COMPARATIVE ANALYSIS OF REFRIGERATION SYSTEMS USED IN SUPERMARKETS

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Abstract. In this paper it was analysed four types of refrigeration systems commonly used in supermarkets in Brazil: direct expansion, direct expansion cascade system, combined secondary glycol / CO2 cascade system and combined CO_2 secondary / cascade system. The cycles were studied using a computer models able to simulate their performance using various types of refrigerants and temperature of condensation and evaporation. For the evaluation of the models, the influence of four refrigerants was studied: R404A, R134a, R1234yf and R22, both a ssociated with CO_2 in three systems. The systems evaluated were simulated for different condensation temperatures, representing the ambient temperature of a city of each Brazilian region throughout the year: Belo Horizonte, Fortaleza, Goiânia, Belém and Porto Alegre. The results obtained in form of COP were compared in order to evaluate the best system for each region. Acording the obtained data, the best systems for brazilan climate are direct expansion system where there is one cold reservoir and combined CO2 secondary / cascade system where there are two different cold reservoir. The best fluids were R134a and R22, but the difference between the COP obtained by those fluids and those obtained by R1234yf is to low, so is indicated the use of R1234yf because their properties are better in sustainability questions.

Keywords: Refrigeration, Cascade system, Thermodynamics, Carbon dioxide

1. INTRODUCTION

Food companies, supermarkets and processors of food supplies typically use cooling systems for multiple direct expansion together with synthetic refrigerants such as R22, R404A and R507. The estimated rates of annual losses for leaks in these systems are between 3% to 35%, whereas older equipment have a higher annual loss (> 25%) and lower rates (<15%) are found in more modern facilities (Sharma et al., 2014). The high Global Warming Potential (GWP) of hydroflurocarbon (HFC) refrigerants commonly used in these systems, combined with large refrigerant charge and the high refrigerant leakage rates, leads to significant direct emissions of greenhouse gases into the atmosphere. Hence, theses multiplex refrigeration systems can directly contribute to the increase in global warming.

In addition, electricity cost is significant to supply such systems throughout the operation. Thus, the operation of refrigeration systems contributes to global warming indirectly for electricity production generates more greenhouse gases (mainly CO_2).

The environmental impact of refrigeration systems can be reduced by two strategies, either replacing the refrigerant to a more sustainable or increasing system efficiency to reduce power consumption.

Refrigerants such as R32, R134a, R717, R744, R290, R600a and R1234yf could be excellent alternatives for the working fluid. However, due to toxicity and flammability of some of these refrigerants prevents them from being used according to some safety standards. Cascade systems and systems with a secondary circuit using CO_2 as a refrigerant can reduce the direct impact on the environment due to their low HFC.

The reduction in energy consumption reduces the impact on the environment indirectly due to the cooling system used. The lower consumption of electricity can be achieved by using more efficient systems and simple actions, using doors (covers) in refrigerators. Substituting less expensive equipment, such as LED lamps is also a good option for saving electricity. The reduction in the consumption of electric power can be up to 50% if such measures are adopted (Rauss et al, 2008; Fricke and Becker, 2010).

Carbon dioxide has recently been considered as an alternative to refrigerants commonly used in supermarket refrigeration systems, in search to develop low environmental impact systems (Bansal 2012; Getu and Bansal, 2008). Although CO_2 has a high critical pressure (7.38 MPa) and a low critical temperature (30.97 °C), high pressure operation lead to a high vapor density and thus a high volumetric cooling capacity. The volumetric capacity of CO_2 cooling (22.545 kJ m^{-3} at 0 °C) is 3-10 times greater than the CFC, HCFC, HFC and HC (Kim et al., 2004). In addition, carbon dioxide has no ozone depletion potential (ODP) and it is non-toxic, non-flammable and low cost; all of them are attractive features when compared to synthetic refrigerants.

In this study, a comprehensive analysis of four CO_2-based refrigeration system configurations that are currently being used in the supermarket refrigeration industry around the world is performed. The paper presents a systematic analysis of each configuration for the same operation conditions. In addition, the performance of more energy-efficient CO_2-based systems is compared each other using bin analyses in five cities from eight climate zones of Brazil.
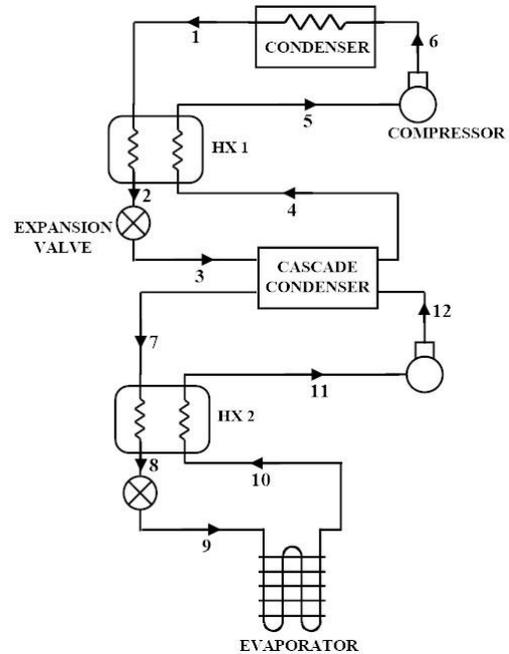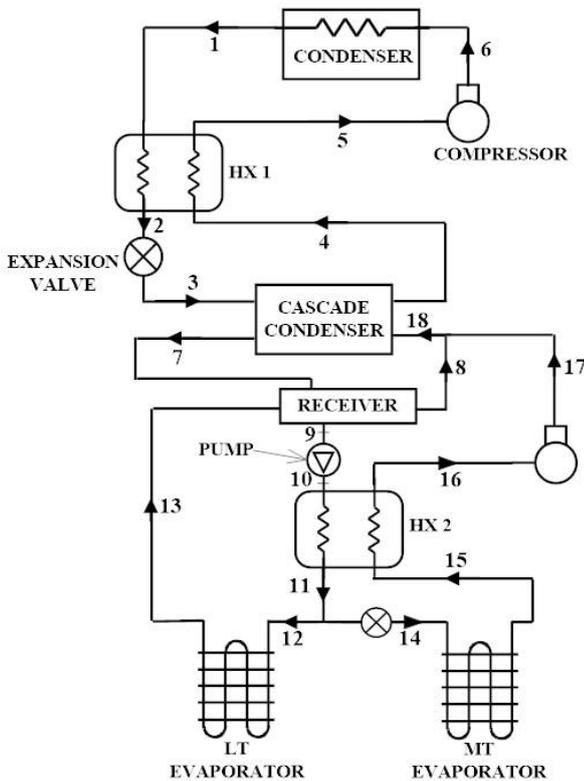
2. METHODOLOGY

2.1 Systems Analyzed

The four systems analyzed in this paper are: Direct expansion system, direct expansion in cascade, Combined CO_2 secondary cascade system and combined glycol/ CO_2 cascade system. These systems are shown in the Fig. 1 and explained in the following sections.
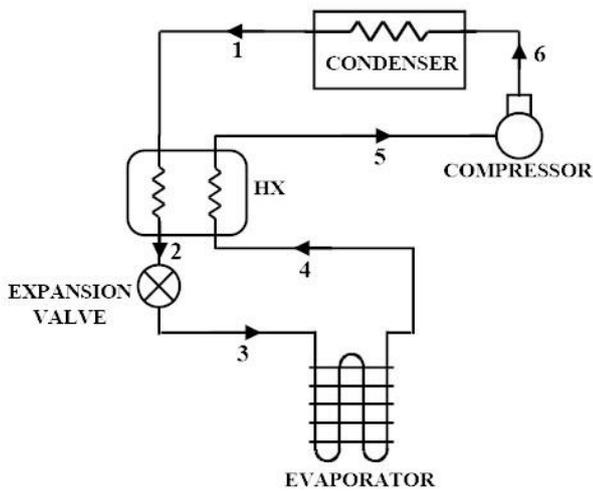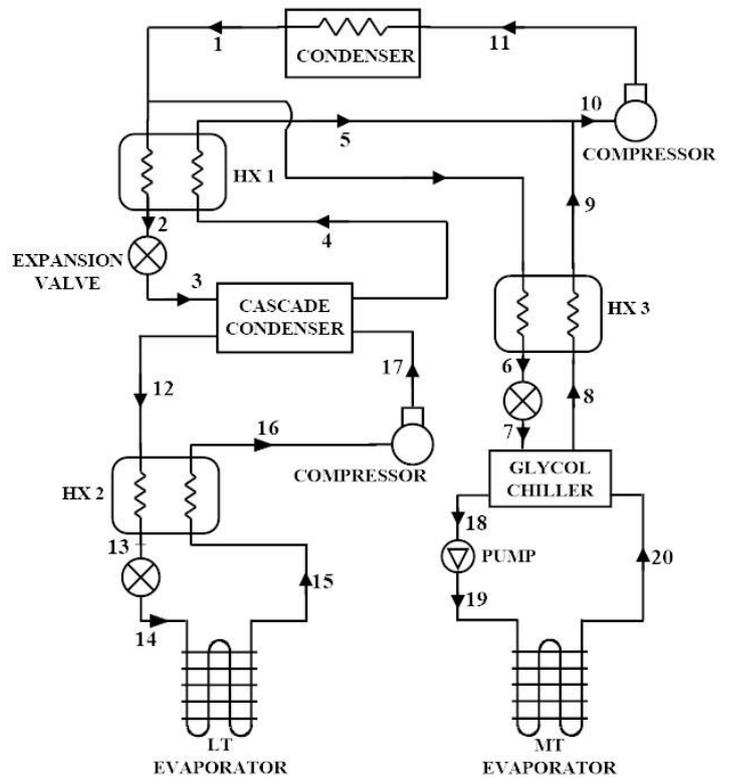
System 1 – Direct expansion system.

System 2 – Direct expansion in cascade.

System 3 - Combined CO_2 secondary cascade.

System 4 - Combined glycol/ CO_2 cascade.

Figure 1. Analyzed systems.

2.1.1 Direct Expansion System – system 1

This is one of the simplest refrigeration system. It is composed by one compressor, one evaporator, one condenser, one expansion device and one heat exchanger. The refrigerant fluid leaves the condenser (point 1) as saturated liquid and enters in the heat exchanger where it loses heat to the stream that flows from point 4 to 5. The fluid as compressed liquid enters in the expansion device where its pressure decreases in an isenthalpic way. The fluid that enter in the evaporator in point 3 is a mixture of liquid and vapor in a lower pressure, this fluid absorbs heat from the ambient and becomes a saturated vapor in point 4. When the fluid enters in the heat exchanger from point 4 it absorbs heat from the stream that flows from 1 to 2 and becomes superheated vapor in point 5. This superheated vapor goes to the compressor and its pressure increases to the value in the condenser. In the condenser, the superheated vapor condenses and loses heat to the environment.

2.1.2 Cascade Direct Expansion System – system 2

This system is basically a junction of two direct expansion systems with different refrigerant fluids in each one. The primary circuit (high temperature circuit) which has the condenser works with refrigerants that have a lower critic point as R404A, R134a and R1234yf. The cascade condenser of this circuit is a heat exchanger that works simultaneously as a condenser of the secondary circuit (low temperature circuit) and evaporator of the primary circuit. The low temperature circuits usually work with fluids with high critical point as CO_2 or fluids that do not change phase in the work temperature, like propylene glycol. This system is indicated when the evaporation temperature is very low, when this temperature is not sufficiently low, the direct expansion system is more profitable.

2.1.3 Combined CO2 secondary Cascade System – system 3

The combined CO_2 secondary cascade system has the advantage over the previous systems that using this circuit is possible to work with two different evaporation temperatures. This system has a high temperature circuits that, as the direct expansion system in cascade, is coupled with the other circuits by a cascade condenser. The medium an low temperature circuits works with a fluid that has a high critical point, as CO_2. The refrigerant that leaves the receiver in point 9 as a saturated liquid and it is pumped to the intermediate heat exchanger when it is cooled. The fluid enters in the medium temperature evaporator (MT Evaporator) as subcooled liquid and absorbs heat until reaching the stage of liquid and vapor mixture.

In the low temperature circuit, part of the refrigerant that leaves the intermediate heat exchanger in the medium temperature circuit goes to an expansion device that lowers the pressure until it becomes a mixture of liquid and vapor than enters in the low temperature evaporator (LT Evaporator). When the refrigerant leaves the evaporator as superheated vapor it goes to the intermediated heat exchanger where it is heated and flows to the compressor, that pumps the fluid to the cascade condenser.

2.1.4 Combined Glycol/ CO2 Cascade System – system 4

This system as the combined CO_2 secondary cascade is made to attend two different evaporation temperatures. In this system, the low temperature circuit, which works with CO_2 as refrigerant fluid, is coupled with the high temperature circuit by a cascade condenser, in the same way that the direct expansion in cascade system is. The medium temperature circuit is coupled with the high temperature system by a chiller that works similarly as the cascade condenser. Part of the fluid of the high temperature circuit goes to the chiller as mixture liquid and vapor and absorbs heat from the stream that goes from the point 20 to 18 to reach the state of saturated vapor. The Glycol circuit uses a mixture (ethylene glycol + water) as working fluid, this fluid, differently them other systems analyzed in this paper do not change phase. The mixture glycol-water works only with a sensible heat in the medium temperature evaporator and in the chiller.

2.2 Numeric Model

In order to simulate the refrigerant systems proposed in this paper, a numerical model for each one using the software Engineering Equation Solver (EES) was performed. Those models calculate the refrigerant mass flux and the thermodynamic proprieties in each point of the systems based in energy and mass balance in all the equipment and split points in the system, the main equations used are shown in Tab. 1. With the proprieties of all the points in the systems it is possible to calculate the power necessary to run the circuits and consequently to calculate the COP, expressed in the Eq. (1), the flux masses and the thermodynamic proprieties in each point for those systems. The Table 2 shows the input of the models.

$$COP = \frac{Q_{evap}}{W_{tot}} \tag{1}$$

Table 1. Energy balance equations.

System	Q_{evap}		W_{tot}	
System 1	$Q_{evap} = m_3(h_4 - h_3)$	(2)	$W_{tot} = m_6(h_6 - h_5)$	(6)
System 2	$Q_{evap} = m_{10}(h_{10} - h_9)$	(3)	$W_{tot} = m_6(h_6 - h_5) + m_{12}(h_{12} - h_{11})$	(7)
System 3	$Q_{evap} = m_{13}(h_{13} - h_{12}) + m_{15}(h_{15} - h_{14})$	(4)	$W_{tot} = m_6(h_6 - h_5) + m_{10}(h_{10} - h_9) + m_{17}(h_{17} - h_{16})$	(8)
System 4	$Q_{evap} = m_{15}(h_{15} - h_{14}) + m_{20}(h_{20} - h_{19})$	(5)	$W_{tot} = m_{11}(h_{11} - h_{10}) + m_{17}(h_{17} - h_{16}) + m_{19}(h_{19} - h_{18})$	(9)

Table 2. Input data.

Input data	
Compressor efficiency	0.65
Intermediate heat exchange efficiency	0.70
Condenser temperature	$T_{Amb}+10°C$
Superheat of the refrigerant leaving the intermediate heat exchange	10°C
Approach temperature in the cascade condenser	3.30 °C
Low evaporation temperature	-30°C
Medium evaporation temperature	-5°C
Medium temperature heat capacity	120 kW
High temperature heat capacity	65 kW

Where $\dot{Q}_{evap}$ is the heat that the system takes from the ambient and $\dot{W}_{tot}$ the total power necessary to run the system, $\dot{m}_i$ and h_i denotes mass flux and specific enthalpy in point i.

The consideration made in the models was:

- The pressure drop and the heat transfer in the along the pipe were disregarded;
- The pressure drop in all the heat exchangers: evaporators, condensers, chillers, intermediate heat exchangers and cascade condensers was disregarded;
- The heat transfer efficiency in the evaporators, condensers, chillers and cascade condensers was assumed 100%.

3.3 COP ANALYSIS

The main propose of this paper is to expand the performance analysis made by (Sharma et al., 2014) with the four studied systems under the Brazilian climate. In order to achieve that, the COP was evaluated in different ambient temperatures, showed in Fig. 2. Those temperatures represent the average values (Inmet 2016) for each month in different cities (Belo Horizonte, Porto Alegre, Goiânia, Fortaleza and Belém), representing each Brazilian region. All the four systems were evaluated in each temperature for different refrigerants working in the high temperature circuit: R404A, R22, R134a and R1234yf.
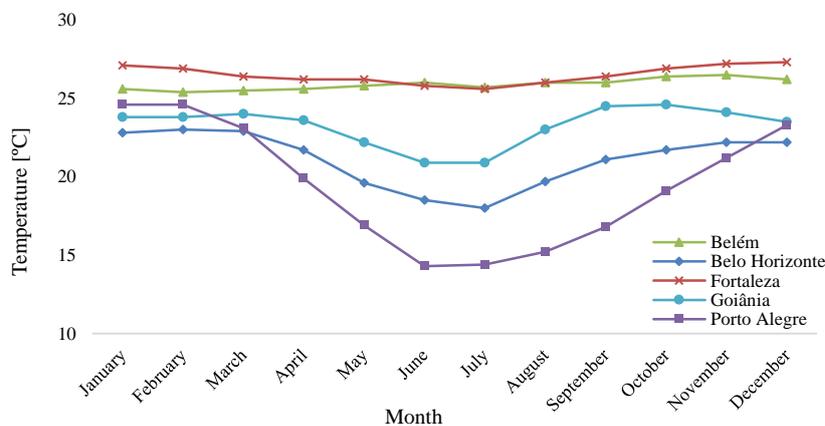

Figure 2. Average temperature for each month in the studied cities

Table 3. Best COP for each system.

Cities	Best COP for System 1	Working fluid	Best COP for System 2	Working fluid
Belo Horizonte	2.127	R134a	1.965	R134a
Fortaleza	1.790	R22	1.720	R134a
Goiânia	1.988	R134a	1.866	R134a
Porto Alegre	2.354	R134a	2.105	R134a/R22
Belém	1.798	R22	1.726	R134a
Cities	Best COP for System 3	Working fluid	Best COP for System 4	Working fluid
Belo Horizonte	3.178	R134a	2.232	R134a
Fortaleza	2.610	R134a	1.897	R134a/R22
Goiânia	2.942	R134a	2.096	R134a
Porto Alegre	3.525	R134a	2.425	R134a
Belém	2.623	R134a	1.905	R134a

4. RESULTS

4.1 Systems with one cold reservoir

It is possible to observe from Tab. 3 that the best COP in the systems studied that has only one evaporator is from the Direct expansion system with R134a for Belo Horizonte, Goiânia and Porto Alegre and R22 for Belém and Fortaleza. Fig. 3 shows the best COP of the year divided by working fluids and cities. It is possible to observe that analyzing the same city with the same fluids the best results are those in system one. The only exceptions of these behaviors are system 2 in Belo Horizonte, working with R1234yf, and Fortaleza, Goiânia and Belém working with R404A. For these cases, the COP in system 2 is bigger than with system 1.

The data shown in Tab. 4 represent the maximum variation of COP in the same system, city and month the year, varying only the working fluid. It is possible to observe that the system 1 has a large variation range of COP depending of the working fluid while system two has a narrow variation.

Table 4. Maximum variation of COP.

Belo Horizonte		Fortaleza		Goiânia		Porto Alegre		Belém	
System	Maximum COP difference	System	Maximum COP difference	System	Maximum COP difference	System	Maximum COP difference	System	Maximum COP difference
1	19.2%	1	10.4%	1	8.9%	1	7.4%	1	10.4%
2	2.5%	2	3.5%	2	2.9%	2	2.1%	2	3.5%
3	5.4%	3	7.0%	3	6.0%	3	4.8%	3	6.9%
4	5.7%	4	7.6%	4	6.4%	4	5.0%	4	7.6%

4.2 Systems with two cold reservoirs

Analyzing Fig. 3 and Tab. 4, it is possible to observe that the biggest COP for all the systems with two different cold reservoirs are those from system 3 for all cities. The best working fluid in major systems are R134a followed by R22, R1234yf and R404A respectively. Although this variation of COP, due to the working fluid that exists, it has a very narrow variation band in most cases. Also, it is possible to perceive that the variation of the COP due to the change of the working fluid is virtually the same for both systems 3 and 4.

5 ANALYSIS

5.1 Analysis of the systems 1 and 2

The analysis of systems 1 and 2 reveals that, for all the cases studied, the best COP happens when the direct expansion system is used. This happens because Brazilian climate has a narrow band of average temperature variation with a relative low average temperature. For the temperatures studied, the variation from the minimum temperature from the maximum is only 13°C with the maximum value of 27.3°C. As shown in Fig. 4a, both systems reduce their COP with the reduction of the temperature of evaporation. The graph reveals that this drop is more marked in system 1 than in system 2. This

behavior of the COP demonstrates that there is an evaporation temperature in which system 2 becomes more advantageous than system 1, with R1234yf as working fluid and ambient temperature as 25°C, this temperature is approximated -31°C.
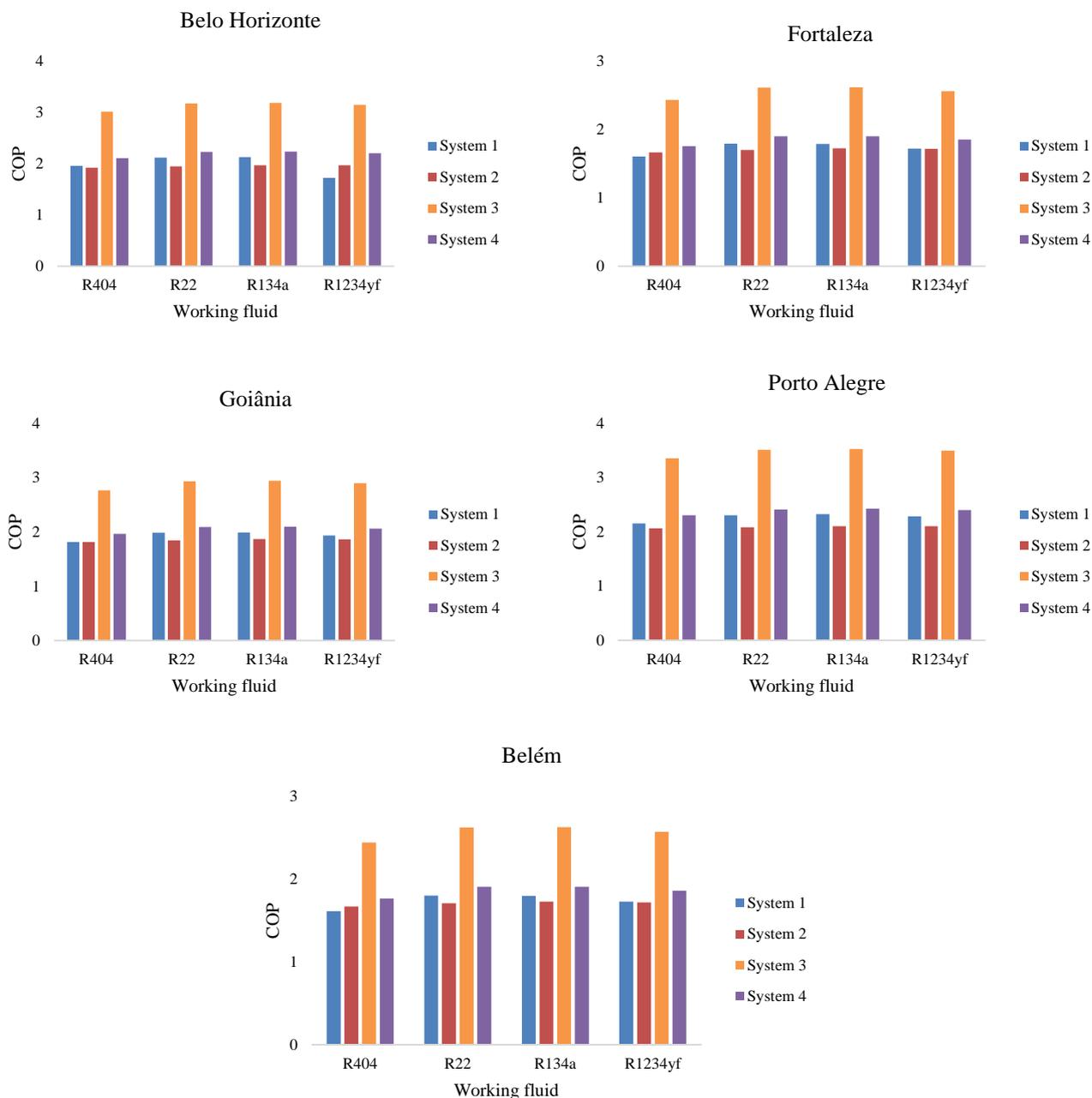

Figure 3. COP for each city analyzed.

The same analysis made for evaporation temperature can be made for ambient temperature, as the environment temperature increases, the COP decreases for both systems, as shown in Fig. 3b. Although both system's COP decreases, the drop suffered by direct expansion system is sharper than the cascade system. For this reason, in the same way that system 2 has an evaporation temperature in which it becomes more advantageous, there is an ambient temperature in which this system is better than the first one. For evaporation temperature of -30°C and R1234yf as working fluid this temperature is approximately 26°C, as is showed in Fig. 4b.
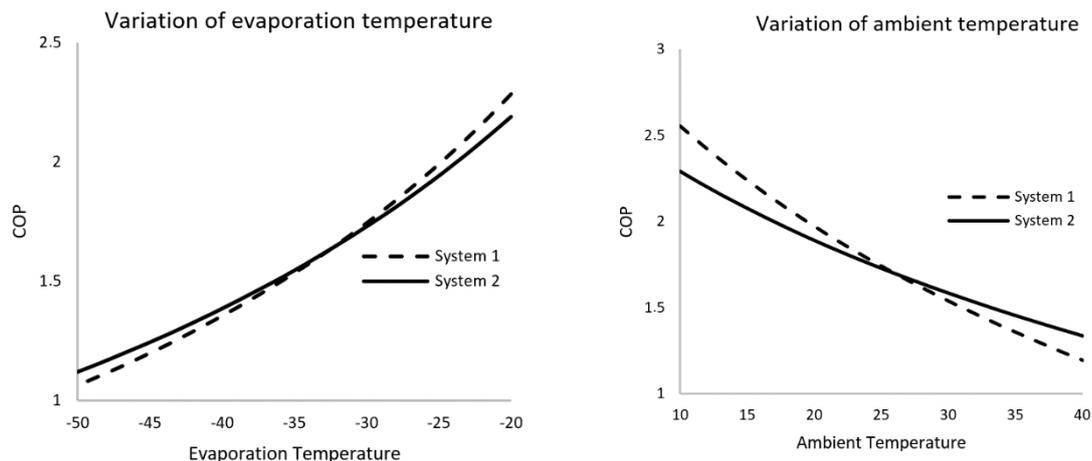
a) COP varring evaporation temperature for the same fluid (R1234yf) and same ambiente temperature

b) COP varring ambient temperature for the same fluid (R1234yf) and same evaporation temperature

Figure 4. Comparison between system 1 and 2.

5.2 Analysis of the systems 3 and 4

The comparison of the systems with two different cold reservoirs show that the system 3 presents the best performance. Differently from comparison between systems 1 and 2, which presents a different result due changes in the ambient and evaporation temperatures, the Combined CO2 secondary Cascade System presents the best COP independently from these parameters. Therefore, the best system for the studied climates is system 3.

The analysis of the dependence of the COP from the working fluid shown in Fig. 2 and Tab. 1 shows that the best results are with R134a and R22. Although the difference presented in the Tab. 4 shows that even though the best performance occurs with these two refrigerants, using R1234yf due to it is ambient friendly proprieties, and the relatively low decrease of the COP that its causes is indicated.

6 CONCLUSION

The comparison between the four systems proposed, considering different ambient temperatures representing different Brazilian climates reveals the follow conclusions:

- The best system for a single low temperature reservoirs with the Brazilian climate is the direct expansion system;
- There is a band of values of ambient temperature and evaporation temperature in which the direct expansion system in cascade is more efficient than the direct expansion system. In some specific places and operation conditions system 2 can be better than system 1;
- The best system for a two different cold reservoirs is the Combined CO_2 secondary Cascade System;
- For system 2, 3 and 4 there is no much difference between COP obtained with the analyzed fluids (R22, R134a, R1234yf and R404A). For this reason, R1234yf is recommended as the less aggressive refrigerant to the environment.

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