EXPERIMENTAL EVALUATION OF A CASCADE REFRIGERATION SYSTEM

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Abstract. *This study evaluates the performance of a cascade system in subcritical operation using the pair R744 / R134, as an option to conventional systems in supermarkets, which usually uses R404A, or R22. The experimental apparatus consists of a variable speed reciprocating compressor for R744 and an electronic expansion valve that promotes direct evaporation of the CO2 inside a cold room (2.3m x 2.6m x 2.5m) to maintain the internal air temperature stable. The high-temperature cycle consists of a reciprocating compressor for R134a, a thermostatic expansion valve, and an air-cooled condenser. A plate heat exchanger, which is at the same time, the condenser for the R744 and evaporator to R134a completes the setup. Two parameters were manipulated: The superheating degree of the R744, 5-20 K, and the R744 compressor operation frequency, 40-65 Hz. In order to contribute to the improvement of the cooling processes, mainly about the sustainability and energy efficiency, a drop-in has been made at the high-temperature cycle, whose R134a load has been replaced by R404A and later R438A. The alternative cooling system (R744 / R404A) was subjected to two stages of tests which allowed the energy comparison between the two refrigerant sets. Through the obtained results, it was estimated maximum COP equivalent to 1.36 and a minimum value of 1.06 for the R744 / R134a pair, demonstrating the applicability of this cascade system of variable thermal load conditions, the values of capacity cooling, settled between 4.09 and 5.13 kW. The minimum value of the air temperature within the cold room was - 28 °C and -5 °C the maximum. Finally, it was found that the results obtained for R744 / R404A pair attended the air temperature condition inside the cold room with similar COP values. Later, was tested the R438A a good choice to replace R22, and the results shown this fluid is better to replace R134a, instead of R404A. However, R744 / R404A and R744 / R438A pairs operated at lower refrigeration capacities, these settled between 2.16 and 4.26 kW. This reduction is due to the large difference between the volumetric cooling capacity values of these HFCs in question, resulting in adaptation problems of the R404A to the compressor and the expansion mechanism, and making the R438A an alternative to the cascade system studied.*

Keywords*: Refrigeration, cascade, R744, R134a, R404A, R438A*

1. INTRODUCTION

The global climate situation, has led to increase use of the "old" refrigerants ammonia and hydrocarbons. Although both are environmentally benign, they can exhibit a certain degree of local danger because of their toxicity and/or flammability. Therefore, carbon dioxide (CO2), an "old" refrigerant used in industrial and marine refrigeration, was proposed by the late Prof. Gustav Lorentzen in 1990 decade to be used as an alternative refrigerant, mainly because of its non-flammability.

The Montreal Protocol regulations on gases that deplete the earth's ozone layer have led to phase out of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) as refrigerants in industrialized countries. In substitution of those, in 90's it was created the hydrofluorocarbons (HFCs), which fluids does not have the element chlorine and so, has no impact in the ozone layer. Another environmental concern regarding the refrigerants is their behavior as greenhouse gases in the atmosphere and this also applies for HFCs, which exert effects of global warming, but at lower intensity than the CFCs and HCFCs.

The destruction of the ozone layer is associated with the use of refrigerants HCFCs (in which is included the R22) and CFCs whose effect is measured / quantified by the ODP index (Ozone Depletion Potential). Although the HFCs gases with null potential for destruction of the ozone layer, ODP = 0, is necessary to note that these same gases (HFCs) imply a high atmospheric warming potential, given by the amount of CO2 resultant from these productions. In some cases the global warming potential (GWP) of those gases are higher than the HCFCs. Natural fluids such as hydrocarbons and carbon dioxide are seen as possible solutions to those issues, with ODP = 0 and GWP the lowest possible.

The quantitative appraisal related to the greenhouse impact is given by GWP100y defined by the mass of CO2 that would produce the same impact for 100 years on global warming as the release to the atmosphere of a single unit (kg) of the given component. The ODP and GWP100y can been seen at the Fig. 1, index calculated according to AR4 (Assessment Report 4) from IPCC (Intergovernmental Panel on Climate Change, 2007).

In environmental terms, the R744 has a null ODP and unitary GWP100y, being therefore a good alternative to solve environmental issues. R134a as well as R404A is an HFC, has a zero ODP and according to IPCC (2007), the equivalent value of GWP for 100 years to this refrigerant is 1430 to R134a and 3922 to R404A.

It is important to mention that the R438A is also a HFC, a blend of R32, R125, R134a, R600 e R601a, has a hydrocarbon component in its formula that is soluble in mineral oil. The GWP for this refrigerant is 2264, 42% lower than R404A. Figure 1 shows the ODP vs GWP100y for some refrigerants. Allgood and Lawson (2010) conducted tests with the R438A and the results showed good applicability of this refrigerant as a substitute of R22.

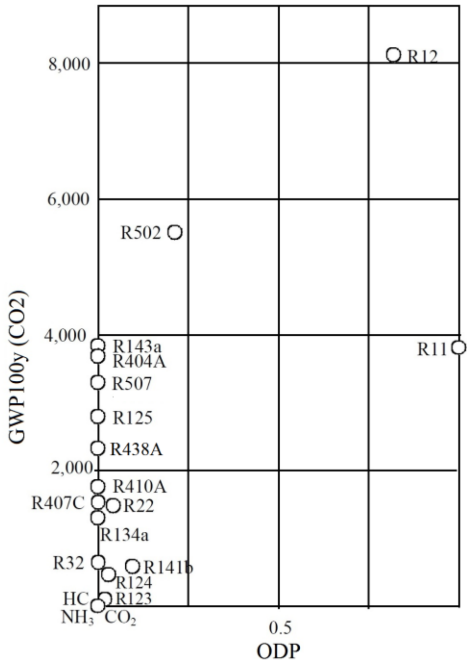


Figure 1. ODP and GWP of several refrigerants.

It is noted that R744 has a great potential for applications in supermarkets, despite being a fluid with high working pressures. There are many works that reference the use of R744 and natural fluids as the working refrigerant.

Sawalha and Chen (2010) considered different refrigeration systems solutions: CO2 transcritical (parallel and booster), NH3/CO2 cascade, R404A/CO2 cascade, and R404A conventional and various heat recovering lay-outs, such as direct heat recovery or heat recovery via heat pumps. They outlined the potentialities of the CO2 transcritical system with heat recovery from the desuperheater in terms of cooling COP and heating COP at moderate heating demands in an average size supermarket in Sweden, with relatively simple and potentially economically competitive lay-out.

Cecchinato et al. (2012) investigated the performance of different lay-out and technological solutions where only natural refrigerants are used and at finding the potential for improving energy efficiency over the traditional systems in different climates. In the analysis, chillers and heat pumps working with ammonia or propane, medium temperature systems working with ammonia or propane and carbon dioxide as heat transfer fluid or with carbon dioxide as the refrigerant and low temperature systems working with carbon dioxide are considered and benchmarked with a state-of-the-art HFCs based plant. The most efficient investigated solution enables an annual energy saving higher than 15% with respect to the baseline solution for all the considered climates.

In an experimental study, Da Silva et al. (2012) tested a cascade system, condensing temperatures of 38-40 ºC, compared single stage R22 and R404A systems with a R404A/CO2 cascade system for the same cooling capacity over a period of one year from November 2008 to 2009. They found that the cascade system was (i) 18.5% more expensive, (ii) required 20% less evaporator surface area, (iii) used only 47 kg (total) refrigerant as compared with 115 kg for R22 and 125 kg for R404A system, and (iv) 22% and 14% more efficient than R404A and R22 systems. It can thus be inferred that cascade refrigeration systems tend to be 10-20% more expensive than the traditional direct expansion systems. However, this cost disadvantage can be negated with two specific significant advantages that CO2 cascade systems offer over conventional systems, namely (i) up to 20% higher energy efficiency, and (ii) less refrigerant charge requirements.

Recently, Hafner and Hemmingsen (2015) estimated an energy saving varying from 11% to 28% related to a R744 unit with a R290 dedicated mechanical subcooling loop beside a R404A direct expansion system. The evaluation was attained by taking into account the weather conditions in several cities located all over the world.

In a recent work, theoretically Gullo et al. (2016) presents a comparison among different commercial refrigeration systems in terms of annual energy consumption and environmental impact. Eight configurations were studied, included

R744/R134a cascade refrigeration system. A transition zone, which occurred between subcritical and transcritical operations, was adopted. They concluded that all the enhanced configurations may achieve a comparable energy saving to the one of the baseline in the selected locations. Moreover, they allow reducing the Total Equivalent Warming Impact (TEWI) by at least 9.6% beside the cascade solution.

The goal of this experimental study is to evaluate the cascade system performance in subcritical operation using the pair R744 / R134a, which was originally installed at the apparatus, and then analyze the cascade cycle behavior replacing the R134a refrigerant by R404A through a drop-in operation. After testing R404A, it's worth to test the refrigerant with slogan "The quick switch to replace R22", commercialized by the name ISCEON™ MO99™, by Chemours. The choice of this refrigerant comes from the large use of the R22 at the refrigeration sector, and the tendency of using R438A to replace it. The choice of R404A was due to its extensive use in the refrigeration sector in supermarkets, even with high values of GWP.

2. MATERIALS AND METHODS

The experimental apparatus consists of a variable speed reciprocating compressor for R744 and an electronic expansion valve that promotes direct evaporation of the CO2 inside a cold room (2.3m x 2.6m x 2.5m) to maintain stable the internal air temperature. Thus, the R744 leaves the compressor in superheated vapor state, is condensed and then stored in a liquid tank. By letting the liquid tank toward the electronic expansion valve, it undergoes a flow Coriolis meter, and expands in the evaporator unit. Finally, the CO2 is returned to the suction of the compressor. Figure 2 illustrates the experimental facility, as the R744 cycle is represented by the Low-Temperature Cycle (LT), and the R134 / R404A / R438A cycles are the High-Temperature Cycle (HT).

The HT cycle consists of a reciprocating compressor for R134a / R404A / R438A, an air-cooled condenser, a flowmeter, and a thermostatic expansion valve. A plate heat exchanger, which is at the same time, the condenser to R744 and evaporator to R134a / R404A / R438A, completes the bench.

Three basic parameters can be changed in the system, first the superheat degree of the R744, second the operation frequency of the R744 compressor and, finally, the thermal load simulation within the cold room, carried by a bank of electrical resistances, which dissipates 1.5 or 3.0 kW of power. Although the cold room walls being well insulated, the heat exchanges by conduction therein, floor and ceiling, in addition to heat radiation are inherent to R744 evaporation process, therefore, the cooling capacity of the cascade system is superior to 3.0 kW.

The HT compressor operates with a variable frequency from 35 to 60 Hz. Therefore, the apparatus requires a secure control strategy which is the minimum necessary for the R744 storage in liquid form. Figure 2 refers to the schematic diagram of the same.

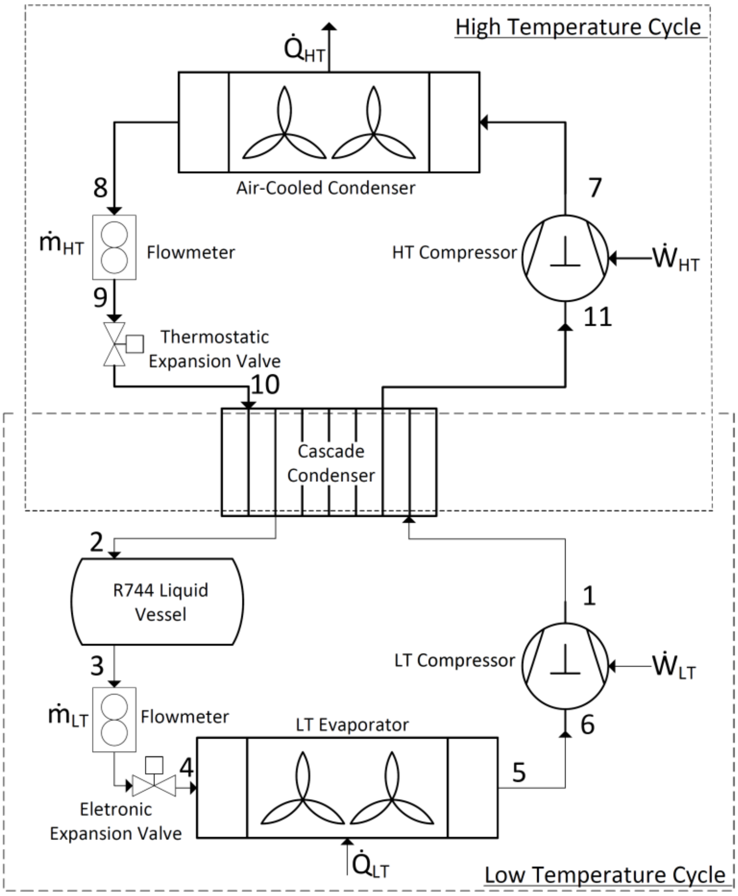
To evaluate the performance and determinate the operability of the cascade system, tests were conducted by controlling the superheat degree of the R744 system in fixed values of 5, 10, 15 or 20 K. LT compressor power has been manipulated by a frequency inverter, enabling the tests execution on six conditions: 40, 45, 50, 55, 60 and 65 Hz.

The system was fully instrumented, making it possible to measure pressure and temperature of various points of interest as well as the power consumed by the compressors. Knowing these properties, the values of variables of interest such as COP system, COP R744 and cooling capacity were estimated.

The tests were performed under steady state conditions, these were divided into three stages and each test lasted, on average, five hours. Control of the superheating degree has been achieved by controlling the pressure at the evaporator outlet, modulating the opening of the electronic expansion valve.

Figure 3, show the differences in thermodynamic properties of the R744 and R134, it can be visualized on a pressure-enthalpy diagram, based on the standard reference state for the International Institute of Refrigeration. The value of specific enthalpy is set to 200 kJ.kg-1 and the value of specific entropy is set to 1.0 kJ.kg-1.K-1 for saturated liquid at 0°C (273.15 K), EES 9.482.

The shown two-phase domes are extremely different, the first point to observe are the distances between each critical point, critical temperature influences refrigerant pressure and vapor density. In this figure, it's also shown the points of for an experimental data, tested on the conditions of R744 frequency 65 Hz, R134a frequency 60 Hz, degree of superheating for R744 at 5 K, and the internal resistance was insulating 3 kW. The internal air temperature at steady state, for this case was -17.2 ºC. It can be observed that R744 pressures are extremely higher than the operation pressures of R134a, and this is why, to refrigerate with CO_2 in subcritical cycle at tropical countries as Brazil, it is necessary to use a cascade system, to maintain the R744 pressures under safe pressures of work.



Sensors List	
Sensor	Description
1	Discharge Temperature LT
2	Condensation Pressure LT
3	Liquid Temperature LT
4	Evaporation Pressure LT
5	Outlet Evaporation Temperature LT
6	Sucction Temperature LT
7	Discharge Temperature HT
8	Condensation Pressure HT
9	Liquid Temperature HT
10	Evaporation Pressure HT
11	Sucction Temperature HT

Figure 2. Schematic diagram of the cascade system, and some sensors indicated

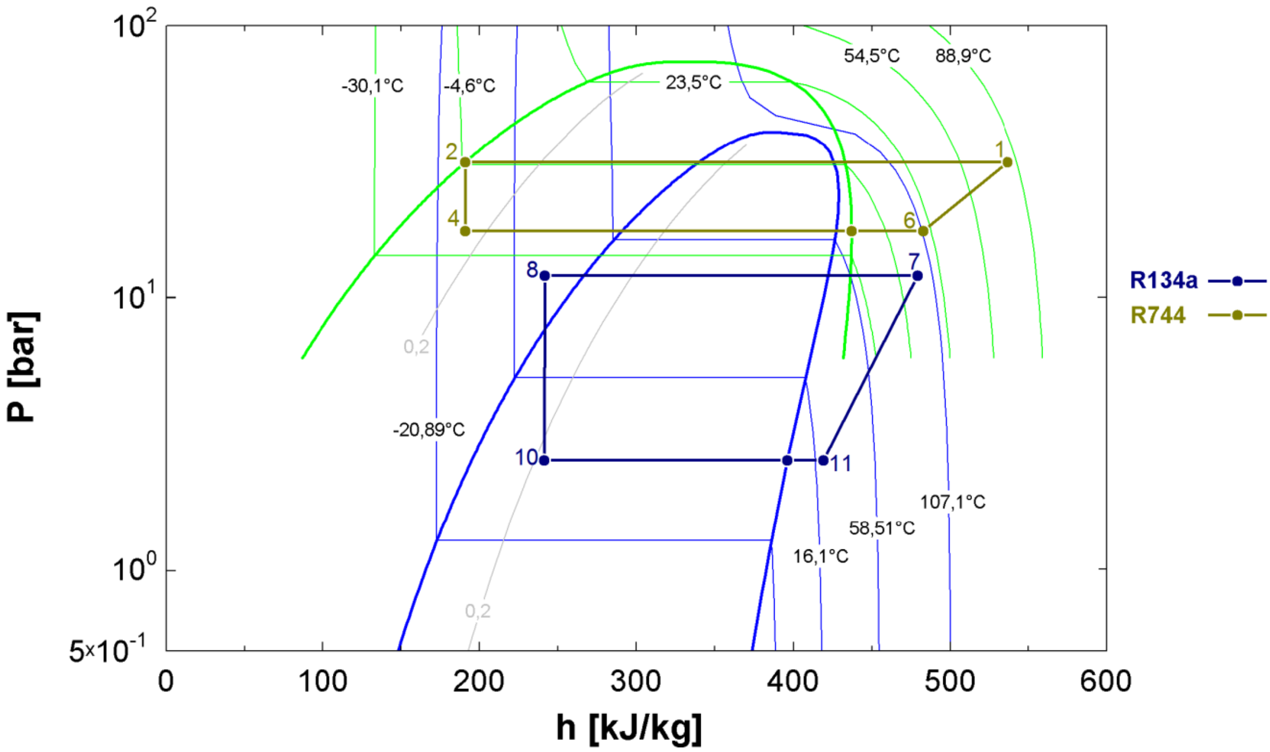


Figure 3. Pressure versus enthalpy diagram for R744 and R134a, with points of operation as shown at Fig. 1

The cooling capacity was calculated according to the First Law of Thermodynamics, Eq. (1), considering a steady state condition in which the refrigerant is the only substance present in the control volume delimited by the evaporator.

$$\dot{Q}_{R744} = \dot{m}_{R744}(\Delta h_{evap}) \quad (1)$$

Piezoresistive pressure transducers (with measurement uncertainty of 25kPa) and PT-100 resistance temperature detectors (with measurement uncertainty of 0.15 °C) were used to measure these properties, thereby enabling the determination of the thermodynamic state of the refrigerant at each point of interest in the vapor compression cycle. A Coriolis flow meter was used to measure the mass flow rate of refrigerant in the R744 circuit, with measurement uncertainty of 0.0015 kg/s. The power consumption by the compressor was measured and the data have an uncertainty of 0.003 kW.

The calculations of the COP were performed for each system (R744 system and cascade system). The COP is the ratio between the cooling capacity and the power consumption by the compressor, Eq. (2) illustrate this parameter for the R744.

$$COP_{R744} = \dot{Q}_{R744}/\dot{W}_{R744} \quad (2)$$

The COP of the cascade system is expressed by the Eq. (3).

$$COP_{System} = \dot{Q}_{R744}/(\dot{W}_{R744} + \dot{W}_{R134a/R404A}) \quad (3)$$

Beyond the proposed study of the energy performance of the cascade refrigeration cycle in different operating conditions, it is also an goal of this study, a comparison between the operation of the original cascade cycle (R744 / R134a) and the alternatives cascade cycle (R744 / R404A and R744 / R438A). For this purpose, it was made a drop-in at the high temperature cycle, replacing the R134a by the R404A and later R438A retaining the same compressor and lubricating oil, as well as heat exchangers and original components.

Accordingly, the new refrigerant has to provide similar values of the cooling capacity and air temperature inside the cold room, to the values obtained by the original system, thus respecting what would be the design conditions of a cold room for storage in a commercial application. COP provided by the new pair of refrigerants, becomes a consequence, and their values are compared to the original fluids.

However, there is a large difference between the values of volumetric cooling capacity of the R134a and the other two studied fluids. This parameter allows the prediction of the dimensions of the displacement mechanisms required a compressor for a given refrigerant and a specific operating condition.

Figure 4 shows the variation of this capacity by the evaporation temperature for different refrigerants. This parameter is a measure of cooling capacity per unit volume of refrigerant passing through the compressor. It is a property of the refrigerant and the system operating point.

As can be seen, the volumetric cooling capacity decreases with the reduction of evaporation temperature values. This is due mainly to the decrease in vapor density at low temperatures. Therefore, it is easily understood that the necessary compressor for operating a R404A cycle must always be smaller than the compressor required for R134a in fixed rotation.

The R404A moves away from the reference in terms of capacity, this fact makes it unsuitable to work at the same speed of the original system. Thus, in order to better adapt the cooling R404A system, a retrofit action was taken. Thus, a frequency inverter was installed and allowed the reduction of the speed of the high-temperature cycle compressor. This strategy allows the system to achieve higher cooling capacity and smaller air temperatures values inside the cold room, approximating the thermal load conditions to of the values of the original system.

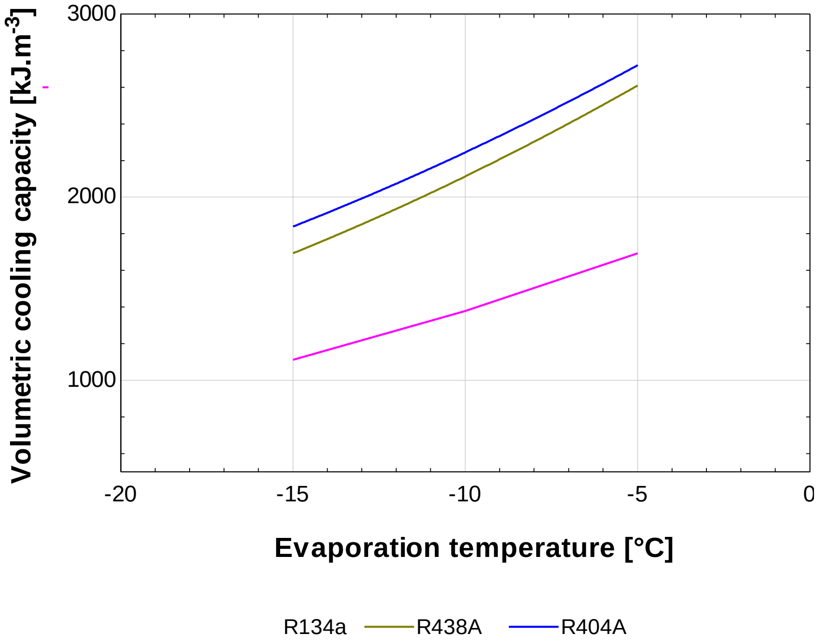


Figure 4. Volumetric cooling capacity relative to different classes of refrigerants. Estimated values at 40 °C condensation temperature, 0 °C of subcooling and 5 °C of superheating

3. RESULTS

The first leg results refers only to the analysis of the original cascade system operating with R134a in the high temperature cycle (HT) and R744 in the low temperature cycle (LT). A total of 24 tests were performed and two basic parameters have changed during these tests: the value of the superheating degree in the LT cycle and the value of the operating frequency of the R744 compressor.

Figure 5 shows the power values consumed by each compressor. It is evident that the R744 compressor has lower power consumption than the R134a compressor, this is due to the high vapor density of R744, even with the pistons displacing a high volume in the process. R744 such properties are also the cause of a compressor of reduced dimensions.

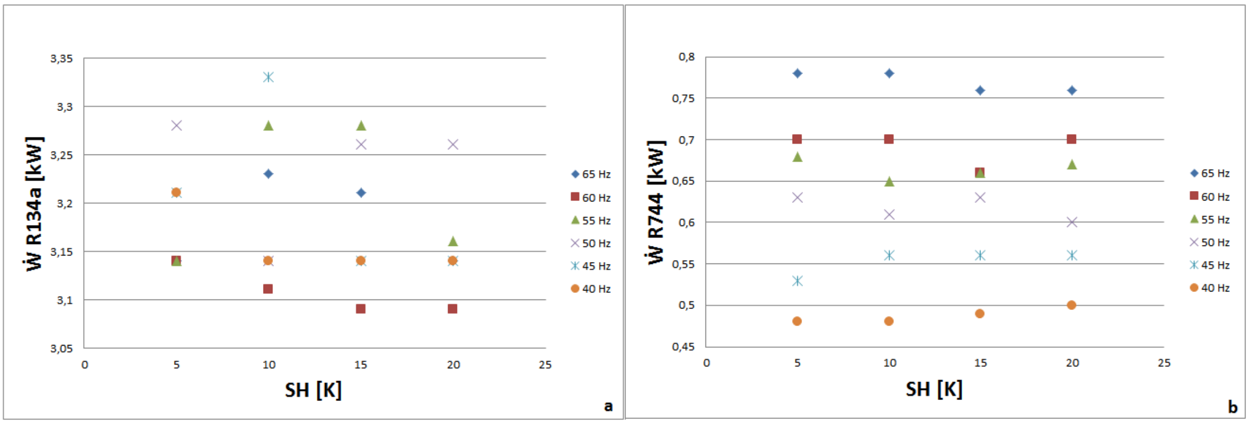


Figure 5. Power consumption of the LT (a) and HT (b) compressors, for different operating frequencies and different superheating degrees

The R744 compressor power consumption increases with the increase of the frequency and the consequent rotation (see Fig. 5b) as such proportionality cannot be observed by R134a compressor (Fig. 5a). Another factor that confirms the lower consumption of the system R744 is the compression ratio of 2:1. In the case of R134a compressor this reason, in some comes to be 10: 1.

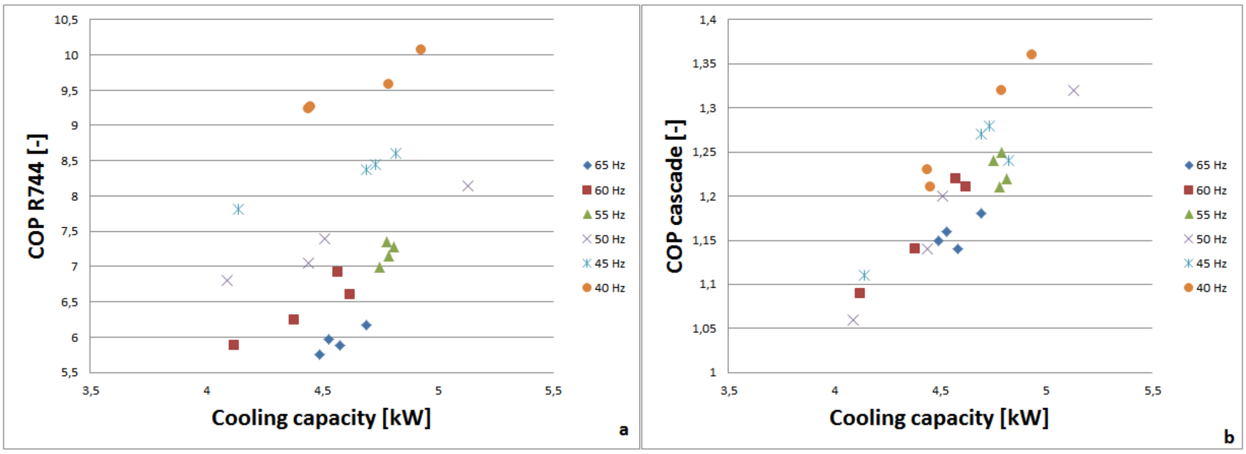


Figure 6. Behavior of the cooling capacity, by the COP values for the LT (a) and the cascade systems R744 / R134a (b)

Figure 6 illustrates the COP values related to the cooling capacity values, note that the COP behavior was physically consistent, the four tests at 40 Hz obtain the highest COPs from the R744 cycle, as the highest 10.07. The tests at 65 Hz equivalent to the worst performances.

The highest cooling capacity developed for the operating frequency of 50 Hz with 15K superheating, 5.13 kW. The values of COP cascade system (see Fig. 6b) follow the same trend COP proportionality for the isolated cycle R744 (Fig. 6a). The greatest value of this amounts to 1.36, operating at 40 Hz and 15 K superheat. The lowest COP of the system obtained was 1.06 for the condition of 65 Hz to 20 K superheating.

According to Fig. 7, the operating point can be determinate from the temperature that is desired to have inside the cold room. It is noticed that with higher frequencies and smaller degrees of superheating, we obtain the lower air temperatures.

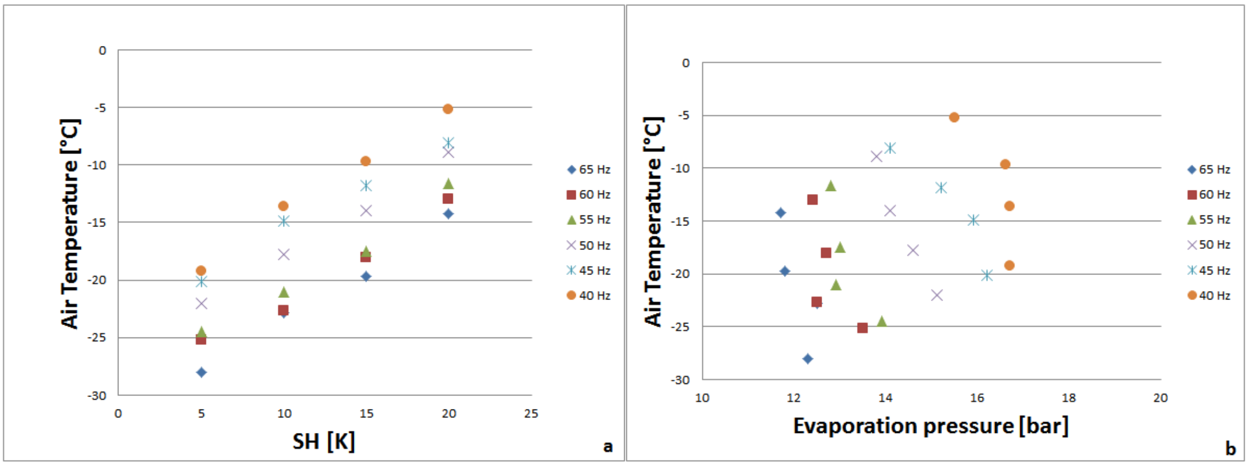


Figure 7. Air temperature behavior within cold room for different operating frequencies depending on the degree of superheat (a) and due to the R744 evaporation pressure (b)

Cooling capacity values were established between 4.09 and 5.13 kW, demonstrating the applicability of this cascade system for different thermal load conditions. The minimum value of the operating temperature of the air within the cold room was - 28 ° C and -5 ° C maximum.

Sanz-Kocket et al. (2014) experimental data, were used as benchmarks for performance values found in this study. They evaluated experimentally, a cascade system R744 / R134a for commercial refrigeration. The experimental apparatus operated under different conditions and has less cooling capacity when compared to, however, the behavior of the main thermodynamic parameters were similar. The authors estimated values for the cascade system COP between 1.05 and 1.65. The cooling capacity values were 7.5 kW to 4.5 kW.

The second step results refers to the comparative analysis of the original cascade system and the alternative system, which operates with R404A in the high temperature cycle (HT) and R744 in the low temperature cycle (LT). A limited number of tests were carried out and three basic parameters were changed during the tests: the value of the superheating degree of the R744, the value of R744 compressor operating frequency and, finally, the compressor operation frequency at the R404A cycle.

Table 1 provides a comparison between the systems studied, this refers to three experimental tests, which the R744 compressor operated at nominal frequency of 65 Hz.

Table 1: Comparison between the pair of refrigerants, results in condition in which R744 compressor operated at nominal frequency of 65 Hz

Systems	$\dot{W}_{Res}$ [kW]	$T_{EV\,LT}$ [°C]	T_{CDLT} [°C]	T_{DLT} [°C]	T_{LLT} [°C]	$\dot{m}_{LT}$ [kg/s]	$\dot{W}_{LT}$ [kW]	$\dot{W}_{HT}$ [kW]	f_{HT} [Hz]	T_{AIR} [°C]	$\dot{Q}_{SYS}$ [kW]	COP_{SYS} [-]
R744/R134a	1.5	-34.40	-8.93	103.5	-9.00	0.0171	0.780	3.14	60.00	-28.0	4.49	1.15
R744/R404A	1.5	-35.95	-23.90	84.3	-23.95	0.0076	0.430	2.40	60.00	-28.0	2.25	0.79
R744/R404A	1.5	-33.59	-13.95	100.0	-14.00	0.0105	0.610	2.30	35.00	-26.0	2.88	0.99
R744/R438A	1.5	-36.26	-23.19	79.5	-23.24	0.0112	0.440	2.05	60.00	-29.0	3.29	1.32
R744/R134a	3.0	-23.72	-3.73	83.8	-3.78	0.0230	0.865	3.31	60.00	-17.2	5.79	1.39
R744/R404A	3.0	-27.08	-14.67	71.5	-14.72	0.0125	0.540	2.95	60.00	-19.2	3.46	0.99
R744/R404A	3.0	-25.74	-6.86	86.3	-6.91	0.0155	0.730	2.60	35.00	-17.3	4.03	1.21
R744/R438A	3.0	-28.12	-16.77	68.0	-16.82	0.0147	0.480	2.55	60.00	-18.8	4.16	1.37
R744/R438A	3.0	-25.42	-6.12	83.9	-6.17	0.0165	0.760	2.15	35.00	-17.2	4.26	1.47

The first test refers to the pair of refrigerants (R744 / R134a), note that the HT compressor cycle ran at 60 Hz and the temperature of the air in the cold room stabilized at -25.2 ° C. The second test, which was conducted after the operation of the drop-in air met the condition of temperature inside the freezer, -26 ° C, however, the pair R744 / R404A has a cooling capacity value 43% less than the original system.

The frequency inverter installed in the HT compressor cycle has allowed the realization of the third test of Tab. 1 in which R404A system operated below the nominal speed (60 Hz) at a frequency of 35 Hz, making it possible to increase the value of the cooling capacity, 2.80 kW. In this condition, the alternative system COP exceeded 8% of the R744 / R134a COP to the same operating cold room temperature, -26 ° C.

The reduced cooling capacity is a result of the large difference between the values of volumetric cooling capacity of the two HFCs. It can be also seen in Table 1, the mass flow rate of R744 is greatly reduced for the system R404A. In addition, the value of the liquid temperature (T_L) for the second test in the table (- 25.79 °C) is very low compared to the value of the original system (- 8.30 °C). By reducing the frequency, the liquid temperature rises at 5.5 °C and the flow rate increases by 10%, however, is not sufficient to promote evaporation condition compatible to the original system. This comparison can be seen in Fig. 8a, where it is seen that the cooling capacity for all tested conditions of R404A fail to achieve similar operation points due to temperature of the air in the cold room.

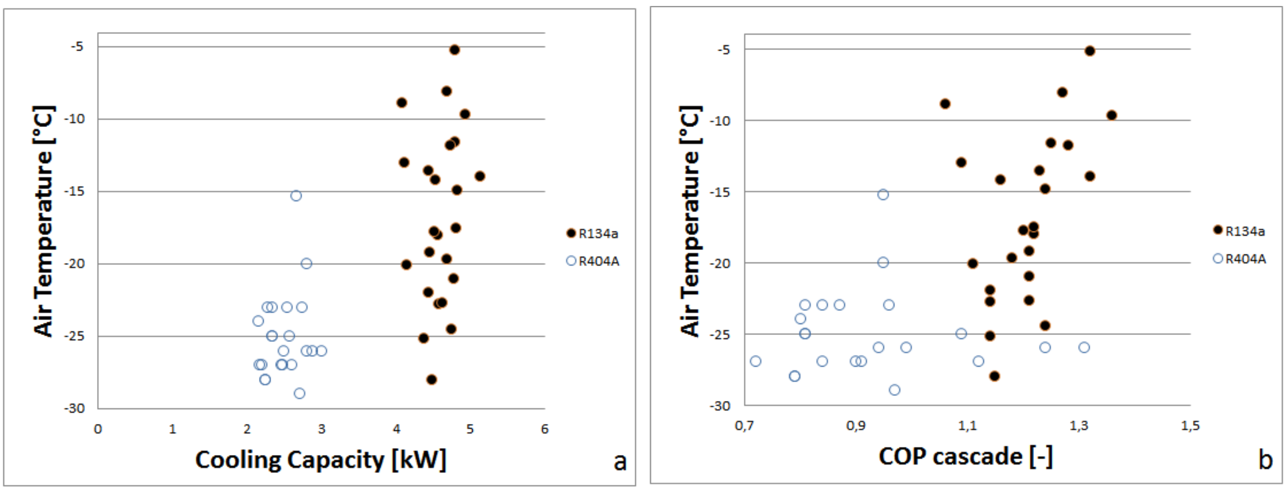


Figure 8. Effect of the COP (a) and cooling capacity (b) on the air temperature, on the overall

Can be observed in a region of Fig. 8b, which tests for that sector, established compatibility between the air temperature in the chamber and the COP for both systems. The pair containing R404A can achieve the best COPs (1.31), when the frequency of the compressor operates in 35 and 40 Hz. However, even though the COP and operating temperature conditions are compatible, the cooling capacity of the alternative system R404A is reduced in all analyzed range, Fig. 8a.

Comparing the results of the R438A with the R404A, it can be observed that the drop-in of this refrigerant achieve better values of COP. It shows the COP is in all case better than the R404A for the same conditions, as can been seen at Tab. 1, and when compared to R134a, it had in almost all cases, higher values for the same evaporation temperature.

The cooling capacity of the R438A, is higher than the R404A, explained by the lower volumetric cooling capacity of the R438A, as can been observed that as the R438A have higher values of this property than R134a, the cooling capacity for the test are lower than when used the R134a.

Figure 9 provides a comparison for energy performance of the two pairs of refrigerants, it is remarkable the supremacy of the cascade system R744 / R134a. The tests were performed for 4 superheating degrees, showed at the figure besides each experimental point. The same operating frequency values for the compressors were maintained, 60 Hz for the high temperature cycle (R404A and R134a) and 65 Hz for the low temperature cycle (R744).

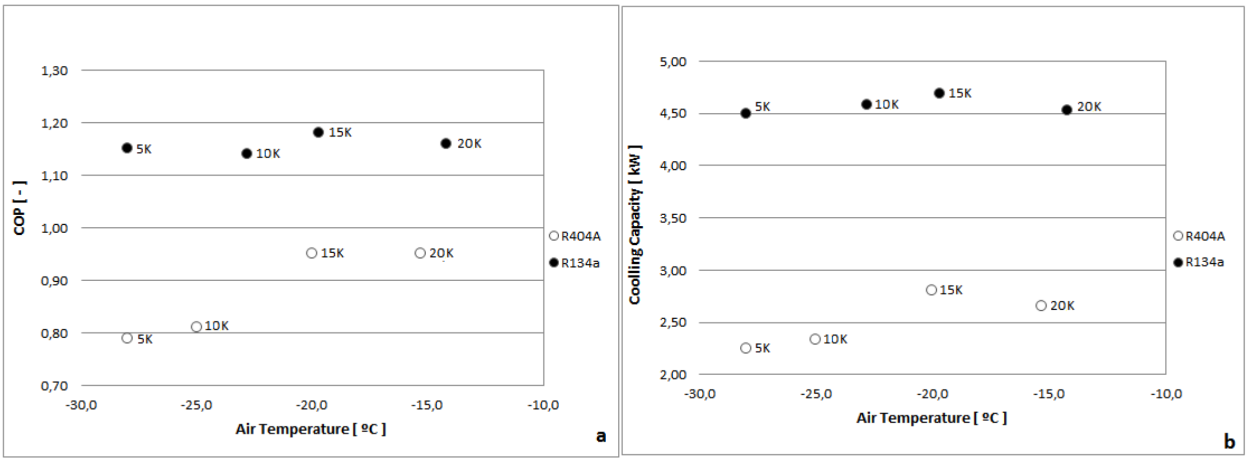


Figure 9. Effect of air temperature on the COP (a) and cooling capacity (b), for a superheating degree range from 5 to 20 K, and same operating frequency values for the compressors of HT and LT

4. CONCLUSION

In order to contribute to the improvement in cooling processes, as well as sustainability and energy efficiency, this experimental study evaluated the performance of a subcritical cascade system using the pair R744 / R134a, which represents the original experimental apparatus installed. On a second step, after replacing the R134a by the R404A, through a drop-in operation, an experimental comparison was performed between the behavior of the original system and the new pair of refrigerants, and later was made some tests with the pair R744 / R438A.

Through the first results, it was observed that the cooling capacity values were established between 4.09 and 5.13 kW, demonstrating the applicability of this cascade system working at variable thermal load conditions. The minimum value of the operative temperature of the air inside the cold chamber was - 28 °C and the maximum value of this parameter is equivalent to -5 °C.

The evaluation of the original system has shown that the highest COP values were obtained at the lower frequencies of operation of the LT compressor, and these values compared to direct expansion systems with HFCs or HCFCs are generally lower. The maximum COP was equal to 1.36 and the minimum value was 1.06 for the pair R744 / R134a.

Furthermore, the cooling capacity values were similar for the 24 tests, however, the desired temperature of the air inside the chamber must also be evaluated to then, determine the degree of superheat and the frequency used at the LT compressor.

At the sequence, an operation of drop-in was established in the HT cycle, where the charge of R134a was replaced by R404A. Moreover, the compressor of the HT cycle has stopped to operate at 60 Hz and started to operate with variable speed. Through the second step (21 tests) it was found that the results obtained for pair R744 / R404A attended the air temperature condition inside the cold chamber, with similar COP values of the original pair. However, R744 / R404A pair operated at much lower cooling capacities, these values has been established between 2.16 and 3.00 kW. This reduction is due to the large difference between the volumetric cooling capacity of both HFCs, which results in adaptation problems of R404A to the original HT cycle, compressor and expansion device.

Finally, the results confirmed that the cascade system R744 / R134a is superior to the alternative system (R744 / R404A). The direct drop-in operation is inefficient in this case because only four test conditions of 21 carried out were compatible to the original system, and even then the cooling capacity values were reduced.

Analyzing the values of the test of R438A, it's worth a future work, to enlarge the data of this pair, but by the time it can be seen that this fluid can be a worth alternative to replace R134a. The modification of the expansion device of the HT cycle (R404A and R438A) will be performed to permit the condensation of R744 at higher temperatures and thus, achieving higher cooling capacity values. In addition, other refrigerants will be evaluated at the HT cycle in order to find the best pair of refrigerants for the original application range.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support given to the reported investigation by CAPES, CNPq, FAPEMIG and also for the technical support provided by the application engineer Alessandro da Silva, Bitzer (USA) and Roberto Possebon Junior, Carel (Brazil).

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