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REFRIGERANT SELECTION FOR A CHILLER AIR CONDITIONING SYSTEM IN BRAZIL

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Abstract. In 2017, electrical air conditioning systems represent an approximate consumption of 20% of the total electrical energy consumed in Brazilian homes. In addition, air conditioning systems may account for 85% of the consumption of residential electric energy in the peak of summer and in commercial establishments approximately 40% of the electric energy consumed is destined for the acclimatization of environments. An innovative technology that can collaborate to mitigate environmental problems and make energy consumption more efficient is thermal energy storage (TES). The TES also helps to decouple the cooling production and the use of it. In that way the cold should be produced during the night, for example and use during the day. This paper proposes a mathematical model using Python language and CoolProp for refrigerant properties. A chiller refrigerant system able to meet a colling capacity of 15 TR is selected. It simulates the operation of refrigeration systems to evaluate the coefficient of performance (COP) during the year of 2020 for three cities in different regions in Brazil: Fortaleza - CE (Northeast), Brasília - DF (Midwest) and Monte Verde – MG (Southeast). In each city will verify the efficiency of three different refrigerant fluids, R134a, R1234yf and R717. The mathematical model of refrigeration system considers a chiller with a TES (Thermal Energy System) to produce and storage cold during the night to be consumed during the day, specially at the peak time. As the condition in the evaporator are keep constant in the system, the model consider only the compressor and the condenser. The mathematical model applied in this study make a comparison between the refrigerant fluids, where R134a is considered as a reference, and comparing with R1234yf and R717. The objective of the manuscript is to select the refrigerant that best suit to the context of the selected cities, considering R134a as a reference, we have that the COP of R717 is greater by about 16.1% for Fortaleza - CE, 14.6% for Brasília - DF and 13.2% for Monte Verde - MG.

Keywords: *Refrigerant selection, Mathematical model, Air conditioning system*

1. INTRODUCTION

Refrigeration systems are increasingly used in people's daily lives. We are increasingly dependent on these systems, whether to produce goods and products, well-being, and quality of life. In the case of well-being, the use of cooling systems is increasingly intense due to the frequent high temperatures or low temperatures that occur on our planet. Over time, environmental awareness and the impacts caused by our occupation have grown in society, so it is extremely important that we have increasingly efficient refrigeration systems that cause the least possible impact on our environment.

In 2017, electrical air conditioning systems represent an consumption of 17% of the total electrical energy consumed in Brazilian homes (EPE , 2018), in addition, there is a study that indicates that electrical air conditioning systems may account for 85% of the consumption of residential electric energy in the peak of summer (LI, LIU and WANG, 2019) and in commercial establishments approximately 40% of the electric energy consumed is destined for the acclimatization of environments (PROCEL, 2008). An innovative technology that can collaborate to mitigate environmental problems and make energy consumption more efficient and that has wide application is thermal energy storage (TES). The use of

TES has two main points. First, it allows for the rationalization of power supply capacity, as TES can reduce demand during peak hours once the cold energy could be produced during the night-time or when you have environmental conditions more favorable.

Therefore, the hydrofluorocarbon R134a has been one of the most important refrigerants over the last two decades for household appliances, air-conditioning, and chillers. However, his GWP (Global Warming Potential) of 1370, which contributes significantly for the greenhouse effect (BELMAN-FLORES, RODRÍGUEZ-MUÑOZ, et al., 2017). As of January 2015, Europe's EU regulation N°517/2014 restricts the use of hydrofluorocarbons, HFCs with a GWP of 150 or more (SCHULZ and KOURKOULAS, 2014)

This paper therefore proposes a mathematical model using Python that can simulate the operation of refrigeration system to evaluate the coefficient of performance (COP) during a year for three cities in different regions in Brazil. Thermo-physical properties were obtained from CoolProp. Three cities were chosen Fortaleza - CE (Northeast), Brasília - DF (Midwest) and Monte Verde - MG (Southeast). The mathematical model considers air condenser and compressor unit of an air-conditioning system. The evaporator conditions are kept constant because of the proposal of storage cold.

2. METHODOLOGY

Figure 1 presents an example of a cooling system as used in the work. Beyond the refrigeration system with basic components (Evaporator, Compressor, Condenser and Expansion Device), the TES to storage cold is presented. The mathematical model that was applied to simulate different scenarios, operating conditions and produce reliable output data is presented in the flowchart (Fig. 2). One of the main advantages of using a mathematical model is the fact that it can be used to simulate different conditions with low costs, since the expenses in the simulations are generally smaller than those involved in the experimental tests, and the results are generated, for the most part, in a shorter time. (Duarte, et al. 2019).

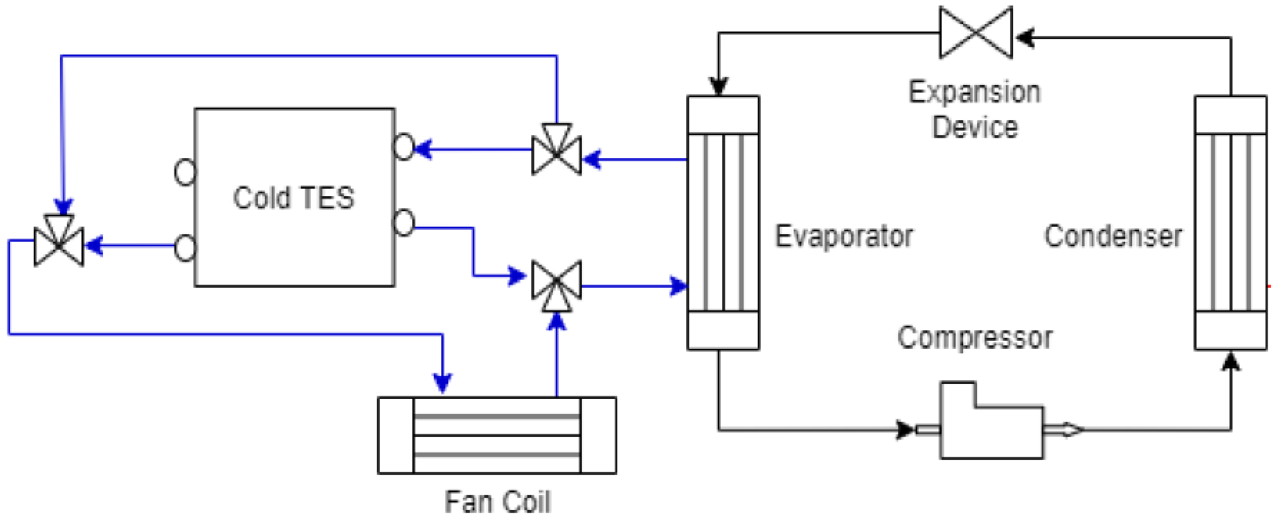

Figure 1 - Air conditioning system coupled with TES

The cooling system was proposed to meet the thermal load of the surroundings where thermal comfort is desired. The HVAC system, during periods when the thermal load of the surroundings is less than the system's cooling capacity and/or during periods when the environmental and economic condition is favorable for operation, the cold is produced and stored in the Phase Change Material (PCM) of the TES. During the operation of the system, the stored cold in the TES is discharged when the heat load is greater than the cold production capacity of the system or at peak times of electricity.

The proposed mathematical model considers only the compressor and the condenser, since the thermal load demand is being considered the same for all fluids, which makes it possible to work with a simpler mathematical model at this stage of the refrigerant fluid selection.

2.1 Compressor Model

The compression process is modeled as isentropic and the mass flow of refrigerant in a constant rotation speed and the consumed electrical power is given by the mathematical model of the compressor. The mass flow rate of the refrigerant through the compressor is given by Eq. (1) (Duarte, et al. 2019).

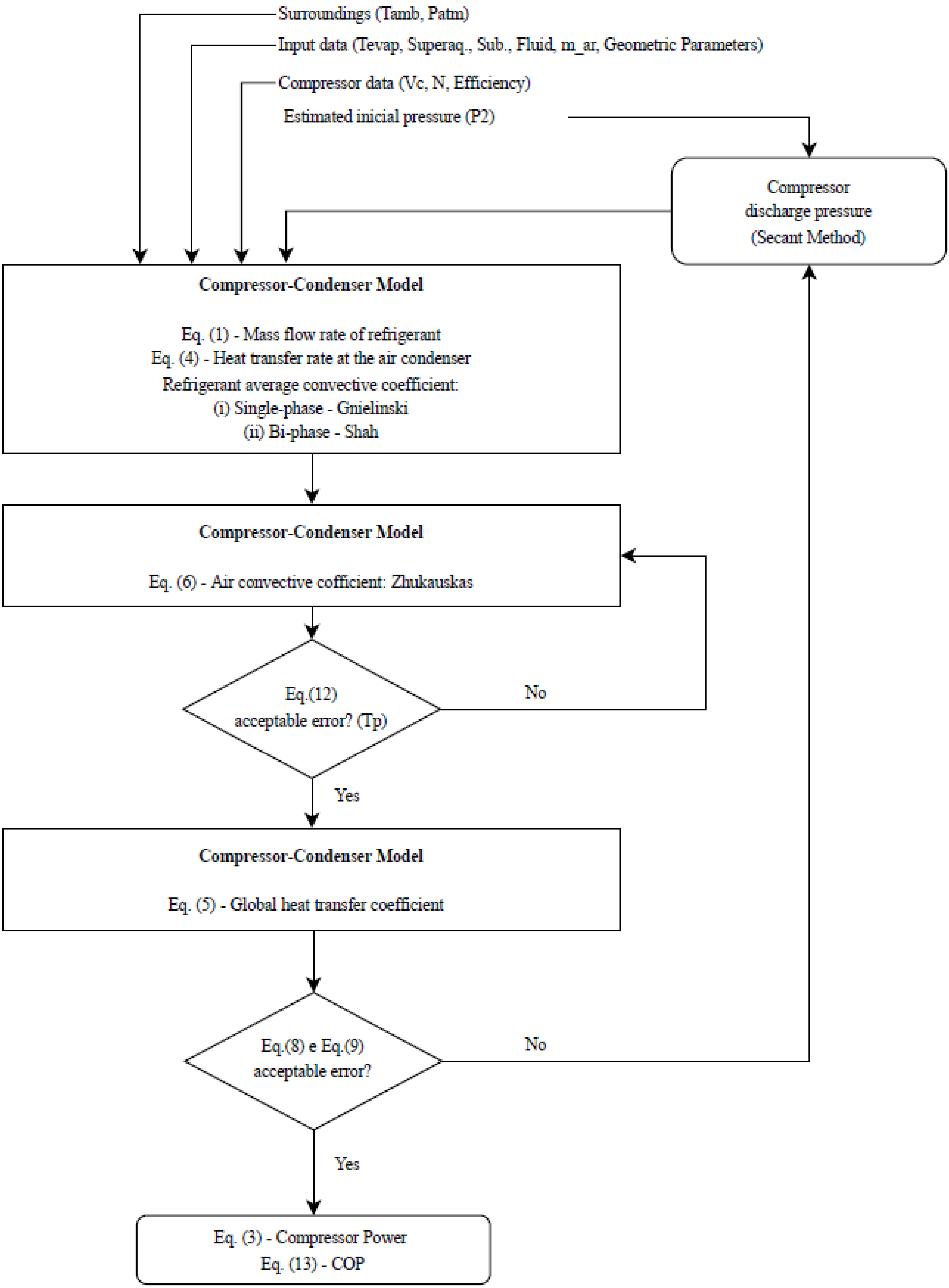

Figure 2 - Flow chart for the calculation

$$m_{ref} = \rho_1 \,.\, N \,.\, V_c \,.\, \eta_V \tag{1}$$

Where:
m_{ref} - mass flow rate of the refrigerant [kg/s]
ρ_1 – density [kg/m³]
N - rotation speed [1/s]
V_C – compressor displacement volume [m³]
η_V- compressor volumetric efficiency
The volumetric efficiency (ηV) was determined according to Eqs. (2) applied by (G. Kosmadakis et al., 2020) for screw compressors.

$$\eta_V = 0.95 - 0.0125\, r \tag{2}$$

Where:
η_V – compressor volumetric efficiency
r – pressure ratio (P1/P2)
The consumed electrical power of the compressor is given by Eq. (3):

$$\dot{W}_C = \dot{m_{ref}} \,.(h_2 - h_1) \tag{3}$$

Where:
W_C – compressor power [W]
m_{ref} – mass flow rate of the refrigerant [kg/s]
h_1 – refrigerant specific enthalpy at the compressor suction port / evaporator outlet [J/kg]
h_2 – refrigerant specific enthalpy at the compressor discharge port / condenser inlet port [J/kg]

2.2 Condenser Model

The heat transfer rate at the air condenser is given by Eq. (4):

$$\dot{Q}_{Cond} = \dot{m_{ref}} \,.\, (h_2 - h_3) = UA(\underline{T_{re}} - T_w) \tag{4}$$

Where:
$\dot{Q}_{Cond}$ - heat transfer rate [W]
$h2$ - refrigerant specific enthalpy at the compressor discharge port / condenser inlet port[J/kg]
$h3$ - refrigerant specific enthalpy at the condenser outlet port / Expansion valve inlet port[J/kg]
UA - global heat transfer coefficient [W/(m² K)]
The global heat transfer coefficient at the air condenser is determined by Eq. (5).

$$UA = \left[\frac{1}{(h_{Cond}\,.A_r) + \frac{\ln(D_{ei} - D_{ii})}{2\pi k_C L_{Cond}} + (h_{air}\,.A_{air})}\right] \tag{5}$$

Where:
UA - global heat transfer coefficient [W/(m² K)]
Lcond - condenser length [m]
hcond - refrigerant average convective coefficient [W/(m² K)]
Ar– inner area of refrigerant tube [m²]
Dei - outer diameter of refrigerant tube [m]
Dii - inner diameter of refrigerant tube [m]
kc – thermal conductivity of material of refrigerant tube
hair - air convective coefficient [W/(m² K)]
Aair - heat exchange area [m²]
The refrigerant average convective coefficient is determined according to proposed by (GNIELINSKI 1976) in single-phase flow and proposed by (Shah 2016) to two-phase flow. The correlation applied to find the air convective coefficient is Eq. (6) proposed by (ZHUKAUSKAS 1972):

$$Nu_D = C \,.\, Re_{D,max} \,.\, Pr^n . \left(\frac{Pr}{Pr_s} \right)^{1/4} \tag{6}$$

$$Re = \frac{\rho \, V_{max} \, D}{\mu} \tag{7}$$

Where:
N_{uD} - air convection coefficient [W/(m² K)]
$Re_{D,max}$ – Reynolds number for maximum diameter at condenser [m]
Pr – Prandtl number
ρ – density [kg/m³]
V_{max} – flow velocity [m/s]
D – pipe diameter [m]
μ – fluid dynamic viscosity [kg/(m.s)]

According to the definition made by Kong et al. (2017), who proposed a 95% heat leakage coefficient Eq. (8) for heat loss in the hot water tank defined as follows:

$$\zeta = \frac{\dot{Q}_{Cond}}{\dot{Q}_{max}} \tag{8}$$

$$\zeta = f\left(NTU, \frac{C_{min}}{C_{max}} \right) \tag{9}$$

Where:
ξ - heat leakage coefficient
$\dot{Q}_{Cond}$ - heat transfer rate [W]
$\dot{Q}_{max}$ – maximum heat transfer [W]
NTU - number of transfer units
C - heat capacity at constant pressure [J/(kg K)]

2.3 Model Convergence

To verify the deviation of the calculated heat transfer rate at condenser were the maximum error acceptable is 5% according to Eq. (12), to define the ambient temperature were applied the Eq. (10) and Eq. (11).

$$q = \frac{\dot{Q}_{Cond}}{A_{HT}} \tag{10}$$

$$q = h \, (T_w - T_\infty) \tag{11}$$

$$error_p = |T_w - T_{w,prev}| \tag{12}$$

Where:
q – heat transfer [J]
$\dot{Q}_{Cond}$ - heat transfer rate [W]
AHT – heat transfer area [m²]
Tw – internal tube temperature [K]
T∞ - surrounding temperature [K]

2.4 Performance of the System

The measured coefficient of performance (COP) of the refrigeration system is obtained from the following Eq. (13)

$$COP = \frac{\dot{Q}_{Cond}}{\dot{W}_C + \dot{W}_{Vent.}} \tag{13}$$

Where:
COP – coefficient of performance
$\dot{Q}_{Cond}$ - heat transfer rate [W]
$\dot{W}_C$– compressor power [W]
$\dot{W}_{Vent.}$– fan power [W]

2.5 Simulation Parameters

The climate data of the selected cities were obtained in the web site of the Brazilian National Institute of Meteorology (INMET), for the year of 2020. Those data are the ones cited as input data in the flowchart in Fig. 2 (the mean for each month). For this paper, 3 cities were selected, each city in 3 different states. The city of Fortaleza, capital of the state of Ceará, which is in the North region of Brazil, the city of Brasília, capital of Brazil, located in the Federal District in the Midwest, and finally the city of Monte Verde, which is a district of the municipality of Camanducaia, were selected, in Minas Gerais, Southeast region. In Fig. 3 we can see the locations of the chosen cities.

The simulation parameters of the compressor and condenser are presented in Tab. 1. Similar equipment is considered during the simulation in order to enable comparison.

3. RESULTS

The simulated results are described in this section. The thermal performance of the air-conditioning system was numerically simulated during a year climatic condition of Fortaleza, Brasília, and Monte Verde.

The comparisons for different fluid refrigerant operating are depicted in Fig. 4, Fig. 5, and Fig. 6. For all cities the R717 presented the best COP in comparison with others refrigerant fluid analyzed. For all cities presented, we obtained the fluid efficiencies in the same order, with R717 being the most efficient and R1234yf the least efficient fluid. The COP values presented for the different fluids in each city are different due to the climatic differences presented in every single city. Fortaleza - CE has the lowest values for the COP, while Monte Verde - MG has the highest values for COP, this difference is given since the average temperatures in Fortaleza can reach up to 57% when compared to Monte Verde - MG. Taking R134a as a reference, we have that the COP of R717 is greater by about 16.1% for Fortaleza - CE, 14.6% for Brasília - DF and 13.2% for Monte Verde - MG. The refrigerant fluid R1234yf had the lowest COP for all cities evaluated, with values 9.9% lower for Fortaleza - CE, 9.4% lower for Brasília - DF and 8.9% lower for Monte Verde - MG, when also compared to R134a. In addition, a similar trend for COP is noticed in Figures 5 and 6 to Brasília - DF and in Monte Verde - MG, respectively. In that Figures the COP increase during the winter. An analogous behavior is presented in Figure 4 for Fortaleza – CE however with little variation because temperatures are more constant throughout the year.

Evaluating the COP for a location, different values are observed for each refrigerant, but the behavior is similar among the refrigerants studied. Works on the selection of refrigerants for different configurations of refrigeration systems show similar behaviors, see as an example (Duarte, et al. 2019) and (de Paula, et al. 2020). The COP values presented for all regions are practically constant throughout the year, the best values are presented during the southern hemisphere winter, during the months of June to September, because due to the drop in ambient temperatures favoring the functioning of the systems of air conditioning. Although all the cities evaluated had a better COP for R717 refrigerant, there is a variation between cities during the year, this variation is due to the geographic location of the cities, being Brazil a country of continental dimensions, we have great variations in climate in its territory. The city that presented the best COP throughout the year was Monte Verde, where the region's climate is tropical at altitude, with an average annual temperature of 15.28 °C. The lowest COP values for R717 refrigerant were presented for Fortaleza, a city located in northeastern Brazil where the climate is hot, with an average annual temperature of 27.25 °C.

The results indicated that for the case of the system to be install in open areas R717 should be a good option to replace R134a. On the other hand, for close areas R1234yf almost meet the performance of R134a. However, another refrigerant options to replace R134a could be investigated in depth.

4. CONCLUSION

In this paper, a comparison was made between the refrigerants of an air-conditioning system in terms of COP. The model is developed in Python language, and it used Thermo-physical properties from CoolProp. Only the condenser and compressor are modeled, and the conditions of evaporator are kept constant. To compare the performance of cooling system, were used 3 different cities located in different regions of Brazil. The ambient conditions are obtained by INMET (National Institute of Meteorology). In the city of Fortaleza, the results show that, among the refrigerants used, R717 has the best COP than R134a and R1234yf in all months of the year, reaching a COP above 24.7% and 16.3% for R1234yf and R134a respectively in November and December. However, when comparing the cities of Monte Verde, Fortaleza and Brasília using the same cooling system with refrigerant R134a, the city of Monte Verde has the best COP.

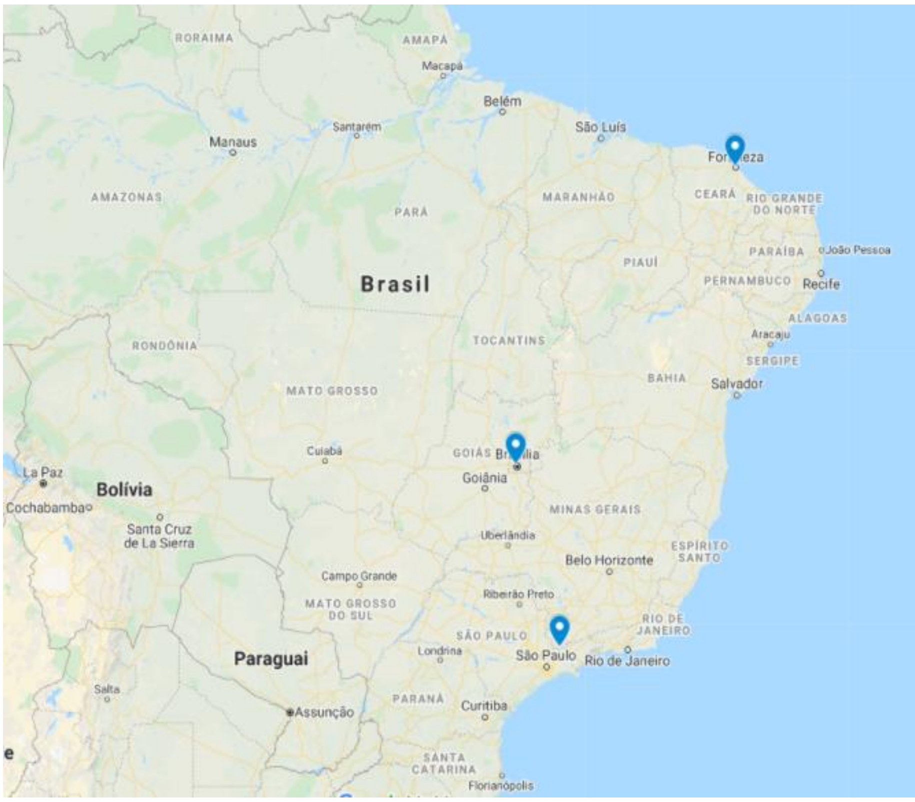

Figure 3 – Cities location *(Image from google maps)*

Table 1. Simulation parameters

System	
Evaporation Temperature:	-10°C
Superheat:	5 K
Subcooling:	7 K
Compressor	
Model:	SE6089GS-O
Manufactured:	EMBRACO
Refrigerant:	R-134a
Displacement:	197.1 cm³/rev
Rotation:	2900 rpm
Condenser	
Model:	AQUASMART® 30EX / 30EV
Manufactured:	Carrier
Air Mass Flow Rate:	15000 m³/h
Face Area:	3.05 m²
Internal diameter:	7.94 mm
External diameter:	9.52 mm
Material:	Cooper
Fan Power:	850 W

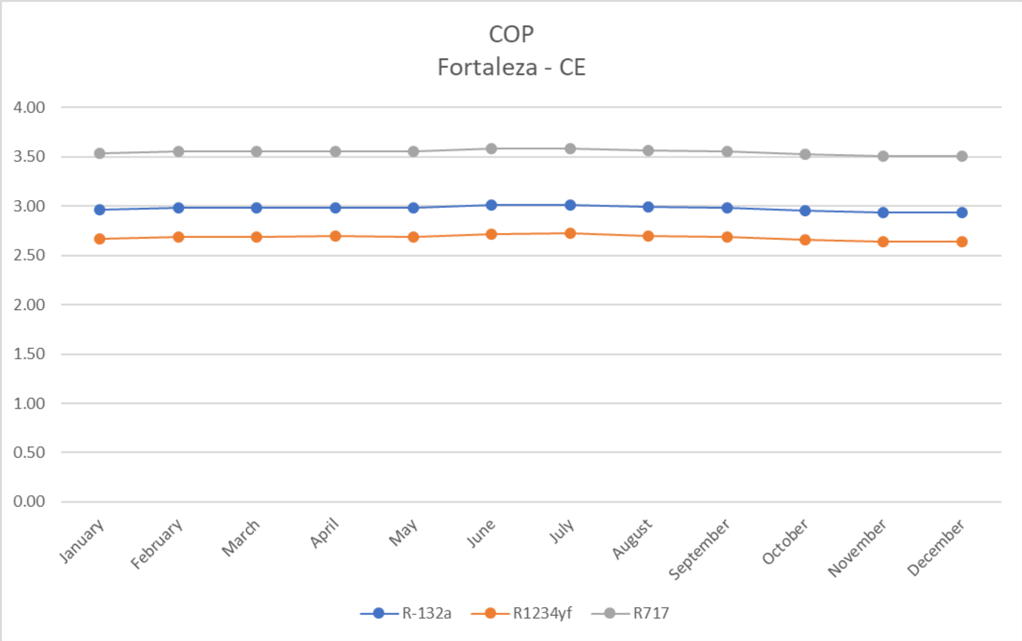

Figure 4 – COP for R134a, R1234yf and R717 for refrigeration system in Fortaleza - CE

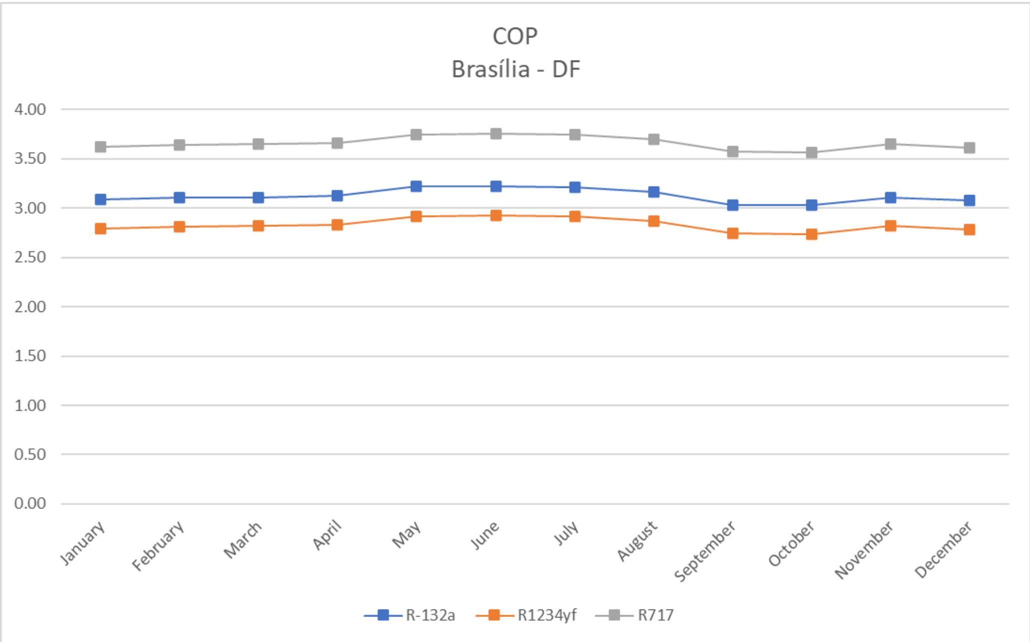

Figure 5 – COP for R134a, R1234yf and R717 for refrigeration system in Brasília - DF

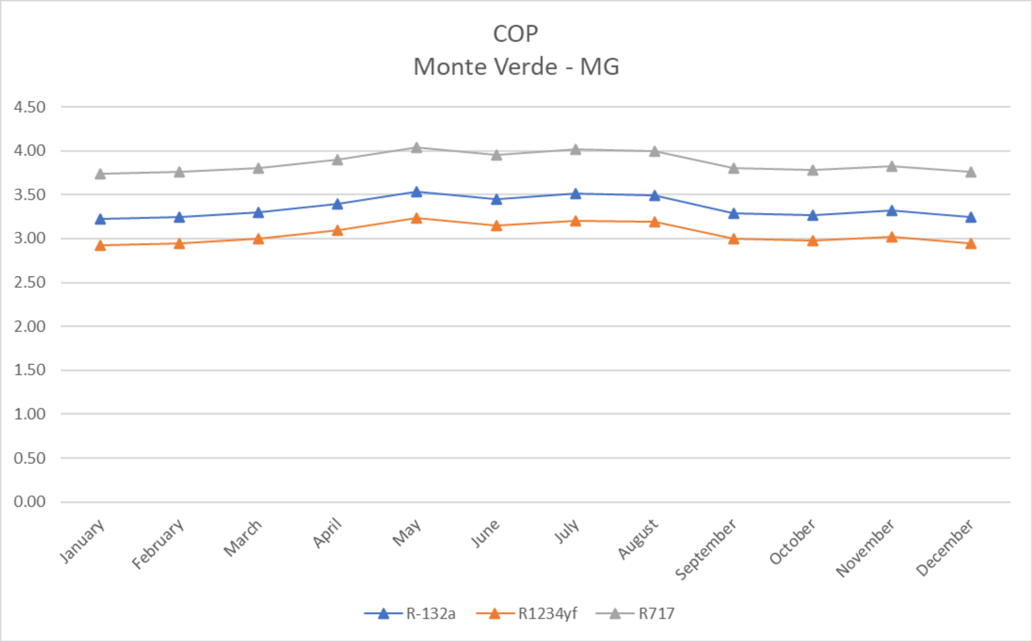

Figure 6 – COP for R134a, R1234yf and R717 for refrigeration system in Brasília - DF

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6. RESPONSIBILITY NOTICE

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7. ACKNOWLEDGMENTS

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