different evaporator temperatures are given in the Figure 4. The exergy efficiency of CCS decreases with condenser temperature increases. At -10 °C evaporator temperature, when the condenser temperature increasing from 30 °C to 40 °C, the exergy efficiency of CCS decreases, but it has not changed significantly. Exergy efficiency of CCS is calculated as 0.5647, at -10 °C and 40 °C evaporator and condenser temperatures.

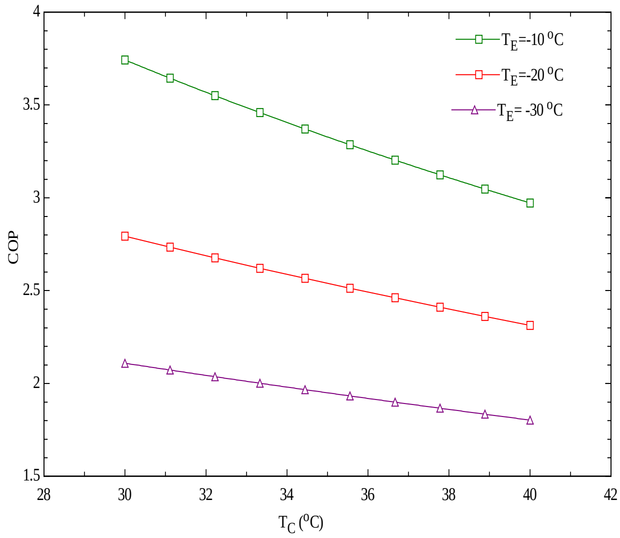

Figure 3. The effect of condenser temperature on COP with different evaporator temperatures

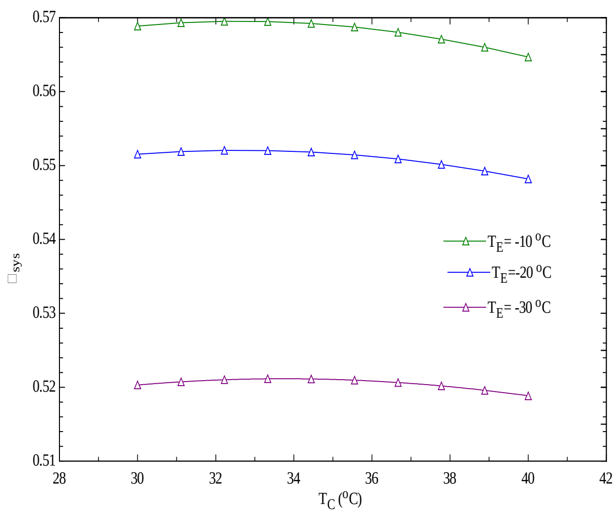

Figure 4 The effect of condenser temperature on exergy efficiency of CCS with different evaporator temperatures

The effect of evaporator temperature on compressor work in LTC and HTC section of CCS are given in Figure 5. According to Figure 5, whereas the evaporator temperature rise up from -40 °C to -10 °C, the energy consumption of compressor-I, and compressor-II are decreases, at 40 °C condenser temperature.

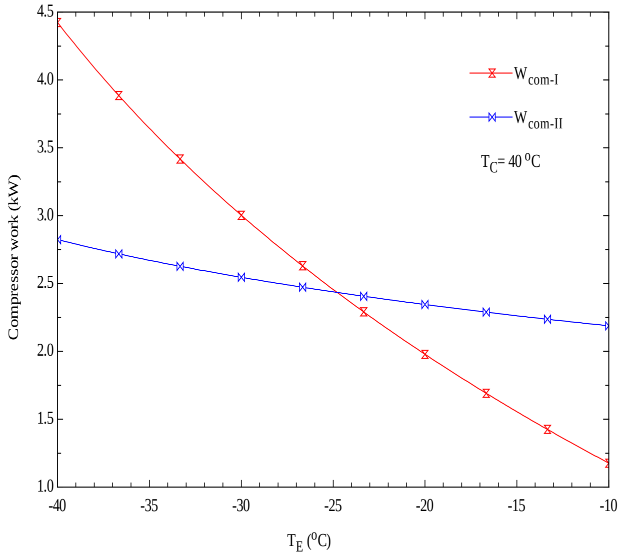

Figure 5. Variation of compressor work on different evaporator temperatures

The effect of heat exchanger effectiveness on COP and exergy efficiency of CCS are given in Figure 6. When the heat exchanger effectiveness is increased from 70% to 90%, the COP and exergy efficiency of CCS also increases, at constant condenser and evaporator temperatures.

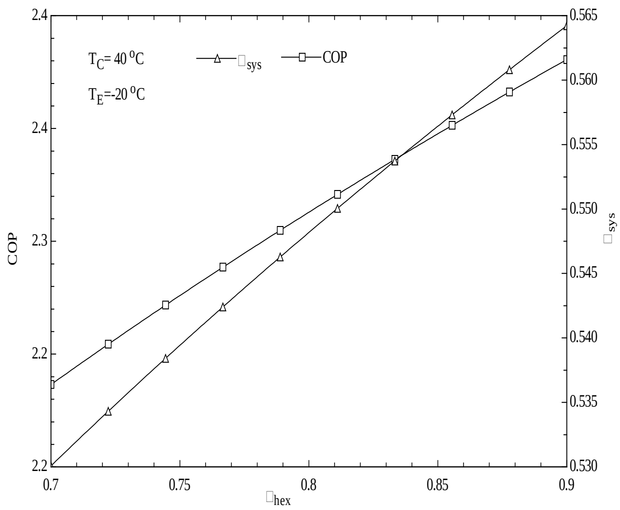

Figure 6. The effect of heat exchanger effectiveness on COP and exergy efficiency

The variation of total exergy destruction rate and exergy efficiency of CCS at different evaporator temperatures are seen in Figure 7. At 40 °C condenser temperature, while the evaporator temperature increasing from -40 °C to -10 °C, the exergy efficiency also increases, but the total exergy destruction rate decreases.

Figure 8, shown that the exergy destruction rates in the components of CCS, at -20 °C and 40 °C constant evaporator and condenser temperatures. The exergy destruction rates of expansion valve-I and II, compressor-I and II, Heat exchanger, condenser and evaporator are calculated as 0.39 kW, 0.26 kW, 1.78 kW, 2.16 kW, 23.16 kW, 11.22 kW and 12.76 kW, respectively. As seen Figure 8, the highest exergy destruction rate is seen in heat exchanger while the lowest exergy destruction rate is observed in expansion valve-II. The total exergy destruction rate is founded as 51.74 kW.

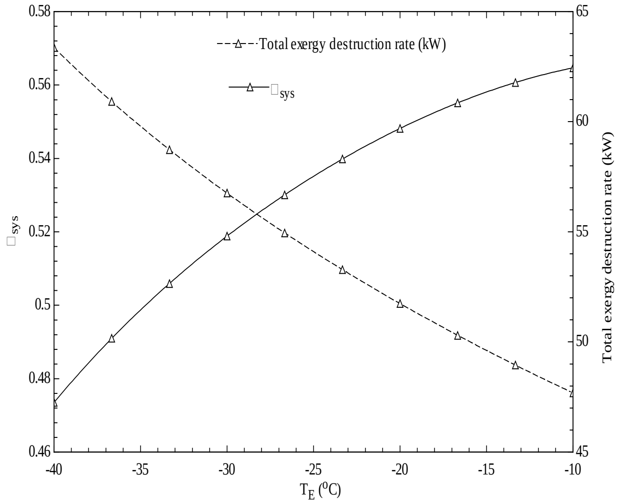

Figure 7. Variation of exergy efficiency and total exergy destruction rate at different evaporator temperatures

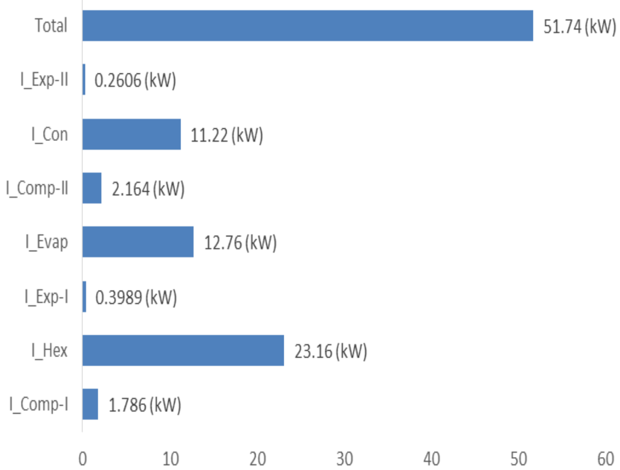

Figure 8. Exergy destruction rates in the components of CCS

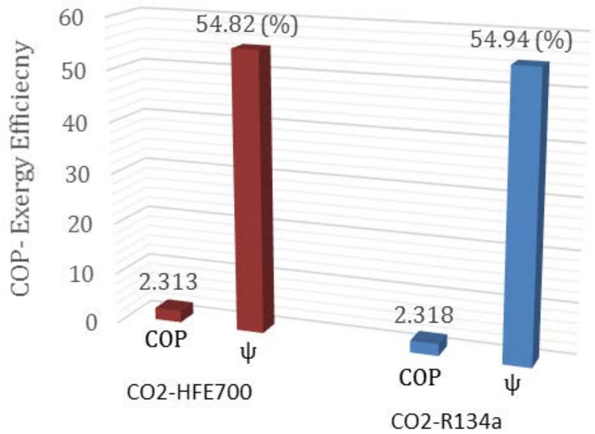

Figure 9. COP and exergy efficiency of CCS with CO_2/HFE7000 and CO_2/R134a refrigerants

The COP and exergy efficiency of CCS for the refrigerant couples CO_2/HFE7000 and CO_2/R134a, at -20 °C and 40 °C evaporator and condenser temperatures have been compared and illustrated in Figure 9.

It is understood that the COP and exergy efficiency are close to each other in CCS for both refrigerant couples. However, GWP value of the HFE7000 refrigerant is approximately 40% lower than R134a value.

4. Conclusion

In this study, the thermodynamic performance assessment outputs of CCS system are proposed in detail. In this context, the energy (COP) and exergy efficiencies of with CO_2/HFE7000 refrigerants are evaluated, according to various parameters. Additionally, energy and exergy efficiencies were compared to HFE7000 and R134a refrigerants. Finally, the results obtained from the study are presented below;

- Increasing condenser temperature induce decrease in the energy and exergy efficiency of the CCS.
- Increasing the evaporator temperature cause in increase in the energy and exergy efficiency of CCS.
- GWP value of HFE7000 refrigerant is lower than R134a.
- The COP and exergy efficiency of CCS with HFE700 refrigerant are 2.313 and 0.5482, at -20 °C evaporator temperature.
- The total exergy destruction rate of CCS is found as 51.74 kW.

In the proposed study, it can be said that HFE7000 refrigerant is a good potential in terms of COP and exergy efficiencies. The result provided that, HFE7000 refrigerant can be used easily in CCS such as R134a refrigerant. In addition, it can be an alternative refrigerant for the R134a refrigerant in cooling systems. This study can be considered as a guide for experimental studies in the coming years.

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