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Energy, Exergy, and Environment Performance Evaluation of Cascade Refrigeration System with Natural Refrigerants

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ABSTRACT

Cascade refrigeration systems are preferred in applications where low temperature cooling is required, such as in some special industrial and laboratory applications. Since, in these systems, the energy consumed by the compressors is less and the compressor outlet temperature is lower. Due to environmental problems, the use of natural refrigerants in cascade refrigeration systems has become to be of great importance. In this study, two cascade systems consisting of R744/R290 (System 1) and R1270/R290 (System 2) natural refrigerant pairs were designed and thermodynamically examined. In the analyzes performed according to different evaporator temperatures, the highest coefficient of performance (COP) value was 3.66 at -20°C evaporating temperature was obtained in the cascade system consisting of the R1270/R290 refrigerant pair. Moreover, it was considered that there was a 17.95% enhancement in exergy efficiency with the use of R1270 refrigerant in the low temperature cycle. By the rise in the evaporator temperature, energy consumption decreases and as a result, the amount of carbon dioxide emissions reduced was attained.

Keywords:
Cascade refrigeration system; R744; R1270; R290; COP

INTRODUCTION

The effective use of the energy and the improvement of systems becomes an important issue because the world's energy resources are limited and gradually decreasing. Nowadays, approximately 17% of the total electricity used in the world is consumed in refrigeration cycles (1,2). In order to use energy efficiently, studies such as reducing energy consumption values, increasing the performance of the system, and selecting the appropriate refrigerant are carried out. On the other hand, when considering system improvements, it should be adapted to human health and the surrounding, and the ozone layer depletion (ODP) and global warming potential (GWP) values of the refrigerants used should be low (3-5).

Low temperature refrigeration processes are widely preferred in various fields, including industrial, medical applications, and scientific research. Cascade refrigeration systems are generally used in low temperature applications because of their better performance and lower operating costs. Luiz et al. (6) evaluated the thermodynamic performance of the refrigerant pairs R744/R1270, R744/R717, and R744/RE170 in the cascade refrigeration system consisting of two vapor compression systems. 14% enhancement in the coefficient of performance (COP) over values obtained with natural refrigerants, the R744/RE170 mixture indicated the best results with a COP of 2.34 and increased exergetic efficiency by up to 30%. In another similar study, Kasi and Cheralathan (7) numerically investigated a cascade refrigeration system in which R170 refrigerant was employed as the low temperature cycle and R32, R515B, and R466A refrigerants were used as the high temperature cycle. R515B/R170 refrigerant pair was shown to offer the best performance than the other refrigerant pairs. As a result, the COP enhanced from 3.626 to 3.781, and the compressor work reduced from 2.757 to 2.645 kJ/s when the evaporation temperature rised from raised 45 K. Mofrad et al. (8) researched the thermodynamic simulation and analysis of the heat recovery cascade refrigeration systems. Energy and exergy analyses of the cascade system using R744 and R744A refrigerants were carried out. It was concluded that it increased COP by 7.6% and exergy efficiency by 12.5% with the heat recovery cascade cooling system.

Soni et al. (9) performed the thermodynamic analysis of the cascade refrigeration system consisting of R134a/R744, R1234yf/R744 and R1234ze/R744 ref-

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rigerants with low global warming potential by creating a mathematical model. The R1234yf/R744 refrigerant pair was found to be the most efficient, with a system efficiency of 58%. Ozyurt et al. (10) carried out a theoretical analysis of a cascade refrigeration cycle using R717 and R744 refrigerants. It was deduced that there was a decrease in exergy destruction by increasing the condenser temperature in the carbon dioxide cycle at -25 °C evaporation and -10 °C condenser temperature, and accordingly, the COP value and the second law efficiency increased. Sun et al. (11) presented a comparative analysis of the thermodynamic performance of R41/R404A and R23/R404A cascade refrigeration systems. The results showed that the input power of the R41/R404A refrigeration system was lower than the R23/R404A system, and the COP was higher than the R23/R404A system. The exergy efficiency of the R41/R404A and R23/R404A systems was obtained as 44.38% and 42.98%, in the same order. According to the theoretical analysis result, it was seen that the R41/R404A system was a more potential refrigerant couple than R23/R404A. Silva et al. (12) suggested a cascade refrigeration system with R744-R404A refrigerant instead of refrigeration systems with R404A and R22 refrigerants for supermarket applications. As a result of the evaluation, when the cascade refrigeration cycle using R744 was compared with the other two systems, it was indicated that the electrical energy consumption was reduced by 24-13%, and the life of the R744 compressor was extended with the low compression ratio.

Huang et al. (13) recommended mechanical subcooling and cascade recooling cycles, which they used as R744 subcycles. It was found that R744 was suitable for these systems and the compressor work was reduced by 28.5%. Chi et al. (14) developed the mathematical model of the R717/R744 ejector subcooled cascade system and performed its thermodynamic analysis. Compared to the conventional cascade system of in this system, 5.4% and 4.8% higher COP and exergy efficiencies were obtained. Yan et al. (15) carried out simulations of the R290/R600A cascade system for domestic freezers. It was observed that the cooling capacity increased by 10.2-17.1% with this refrigeration pair. Cabello et al. (16) compared the performance of R290, R1270, R600A and R1234ze(E) alternatives instead of R134A in the R134A/R744 cascade system. The best results were achieved in the cooling capacity of the R290 and R1270 refrigerants. Zhu et al. (17) studied the low and high temperature circuits in the R744/R717 cascade system and the multi-target temperature cascade system in which the R1270 refrigerant was used. With the multi-target temperature cascade system, 25% and 10% improvement in COP and 19% and 5% rise in exergy efficiency were obtained according to low and high temperature cycling, respectively.

Recently, the use of natural refrigerants, which are found in nature and do not have harmful effects on the environment, has become widespread instead of synthetic refrigerants. Considering the literature survey, the use of natural refrigerants in cascade refrigerant systems provides great advantages. In this study, two different cascade systems are proposed using three different natural refrigerants. The performance of these two systems under the same conditions was compared. Energy, exergy and environmental analyzes were carried out. The novelty of this study is the use of R744/R290 and R1270/R290 refrigerant pairs, which have very low GWP values, in the cascade system.

SYSTEM DESCRIPTION

The cascade refrigeration system including two basic vapor compression refrigeration cycles, one the low temperature cycle (LTC) and the other the high temperature cycle (HTC). The LTC cycle and HTC cycle are connected to each other via a cascade condenser. Fig. 1 depicts the schematic representation of the typical cascade refrigeration system. On the other hand, the P-h diagram of the cascade cooling system is demonstrated in Fig. 2.

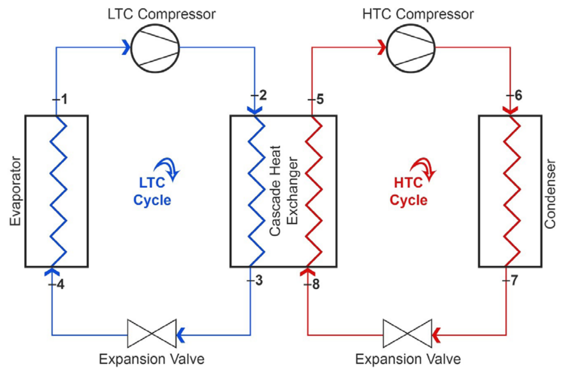

Figure 1. Schematic illustration of cascade cooling system

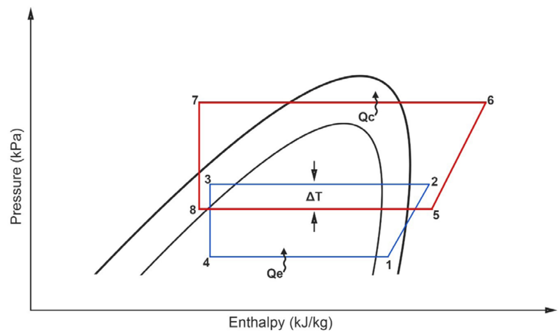

Figure 2. P-h diagram of the cascade cooling system

In this study, two different cascade refrigeration systems using three different natural refrigerants were investigated thermodynamically. Refrigerants R744 and R1270 were chosen for LTC cycles whereas R290 was chosen for the HTC cycle. Moreover, the R744/R290 refrigerant pair was called System 1, and the R1270/R290 refrigerant pair was as System 2. Table 1 demonstrates the properties of the commonly used natural refrigerant.

Table 1. The properties of some natural refrigerants (18)

Refrigerants	Chemical Formula	Flammability Classification	Global Warming Potential (GWP)	Ozone Depletion Potential (ODP)	Critical Temperature (°C)	Critical Pressure (MPa)	Normal Boiling Temperature (°C)
R744	Co_2	A1	1	0	30.98	7.38	-78.46
R290	C_3H_8	A3	3	0	96.74	4.25	-42.11
R1270	C_3H_6	A3	1.8	0	92.42	4.55	-47.62
R600a	C_4H_{10}	A3	4	0	134.66	3.83	-11.75
R717	NH_3	B2L	0	0	132.25	11.33	-33.33
R170	C_2H_6	A3	6	0	32.12	48.72	-88.7

The necessary assumptions are given in Table 2 to determine the performance parameters of the system. The following reasonable assumptions were made in the energy, exergy and environmental analyzes of the cascade cooling system:

- Pressure and heat losses and gains in the system were neglected.
- It was assumed that all components in the system were in a steady state.
- Compressors, expansion valves, and phase changes in a cascade condenser were adiabatic.
- Evaporation and condensation processes were isobaric.

Table 2. Assumptions required for analyses

Parameters	Value
Cooling Capacity	15 kW
Evaporator Temperature, T_{evap}	-20°C, -25°C, and -30°C
Condenser Temperature, T_{con}	45°C
Ambient Temperature, T_o	25°C
Mechanical efficiency of compressors, n_{mec}	90%
Electrical efficiency of compressors, n_{el}	93%
Superheating (in LTC and in HTC)	5°C
Refrigerants	R744, R1270, R290

THEORETICAL ANALYSIS

The basic vapor compression refrigeration cycles consist of compressor, condenser, expansion valve and evaporator. The required heat is provided by the HTC condenser of the cascade system including HTC and LTC cascade cycles. The heat supplied by the condenser is expressed in the following equation (19):

$$\dot{Q}_{con} = \dot{m}_{r,HTC}\left(h_{con,i} - h_{con,o}\right) \tag{1}$$

The evaporator capacity of the cascade system is given as follows:

$$\dot{Q}_{evap} = \dot{m}_{r,LTC}\left(h_{evap,o} - h_{evap,i}\right) \tag{2}$$

The energy equation for the cascade condenser (heat exchanger of cascade system) can be defined as (20):

$$\dot{m}_{r,LTC}\left(h_{hx(LTC),i} - h_{hx(LTC),o}\right) = \dot{m}_{r,HTC}\left(h_{hx(HTC),o} - h_{hx(HTC),i}\right) \tag{3}$$

The compressors power of LTC and HTC refrigeration cycles can be given as:

$$\dot{W}_{comp,LTC} = \dot{m}_{r,LTC}\left(h_{comp(LTC),o} - h_{comp(LTC),i}\right) / \eta_{is}\eta_{mec}\eta_{el} \tag{4}$$

$$\dot{W}_{comp,HTC} = \dot{m}_{r,HTC}\left(h_{comp(HTC),o} - h_{comp(HTC),i}\right) / \eta_{is}\eta_{mec}\eta_{el} \tag{5}$$

The isentropic efficiency of the compressors is (21):

$$\eta_{is} = 1 - \left(0.04xPR\right) \tag{6}$$

Total compressor power requirement:

$$\dot{W}_{comp,total} = \dot{W}_{comp,LTC} + \dot{W}_{comp,HTC} \tag{7}$$

The COP value of the cascade refrigeration system can be found as follows:

$$COP_{system} = \frac{\dot{Q}_{evap}}{\dot{W}_{comp,total}} \tag{8}$$

While calculating the exergy efficiency of the cascade refrigeration system, the exergy destruction equations of the cooling components are used. These equations are given below (22):

$$\dot{Ex}_{d,evap} = \left(\dot{Ex}_{evap,o} - \dot{Ex}_{evap,i}\right) + \dot{Q}_{evap}\left(1 - \frac{T_o}{T_{evap}}\right) \tag{9}$$

$$\dot{Ex}_{d,con} = \left(\dot{Ex}_{con,i} - \dot{Ex}_{con,o}\right) + \dot{Q}_{con}\left(1 - \frac{T_o}{T_{con}}\right) \tag{10}$$

$$\dot{Ex}_{d,hx} = \left(\dot{Ex}_{hx(LTC),i} - \dot{Ex}_{hx(LTC),o}\right) + \left(\dot{Ex}_{hx(HTC),i} - \dot{Ex}_{hx(HTC),o}\right) \tag{11}$$

$$\dot{Ex}_{d,comp(LTC)} = \dot{Ex}_{comp(LTC),o} - \dot{Ex}_{comp(LTC),i} \tag{12}$$

$$\dot{Ex}_{d,comp(HTC)} = \dot{Ex}_{comp(HTC),o} - \dot{Ex}_{comp(HTC),i} \tag{13}$$

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$$\dot{E}x_{d,ex(LTC)} = \dot{E}x_{ex(LTC),i} - \dot{E}x_{ex(LTC),o} \tag{14}$$

$$\dot{E}x_{d,ex(HTC)} = \dot{E}x_{ex(HTC),i} - \dot{E}x_{ex(HTC),o} \tag{15}$$

$$\eta_{\ddot{y}} = \frac{\dot{E}x_{evap,o} - \dot{E}x_{evap,i}}{\dot{W}_{comp,total}} \tag{16}$$

Another exergy performance criterion is the exergetic performance coefficient (EPC). EPC is the ratio of exergy output to total exergy destruction. The EPC of this proposed cascade refrigeration system can be defined as follows (23, 24):

$$EPC = \frac{\dot{Q}_{evap}\left(1 - T_0 / T_{evap}\right)}{\dot{E}x_{d,total}} \tag{17}$$

The calculation of CO_2 emissions for the cascade refrigeration system based on the power consumption of the compressor is given in the equation below:

$$\Phi_{CO_2} = \Psi_{CO_2} \; x \; \dot{W}_{comp,total} \tag{18}$$

where Φ_{CO2} is the amount of CO_2 (kg CO_2/h) reduced per hour and and Ψ_{CO2} denotes the average amount of CO_2 emissions (2.08 kg CO_2/kWh) obtained during power generation from coal (25). For example, if the energy consumption of the total compressors in a cascade system is 5 kW, the amount of CO_2 is 10.4 kg, and the annual CO_2 emission is 3.79 tons.

RESULTS AND DISCUSSION

In this study, R744 was chosen as the refrigerant in the LTC cycle in the System 1 cascade system, and R1270 as the refrigerant in the LTC cycle in the System 2 cascade system. In both systems, R290 was used as a refrigerant in the HTC cycle. Total energy consumption graph according to -20°C, -25°C, and -30°C evaporator temperatures for System 1 and System 2 is given in Fig. 3. When R744 was used in the LTC cycle, it was observed that the total energy consumption was 5.93 kW, which was the highest at -30°C evaporator temperature. However, when R1270 was used in the LTC cycle in System 2, it was deduced that it had the lowest total energy consumption. As the evaporator temperature decreases, the compressor work increases even more. Therefore, the energy consumption of both systems had increased proportionally.

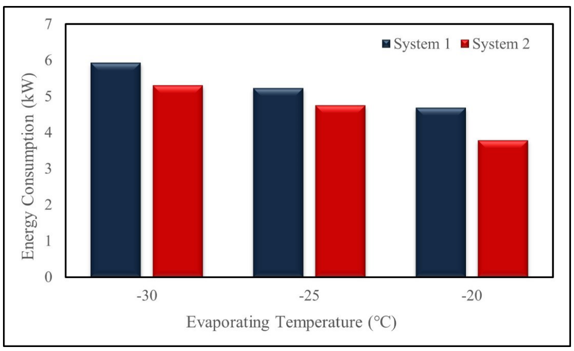

Figure 3. The energy consumption values according to evaporator temperatures

The performance of a refrigeration cycle is determined by the COP given in Eq. (8). COP values calculated for System 1 and System 2 are demonstrated in Fig. 4. COP values in System 1 and System 2 were obtained as 2.53, 2.86, 3.19 and 2.83, 3.16, 3.66 at -20°C, -25°C, and -30°C evaporator temperatures, respectively. As COP is the evaporator capacity provided in response to the work done by the compressor, it appears to be inversely proportional to energy consumption. In other words, the increase in the evaporator temperature causes a decrease in the compressor power in both systems, thus increasing the performance. It was observed that System 2 was 12.84% more efficient than System 1 at -20°C evaporator temperature.

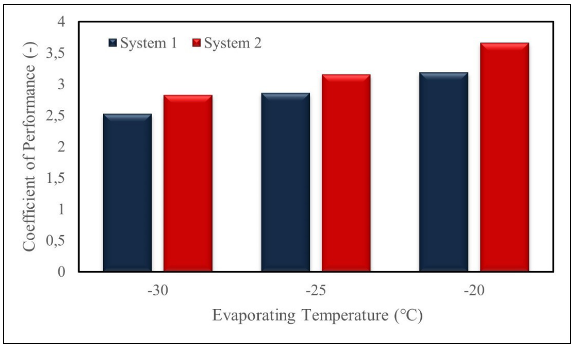

Figure 4. The COP values according to evaporator temperatures

The maximum useful energy value in refrigeration systems is defined by the exergy efficiency, which is the second law, and is calculated as given in Eq. (16). The exergy efficiency values of the System 1 and System 2 cascade refrigeration systems for the same operating conditions are given in Fig. 5. The exergy efficiency values for System 1 and System 2 were determined as 15.5%, 17.6%, 20.1%, and 21.2%, 22.6%, 24.5% respectively, according to -30°C, -25°C, -20°Cevaporator temperatures. According to every 5°C evaporator

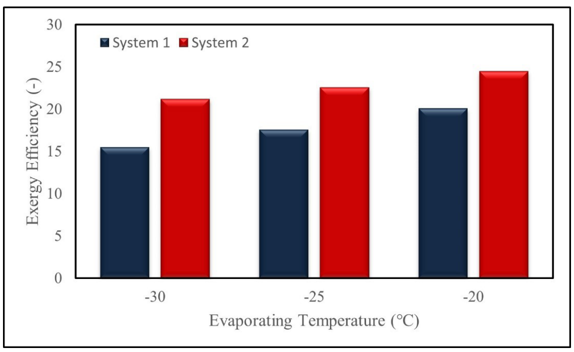

Figure 5. The exergy efficiency values according to evaporator temperatures

temperature rise, exergy efficiency increased by 11.93% and 12.44% for System 1 and 6.19%, 7.75% for System 2, in the same order.

The EPC values of System 1 and System 2 are given in Fig. 6. In both systems, it was observed that EPC values decreased as the evaporating temperature reduced. EPC values in System 2 were higher than in System 1 at all evaporating temperatures. The highest EPC value was obtained in System 2 at 0.28 to -30°C evaporating temperature. On the other hand, the lowest EPC value was found as 0.20 in System 1 at an evaporating temperature of -20°C.

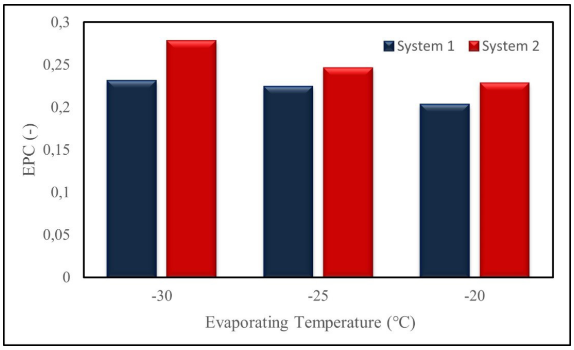

Figure 6. The EPC values according to evaporator temperatures

The annual total amount of CO_2 released according to three different evaporator temperatures for System 1 and System 2 is shown in Fig. 7. It was considered that coal fuel was used in electricity generation. The amount of CO_2 released by the burned coal fuel against the amount of energy consumed (kWh) was calculated separately for both systems. Accordingly, the annual total maximum CO_2 amount was calculated as 4.5 and 4.03 tonsCO_2/year for System 1 and System 2 at -30°C evaporator temperature. On the other hand, the lowest total annual CO_2 amount was obtained as 2.82 tonsCO_2/year at -20°C evaporator temperature in System 2.

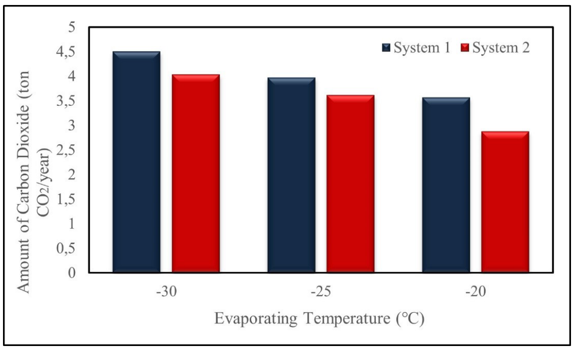

Figure 7. The amounts of CO2 released according to evaporator temperatures

CONCLUSION

In this study, energy, exergy, and environmental analyzes of the cascade refrigeration system containing different refrigerants were made and the results were discussed. Moreover, natural refrigerants were used instead of synthetic refrigerants that cause global warming and ozone layer depletion in the cascade refrigeration system. R744 and R1270 natural refrigerants were selected in the LTC and R290 in HTC. The results obtained as a result of the thermodynamic analysis for two different systems designed using different refrigerants can be summarized:

- It was attained that the energy consumption of System 1 was 9.2% higher than System 2.
- In System 2, the best COP with 3.66 and the best exergy efficiency with 24.5% were determined at -20°C evaporator temperature.
- The highest EPC value of 0.28 was achieved in System 2.
- It was seen that CO_2 emissions were reduced by 19.4% with the use of R1270.
- It was obtained that the variation of the evaporator temperature was much more effective on the cooling performance of the whole system. In addition, the use of R1270 refrigerant in the LTC cycle was found to be more efficient than R744.

As a result, it was observed that the R1270/R290 refrigerant pair was determined thermodynamically more efficient for the cascade refrigerant system. Therefore, it is important to experimentally examine this system and verify it with theoretical results in future studies. This study will make a great contribution to industrial refrigeration systems that care about environmental problems.

CONFLICT OF INTEREST

The author deny any conflict of interest.

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