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A CASCADE R134a/R744 REFRIGERATION CYCLE THERMAL ANALYSIS: EVALUATION OF THE INTERMEDIATE HEAT-EXCHANGER PARAMETERS.

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Abstract. *This work analyses a cascade refrigeration cycle with R134a and R744 as working fluids, evaluating the parameters of the intermediate heat exchanger (IHX). The IHX couples the upper and bottom cycles, and its energy level has an impact on the cycle performance. Parameters such as temperature, pinch point and pressure should be right tuned for the best cycle performance. A thermal simulation is carried out in the refrigeration cycle, as well as a sensitivity analysis of the IHX over the cycle performance. The results show that the cycle performance has a maximum for each temperature and pinch point pair, and this maximum decreases with lower temperature levels in the IHX.*

Keywords: *Cascade Refrigeration Cycle, Carbon Dioxide, Intermediate Heat Exchanger*

1. INTRODUCTION

The use of natural refrigerants in vapor compression refrigeration systems has increased due to tighten regulations against compounds that contains fluorine (HFCs) and chlorine (CFCs). In 90's the CFCs were phased out due their ozone layer depletion potential and replaced mainly by HFCs. Now, due global warming effects, HFCs are being phased out and alternatives to replace them are being search. Natural refrigerants as butane, propane, ammonia and carbon dioxide have low global warming potential and they are substitutes to HFCs.

In the first decades of refrigeration, prior the introduction of CFC in the 60's, carbon dioxide (R744) was one of the most used refrigerants. Among natural refrigerants, it has advantages as low toxicity, compared with ammonia, and low flammability, compared with hydrocarbons. A drawback is the carbon dioxide critical point, which has a low temperature ($\mathrm{T_c} = 31.1^{\circ}\mathrm{C}$) and high pressure ($\mathrm{P_c} = 7.39\mathrm{MPa}$).

Two main R744 refrigeration cycle configurations exist, a transcritical and a subcritical. The transcritical operates above the critical point for heat rejection, and it has a gas cooler instead of a condenser. The subcritical operates below the critical point, with lower pressures in the compressor discharge and lower than critical temperature in the condenser. This latter condition imposes a limit, as the condensing temperature is normally below typical outdoor temperatures. An way to overcome the temperature limitation is to use a cascade refrigeration cycle, where an upper cycle is coupled to the R744 cycle to pump out the heat (Kim *et al.*, 2004). Many studies in the literature investigated experimentally and numerically different cascade cycles configurations, high temperature cycle fluids, their performance and viability.

Some focus is over the Ammonia and Carbon Dioxide pair. Getu and Bansal (2008) did a numerical study on a cascade cycle with R717 (Ammonia) and R744 (CO2). They investigated how the condensing, evaporating, superheating and subcooling temperatures as well as, the temperature difference in the intermediate heat exchanger affect the cycle performance. A multilinear regression of these temperatures was done to evaluate the maximum COP for each analyzed condition. Messineo (2012) analyzed thermodynamically a R717/R744 cascade cycle. The author investigated parameters such as condensing, evaporating, subcooling and superheating temperatures, in both high and low cycles. The results were compared against a R404A two-stage compressor cycle, that presented a similar performance. The advantage for the R744/R717 cycle was pointed as being more environmental friendly. Ma *et al.* (2014) studied experimentally a R717/R744 cascade cycle with falling film intermediated heat exchanger. The analysis presented a better performance with this type of heat exchanger due the low temperature difference between condensing and evaporating fluids.

Another common refrigerant that is paired with R744 in a cascade cycle is the R134a. Gullo *et al.* (2016) investigated numerically alternative configurations for a R744 booster system, focused on a supermarket application. A R134a/R744 cascade cycle was used as a baseline for comparison among the different schemes. The schemes that used parallel compression or mechanical subcooling achieved higher performances than the baseline cycle, but increased the cycle complexity. Queiroz *et al.* (2016) studied experimentally a R134a/R744 baseline cycle, where the R134a was replaced by R404A. The results showed that both cycles had the same COP, but the pair R404A/R744 presented lower refrigeration capacity. Cabello *et al.* (2017) experimentally studied the replacement of R134a by R152a as pair with R744, in a cascade system. As both fluids are from the HFC family, a drop-in replacement could be made. The substitution was motivated by fact that the R152a has almost ten times lower global warming potential, than the R134a. The results presented that the plant using R152a performed similar to the plant using R134a, without any further technical adaptation.

Another work from da Silva *et al.* (2012) experimentally investigated the performance of two direct expansion systems with R22 and R404A and one cascade system with R404A/R744 for supermarket applications. The study concluded that the cascade system has lower energy consumption (13% to 24%) than the direct expansion system.

From the literature review, it can seen that most papers about R134a/R744 systems were experimental works, little numerical investigations has been done an that cycle configuration. In a cascade cycle, the intermediate heat exchanger coupling condition plays a important role in the cycle overall performance. The objective of this paper is to investigate the coupling conditions, temperature and pressure, in the intermediate heat exchanger that maximize the coefficient of performance (COP) of a cascade cycle, with R134a and R744 as working fluids.

The paper is organized presenting firstly the thermodynamic model and the hypotheses, secondly the results of analyzed parameters and finally by conclusions.

2. THERMODYNAMIC MODEL

Figure 1 presents the cascade cycle diagram with the state points. It is composed by two single stage vapor compression cycles, the high temperature one, which has R134a as working fluid, and the lower temperature one, which has R744 as working fluid. The high and low temperature cycles are coupled by an intermediated heat exchanger (IHX). The processes along both cycles are modeled equal, with the following hypotheses:

- The compression process is modeled as adiabatic, with constant isentropic efficiency.
- The expansion process is modeled as isenthalpic.
- It was not considered superheating in the the evaporator outlet, neither supercooling in the condenser outlet.
- There is no pressure or heat losses along the piping and components.
- Kinetic and potential energies variations are neglected.

Figure 2 displays the single stage cycles in their respective T-s and P-h diagram, with state points. With these assumptions, an energy balance for each system component resulted in the following system of equations.

The compressor work power $\dot{\mathrm{W}}$ $[\mathrm{kW}]$ is given by

$$\dot{W} = \dot{m}(h_2 - h_1) \tag{1}$$

where $\dot{\mathrm{m}}$ $[\mathrm{kg/s}]$ is the mass flow, $\mathrm{h_1}$ and $\mathrm{h_2}$ $[\mathrm{kJ/kg}]$ are the inlet and outlet enthalpies, respectively. The compressor isentropic efficiency η is defined by

$$\eta = \frac{h_2 - h_1}{h_{2s} - h_1} \tag{2}$$

where $\mathrm{h_{2s}}$ $[\mathrm{kJ/kg}]$ is the outlet enthalpy if the compression process is isentropic. The R744 evaporator heat absorption capacity $\mathrm{Q_{ev}}$ $[\mathrm{kW}]$ is given by:

$$\dot{Q}_{ev} = \dot{m}_{R744}(h_1 - h_4) \tag{3}$$

where $\dot{\mathrm{m}}_{\mathrm{R744}}$ $[\mathrm{kg/s}]$ is the carbon dioxide mass flow, $\mathrm{h_1}$ and $\mathrm{h_4}$ $[\mathrm{kJ/kg}]$ are the outlet and inlet enthalpies, respectively. The R134a condenser heat rejection $\mathrm{Q_{cd}}$ $[\mathrm{kW}]$ is given by

$$\dot{Q}_{cd} = \dot{m}_{R134a}(h_2 - h_3) \tag{4}$$

where $\dot{\mathrm{m}}_{\mathrm{R134a}}$ $[\mathrm{kg/s}]$ is the 1,1,1,2-Tetrafluoroethane mass fluid flow, $\mathrm{h_2}$ and $\mathrm{h_3}$ $[\mathrm{kJ/kg}]$ are the condenser inlet and outlet enthalpies, respectively. The intermediate heat exchanger (IHX) heat balance results in

$$\dot{m}_{R744}(h_2 - h_3) = \dot{m}_{R134a}(h_1 - h_4) \tag{5}$$

The overall coefficient of performance COP for the cycle can be calculated as:

$$COP = \frac{\dot{Q}_{ev}}{\dot{W}_{R134a} + \dot{W}_{R744}} \tag{6}$$

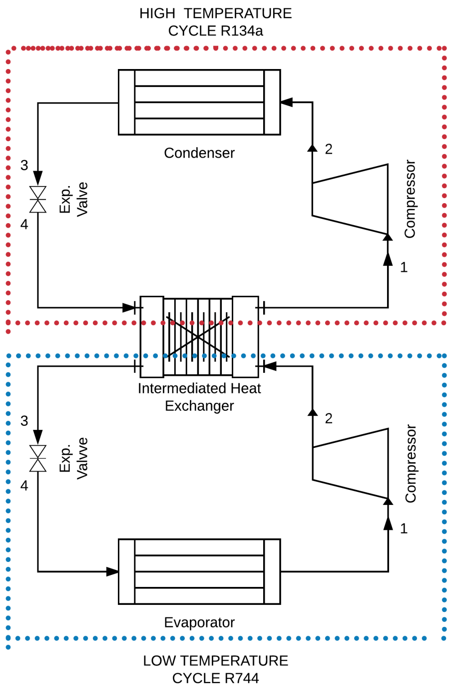
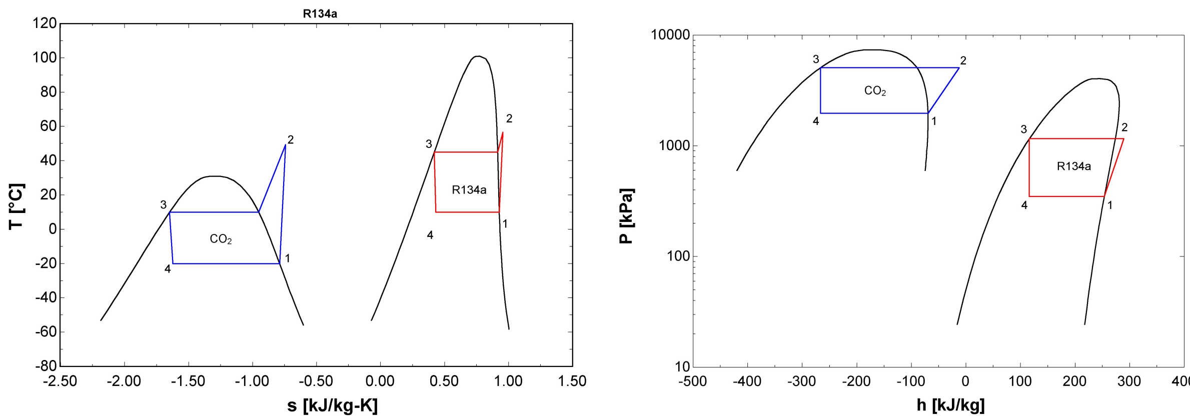


Figure 1: Diagram of the cascade cycle with the R134a high temperature circuit (red dots) and the R744 low temperatura circuit (blue dots)



(a) T-s diagram

(b) P-h diagram

Figure 2: T-s and P-h diagrams for the cascade cycle. The state points in the figure correspondes to that in the Fig. 1

The pinch point is the minimum temperature difference between two streams in a heat exchanger. In this paper, the IHX pinch point temperature was varied from 0^{o}C to 10^{o}C. The R134a IHX evaporating temperature was varied from -10^{o}C to 10^{o}C. This means that, the R744 IHX condensing temperature is the R134a IHX temperature plus the pinch point. Table 1 resumes the simulation parameters.

Table 1: Simulation parameters

Parameter	Variable	Value
Evaporator Temperature	$\mathrm{T_{1,R744}}$	-20^{o}C
Condenser Temperature	$\mathrm{T_{3,R134a}}$	45^{o}C
R134a IHX Temperature	$\mathrm{T_{1,R134a}}$	-10^{o}C to 10^{o}C
IHX Pinch Point Temp.	$\mathrm{T_{PP,IHX}}$	0^{o}C to 10^{o}C
Refrigeration Capacity	$\dot{\mathrm{Q}}_{\mathrm{ev}}$	$10,000$ kW
Isentropic Efficiency	η	$0,7$

The system of equations was solved using the Engineering Equation Solver (EES, 2017) sofware. This software has an extensive thermophysical proprieties library for almost any common fluid used in thermodynamic processes. Also, EES is capable to perform optimization, sensitivity and uncertainty propagation analysis.

3. RESULTS

The first analyzed case was how the R134a IHX temperature and R744 pinch point influence the COP. The R134a temperature was varied from -10^{o}C to 10^{o}C and the R744 pinch point was varied from 0^{o}C to 10^{o}C. Figure 3 presents the results, where can be seem that for each $T_{R134a,IHX}$ and $T_{PP,R744}$ pair there is a maximum value for the COP. The dash blue line traces through maximum COP points. As the pinch point temperature is decreased, higher is the R134a temperature for the maximum COP. The shift of the maximum COP point is due the fact that, as the pinch point is reduced, lower the R744 condensing temperature, what causes the R744 cycle COP to increase, contributing positively to the cascade cycle COP. This effect is conjugated with the R134a evaporating temperature, that as it increases, higher the R134a cycle COP and consequently higher the cascade COP.

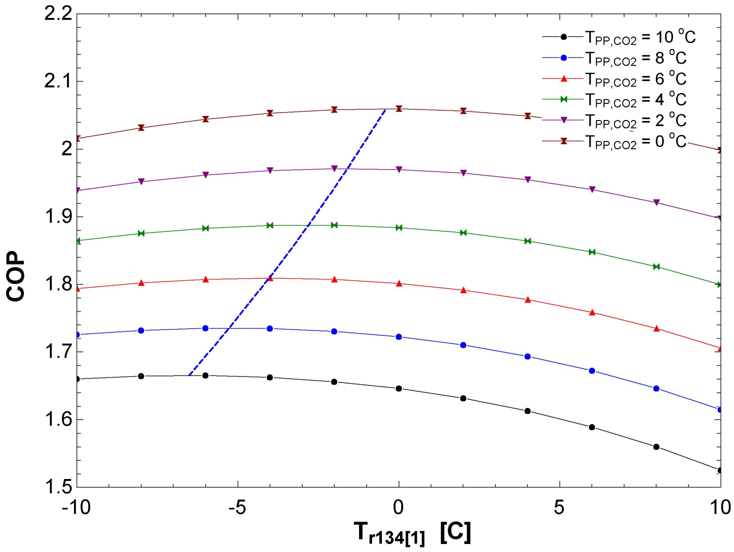


Figure 3: Coefficient of performance for different IHX temperatures and pinch points. The blue dot line corresponds to the maximum COP for each R134a temperature and R744 pinch point pair.

A linear regression through the maximum COP points gives a correlation between the R744 pinch point temperature and the R134a temperature.

$$T_{R134a,1} = -3.91545195\text{E}{-1} - 6.10413192\text{E}{-1}\, T_{PP,R744} \tag{7}$$

Figure 4 presents the COP behavior as the R744 pressure and temperature pinch point are varied. The COP presents a maximum for each pressure and pinch point pair, with the maximum COP increasing as the pressure decreases. This behavior can be explained by means that with lower pinch points, lower the R744 condensing temperature, increasing the cascade COP. As the R744 pressure is reduced, less work is done by the bottom cycle and more work is done by the upper cycle, reducing the cycle overall COP.

A correlation between the R744 pressure and the pinch point temperature for maximum COP is given by,

$$P_{R744,IHX} = 3.44725300\text{E}3 + 3.70430898\text{E}1\, T_{PP,IHX} \tag{8}$$

Figure 5 plots individually the COP of each cycle as function of R134a IHX temperature and pinch point. The behavior is consistent with the thermodynamics, where for higher R134a evaporating temperatures, higher the R134a cycle COP because less work is done by the upper cycle, and higher the R744 condensing temperature (higher pinch point), lower the R744 cycle COP because more work is done by the lower cycle. When compared against Fig. 3, it can be seem that the COP of each cycle and the cascade COP do not correlate easily, but as one increases and the other decreases with the IHX temperatures an maximum point appears. The R744 cycle COP is higher when compared with the R134a cycle COP, the reason is mainly by the thermophysical proprieties diferences between the two fluids and the working conditions. The R744 vapor specific volume is approximately ten times lower than the R134a vapor specific volume, which results is less work done by the R744 compressor to the same amount of cooling capacity. The R744 works with a lower pressure ratio between the compressor outlet-inlet than the R134a, which also results in less work done.

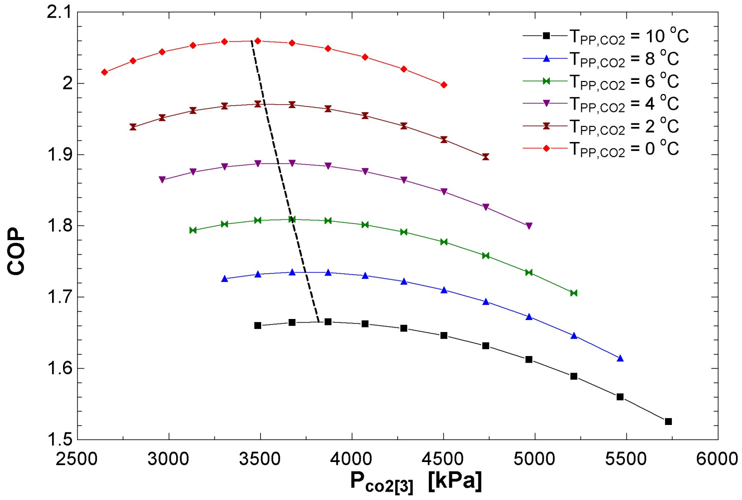


Figure 4: Coefficient of performance for different R744 IHX pressures and pinch points.

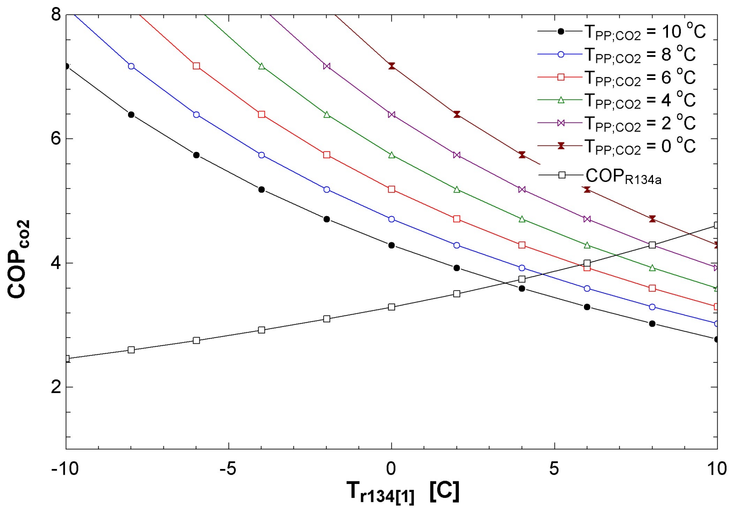


Figure 5: R744 and R134a cycles COP for different IHX and pinch point temperatures

4. CONCLUSION

This paper presented the thermodynamic analyze of a cascade refrigeration cycle, using R134a and R744 as working fluids. The intermediated heat exchanger parameters as temperatures and pressure was varied to study their effect on the cycle coefficient of performance. A system of equations based on energy balance and proper hypotheses were computationally solved. The results presented the following conclusions.

- For each R134a evaporating temperature and R744 condensing temperature pair in the IHX there is a maximum COP.
- For each R744 pressure and pinch point temperature pair in the IHX there is a maximum COP.
- The upper (R134a) and bottom (R744) cycles COPs varied with the IHX parameters, but them do not correlated directly to the cascade COP.

Also, two correlations for the maximum cycle COP were presented, one that gives the R134a temperature for a given R744 pinch point, and other that gives the R744 pressure for a given R744 pinch point.

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