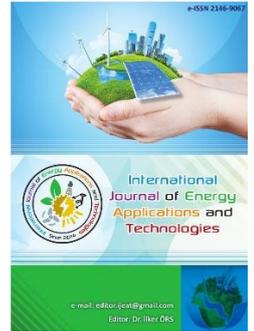




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Original Research Article

Comparative exergy analysis of the cascade cooling system for alternative refrigerant couples

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ABSTRACT

In this work, a comparative exergy analysis of cascade cooling system working with alternative refrigerant couples has been carried out. In study; R454C and R-744 as low temperature cycle (LTC) refrigerant and R1234ze, R1234yf and R717 as high temperature cycle (HTC) refrigerant were used. The refrigerants used in the study have zero ODP and low GWP values. Exergy analysis was carried out to investigate the effect to exergy efficiency of operation parameters in cascade cooling system. The exergy efficiency values of the cascade cooling system decreases with increasing evaporator temperature for all refrigerant couples. The exergy efficiency values of the cascade cooling system decreases with increasing the condenser temperature. Obtained results show that in all cases, the refrigerant couple R454C/R717 has the highest exergy efficiency.

Keywords: Cascade cooling system; Exergy; Refrigerant; Thermodynamic analysis

1. Introduction

To use a single stage cooling system in low temperature applications is not economical. Cascade cooling systems can be used for these applications [1]. Cascade cooling system consists of two cycles, low temperature (LTC) and high temperature cycle (HTC). In addition, it is important that the refrigerant couples used in these systems are environmentally friendly and not harmful to the environment. Many studies on energy and exergy analysis of cascade cooling systems operating with different refrigerant couples are available in literature. Sun et al. performed energy and exergy analysis of cascade cooling system with low GWP refrigerants. The effect of system parameters, such as evaporator temperature and condenser temperature, on the system performance was investigated [1]. Gholamian et al. performed modeling of a carbon dioxide ammonia cascade cooling system. Advanced exergy analysis was applied to the system [2]. Kilicarslan and Hosoz carried out energy and exergy analysis of a cascade

cooling system by using different refrigerant couples [3]. Roy and Mandal performed exergy analysis of cascade cooling system operating with refrigerant couples R41-R404A and R41-R161. Obtained results present that R41-R161 gives better results than R41-R404A [4]. Kanoğlu carried out exergy analysis of cascade cooling cycle used for natural gas liquefaction. The exergy efficiency of the multistage cascade cooling cycle is determined to be 38.5% [5]. Dopazo et al. investigated performance and exergy efficiency of cascade cooling system with CO₂-NH₃. Moreover, an optimization study was performed [6]. Rezayan and Behbahaninia carried out optimization and exergy analysis of cascade cooling system with CO₂-NH₃ [7]. The other studies on cascade cooling systems are available in literature [8-17].

In this work, exergy analysis of the cascade cooling system was carried out using alternative refrigerants with zero ODP and low GWP values as different from the literature. Depending on the different operating parameters of the

system, exergy efficiencies were examined. Comparative exergy analysis of the cascade cooling system using different refrigerant couples was made using EES (Engineering Equation Solver) [18].

2. Thermodynamic Analysis

Fig. 1 shows schematic diagram of cascade cooling system. Cascade cooling system occurs of low temperature cycle (LTC) and high temperature cycle (HTC). Fig. 2 shows T-s diagrams of cascade cooling system.

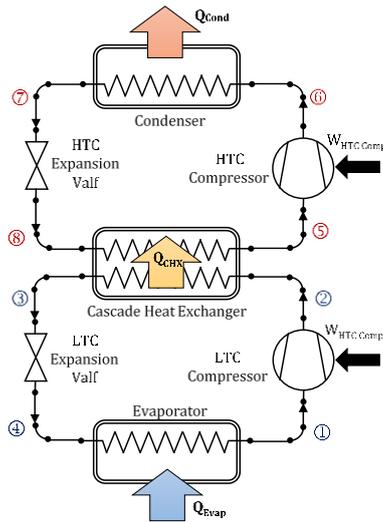


Fig. 1. Schematic diagram of cascade cooling system

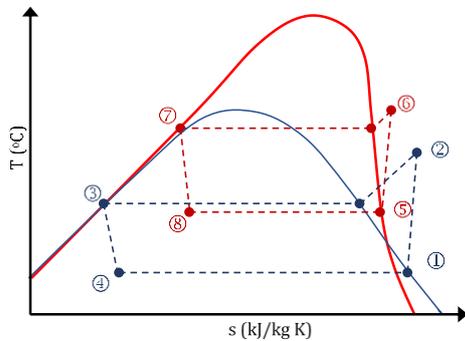


Fig. 2. T-s diagram of cascade cooling system.

Refrigerant couples used in LTC and HTC and their properties are given in Table 1.

Table 1. Thermo physical Properties of refrigerants

Refrigerant	Boiling Point (°C)	Critical Temperature (°C)	Critical Pressure (bar)	ODP	GWP	
L T C	R-454C	45.91	82.40	43.50	0	146
	R-744	78.40	31.10	73.17	0	1
H T C	R-1234ze	18.98	108.0	35.39	0	1
	R-1234yf	29.49	94.70	32.69	0	1
	R-717	33.30	132.30	113.30	0	0

The following assumptions were made in the thermodynamic analysis.

- Heat losses and pressure drops in the system components are neglected.
- All the components are at steady state condition.
- Cooling capacity of the system is accepted as 15 kW.
- No subcooling and superheating is considered.
- The enthalpy is constant in the throttling process in the throttling valves in HTC and LTC cycles.
- The compression in HTC and LTC is isentropic.
- Ambient temperature is 25 °C.

Based on the above assumptions, balance equations are written to obtain the mass flow rate, the compressor work, the heat transfer rates and the exergy destruction rate as follows:

Mass balance:

$$\sum \dot{m}_l = \sum \dot{m}_o \quad (1)$$

Energy balance:

$$\dot{Q} - \dot{W} = \sum \dot{m}_o \left(h_o + \frac{v_o^2}{2} \right) - \sum \dot{m}_l \left(h_l + \frac{v_l^2}{2} \right) \quad (2)$$

Exergy balance:

$$\sum \dot{E}D = \sum \dot{E}x_i - \sum \dot{E}x_o \quad (3)$$

Energy and exergy balance equations of cascade cooling system are given in Table 2.

Total exergy destruction of the system and can be written as:

$$\begin{aligned} \dot{E}D_{total} = & \dot{E}D_{HTC\ comp} + \dot{E}D_{Cond} + \dot{E}D_{HTC\ EV} + \dot{E}D_{CHX} \\ & + \dot{E}D_{LTC\ comp} + \dot{E}D_{LTC\ EV} + \dot{E}D_{Cond} \end{aligned} \quad (4)$$

The coefficient of performance (COP) can be defined as:

$$COP = \frac{Q_E}{W_{HTC} + W_{LTC}} \quad (5)$$

Exergetic efficiency of cascade cooling system can be written as:

$$\eta_{ex} = \frac{W_{HTC} + W_{LTC} - \dot{E}D_{total}}{W_{HTC} + W_{LTC}} \quad (6)$$

3. Results and Discussion

Exergy analysis of the cascade cooling system using R454C and R-744 as LTC refrigerant and R1234ze, R1234yf and R717 as HTC refrigerant has been carried out. Fig. 3 shows the variation in the exergy efficiency of the refrigerant couples with evaporator and condenser temperature. In Fig. 3, it is seen that the exergy efficiency decreases with the increase of the evaporator temperature and the exergy efficiency decreases with the increase of the condenser temperature in the cascade cooling system operating with all refrigerant couples.

Table 2. Energy and exergy balance equations of cascade cooling system

Component	Energy balance	Exergy balance
HTC compressor	$W_{HTC\ comp} = m_H(h_6 - h_5)$	$ED_{HTC\ comp} = T_0 m_{HTC}(s_6 - s_5)$
Condenser	$Q_{Cond} = m_{HTC}(h_6 - h_7)$	$ED_{Cond} = T_0 m_{HTC}(s_7 - s_6) + Q_{Cond}$
HTC expansion valve	$h_7 = h_8$	$ED_{HTC\ EV} = T_0 m_{HTC}(s_8 - s_7)$
Cascade heat exchanger	$Q_{CHX} = m_{LTC}(h_2 - h_3) = m_{HTC}(h_5 - h_8)$	$ED_{CHX} = T_0 [m_{LTC}(s_3 - s_2) + m_{HTC}(s_5 - s_8)]$
LTC compressor	$W_{LTC\ comp} = m_{LTC}(h_2 - h_3)$	$ED_{LTC\ comp} = T_0 m_{LTC}(s_2 - s_1)$
LTC expansion valve	$h_3 = h_4$	$ED_{LTC\ EV} = T_0 m_{LTC}(s_4 - s_3)$
LTC evaporator	$Q_{Evap} = m_{LTC}(h_1 - h_4)$	$ED_{Cond} = T_0 m_{LTC}(s_1 - s_4) + Q_{Evap}$

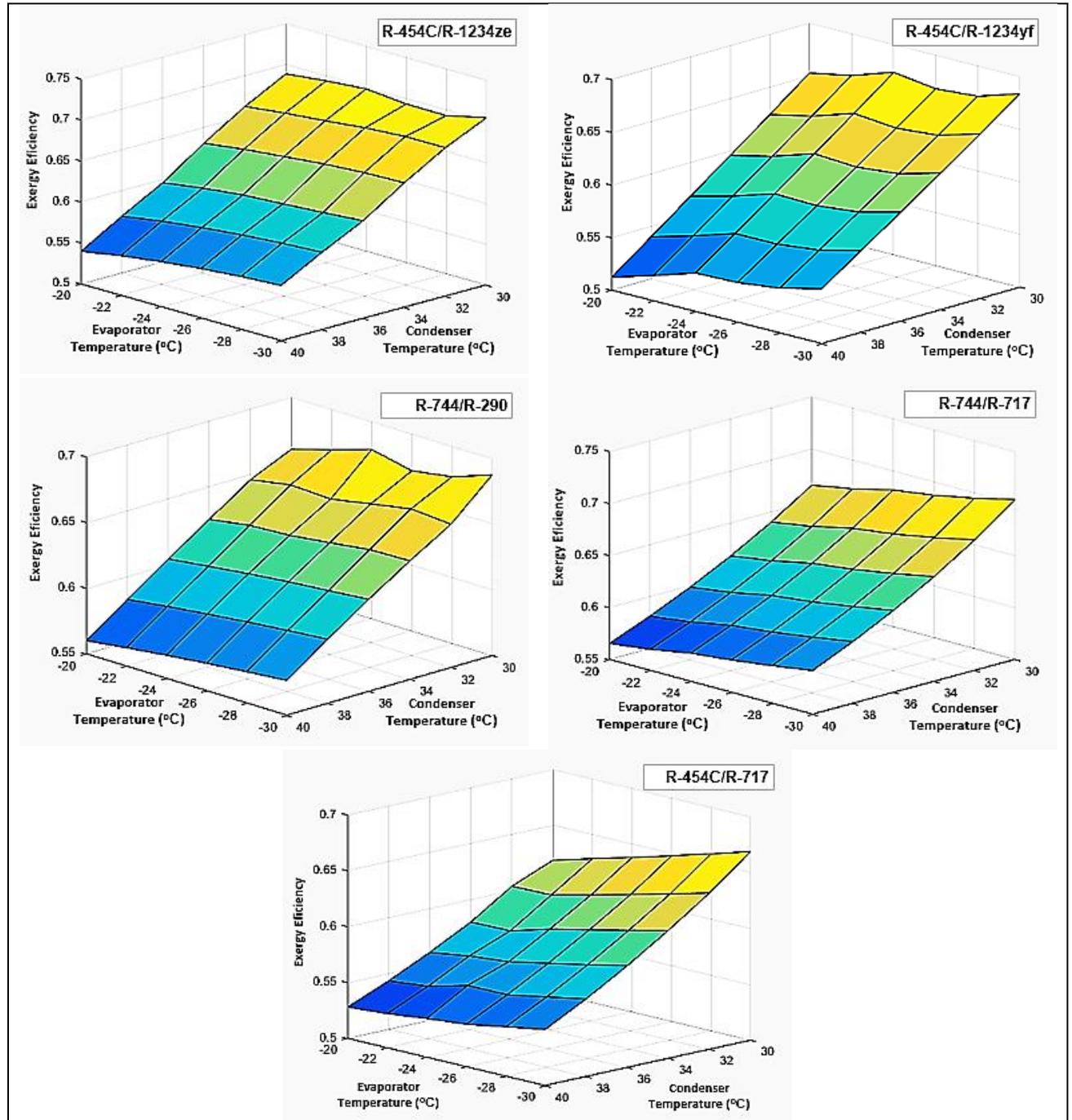


Fig.3. Variation of exergy efficiency with condenser and evaporator temperatures for different refrigerant couples

Fig.4 shows the effect of evaporator temperature on exergy efficiency in cascade cooling system using different refrigerant couples. By keeping the condenser temperature constant at 40 ° C, the exergy efficiencies were calculated by changing the evaporator temperature values in the LTC from -30 ° C to -20 ° C. Exergy efficiency of the system for all refrigerant couples decreased with the increase of evaporator temperature. The exergy efficiency of the system operating with R454C / R717 was found to be higher than the exergy efficiency values of the system working with other refrigerant couples. The lowest exergy efficiency for the same operating parameters was found to be 0.51 in the system operating with the R454C / R1234yf. The highest exergy efficiency was found as 0.59 in the system working with R454C / R717.

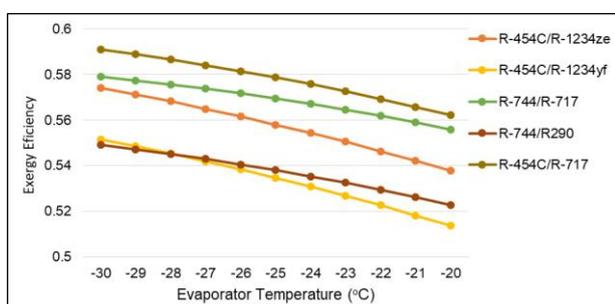


Fig.4. Comparison of the impact of evaporator temperature on exergy efficiency value for alternative refrigerant couples

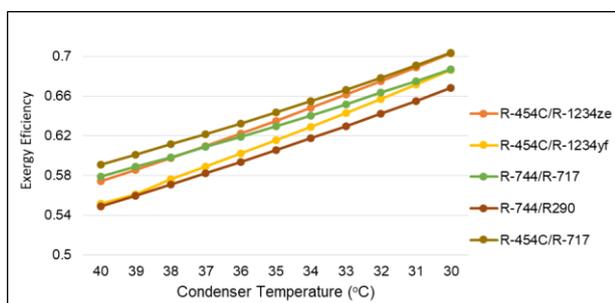


Fig.5. Comparison of the impact of condenser temperature on exergy efficiency value for alternative refrigerant couples

In Fig. 5, the variation of exergy efficiencies with the condenser temperature is given in a cascade cooling system operating with different refrigerant couples. Exergy efficiency value was calculated by changing the condenser temperature values between 30 ° C and 40 ° C by keeping the evaporator temperature constant at -30 ° C. Exergy efficiency of the system for all refrigerant couples decreased with increasing condenser temperature. The exergy efficiency of the system by working with R454C / R717 refrigerant couple was found to be higher than the exergy efficiency of the system working with other refrigerant couples. The lowest exergy efficiency for the same operating parameters was found to be 0.55 in the system operating with the R744 / R290 refrigerant couple. The highest exergy efficiency value was found as 0.7 in the system working with R454C / R717 refrigerant couple.

4. Conclusions

The negative effects of refrigerants used in cooling systems on the environment are great. Many efforts are made to develop alternative refrigerant pairs suitable for low GWP and high efficiency cascade cooling systems.

In this work, exergy analysis of the cascade cooling system working with R454C and R-744 as LTC refrigerant and R1234ze, R1234yf and R717 as HTC refrigerant with zero ODP value and low GWP value was performed. Analyzes were made using the EES program. It has been observed that the exergy efficiency values of the system working with R454C in the LTC cycle and the R717 refrigerant couple in the HTC cycle are higher than the exergy efficiency values of the system working with other refrigerant couples. The lowest exergy efficiency value for the same operating parameters was found to be 0.51 in the system operating with the R454C / R1234yf refrigerant couple. The highest exergy efficiency value was found to be 0.7 in the system working with R454C / R717 refrigerant couple.

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