19th Brazilian Congress of Thermal Sciences and Engineering
November 06th-10th, 2022, Bento Gonçalves - RS - Brazil

ENC-2022-0502
CONDENSING TEMPERATURE OPTIMIZATION OF CASCADE CONDENSER IN A SUBCRITICAL REFRIGERATION SYSTEM WITH R1234YF/R744

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Abstract. *In this paper a thermodynamic analysis of a subcritical refrigeration cycle is presented, emulating a supermarket application in a tropical climate, using the refrigerants R1234yf at the high temperature cycle and R744 at the low temperature cycle. These mentioned fluids are characterized by a low GWP and a zero OPD. In the study of a cascade condenser, a multiple linear equation is proposed using genetic algorithm, which expresses the COP values as a result of the condensing temperature at the low temperature cycle and the difference of temperatures between the high and low temperature cycles. These parameters are important, since it reflects directly on the efficiency of the cascade refrigeration system. Once the regression was obtained, the previously mentioned parameters were optimized for a maximum coefficient of performance, obtaining a maximum value of 1.97 for the condensing temperature of 1.4 °C and a temperature difference between the cycles of 1 °C at the cascade condenser.*

Keywords: *Refrigeration, Condenser, Cascade, Optimization.*

1. INTRODUCTION

Global energy consumption is increasing day to day, and is expected to rise by 50% between 2010 and 2040 (Ahmed et al., 2021). In addition, the increasing cost in electricity generation makes it necessary to have a solution where cooling systems are energy efficient (Bista et al., 2018). Overall, refrigeration and air conditioning systems account for almost 50% to 65% of total electricity consumption, and more than 80% of these electrical energies are derived from burning fuels (Khalilzadeh et al., 2019).

Refrigerants are used in refrigeration systems that make a significant contribution to global warming potential (GWP). Refrigerants that have a high GWP generate environmental impacts that are characterized and quantified through direct and indirect emissions. Direct emissions occur from refrigerant leakage while indirect emissions arise from the generation of electricity that is used to power the refrigeration systems (Solomon et al., 2007; Tassou et al., 2011).

Currently, low-GWP refrigerants are being promoted and used as a way to decrease direct emissions, and refrigeration systems that employ high-GWP refrigerants are being retrofitted or replaced. However, refrigerant replacement may have an adverse effect if the refrigeration system is not properly designed, and may cause increased power consumption of the compressor, contributing to indirect emissions, leading to a greater negative impact than a beneficial effect. Nevertheless, meeting the demand for energy while reducing CO2 emissions is not a simple task.

Therefore, one of the main challenges in the refrigeration industry is to increase efficiency in order to decrease power consumption and CO2 emissions (Deymi-Dashtebayaz et al., 2021). One approach to achieving this is by using the cascade refrigeration cycle (CRC). This system can provide low-temperature cooling demands with high COP (coefficient of performance) values compared to the conventional refrigeration cycle and is used in the supermarket sector (Nebot-Andrés et al., 2017; Parolin et al., 2019). In addition, it is widely implemented in high condensing temperatures (hot climates) (Zhang et al., 2020). The CRC besides providing better energy performance, this cycle can reduce direct emissions, because it normally uses CO2 (R744 characterized for having low GWP) in the low temperature cycle and in turn an environmentally friendly refrigerant in the high temperature cycle. Therefore, optimization has been widely used in the design, modeling and operation of refrigeration systems, and is the focus of different research in CRCs in order to increase the coefficient of performance (COP) and at the same time decrease CO2 emissions that contribute to the greenhouse effect by using refrigerants with low GWP.

In the literature, different CRC works have been carried out proposing different correlations that express the coefficient of performance (COP) as a function of different parameters, such as: temperature difference in the cascade condenser (DT), evaporation temperature (T_E), condensing temperature in the cascade condenser ($T_{Casc,C}$) evaporating temperature in the cascade condenser ($T_{Casc,E}$) and the condensing temperature (T_C). Yilmaz et al., (2018) developed a correlation to estimate the COP of CRC operating with R717/R744 as a function of the $T_{Casc,C}$ and T_C parameters. Furthermore, they compared the results of the correlation with an experimental work achieving a maximum deviation of 15.1 % for a T_E=-40 °C. Yilmaz et al., (2014) thermodynamically analyzed the CRC running on R404A/R744, developing several correlations that express the COP values for different temperature conditions in a cold room, obtaining determination coefficients ranging from 96.5% to 99.2%. Alhamid et al., (2010) proposed CRC correlations that work with mixtures of (R744+R171-R290), to estimate Coma, as a function of T_E, DT, and T_C, obtaining a 99.8 % coefficient of determination. Dopazo et al., (2009) and Dubey et al., (2014) developed correlations for CRC operating with R717/R744, estimating a linear regression to determine the optimal $T_{Casc,C}$ and $T_{Casc,E}$ (conditions that maximize COP) as a function of the T_E, T_C, and DT parameters, achieving correlation coefficients of 99.45 % and 94.95 %, respectively. In addition to the works cited above, Nasruddin et al., (2016) performed a multi-objective optimization using genetic algorithm (GA) of CRC operating with C3H8 and C2H6/CO2 in high and low temperature cycles, aiming to increase energy efficiency and investment costs. Golbaten Mofrad et al., (2020) performed multi-objective optimization of CRC running R744A/R744 using genetic algorithm with NSGA II, analyzing the values of COP, exergetic efficiency, total product cost and environmental impact.

Therefore, the main objective of this work is to optimize the energy performance of the cascade refrigeration cycle using genetic algorithm, performing a multiple linear equation parameter estimation as a function of $T_{Casc,C}$ and DT values for the conditions of T_E=-30 °C and T_C=45 °C, with the help of a thermodynamic model. Furthermore, low GWP refrigerants are tested in this refrigeration system, with R1234yf/R744 fluids being used for the high and low temperature cycles, respectively.

2. METHODOLOGY

The cascade refrigeration cycle works with two refrigeration cycles, known as the high and low temperature cycle, that operate with independent refrigerants at different pressures and temperatures for each cycle, these cycles are thermally connected by the cascade heat condenser, which is the condenser for the low temperature cycle and at the same time is the evaporator for the high temperature cycle. This system allows multiple compressors to operate under more acceptable conditions due to the fact that each stage operates at a lower compression ratio, resulting in a decrease in energy consumption (Stoecker and Saiz, 2018). The thermophysical properties for each refrigerant were obtained in the EES, for each of the points representing each state, as shown in Fig. 1a and b.

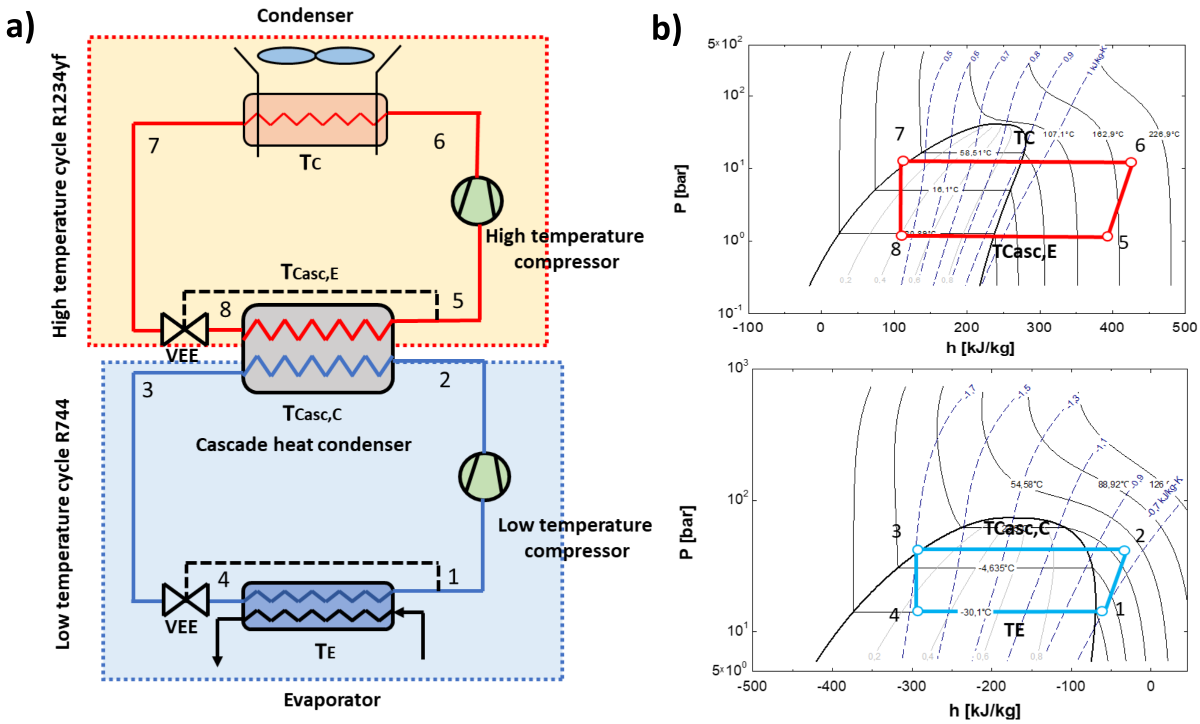

Figure 1 Cascade refrigeration cycle R1234yf/R744. a) schematic diagram b) P-h diagram

The low temperature cycle works as follows, the compressor absorbs the R744 vapor in the suction (point 1) and compresses it at high pressure into superheated vapor (point 2), entering the cascade heat condenser. Next, the R744 is condensed to saturated liquid (point 3), feeding the expansion valve. Subsequently, the fluid is expanded entering the evaporator at (point 4). The high temperature cycle operates in a similar way to the low temperature cycle, however, in this cycle the R1234yf is used. At (point 5) the compressor receives the vapor in the suction and compresses it to high pressure in superheated vapor (point 6), entering the condenser. Subsequently, the R1234yf is condensed to the saturated liquid state (point 7), feeding the expansion valve. Next, the fluid is expanded entering the cascade heat condenser (in this case the evaporator).

The thermodynamic analysis of the cascade refrigeration cycle for each stage was performed based on the following assumptions:

- The expansion processes are assumed to be isoenthalpic.
- Pressure losses and heat transfer in the environment are neglected in the piping and system components.
- Kinetic and potential energy changes are negligible.
- The cooling capacity is 4 kW at an evaporation temperature of -30 °C (frozen food).
- The condensing temperature is 45 °C (tropical climate).
- The degree of subcooling and superheating for each of the cycles was 0 K, conditions where the heading was x=0 and x=1, respectively.
- The isentropic efficiency of each compressor was 0.86 (obtained experimentally).

Based on the assumptions presented above, mass and energy balances illustrated in Eqs. 1 and 2 are applied to determine the mass flow rate in each of the cycles, the power consumption of each compressor, and the heat transfer rates of the evaporator, cascade heat condenser, and condenser.

$$\sum_{Input} \dot{m} = \sum_{Output} \dot{m} \tag{1}$$

$$\dot{Q} - \dot{W} = \sum_{Output} \dot{m}.h - \sum_{Input} \dot{m}.h \tag{2}$$

The total coefficient of performance (COP_{Total}) was calculated by the following relation presented in Eq. 3. Where $\dot{Q}_E$ is the refrigeration capacity, $\dot{W}_{HTC}$ is the power consumption in the compressor of the high temperature cycle and $\dot{W}_{LTC}$ is the power consumption in the compressor of the low temperature cycle.

$$COP_{Total} = \frac{\dot{Q}_E}{\dot{W}_{HTC} + \dot{W}_{LTC}} \tag{3}$$

In order to determine the low temperature cycle mass flow rate ($\dot{m}_{LTC}$), a first law balance is done on the evaporator, based on the refrigeration capacity. Once the low temperature cycle mass flow rate has been estimated, the high temperature cycle mass flow rate ($\dot{m}_{HTC}$) is calculated. This flow rate is determined by doing an energy balance in the cascade heat condenser obtaining Eq. 4. The isentropic efficiency of each compressor was determined experimentally from the work of Blanco, (2021), who worked with cascade refrigeration system operating with semi-hermetic compressors.

$$\frac{\dot{m}_{HTC}}{\dot{m}_{LTC}} = \frac{h_2 - h_3}{h_5 - h_8} \tag{4}$$

The equation used for each of the components of the cascade refrigeration system is shown in Table 1. While the points of each thermodynamic state of the cascade refrigeration cycle are illustrated in Table 2.

Table 1 Mass and energy balance equations for each system component.

Component	**Mass balance**	**Energy balance**
Low temperature cycle R744		
Compressor	$\dot{m}_1 = \dot{m}_2$	$\dot{W}_{LTC} = \frac{m_1(h_{2s} - h_1)}{\eta_{m,LTC}}$
Expansion device	$\dot{m}_3 = \dot{m}_4$	$h_3 = h_4$
Evaporator	$\dot{m}_4 = \dot{m}_1$	$\dot{Q}_E = \dot{m}_1(h_1 - h_4)$
Cascade heat exchanger	$\dot{m}_2 = \dot{m}_3, \dot{m}_8 = \dot{m}_5$	$\dot{Q}_{Cas} = \dot{m}_2(h_2 - h_3) = \dot{m}_5(h_5 - h_8)$
High temperature cycle R1234yf		
Compressor	$\dot{m}_5 = \dot{m}_6$	$\dot{W}_{HTC} = \frac{m_5(h_{6s} - h_5)}{\eta_{m,HTC}}$
Condenser	$\dot{m}_6 = \dot{m}_7$	$\dot{Q}_C = \dot{m}_6(h_6 - h_7)$
Expansion device	$\dot{m}_7 = \dot{m}_8$	$h_7 = h_8$

Table 2 Calculation of thermodynamic states for each point of the cascade cooling system using ESS

Evaporator outlet	**Compressor output**	**Condenser outlet**	**Expansion device output**
Low temperature cycle R744			
$T_1 = T_E$ $P_1 = f(T_1, x=1)$ $h_1 = f(T_1, x=1)$ $s_1 = f(T_1, x=1)$	$s_2 = s_1$ $P_2 = f(T_{Cond,LTC}, x=0)$ $T_2 = f(P_2, s_2)$ $h_{2s} = f(P_2, s_2)$ $h_2 = (h_{2s} - h_1) / n_{isent} + h_1$	$T_3 = T_{Casc,C}$ $P_3 = P_2$ $h_3 = f(T_3, x=0)$ $DT = T_{Casc,C} - T_{Casc,E}$	$P_4 = P_1$ $T_4 = T_1$ $h_4 = h_3$
High temperature cycle R1234yf			
$T_5 = T_{Casc,E}$ $P_5 = f(T_5, x=1)$ $h_5 = f(T_5, x=1)$ $s_5 = f(T_5, x=1)$	$s_6 = s_5$ $P_6 = f(T_C, x=0)$ $T_6 = f(P_6, s_6)$ $h_{6s} = f(P_6, s_6)$ $h_6 = (h_{6s} - h_5) / n_{isent} + h_5$	$T_7 = T_C$ $P_7 = P_6$ $h_7 = f(T_7, x=0)$	$P_8 = P_5$ $T_8 = T_5$ $h_8 = h_7$

In the study of the cascade refrigeration cycle, it is observed that the temperature difference in the cascade condenser plays a key role in the performance coefficient of this refrigeration system. The calculation of the temperature difference is presented in Eq. 5, which is subtraction between the condensing and evaporating temperature in the cascade condenser.

$$DT = T_{Casc,C} - T_{Casc,E} \tag{5}$$

In the literature, it is widely observed that the cascade refrigeration cycle can be modeled by 4 design parameters as a function of temperatures T_E, $T_{Casc,C}$, DT, and T_C as presented in Eq. 6.

$$(COP_{Total}) = f(T_E, T_{Casc,C}, DT, T_C) \tag{6}$$

However, in this study the behavior of the cascade heat condenser is analyzed for the conditions of frozen food in a tropical environment, therefore Eq. 6 is reduced to Eq. 7, and the effects of $T_{Casc,C}$ and DT on the coefficient of performance of the cascade refrigeration cycle operating with R1234yf/R744 are studied. In the analysis, twenty cascade heat condenser temperatures ($T_{Casc,C}$= -15 °C to 5 °C in a range of 1 each) and five cascade heat condenser temperatures (DT=1 °C, 3 °C, 5 °C, 7 °C and 9 °C) were considered as input parameters, obtaining a total of 105 data. The results were obtained using the Equation Engineering Solver software (EES commercial version 9.994). To subsequently develop a mathematical equation that expresses the values of the performance coefficient as a function of the input parameters.

$$(COP_{Total}) = f(T_{Casc,C}, DT) \tag{7}$$

3. RESULTS

The EES version 9.994 was used to perform the calculations and graphics, while the Matlab software version 2015 was used for the regression analysis using genetic algorithm, aiming to obtain the optimal $T_{Casc,C}$ and DT that maximize the coefficient of performance. The following are the parameters that were assumed constant for the calculation of the results.

- Evaporation temperature, TE= -30 °C.
- Condensing temperature, TC= 45 °C.
- Effectiveness of cascade heat condenser, evaporator and condenser=1.

Fig. 2 shows the effect of DT on the corresponding COP_{Total} for each value of $T_{Casc,C}$. In this figure it is observed that with increasing temperature difference in the cascade heat condenser the COP_{Total} decreases. Several authors have verified this same behavior, which is explained by the increase in the compression ratio in the compressors, causing the increase in energy consumption M. Idrus Alhamid et al., (2010); Dubey et al., (2015); Tripathy et al., (2014). It is also seen in this figure that in the range of values from 5 °C to -5 °C in $T_{Casc,C}$. there are less expressive variations in COP_{Total}, while values from -6 °C to -15 °C provides greater variations. Likewise, a linear behavior between COP_{Total} and $T_{Casc,C}$ and DT parameters is contemplated.

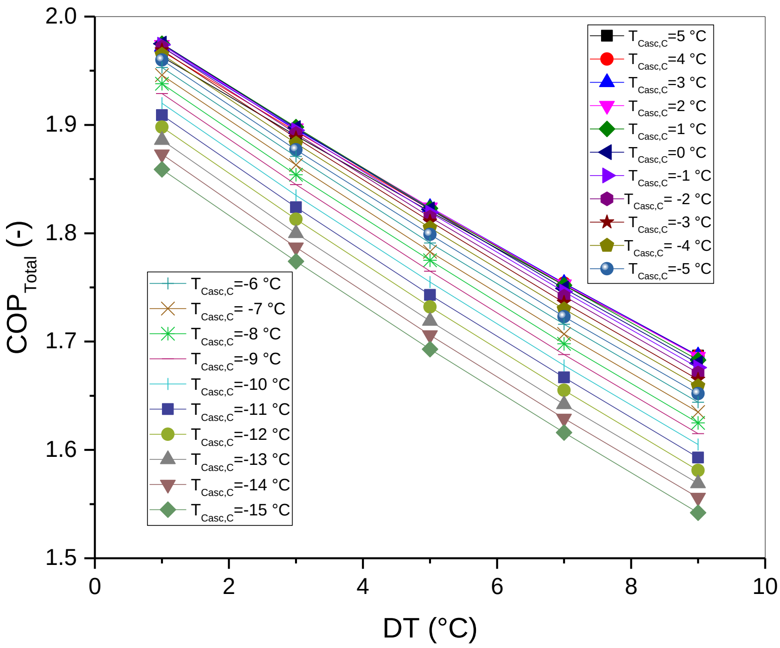

Figure 2 Influence of the condensing temperature in the cascade condenser on the COP_{Total}.

Fig 3 shows the effect of $T_{Casc,C}$ on the corresponding COP_{Total} for each DT value. In this illustration it can be seen that with the increase of the condensing temperature in the cascade condenser, the COP_{Total} tends to increase up to a certain value, after this value the COP_{Total} tends to decrease, observing the behavior of a curve.

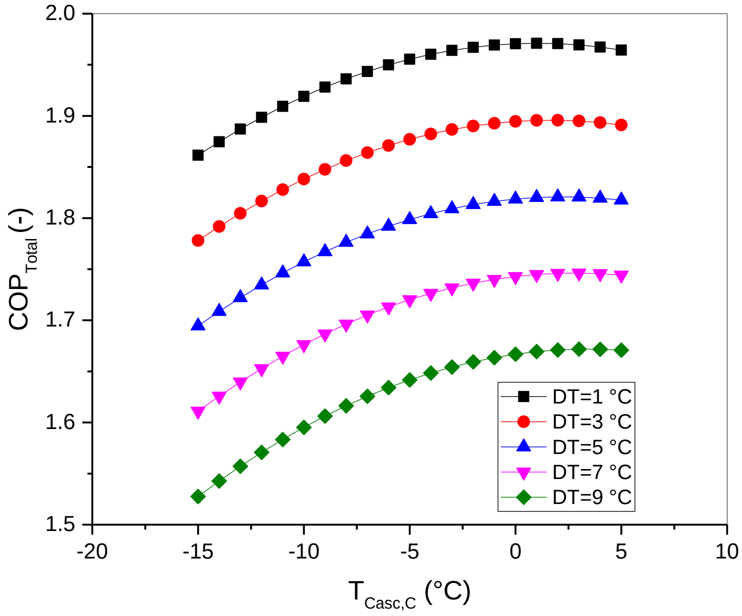

Figure 3 Influence of the condensing temperature in the cascade condenser on the COP_{Total}.

The effects of $T_{Casc,C}$ and DT parameters for T_E=-30 °C and T_C=45 °C conditions on the performance of the cascade refrigeration system were found. Therefore, a mathematical equation was developed as a guide to define the optimal thermodynamic design parameters. Thus, a parameter estimation is performed using genetic algorithm in order to obtain an equation that represents the behavior of the cascade heat condenser as a function of the aforementioned parameters. In Eq. 8, the multiple linear equation to be fitted is presented, where of the coefficients β0, β1, β2, β3 and β4 represent the design variables of the genetic algorithm, where the search space for each of them was stipulated between -5 and 5. The values of TCasc,C and DT represent the input parameters while COPmax represents the output parameter, these values are obtained from simulation in EES, obtaining a total of 105 tests for fitting this equation. The units of the temperatures in Eq. 8 is given in celsius (°C).

$$COP_{max} = \beta0 + \beta_1 T_{Cond,LTC} + \beta_2 DT + \beta_3 T_{Cond,LTC}^{\ 2} + \beta_4 T_{Cond,LTC} DT \quad (8)$$

In Tab. 3 the values of the design variables as well as the objective function obtained from Eq. 8 are reported. In the parameter estimation a number of population and generations of 100 and 300, respectively, was required, obtaining in total 30100 evaluations. In the analysis, 10 runs were considered representing the randomness of the fitted parameters achieving close objective function values. To determine the values of the number of population and generations of the genetic algorithm, tests not reported here were performed aiming at an ideal condition in which the number of evaluations is smaller allied with a good convergence.

Table 3 Values of the coefficients of Eq. 8 and objective function for a population number of 100 and number of generations of 300 in GA.

Runs	**β_0**	**β_1**	**β_2**	**β_3**	**β_4**	**F_{min}**
0	2,00752	0,00090	-0,03675	-0,00043	0,00024	0,00113
1	2,00725	0,00094	-0,03672	-0,00043	0,00025	0,00112
2	2,00721	0,00119	-0,03678	-0,00041	0,00023	0,00116
3	1,97124	-0,00978	-0,02964	-0,00085	0,00140	0,06582
4	2,00722	0,00094	-0,03671	-0,00042	0,00025	0,00112
5	2,00729	0,00094	-0,03672	-0,00043	0,00025	0,00112
6	2,00728	0,00094	-0,03672	-0,00043	0,00025	0,00112
7	2,00721	0,00093	-0,03671	-0,00043	0,00025	0,00112
8	2,00720	0,00093	-0,03671	-0,00043	0,00025	0,00112
9	1,98020	0,00111	-0,03264	-0,00008	0,00082	0,02628
Average	2,00096	-0,00010	-0,03561	-0,00043	0,00042	0,01011
Standard deviation	0,01347	0,00340	0,00246	0,00018	0,00039	0,02111

In Eq. 9 the values of the coefficients obtained in the genetic algorithm are illustrated, these parameters were chosen from seed 2, because in this condition it presented the lowest value of the objective function.

$$COP_{max} = 2{,}00720 + 0{,}00093.T_{Cond,LTC} - 0{,}03670\ .DT - 0{,}00043.T_{Cond,LTC}^{\ 2} + 0{,}00025.T_{Cond,LTC}.DT \tag{9}$$

Fig. 4 illustrates the theoretical results with the calculated values that were estimated using Eq. 9. In the analysis, a coefficient of determination of 99.5% between the theoretical and calculated values was acquired. Therefore, it can be concluded that the estimated regression, fits with a good accuracy with the theoretical values.

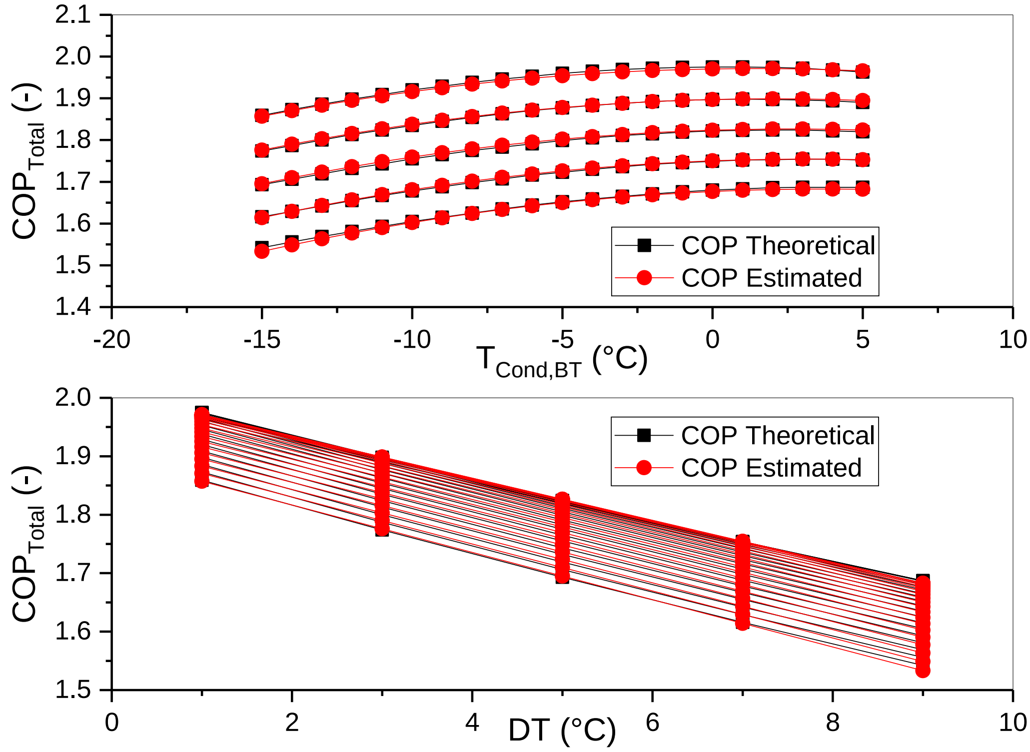

Figure 4 Results of theoretical and calculated COP as a function of $T_{Casc,C}$ and DT parameters.

In Fig. 3 the behavior of COP_{Total} as a function of $T_{Casc,C}$ is observed, these results indicate that there is an optimal value of $T_{Casc,C}$ for each DT condition at which COP_{Total} is maximum. Therefore, Eq. 9 was used using genetic algorithm to determine the optimal value of $T_{Casc,C}$ between -15 to 9 °C for each DT condition for values of 1 °C, 3 °C, 5 °C, 7 °C, and 9 °C, which maximize the COP_{Total}. These results are summarized in Table 4. Where the values of $T_{Casc,E}$ were obtained by means of Eq. 5. In obtaining these parameters, the conditions of the number of population and generations, specified previously, were used.

Table 4 values of $T_{Casc,C}$ and $T_{Casc,E}$ that maximize the COP for different DT parameters.

DT (°C)	$T_{Casc,C}$ (°C)	$T_{Casc,E}$ (°C)	COP_{max} (-)
1	1,39	0,39	1,97
3	1,98	-1,02	1,90
5	2,57	-2,43	1,83
7	3,17	-3,83	1,75
9	3,76	-5,24	1,68

The values obtained from Table 4 can be used to obtain the COP_{max} for different pressure ratios, because the pressure ratio in high and low temperature compressors reflect in the DT. In this way, the design conditions of various compressor models are met, obtaining optimum values of $T_{Casc,C}$ and $T_{Casc,E}$ for a given specific condition.

4. ACKNOWLEDGEMENTS

The authors thank the CAPES, FAPEMIG and CNPq research promotion entities for the financial support received.

5. CONCLUSIONS

This work evaluated the maximum coefficient of performance for a cascade refrigeration system operating with R1234yf/R744 in reference to two design parameters: condensing temperature in the cascade condenser and temperature difference in the cascade heat condenser. The main conclusions from the analytical results of this work are listed below:

- The results in the literature showed that by selecting the optimal cascade refrigeration system design, suitable operating conditions and refrigerant, the refrigeration cycle efficiency can be increased while emissions can be reduced.
- For the operating conditions designed in this refrigeration system, a multiple linear equation was obtained by the genetic algorithm, requiring a number of population and generations of 100 and 300, respectively, giving a total of 30100 evaluations. This equation expresses the COP values as a function of DT and $T_{Casc,C}$, obtaining a determination coefficient of 99.5 %, obtaining a good fit between the correlation and the theoretical values.
- An increase in DT decreases the COP_{Total}, showing a linear decreasing behavior. While an increase in $T_{Casc,C}$ raises the COP_{Total} to a certain range of values presenting the behavior of a curve, indicating that there is an optimal value of $T_{Casc,C}$ for each DT condition that maximizes the COP_{Total}.
- With the multiple linear equation genetic algorithm was used to calculate the optimal values of $T_{Casc,C}$, $T_{Casc,E}$ and DT that maximize the COP, estimating a COP_{max} of 1.97 for the conditions $T_{Casc,C}$=1.39 °C and $T_{CasC,E}$=0.39 °C for DT=1 °C.

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