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SUBCRITICAL R744 REFRIGERATION SYSTEMS FOR SUPERMARKET APPLICATIONS: A REVIEW

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Abstract. *This work presents a review of the arrangements propose in literature for subcritical refrigeration systems with R744, generally used in supermarkets. Therefore, are described different configurations with direct and indirect expansion such as: medium and low temperature evaporator configuration in the low temperature cycle and the medium temperature evaporator configuration in the high temperature cycle and the expansion configuration indirect with R744 and ethylene glycol. In addition, are presented the main performance results of the cascade refrigeration cycles that operate with different refrigerants in the high temperature cycle, as: R717, R290, R134a and R404A. The results indicate that the cascade configuration with flooded evaporator is the most promising configuration in terms of performance in cascade cooling systems with R744. However, the implementation of this system is more complex and costly, due to the use of the circulation pump.*

Keywords: *Supermarkets, Refrigeration, cascade, R744, Performance.*

1. INTRODUCTION

In last decades synthetic refrigerants as chlorofluorocarbons (CFC's), hydrochlorofluorocarbons (HCFC's) and hydrofluorocarbons (HFC's), were massive used in refrigeration systems of all kind. However, different studies has been proved that these refrigerants cause environmental problems associated with global warming and ozone depletion through direct and indirect emissions. While direct emissions are related to leakage of refrigerant, indirect emissions are due to the large consumption of energy and can be less representative.

In this sense, the European Union approved Regulation (EU) No. 517/2014 (REGULATION (EU) N° 517/2014, 2014) also known as F-gas, as a prevention and conservation measure of the environment. In there, are established the steps for containment, use, recovery and destruction of fluorinated gases. The regulation also imposes marketing limits and conditions for the use of these types of substances. In addition, the Kigali Amendment approved by 197 countries including Brazil enters into force in January 2019. The Kigali Amendment defines a schedule for reducing the production and consumption of HFCs to a minimum level, since HFCs have a high impact on the global climate system. In this way the Kigali Amendment arise as a complement to the Montreal Protocol that initially do not contemplates the HFCs, providing a solution to the greenhouse gases produced by HFCs, making a significant contribution to decelerating global warming and climate change, introducing stages of global reduction in the production and consumption of HFC's (Polonara et al., 2017). Figure 1b and 1b, shows the quotas stablished by the Kigali Amendment in Europe, and the price increments of the HFC's refrigerants conventionally used.

Hence, refrigeration sector and research centers joined forces in order to seek new alternatives with systems that have high energy efficiency and reduced environmental impact as returning to the use of natural refrigerants, such as hydrocarbons, ammonia (R717) and carbon dioxide (CO2). These fluids have arisen as a promising solution to replace conventional refrigerants, since they are environmentally friendly fluids and do not generate significant damage to the environment. In the work of the Lorentzen, (1994b, 1994a) it is proposed the resumption of studies on the use of carbon dioxide (R744) as a refrigerant, because it is a natural fluid (cheapest than other refrigerant fluids), non-toxic and non-flammable with zero Ozone Depletion Potential (ODP) and unitary Global Warming Potential (GWP).

The attraction for the use of R744 in refrigeration systems is based on its thermo-physical properties: reduced viscosity, high thermal conductivity and specific mass in the vapor phase. These properties lead to intensify the heat transfer in the main components of the refrigeration cycle, such as: evaporators, condensers and gas coolers. This allows the use of smaller components compared to those used with CFC's and HCFC's refrigerants (ASHRAE, 2018).

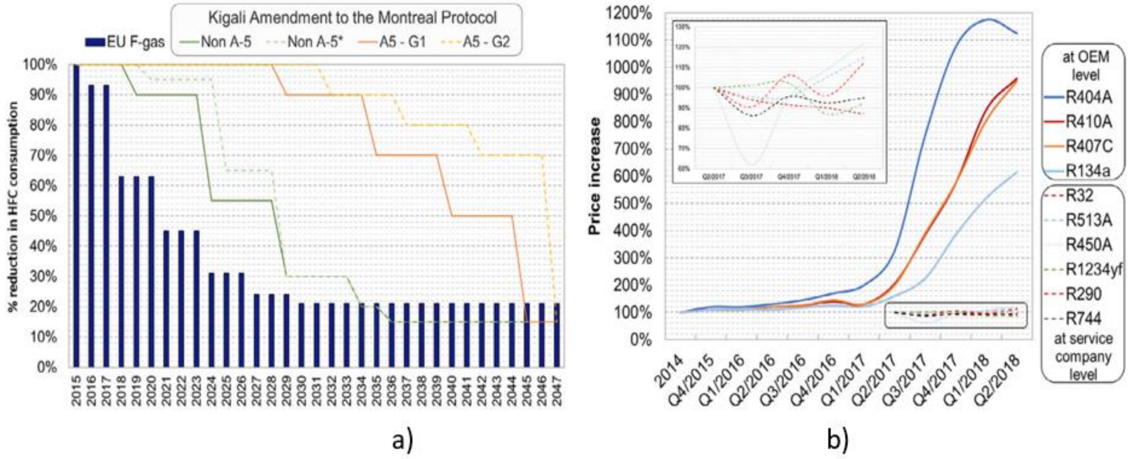

Figure - 1 a) Quotas for HFC's global reduction from Kigali Amendment b) price of most relevant HFC's. (Mota-Babiloni et al., 2020)

In addition, R744 has high solubility with lubricants and low cost when compared to synthetic refrigerants In addition, R744 has high solubility with lubricants and low cost when compared to synthetic refrigerants (Niu and Zhang 2006). Carbon dioxide is characterized by its high pressure at low temperatures and, depending on the ambient temperature, the system can operate in transcritical or subcritical mode. Subcritical mode in the refrigeration cycle consist in use R744 as a secondary fluid in indirect systems or in cascade applications, where R744 is used at low temperature, guaranteeing its operation below the critical point (Llopis et al., 2014).

In applications with a large difference between the ambient temperature and the refrigerated space temperature, a single or a booster double stage refrigeration cycle becomes insufficient, making it necessary to implement a two-stage refrigeration circuit (Nebot-Andrés et al., 2017a). Hence, there are used cascade refrigeration cycles that allows working with two separate refrigerant fluids, operating at different pressures and temperatures for each cycle. In addition, it allows the use of reduced amounts of refrigerant fluids in the high temperature cycle, minimizing the cost and risk in the event of a leak (Ouadha et al., 2007). Cascade refrigeration systems are used mainly in hot climate applications, as long as pressure and operational safety are resolved (Zhang et al., 2020).

Although refrigeration systems that operate with R744 have been extensively covered in the past decade, the application of natural refrigerants in supermarkets is a current trend. Consequently, the purpose of this review is to make a literature survey of the latest research on cascade refrigeration cycles and indirect expansion systems with application in supermarkets. Focusing on the refrigerant fluids used in the high temperature cycle and the different configurations that allow to improve the performance of the system.

1.1 Basic Cascade Cooling Cycle

The cascade refrigeration cycle contains two stages, these are connected by a heat exchanger, which serves as an evaporator for the upper cycle (high temperature cycle) and as a condenser for the lower cycle (low temperature cycle). Assuming the heat exchanger is well insulated, the heat gain in the lower cycle fluid should be equal to the heat transfer from the upper cycle fluid. Thus, there is a need for a temperature difference between the two fluids for the heat transfer to occur (Çengel and Boles, 2001). The temperature difference is a high interested parameter in the study of the cascade refrigeration cycle, as it plays a very important role in deciding the performance coefficient (COP) (Sachdeva et al., 2014). The value of the temperature difference is reflected in the power consumption in the high and low temperature cycle compressors, a reasonable balance to maintain low consumption is the use of a temperature difference between 2.5 ° C and 5 ° C (Bansal and Jain, 2007). In Fig. 2 (a) is shown the cascade refrigeration cycle operating with R717 and R744 in the high and low cycle, respectively. In Fig. 2 (b) and Fig. 2 (c) are plot, the temperature-entropy and pressure-enthalpy diagrams of the cascade refrigeration cycle, with the points corresponding to each phase of the cycle. Basically, the main function of the high temperature cycle is to maintain the operating conditions of the R744 in a subcritical mode, that is, below the pressure and temperature of the critical point, 73.77 Bar and 30.98 ° C, respectively.

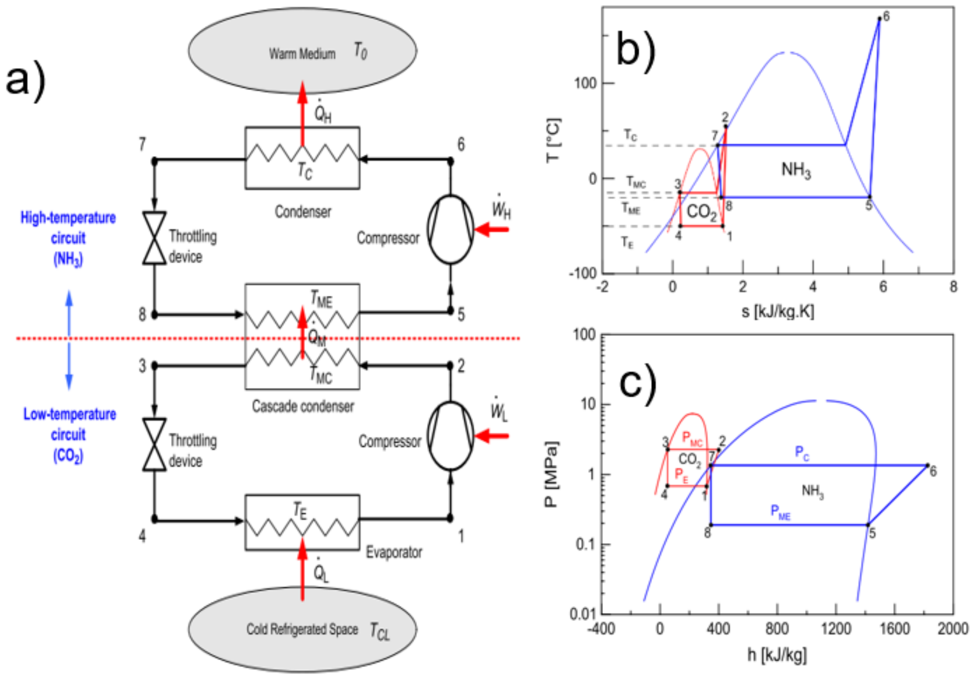

Figure – 2 Refrigeration cycle operating with R717/R744 a) Basic cascade refrigeration cycle b) T-s cycle c) P-h cycle (Lee et al., 2006).

In this refrigeration cycle, suitable refrigerants are studied for the high temperature cycle that provides the highest efficiency in the system. For this, different refrigerants are evaluated, such as: R22, R404A, R290, R717, R1270, R12, R134a (Kilicarslan and Hosoz, 2010; Sun et al., 2016).

2. APLICATION IN SUPERMARKETS

Currently, the energy consumption in supermarkets due to refrigerating foods are responsible for the 3% to 4% of annual energy consumption in industrialized countries (Tassou et al., 2011). Refrigeration systems represent applications in the food retail sector, consuming high rates of electricity that contribute to indirect emissions of greenhouse gases (Gullo et al., 2018a). These arguments support the main reason for exchanging halogen refrigerants used in conventional refrigeration systems for natural refrigerants, in this case R744.

Safety is a very important aspect in supermarkets, since a large number of people who may be affected in case of leaks. These leaks appear over time due to the lack of maintenance in the refrigeration system, being highly harmful because of their composition, which can be toxic or highly flammable. (Sawalha, 2008) developed a mathematical model to calculate the concentration levels of R744, resulting from leaks in different supermarket scenarios. From the results, they showed that the use of R744 is an efficient solution in supermarket refrigeration systems, as it does not create exceptional risks to the health of customers and workers in the commercial area.

In supermarket applications, two temperature levels are required for chilled and frozen products, with temperatures of 3 ° C and -20 ° C, respectively. To achieve this objective, it is favorable to use a cascade refrigeration cycle, having the low temperature cycle R744 and the high temperature cycle R404, R290, R717 or R134a (Sawalha, 2005). The cascade refrigeration cycle is recommended from an energy point of view from temperatures equal to or greater than -20 ° C, due to the large temperature difference between the evaporation and condensation line (Nebot-Andrés et al., 2017a). The following are the two main cascade refrigeration circuits used in supermarket applications.

2.1 Cooling system with low and medium temperature evaporator in the low temperature cycle

The cascade refrigeration circuit that uses low and medium temperature evaporators in the low temperature cycle is shown in Fig. 3 (a).

Amaris et al., (2017) performed the thermodynamic analysis of a cascade refrigeration cycle that operates with R717/R744, this system operates with a double stage compressor in the low temperature cycle. In the results obtained, the COP ranges from 2.19 to 1.56 for ambient temperatures of 7 to 40 ° C. Amaris et al, (2018) carried out the thermodynamic study, for the refrigeration cycle with booster compression, parallel compression and cascade refrigeration cycle that operates with R717/R744. In the results obtained, the systems with booster compression and parallel compression have a higher COP.

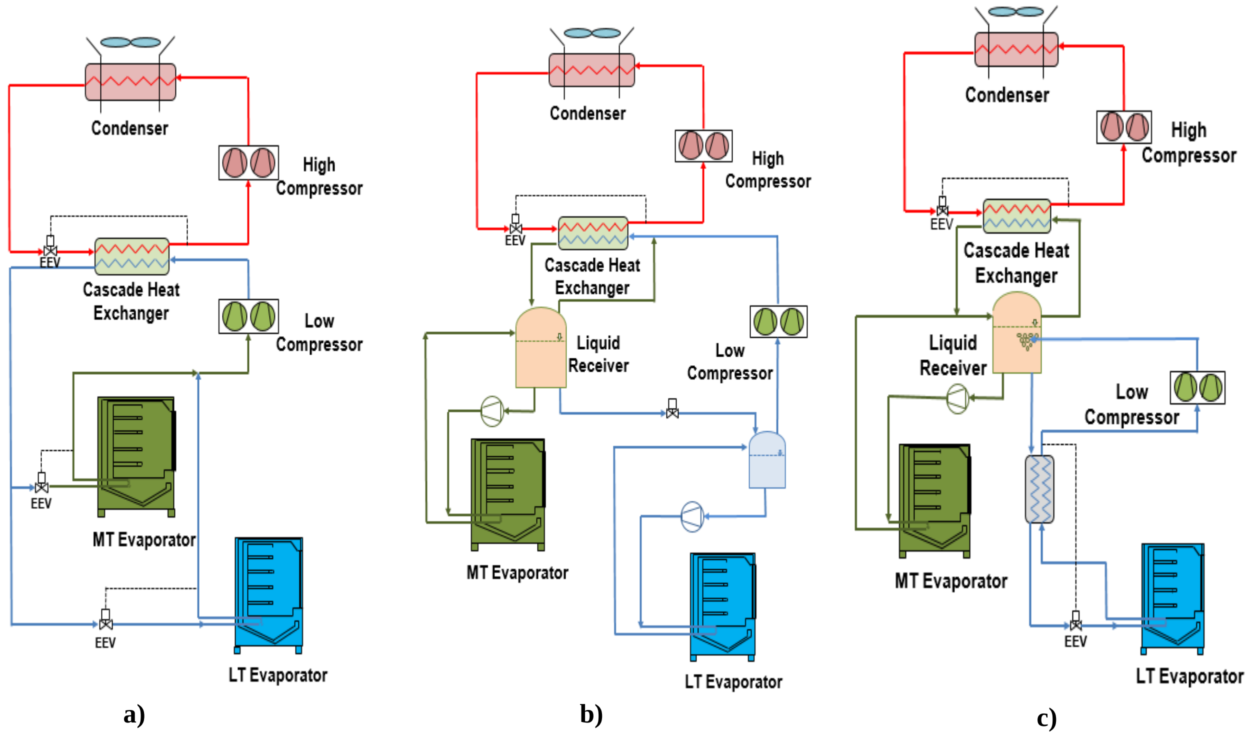

Figure – 3 Low temperature cycle cascade refrigeration system operating with two evaporators: a) Direct double evaporation b) double flooded evaporation c) flooded mid-temperature evaporator. Adapted from: (Mylona et al., 2017), (Sawalha, 2008) and (Sawalha and Rogtsam, 2016), respectively.

However, the cascade cooling system presents better performance for refrigeration capacities lower than 30 kW and at ambient temperatures higher than 26 ° C, this can be explained why the low temperature circuit is isolated for the high temperature cycle. Mylona et al., (2017); Tsamos et al., (2019) theoretically evaluated in terms of refrigeration capacity and total impact of global warming (TEWI), three types of topologies used in supermarket refrigeration. Analyzing the following refrigeration cycles: refrigeration cycle with booster compression, cycle with parallel compression and cascade refrigeration cycle that operates with R134a / R744 and R717/R744. They concluded that the cascade system with R717/R744 presents lower energy consumptions, obtaining decreases of 11.6 and 9.2% for booster systems and parallel compression in hot weather conditions. In addition, the R134a / R744 cascade system offers a good balance of emissions with a TEWI of 16%. Da Silva et al., (2012) made an experimental comparison studying the energy efficiency and the efficiency of the cascade refrigeration cycle that operates R404A/R744 with the direct expansion systems with R404A and R22A. They concluded that the cascade system with R404A/R744 in comparison with the systems of direct expansion, presents a reduction of the consumption of electric energy of 13% to 24%. Zhang (2006) modeled the refrigeration cycle with parallel compression with R404A, indirect expansion with water / glycol and cascade refrigeration cycle with R290/R744. Evaluating the systems from the point of view of energy efficiency and TEWI. They concluded that distributed systems have a lower energy consumption of 6 to 9%.

In some systems the flooded evaporation technique is used, this means that the “evaporation” of the R744 occurs in liquid. For this, the evaporator works together with a recirculation pump that floods it with liquid, making the heat transfer coefficient higher in comparison to direct evaporation systems. These systems are shown in Fig. 3 (b) and Fig. 3 (c). Sawalha and Rogstam (2016) theoretically analyzed a cascade cooling system that operates with R717/R744, they concluded that the flooded evaporator effect produces better performance due to the heat transfer properties. Karampour and Sawalha (2018) reviewed the state of the art of different refrigeration systems with R744 in application for supermarkets, they concluded that evaporation flooded with medium temperature recirculation pump is a promising solution in hot climates. Sharma et al., (2014) investigated different topologies used in cascade refrigeration systems that operate with R404A/R744 for different climatic conditions in 8 cities at USA. The results showed that the cascade refrigeration system with R744 flooded medium temperature evaporator is more efficient in Chicago, Minneapolis and Duluth. Purohit et al., (2017) theoretically analyzed a cascade cooling system that operates with R1234ze in the high temperature cycle. In this configuration, the medium and low temperature evaporators are flooded, allowing better performance in the refrigeration system in extremely hot climates, compared to parallel compression refrigeration systems.

2.2 Cooling system with medium temperature evaporator in the high temperature cycle

The cascade refrigeration circuit that uses an evaporator in the low temperature cycle and medium temperature evaporator in the high temperature cycle, is shown in Fig. 4 (a) and in Fig. (B) presents the cycle that operates with half-temperature evaporator flooded.

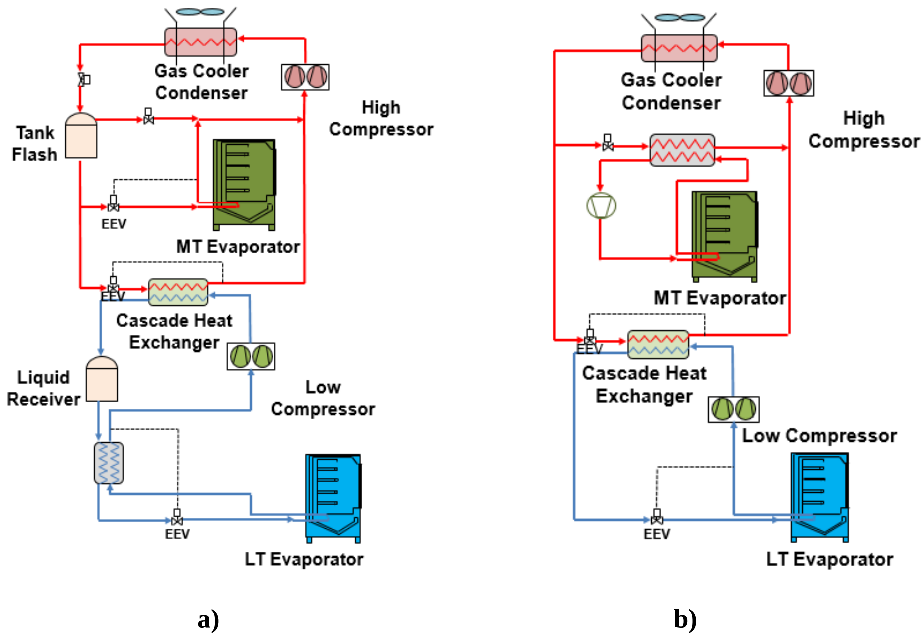

Figure – 4 Cascade refrigeration cycle operating with mid-temperature evaporator on the high temperature cycle: a) mid-temperature evaporator with direct evaporation b) mid-temperature evaporator with flooded evaporation. Adapted from: (Tsamos et al., 2017), (Beshr et al., 2015), respectively.

Tsamos et al., (2017) analyzed four types of refrigeration systems assessing the refrigerating capacity, COP, environmental impact and power consumption. They concluded that the cascade cooling system that operates with R744/R744 with compression bypass has improvements in the COP of 3.6% and 2.1% in hot and moderate climates, respectively. This can be explained by the reduction in power in the high temperature compressor. Ge and Tassou (2014) modeled the cascade refrigeration system used in supermarkets, in order to implement a control system to optimize heat recovery. They obtained that the pressure control can satisfy the supermarket's heat demand with the heat recovery from the refrigeration system, however, by increasing the heat recovery it increases the energy consumption of the compressor. Sánchez et al., (2016) Experimentally compared the impact on energy consumption of the convertion of a direct cascade refrigeration cycle with R134a / R744, to an indirect refrigeration system that contains a secondary fluid with a mixture of propylene glycol and water of 60 and 40% volume. They concluded, that the two systems achieve the projected needs and the energy consumption increases by 14% at a condensing temperature of 45 ° C, when the direct system is converted to indirect. Gullo et al., (2016) theoretically analyzed eight different commercial refrigeration systems evaluating the energy consumption and environmental impact of each one. They concluded that the refrigeration system with R744 type booster that operates with subcooling and uses R290 has a higher COP and less environmental impact. Sooben et al., (2019) carried out an energy consumption and environmental impact analysis for different alternatives in supermarket refrigeration systems, showing that the cascade cooling system with R134a/R744 and R1234ze/R744 has the largest COP. However, the system with R1234ze/R744 provides a reduction of about 42.6% of the TEWI impact, proving to be an alternative in replacement of the R134a. Beshr et al., (2015) studied the LCCP of different refrigeration systems used in supermarkets. The analyzed cascade system operating with R448A/R744 with a configuration using a heat exchanger together with the medium temperature evaporator flooded in R448A liquid. This arrangement significantly improved the system COP at low temperatures condensation.

2.3 Refrigeration system with R744 with indirect expansion

Since 1995, the R744 has been studied as an alternative refrigerant to replace conventional synthetic refrigerants. This refrigerant has been widely used in Nordic countries as a secondary fluid in supermarket applications with indirect systems. The safety aspects, the good thermo-physical properties of the R744 and the good heat transfer, implies a reduction in the size of the piping, being appropriate in indirect systems (Kim; Pettersen; Bullard, 2004). In addition, the indirect cooling system allows for a reduction in the load of HCFC's HFC's refrigerants, also reducing the annual leakage rate and indirect emissions Llopis et al., (2018). However, the implementation of an indirect expansion system implies an increase in energy consumption, due to the implementation of the secondary pump. In some refrigeration plants that operated with conventional refrigerants such as: R12 or R502, it was necessary to convert the systems by changing piping and heat exchangers in the freezers to use the R744 in indirect application with R290 or R717 (Sawalha and Palm, 2003). In fig. 5. (a) the indirect cooling system that operates with R744 is shown and in Fig. 5. (b) is presented an indirect system that operates in the high temperature cycle with ethylene glycol as a secondary fluid. Another advantage of indirect systems is cost.

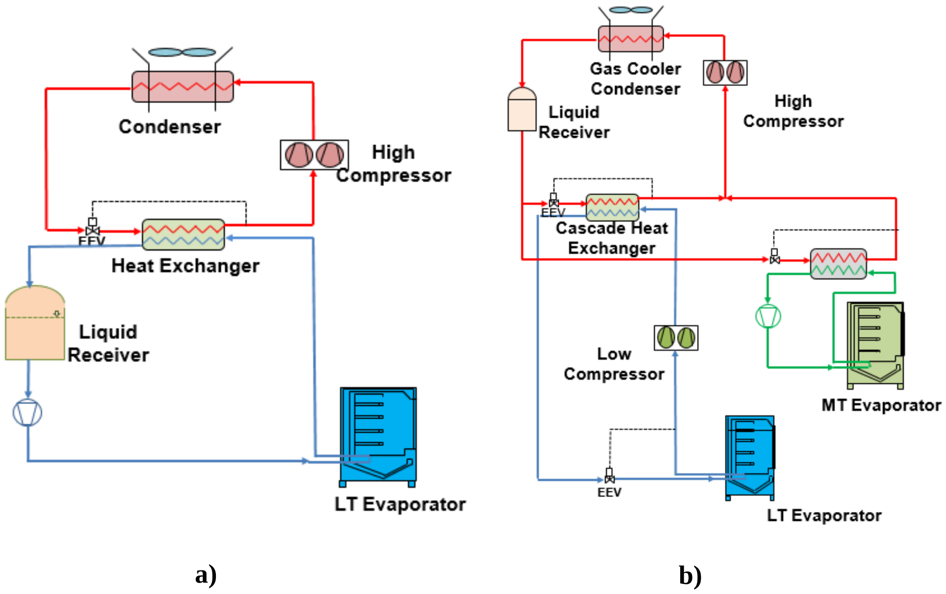

Figure - 5 Refrigeration cycle with R744: a) indirect refrigeration system with R744 b) indirect refrigeration system with Ethylene Glycol on the high-temperature cycle. Adapted from: (Sawalha and Palm, 2003), (Sánchez et al., 2016), respectively.

Sánchez et al., (2017) converted a cascade refrigeration cycle from a direct system to an indirect cooling system and analyzed the impact on energy consumption. The direct refrigeration cycle consists of R134a/R744 and the indirect refrigeration cycle consists of a medium temperature cabin that uses secondary fluids: Temper®−20 and a mixture of propylene glycol-water with volume concentrations of 60 and 40 %, respectively. They concluded that the two indirect systems show energy increases of 11.11% and 14% for secondary fluids. Girotto et al., (2004) made a comparison of a direct cooling system that operates with R404A and an indirect cascade cooling system that operates with R744 and with water as a secondary fluid. The cascade system shown a better COP compared to R404A, however the installation cost of the system with R744 was 20% higher compared to the direct cooling system with R404A. Sánchez et al., (2019) experimentally evaluated the environmental impact and energy consumption of a cascade cooling system that operates with R134a/R744 with direct expansion and a system with indirect expansion that operates with R152a, R1234ze, R209 and R1270, with Temper®−20 as secondary fluid. They concluded that the use of the indirect system reduces the refrigerant charge between 58.5% and 68.5%. However, the reduction of the refrigerant charge affects the TEWI which is highly influenced by the energy consumption of the installation. In the high temperature cycle fluids, the R152a provides a TEWI reduction of up to 30%. Nilson et al., (2006) analyzed a refrigeration system with R717 and R744 as a secondary fluid, aiming to improve heat transfer and pressure drop in copper tubes. They developed a mathematical model for different refrigeration circuits, varying the diameter of the tube and different rates of circulation of the refrigerant. The results shown that the 0,5-inch diameter pipe presents the better conditions of pressure drop and heat transfer.

In Figure 6 are summarized the main results of COP Vs ambient temperature of the different researches in the literature for cooling systems in supermarkets. It could be highlighted that the works developed by Sharma et al., (2014) and Amaris et al., (2018) present higher indexes of yield.

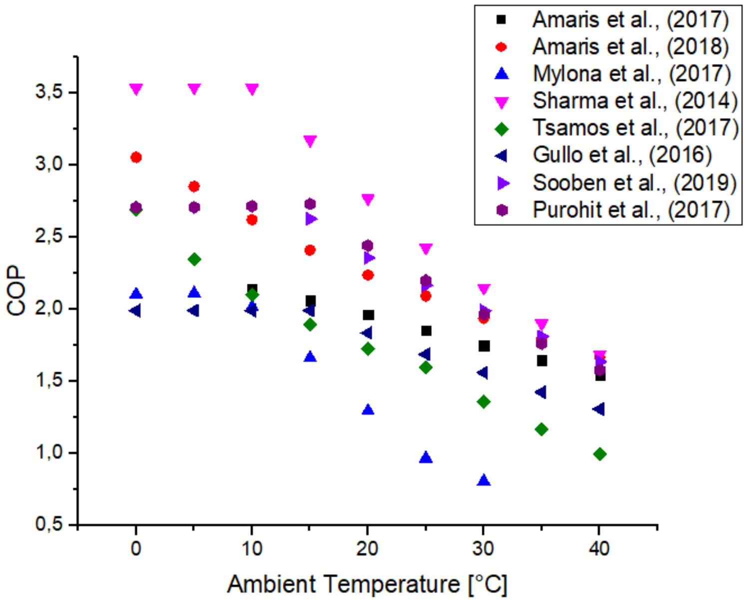

Figure - 6 COP VS ambient temperature variation.

3. CONCLUSIONS

In this work was presents a detailed review of the different configurations propose in literature for subcritical refrigeration systems with R744 used in supermarkets, such as: medium and low temperature evaporator in the low temperature cycle; medium temperature evaporator in the high temperature cycle and indirect expansion with R744 and secondary fluids. In this sense, the following conclusions were made:

- The reviewed works prove that cascade refrigeration configuration using R744 are efficient solutions for supermarket refrigeration systems. This can be explained by the fact that it is a refrigerant that has good heat transfer characteristics and does not affect the environment.
- The refrigerants most frequently used for the high temperature cascade cycle were: R717, R290, R134a, R404A, R1234ze, R1270 and R152a. Therefore, it allows a decrease in the refrigerant fluid charge based on halogens, thus contributing to the reduction of direct and indirect emissions that cause damage to the environment.
- The cascade cycle with flooded evaporation is the most promising configuration in terms of performance coefficient. This can be explained by the use of heat transfer properties when the refrigerant is in the liquid phase in the evaporator, maintaining a high heat transfer coefficient compared to direct evaporation systems. However, the implementation of this system has a refrigeration circuit of greater complexity and cost, due to the use of recirculation pumps.
- The cascade cooling system with R744 proved to be a promising alternative in warm climes.
- Indirect refrigeration systems proved to be effective in the reduction of HCFC's and HFC's-based refrigerant fluids. However, they are systems that can increase the power consumption due to the implementation of a secondary pump, making it necessary to study the optimization of the cooling system.

4. ACKNOWLEDGEMENTS

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