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THERMO-ECONOMIC AND ENVIRONMENTAL ANALYSIS OF A VAPOR COMPRESSION REFRIGERATION SYSTEM USING R744 AS A REPLACEMENT FOR R134A

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Abstract: *This paper presents a mathematical model to design a vapor compression refrigeration system that simultaneously produces chilled water (5°C) for an indirect expansion air-conditioning system and hot water (40°C) for bath. Besides, the proposed model uses commercial diameters in the modeling of the heat exchangers and volumetric and global efficiency curve obtained from commercial compressors available in the market. The environmental analysis was performed based on TEWI (total equivalent warming impact), while the thermo-economic analysis was performed based on COP (Coefficient of Performance), Exergy Efficiency and Total plant cost rate. The thermo-economic and environmental analysis indicated that the system with R744 has lower energy, exergy and economic performance and higher environmental performance for an evaporation temperature of -3°C and condensation/gas cooling temperature of 45°C. Therefore, the system operating with R744 is not suitable to replace the system with R134a because the system with R744 is more expensive.*

Keywords: *TEWI, COP, Exergy efficiency, Total plant cost rate, Vapor compression refrigerating system*

1. INTRODUTION

In recent decades, vapor compression refrigeration systems operating with R134a have been widely used in domestic refrigeration. According to Gill et al. (2019), these systems with R134a have high energy consumption and produce relevant environmental impact due to high GWP (more than 1000 times the standard reference). In this way, the R134a refrigerant is classified as greenhouse gas, according to de Paula et. al (2020). The control and elimination of this gas was proposed in the Kyoto protocol and restrictions were reaffirmed in the Kigali amendment. In recent years, several researches have carried out works oriented to develop energy-efficient vapor compression refrigeration system (VCRS) that operate with ecological refrigerants (low GWP), such as R744. Among these works, we can highlight the following papers: Paulino et al. (2019) developed a dynamic model to analyze the evaporator response of a direct expansion solar assisted heat pump with R744 to sudden variations in the solar radiation. Faria et al. (2016) developed a dynamic model to investigate the behavior of the solar evaporator and expansion valve assembly of a heat pump operating with R744 under transient and steady operational conditions. The conditions analyzed were solar radiation, ambient temperature, wind speed and atmosphere conditions and Rabelo et al. (2019) developed a steady-state model and performed an experimental analysis to evaluate the influence of the expansion valve opening on the pressure, power consumption of the compressor, COP, mass flow rate and difference of enthalpy of a small size solar assisted heat pump. Another essential parameter in this process is economic viability because a VCRS with ecological refrigerant should also have a competitive cost to become a good candidate to replace the old systems that operate with non-ecological refrigerants.

Some papers have been published in the literature focusing on the evaluation of the economic viability of these new systems. In this context, we can highlight the following papers that assess the economic viability of the system with R744: Fazelpour and Morosuk (2014) developed a model to assess the energy, exergy and economic performance of a transcritical VCRS to propose improvements in order to make the system more energy and cost efficient. Aminyavari et. al (2014) developed a model of a R744/R717 cascade VCRS to analyze energy, exergy, and economic performance. This model used a genetic algorithm technique to optimize the design parameters of the system. Keshtkar and Talebizadeh (2019) developed a model to optimize a cascade VCRS operating with R744/R134a based on a thermo-economic analysis. The model used a genetic algorithm and a TOPSIS decision-making procedure with Pareto boundary to perform the optimization task. As notes, the strategy adopted by the authors to develop new systems was to build mathematical models.

The main goal of this paper is to propose a steady-state model to design a vapor compression refrigeration system operating with R744 and R134a, and to compare the energy, exergy, environmental and economic performance these systems. Finally, the proposed model uses commercial diameters in the modeling of the heat exchangers, and also volumetric and global efficiency curve obtained from commercial compressors available in the market.

2. MATHEMATICAL MODEL

The steady-state model was developed using the software Equation Engineering Solver (EES), considering the pressure drop on the water side in both evaporator and condenser/gas cooler. The pressure drop on the refrigerant side in the heat exchangers was not considered. A thermostatic expansion valve (TEV) was considered as expansion device and this device was modeled as isenthalpic. The pipeline was considered two meters long each. The input and output variables of the model are shown on the left and the right, as shown in Fig.1. Figure 2 shows the VCRS layout, as proposed by de Paula et. al (2020).

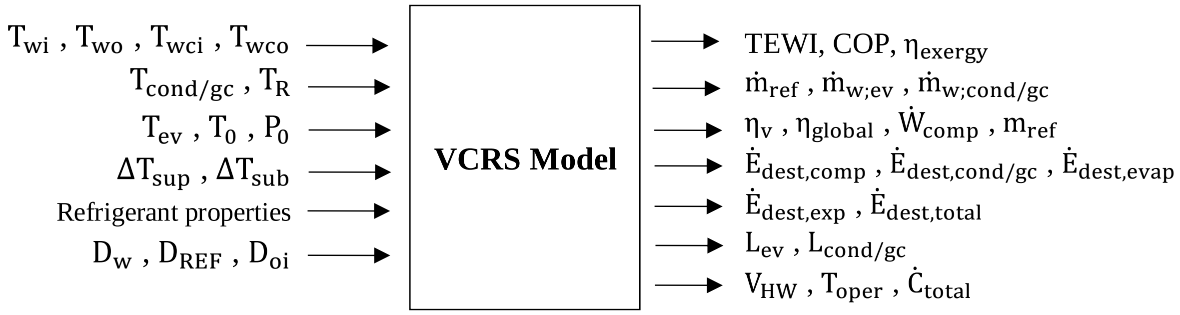

Figure 1. Scheme of the input and output variables of the model.

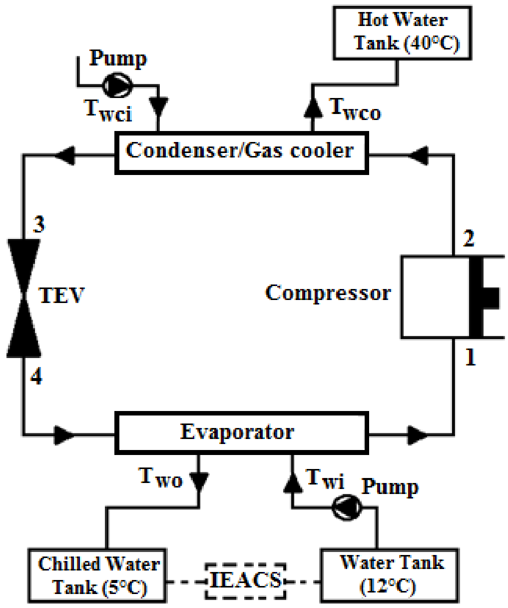

Figure 2. VCRS layout under study.

The proposed system was designed to produce and store 1200 liters of chilled water (5°C) for an indirect expansion air-conditioning system (IEACS) because the system operates in a period with a lower electricity tariff. Thus, reducing the energy cost, as proposed by de Paula et. al (2020).

Finally, this system was also designed to produce and store at least 600 liters of hot water (40°C) for the bath of a group of 12 people for the following purposes: energy cost reduction and to take advantage of the heat rejected by the condenser/gas cooler, as proposed by de Paula et. al (2020).

2.1. Reciprocating compressor

The refrigerant mass flow rate in the compressor ($\dot{m}_{ref}$) is given by Eq. (1).

$$\dot{m}_{ref} = \rho_1 \cdot \forall_{cil} \cdot N \cdot \eta_v \tag{1}$$

Where ($\forall_{cil}$) is the compressor displacement volume [m³], (N) is the rotation speed of the compressor [Hz], (ρ_1) is the refrigerant density in the compressor inlet [kg/m³] and (η_v) is volumetric efficiency. The electrical power consumption ($\dot{W}_{comp}$) is given by Eq. (2), according to Da Riva (2011).

$$\dot{W}_{comp} = \frac{\dot{m}_{ref} \cdot (i_2 - i_1)}{\eta_{global}} \tag{2}$$

The volumetric (η_v) and global (η_{global}) efficiency curves of a compressor operating with R134a and R744 were obtained by a polynomial regression in function of pressure ratio ($r_p = P_2/P_1$). This polynomial regression was performed on the efficiency data supplied by commercial compressors. The most suitable commercial compressor for each refrigerant was selected according to the following criteria, as proposed by de Paula et. al (2020):

I. Reference cooling capacity of 1.2 kW.

II. Based on the cooling capacity adopted, for a voltage of 220 V, frequency of 50 Hz, evaporation temperature equal to -5 ° C and condensation/gas cooling temperature equal to 50 °C, the commercial compressors were selected, as presented in the Tab. 1.

Table 1. Selected Compressors.

Refrigerant	Model	Manufacturer	Displacement (cm³)	Rotation (rpm)
R134a	NT6217ZV	Embraco	20.4	2900
R744	CD200/CD150M	Dorin Innovation	6.44	1450

This regression was performed on the efficiency data supplied by the manufacturer and the order chosen for this polynomial was the one that best fit the regression curve to the data, considering according to the manufacturer an uncertainty of 5%, as shown in the Tab. 2.

Table 2. Global and volumetric efficiency curves.

Refrigerant	R134a	R744
Volumetric efficiency	$\eta_v = 1.0368 - 0.1517r_p + 0.0243{r_p}^2 - 0.0014{r_p}^3$	$\eta_v = 1.0199 - 0.1390r_p + 0.0080{r_p}^2$
R² of η_v	85.14 %	99.32 %
Global efficiency	$\eta_{global} = 0.2819 + 0.0766r_p - 0.0058{r_p}^2$	$\eta_{global} = 0.6038 + 0.0216r_p - 0.0075{r_p}^2$
R² of η_{global}	94.42 %	96.34 %

2.2. Energy and environmental analysis

The coefficient of performance (COP) of the refrigeration system is given by Eq. (3), according to de Paula et al. (2020a).

$$COP = \frac{\dot{Q}_{ev}}{\dot{W}_{comp} + \dot{W}_{ev} + \dot{W}_{cond/gc}} \tag{3}$$

Where ($\dot{Q}_{ev}$), ($\dot{W}_{cond/gc}$) and ($\dot{W}_{ev}$) are respectively the cooling capacity and electrical power consumption by the pump in the condenser/gas cooler and evaporator. These parameters are calculated by Eq. (4) and Eq. (5).

$$\dot{W}_{cond/gc} = \frac{\dot{m}_{w;cond/gc} \cdot \Delta P_{cond/gc}}{\rho_w \cdot \eta_{pump}} \tag{4}$$

$$\dot{W}_{evap} = \frac{\dot{m}_{w;evap} \cdot \Delta P_{evap}}{\rho_w \cdot \eta_{pump}} \tag{5}$$

In these equations, η_{pump}, $\Delta P_{cond/gc}$ and ΔP_{evap} are respectively the overall pump efficiency and the pressure drop on the water side in the condenser/gas cooler and evaporator. These parameters are calculated by Eq. (6) and Eq. (7).

$$\Delta P_{evap} = \frac{8 \cdot f \cdot L_{total} \cdot \dot{m}^2_{w;evap}}{\pi^2 (D_W - D_{REF})^5 \rho_w} \tag{6}$$

$$\Delta P_{cond/gc} = \frac{8 \cdot f \cdot L_{total} \cdot \dot{m}^2_{w;cond/gc}}{\pi^2 (D_W - D_{REF})^5 \rho_w} \tag{7}$$

Where f is the Darcy friction factor and L_{total} is the total length of the pipe. L_{total} is the sum of the heat exchanger length with an equivalent length. Mathematically, this equivalent length is the sum of the straight lengths of the tubes that connect the tanks (chilled water or hot water) to the respective heat exchanger (evaporator or condenser), with the corresponding straight length related to the curves and connections. In this paper, the curves and connections, as well as the straight lengths of the tubes, were not defined. The equivalent length was considered seven meters long and η_{pump} equal to 0.5.

The environmental performance of the refrigeration system was evaluated by Total Equivalent Warming Impact (TEWI) and it is calculated by Eq. (8), according to (Antunes, 2016). This parameter takes into account both direct emissions (due to refrigerant leakage during the life of the equipment) and indirect emissions (due to the compressor's electricity consumption over the life of the equipment).

$$\text{TEWI} = \text{TEWI}_{Direct} + \text{TEWI}_{INDirect} \tag{8}$$

$$\text{TEWI}_{Direct} = \text{GWP} \cdot m_{ref} \cdot L_{rate} \cdot L_{time} + \text{GWP} \cdot m_{ref} \cdot (1 - \alpha_{recup}) \tag{9}$$

$$\text{TEWI}_{INDirect} = 365 \cdot T_{oper} \cdot (\dot{Q}_{ev}/\text{COP}) \cdot \beta \cdot L_{time} \tag{10}$$

In which (m_{ref})is the refrigerant charge, (L_{rate}) is the annual rate of refrigerant emitted (replacement and leaks), (L_{time}) is the useful life of the refrigeration, (α_{recup}) is the refrigerant life recovery rate and (β) is the CO_2 emission factor in producing electricity. Finally, (T_{oper}) is the operating time and it represents the required time for the system to produce 1200 liters of chilled water (5°C) and at least 600 liters of hot water (40°C) for the bath of a group of 12 people.

2.3. Exergy analysis

The exergy efficiency (η_{exergy}) is defined by Eq. (11), according to Shikalgar and Sapali (2019).

$$\eta_{exergy} = 1 - \frac{\dot{E}_{dest,total}}{\dot{W}_{comp}} \tag{11}$$

In this equation ($\dot{E}_{dest,total}$) is the total exergy destruction from the system. This is the sum of exergy destruction of the compressor ($\dot{E}_{dest,comp}$), condenser/gas cooler ($\dot{E}_{dest,cond/gc}$), evaporator ($\dot{E}_{dest,evap}$) and expansion valve ($\dot{E}_{dest,exp}$), according to de Paula et al. (2020a).

$$\dot{E}_{dest,comp} = \dot{E}x_1 - \dot{E}x_2 + \dot{W}_{comp} \tag{12}$$

$$\dot{E}_{dest,cond/gc} = \dot{E}x_2 - \dot{E}x_3 - \dot{Q}_{cond/gc} \cdot \left(1 - \frac{T_0}{T_R}\right) \tag{13}$$

$$\dot{E}_{dest,evap} = \dot{E}x_4 - \dot{E}x_1 + \dot{Q}_{ev} \cdot \left(1 - \frac{T_0}{T_{ev}}\right) \tag{14}$$

$$\dot{E}_{dest,exp} = \dot{E}x_3 - \dot{E}x_4 \tag{15}$$

Exergy of a refrigerant circulating in the VCRS is calculated by Eq. (16).

$$\dot{E}x = \dot{m}_{ref} \cdot [(h - h_0) - T_0(s - s_0)] \tag{16}$$

In which (h_0) and (s_0) are the enthalpy and entropy values of the dead state at the pressure (P_0) and temperature (T_0). T_R is the reference temperature adopted to calculate ($\dot{E}_{dest,cond/gc}$), as follows: ($T_R = T_{cond/gc}$) for refrigeration system with subcritical cycle and ($T_R = 45°C$) for refrigeration system with transcritical cycle. The reference temperature was chosen based on the temperature distribution profile of the gas cooler, as proposed by de Paula et. al (2020a).

2.4. Economic analysis

Total plant cost rate $(\dot{C}_{total})$ is given by Eq. (17), according to Roy and Mandal (2019) and de Paula et al. (2020b).

$$\dot{C}_{total} = \dot{C}_{CM} + \dot{C}_{op} + \dot{C}_{env} \tag{17}$$

Where $(\dot{C}_{CM})$ is the capital and maintenance cost rate, $(\dot{C}_{op})$ is the operational cost rate and $(\dot{C}_{env})$ is the penalty cost rate due to CO_2 emission. The capital and maintenance cost rate is calculated by Eq. (18).

$$\dot{C}_{CM} = \left(C_{evap} + C_{cond/gc} + C_{comp} + C_{TEV} + C_{p;evap} + C_{p;cond/gc}\right) \cdot \varphi \cdot CRF \tag{18}$$

In this equation (C_{evap}), $(C_{cond/gc})$, (C_{comp}), (C_{TEV}), $(C_{p;evap})$ and $(C_{p;cond/gc})$ are the capital cost function of the evaporator, condenser/gas cooler, compressor, thermostatic expansion valve, pump related to the evaporator circuit and pump related to the condenser/gas cooler circuit, respectively. In addition, (φ) is the maintenance factor and (CRF) is the capital recovery factor which can be calculated by the Eq. (19).

$$CRF = \frac{i(1+iR)^n}{(1+iR)^n - 1} \tag{19}$$

Where (iR) corresponds to the interest rate and (n) is the refrigeration plant lifetime.

Table 3. Capital cost function of the main components.

Components	Capital cost (R$/year)	Reference
Evaporator	$C_{evap} = 516.62 \cdot A_{evap} + 268.45$	Tontu et. al (2019), Mosaffa and Farshi (2016)
Condenser/gas cooler	$C_{cond/gc} = 516.62 \cdot A_{cond/gc} + 268.45$	Tontu et. al (2019), Mosaffa and Farshi (2016)
Compressor	$C_{comp} = \frac{39.5 \cdot \dot{m}_{ref}}{(0.9 - \eta_{global})} \cdot r_p \cdot \ln(r_p)$	Mosaffa and Farshi (2016), Mansuriya et. al (2020)
TEV	$C_{TEV} = 114.5 \cdot \dot{m}_{ref}$	Roy and Mandal (2019), Mansuriya et. al (2020)
Pump-evap	$C_{p;evap} = 2100 \cdot (\dot{W}_{evap})^{0.26} \left(\frac{1-\eta_{pump}}{\eta_{pump}}\right)^{0.5}$	Mansuriya et. al (2020)
Pump-cond/gas cooler	$C_{p;cond/gc} = 2100 \cdot (\dot{W}_{cond/gc})^{0.26} \left(\frac{1-\eta_{pump}}{\eta_{pump}}\right)^{0.5}$	Mansuriya et. al (2020)

The operational cost rate and penalty cost rate due to CO_2 emission are calculated by Eq. (20) and Eq. (21), respectively.

$$\dot{C}_{op} = \dot{W}_{comp} \cdot 365 \cdot T_{oper} \cdot C_{ele} \tag{20}$$

$$\dot{C}_{env} = \beta \cdot 365 \cdot T_{oper} \cdot (\dot{Q}_{ev}/COP) \cdot C_{CO_2} \tag{21}$$

Where (C_{ele}) is the electricity unit cost and (C_{CO_2}) is the unit damage cost of carbon dioxide emission.

2.5. Simulation parameters

The thermodynamic considerations adopted were based on literature review and they are presented in Tab. 4.

Table 4. Thermodynamic considerations.

Variable	Value considered
Evaporation temperature $(\mathbf{T_{ev}})$	-5 °C, -4°C, -3°C
Condensation/gas cooling temperature $(\mathbf{T_{cond/gc}})$	45°C, 50 °C
Superheating degree $(\Delta\mathbf{T_{sup}})$	7 °C
Subcooling degree $(\Delta\mathbf{T_{sub}})$	5 °C
Water temperature in the evaporator inlet $(\mathbf{T_{wi}})$	12 °C

Water temperature in the evaporator outlet ($\mathbf{T_{wo}}$)	5 °C
Water temperature in the condenser/gas cooler inlet ($\mathbf{T_{wci}}$)	25 °C
Water temperature in the condenser/gas cooler outlet ($\mathbf{T_{wco}}$)	40 °C
inner diameter of the outer tube ($\mathbf{D_W}$)	26.8mm, 20.8mm, 14mm
outer diameter of the inner tube ($\mathbf{D_{oi}}$)	7.94mm, 9.52mm, 12.7mm
inner diameter of the inner tube ($\mathbf{D_{REF}}$)	6.36mm, 7.94mm, 11.12mm
Dead state temperature ($\mathbf{T_0}$) and pressure ($\mathbf{P_0}$)	25°C, 101.3 kPa

The main considerations for calculating of the TEWI are presented in Tab. 5.

Table 5. Considerations for calculating of the TEWI parameter.

Variable	Consideration	Reference
$L_{time} = 15$ [Years]	Equipment operating with economic useful life	Makhnatch and Khodabandeh (2014), de Paula et al. (2020a)
$\alpha_{recup} = 70\%$.	Refrigerant mass less than 100 kg	Airah (2012), de Paula et al. (2020a), de Paula et al. (2020b)
$\beta = 0.082[kgCO_2/kWh]$	Reference value for Brazil	Rees (2016), de Paula et al. (2020a), de Paula et al. (2020b)
$L_{taxa} = 12.5\%$	Centralized system, normal operation, catastrophic losses during service and maintenance	Airah (2012), de Paula et al. (2020a), de Paula et al. (2020b)

The values considered for the input parameters to calculate the $(\dot{C}_{total})$ are presented in Tab. 6.

Table 6. Input parameters to calculate the Total plant cost rate.

Parameter	Adopted value	Reference
φ	1.06	Roy and Mandal (2019), Tontu et. al (2019), Mosaffa and Farshi (2016), Mansuriya et. al (2020)
iR	14%	Mosaffa and Farshi (2016), Roy and Mandal (2019), de Paula et al. (2020b)
n	15 [years]	Mosaffa and Farshi (2016), Mansuriya et. al (2020), Roy and Mandal (2019)
C_{ele}	0.956 [R$/kWh]	Duarte et. al (2019), de Paula et al. (2020b)
C_{CO_2}	0.09 [USD/kgCO₂]	Mosaffa and Farshi (2016), Roy and Mandal (2019)

3. RESULTS AND DISCUSSION

The thermo-economic and environmental analysis was carried out considering three different evaporation temperatures and two condensation temperatures. All systems obtained the highest environmental, energy, exergy and economic performance for evaporation temperature of - 3°C and condensation/gas cooling temperature of 45°C. In addition, a series of possible combinations between D_{REF} (diameter for the refrigerant side) and D_W (diameter for the water side) were analyzed by the authors, where it was observed that the best combination for the systems studied is D_{REF} = 6.36 mm and D_W = 14 mm.

Based on the adopted considerations, the proposed model was used to detail the geometric, energy, exergy, economic and environmental characteristics of each evaluated system, as presented in Tab. 7.

Table 7. Geometric, energy, exergy, economic and environmental characteristics of the systems.

Refrigerating Fluid	$\dot{W}_{comp}$ (W)	$\dot{Q}_{ev}$ (W)	$L_{cond/gc}$ (m)	L_{evap} (m)	**COP**	**TEWI** ($kgCO_2$)	η_{exergy} (%)	$\dot{C}_{total}$ (R$/year)	$\dot{E}_{dest,total}$ (W)	T_{oper} (h/day)	V_{HW} (l)
R134a	570	1310	14.00	23.00	2.3	2857	41.11	1776	333.7	7.45	686.2
R744	700	1543	19.68	32.24	2.2	2277	26.83	2117	512.6	7.22	818.5

Analyzing the results presented in Tab. 7, it is observed that from a purely environmental point of view, the system with R744 can replace the system with R134a because this system has higher environmental performance (lower TEWI value). However, the system with R744 has lower energy and exergy performance due to its lower COP value and mainly lower η_{exergy} value. Analyzing these parameters, it is clear that these results occur because the system with R744 has lowest total electrical power consumption in the compressor. The exergy performance of the system with R744 is less due to its greater total exergy destruction, according to Table 7. Analyzing the exergy destruction in each component in the two systems, it was observed that the exergy destruction in the gas cooler is considerably higher in the system with

R744. This is related to the large temperature variation that occurs in the gas cooler due to the system with R744 has a transcritical refrigeration cycle. In this process, a large amount of entropy is generated and thus an enormous amount of exergy is destroyed (de Paula et al., 2020). Finally, the compressor is the component of the system where the greatest exergy destruction occurs.

Besides, the system with R744 has higher total plant cost rate ($\dot{C}_{total}$) value compared to the system with R134a, according to Table 7. Thus, the system with R744 is more expensive. Evaluating the contribution of each cost rate in $\dot{C}_{total}$, it is clear that the $\dot{C}_{op}$ is the most relevant, and it corresponds to 83.37% and 82.88% of the $\dot{C}_{total}$ value for system with R744 and R134a. This cost rate has a direct relationship with the electrical power consumption $\left(\dot{W}_{comp}\right)$, according to de Paula et al. (2020a). On the other hand, the $\dot{C}_{env}$ is the least relevant cost rate, and it corresponds to 2.72% and 2.70% of the $\dot{C}_{total}$ value for system with R744 and R134a.

4. CONCLUSIONS

The main conclusions of this paper are summarized as follows:

- The COP analysis showed that the energy performance of the system with R744 is 4.55% lower than the system with R134a.
- The TEWI analysis showed that the environmental performance of the system with R744 is 25.47% higher.
- The exergy efficient (η_{exergy}) analysis showed that the exergy performance of the system with R744 is 53.22% lower.
- The $\left(\dot{C}_{total}\right)$ analysis indicated that the economic performance of the system with R744 is 19.2% lower.

Therefore, evaluating the results above, it can be concluded that the system with R744 is not suitable to replace the system with R134a because the system with R744 is more expensive. Therefore, other ecological refrigerants must be analyzed, such as R290 and R600a, for example.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Aminyavari, M., Najafi, B., Shirazi, A., Rinaldi, F., 2014, "Exergetic, economic and environmental (3E) analyses, and multi-objective optimization of a CO2/NH3 cascade refrigeration system", Applied Thermal Engineering, Vol. 65, pp. 45-50.

Ariah, 2012, "Methods of calculating Total Equivalent Warning Impact (TEWI)", The Australian Institute of Refrigeration, Air Conditioning and Heating.

Da Riva, E., Del Col, D., 2011, "Performance of a semi-hermetic reciprocating compressor with propane and mineral oil", International Journal of Refrigeration, Vol. 34, pp. 752-763.

de Paula, C. H., Duarte, W. M., Rocha, T. T. M., de Oliveira, R. N., Maia, A. A. T., 2020a, "Optimal design and environmental, energy and exergy analysis of a vapor compression refrigeration system using R290, R1234yf, and R744 as alternatives to replace R134a", International Journal of Refrigeration, Vol. 113, pp. 10-20.

de Paula, C. H., Duarte, W. M., Rocha, T. T. M., de Oliveira, R. N., de Paoli Mendes, R., Maia, A. A. T., 2020b, "Thermo-economic and environmental analysis of a small capacity vapor compression refrigeration system using R290, R1234yf, and R600a", International Journal of Refrigeration, Vol. 118, pp. 250-260.

Duarte, W. M., Tavares, S. G., Paulino, T. F., Machado, L., Maia, A. A. T., 2019, "Feasibility of solar geothermal hybrid source heat pump for producing domestic hot water in Brazilian climates", In: 25th ABCM International Congress of Mechanical Engineering, Uberlandia, Brazil.

Fazelpour F., Morosuk T., 2014, "Exergoeconomic analysis of carbon dioxide transcritical refrigeration machines", International Journal of Refrigeration, Vol. 38, pp. 128-139.

Gill, J., Singh, J., Ohunakin, O. S., Adelekan, D. S., 2019, "Exergy analysis of vapor compression refrigeration system using R450A as a replacement of R134a", Journal of Thermal Analysis and Calorimetry, Vol. 136, pp. 857-872.

Makhnatch, P., Khodabandeh, R., 2014, "Selection of low GWP refrigerant for heat pumps by assessing the life Cycle Climate Performance (LCCP)", In: 11TH International Energy Agency Heat Pump Conference Montreal.

Mansuriya, K., Patel, V. K., Raja, B. D., Mudgal, A., 2020, "Assessment of liquid desiccant dehumidification aided vapor-compression refrigeration system based on thermo-economic approach", Applied Thermal Engineering, Vol. 164, pp. 114542.

Mosaffa, A. H., Farshi, L. G., 2016, "Exergoeconomic and environmental analyses of an air conditioning system using thermal energy storage", Applied Energy, Vol. 162, pp. 515-526.

Rees, S. J., 2016, "An introduction to ground-source heat pump technology", In: Advances in Ground-Source Heat Pump Systems, pp. 1-25.

Roy R., Mandal B. K., 2019, "Thermo-economic assessment and multi-objective optimization of vapour compression refrigeration system using low gwp refrigerants", 8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO). IEEE, pp. 1-5.

Shikalgar, N. D., Sapali, S. N., 2019, "Energy and exergy analysis of a domestic refrigerator: Approaching a sustainable refrigerator", Journal of Thermal Engineering, Vol. 5, pp. 469-481.

Tontu, M., Sahin, B., Bilgili, M., 2019, "Exergoeconomic analysis of steam turbine driving vapor compression refrigeration system in an existing coal-fired power plant", Arabian Journal for Science and Engineering, Vol. 44, pp. 7553-7566.

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