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COMPARATIVE ANALYSIS OF AUTOMOTIVE AIR CONDITIONER WITH WATER-COOLED AND AIR-COOLED CONDENSER

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Abstract. *Due to more stringent environmental legislation over the years, the automotive sector seeks alternatives to reduce the emission of pollutants. The air conditioning system consumes a good deal of energy from the combustion engine. This work presents a comparative analysis of conventional and an air conditioning with water-cooled condenser using R134a and R1234yf. In order to evaluate the performance of the conventional air conditioner and the water-cooled condenser a steady-state model was developed using the Equation Engineering Solver (EES). The model uses empirical correlation obtained from performance map provide by manufacture to evaluate the effectiveness of the heat exchangers, the mass flow rate and the power consumption of the compressor. The results show that COP and cooling capacity of water-cooled condenser is smaller than air-cooled condenser. In addition, the R134a has a COP 20% higher than R1234y, difference that are in the range found in the literature. The Cooling Capacity of R1234yf is lower than R134a.*

Keywords: *Air conditioning, water-cooled condenser, automobile industry, R134a, R1234yf.*

1. INTRODUCTION

In the last few years, the worldwide regulatory agencies of the automobile industry has intensified actions related to environmental issues, resulting in several international regulations for the automotive sector. In Brazil, the government recently announced a new law, ROTA 2030 (Brazil, 2018), proposing tax benefits for companies that meet the requirements, including the implementation of new technologies to reduce pollutant emissions. At the moment, the challenge for technicians is the development of more efficient systems and, consequently, with less impact on the environment. In this context, the car's air conditioning (AC) is one of the most important systems, since it requires significant power. Khayyam *et al.* (2009) reported that the mechanical compressor can increase fuel consumption by up to 12-17 per cent for subcompact to mid-size cars. Rugh *et al.* (2004) determined the magnitude of the potential reduction in fuel use due to incremental improvements in AC coefficient of performance (COP) over a baseline and the potential fuel saved per vehicle. For example, with a 25% improvement in AC COP, a car in Arizona could save 15.7 gallons per year.

In researching new technologies for the AC system, Li *et al.* (2009) showed that variable refrigerant flow system with water-cooled condenser can offer several interesting characteristics for potential users basis of a typical office building in Shanghai. The simulation results show that, during the whole cooling period, the fan-coil plus fresh air system consumes about 20% more power than the water-cooled condenser system does. In this way of AC with water-cooled condenser, Di Battista and Cipollone (2015) studied the opportunity to have an AC condenser cooled by a water circuit instead of the external air linked to the vehicle speed, as in the actual traditional configuration. And noted that the air conditioning could be housed on a low temperature water circuit, reducing the condensing temperature of the refrigeration cycle with a considerable efficiency increase.

Not only the concern with the reduction of engine consumption, but also AC has another important role with the environment, the protection of the ozone layer and the elimination of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Considering these factors, a given chemical substance can be associated with a global warming potential (GWP) to determine the degree that this substance contributes to global warming. The values of GWP, as well as ozone depletion potential (ODP) are calculated in relation to a substance adopted as a reference. Carbon dioxide is admitted with a value of 1.0. All other gases receive a value relative CO2 (Stocker *et al.*, 2014). EU F-Gases Regulation and European car's AC directives ban fluorinated gases with a GWP higher than 150 (Union, 2006). Nowadays the refrigerant used in most cars is the R134a, this refrigerant has a GWP 1430, therefore, in the last few years alternative refrigerants have been researched, and one that has stood out is R1234yf which has its GWP of 4 (Illán-Gómez and García-Cascales, 2019). However studies are showing that it can be used by making some modifications to the AC system (Meng *et al.*, 2018). Due to Daviran *et al.* (2017) showed in his study that the refrigerant-side overall heat transfer coefficient of R1234yf is 18% - 21% lower than that of R134a, and the pressure drop is 24% - 20% smaller than R134a during condensing and evaporating processes, respectively.

In this work, a mathematical model will be developed to investigate the feasibility of using water condensers in vehicle.

2. METHODOLOGY

The two system considered in this study are shown in Fig. 1. In the conventional system the main components are the hermetic reciprocating compressor, two cross flow unmixed air-cooled heat exchanger and a capillary tube. The main difference of the conventional system and proposed system is the water-cooled condenser. The refrigerants chosen are the R134a and R1234yf. The first one is most used in air conditioner system and the second is one option to replace the use R134a due the its high impact in global warming (Daviran *et al.*, 2017; Garcia *et al.*, 2018; Duarte *et al.*, 2019a).

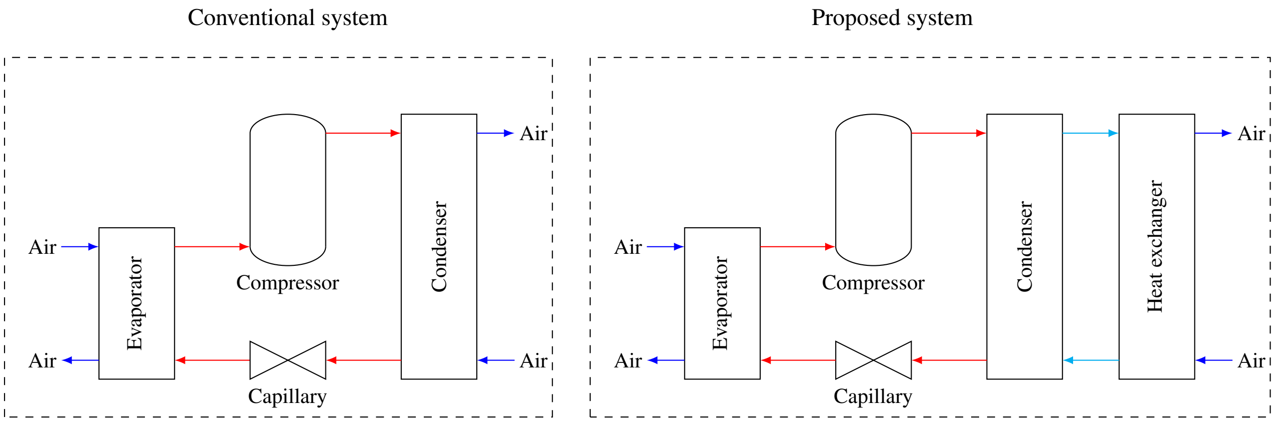

Figure 1. Main components of conventional and proposed air conditioner system.

In order to evaluate the performance of the geothermal and conventional air conditioner a quasi-steady-state model was developed using the Equation Engineering Solver (EES). The losses in the tubes between components was considered negligible. The evaporator and condenser was assumed as isobaric and a lumped model was used. Following is described the modelling equation for each component.

2.1 Compressor model

In the literature, there are some very detailed model of compressors (Duprez *et al.*, 2007; Ndiaye and Bernier, 2010; Duarte *et al.*, 2019b) but these models required many parameters and geometrical details that are not provide by the manufactures of the compressors. Additionally, the compressor model used in the complete model of the refrigeration system is a simple one, assuming a isentropic compression process, as those employed in other works (Minetto, 2011; Rabelo *et al.*, 2019; de Paula *et al.*, 2020). The refrigerant mass flow rate ($\dot{m}_r$) in a reciprocating compressor is given by (Minetto, 2011):

$$\dot{m}_r = \rho_1 \dot{V}_{cp} \tag{1}$$

where ρ is the refrigerant density, $\dot{V}_{cp}$ is the compressor volumetric flow rate. The compressor power consumption ($\dot{W}_{cp}$), and the volumetric flow rate, in m^3/h, is evaluated by:

$$\dot{V}_{cp} = 0.225 N^{0.652} \left(\frac{P_2}{P_1}\right)^{-0,6348} \tag{2}$$

$$\dot{W}_{cp} = 3.009 N^{1.023} \left(\frac{P_2}{P_1}\right)^{-0.5165} \tag{3}$$

where P is pressure, N is the rotation speed, in rpm, and the subscript 1 and 2 refers to compressor inlet and outlet of compressor. This equations was adjusted to the performance data given by the manufacturer using optimization algorithms to minimize the mean absolute difference and the maximum absolute difference between (EQ. 4) the values of equation adjusted and the performance data.

$$\text{MAD} = \frac{1}{n}\sum_{j=1}^{n}\left|\frac{\dot{W}_{calc} - \dot{W}_{per}}{\dot{W}_{per}}\right| \tag{4}$$

2.2 Evaporator

The evaporator and condenser are modeled using the using the effectiveness-NTU method as made by Rabelo *et al.* (2019). The balance of energy in the refrigerant is given by:

$$\dot{Q}_{re} = \dot{m}_r(i_1 - i_4) \tag{5}$$

where $\dot{Q}_e$ is the heat transfer rate in the evaporator, i is the refrigerant specific entalphy and the subscripts 4 and 1 refers to the refrigerant inlet and outlet of the evaporator, respectively. The balance of energy in the humid air is given by (Borgnakke and Sonntag, 2018):

$$\dot{Q}_{ae} = \dot{m}_e((h_{ei} - h_{eo}) + (\omega_{ei} - \omega_{eo})h_l) \tag{6}$$

where $\dot{m}_e$ is the mass flow rate of dry air in the evaporator, h is the entalphy per mass of dry air, ω is the absolute humid and the subscripts ei and eo refers to the air inlet and outlet of the evaporator, respectively. In this work the relative humidity in the inlet and outlet of evaporator is assumed constant at 60% and 95%, respectively. The effectiveness (ε) of evaporator is evaluated as by EQ. 7 and the maximum heat transfer heat ($\dot{Q}_{max}$) is evaluated in similar way of EQ. 6 but considering the air outlet temperature equal to the evaporating temperature and the value of relative humidity of 100% (Incropera *et al.*, 2007; Borgnakke and Sonntag, 2018).

$$\varepsilon_{ea} = \frac{\dot{Q}_e}{\dot{Q}_{max}} \tag{7}$$

The effectiveness of the evaporator was obtained adjusting the EQ. 8 to the performance data given by the manufacturer with coefficient of determination (R^2), as described by Chapra and Canale (2008), of 99.8%.

$$\varepsilon_{eb} = 1.0514 - 0.03734(T_{eo} - T_4) \tag{8}$$

2.3 Condenser

The heat transfer rate loss by the refrigerant in the condenser ($\dot{Q}_{cd}$) is given by:

$$\dot{Q}_{cd} = \dot{m}_r(i_2 - i_3) \tag{9}$$

where the subscript 3 refers to outlet of condenser. The heat transfer rate gain by the air in the air-cooled condenser is given by:

$$\dot{Q}_{cd} = \dot{m}_{cd}C_{pa}(T_{co} - T_{ci}) \tag{10}$$

where $\dot{m}_{cd}$ is the mass flow rate of air in the condenser, C_{pa} is heat capacity at constant pressure of air the subscripts ci and co refers to the air inlet and outlet of the condenser, respectively. The effectiveness (ε) of condenser is:

$$\varepsilon_{ca} = \frac{\dot{Q}_{cd}}{\dot{Q}_{max}} \tag{11}$$

the maximum heat transfer heat ($\dot{Q}_{max}$) is evaluated by:

$$\dot{Q}_{max} = \dot{C}_{min}(T_2 - T_{ci}) \tag{12}$$

In this equations, $\dot{C}_{min}$ is the smaller heat capacity rate between air and refrigerant. The heat capacity rate of air and refrigerant can be expressed as:

$$\dot{C}_{cd} = \dot{m}_{cd}C_{pa} \tag{13}$$

$$\dot{C}_r = \dot{m}_r\frac{i_1 - i_4}{T_1 - T_4} \tag{14}$$

Table 1. Main simulation parameters

Parameter	Value	Parameter	Value	Parameter	Value
Atmospheric Pressure	92 kPa	Evaporator fan power	100W	Condenser fan power	100W
Super-heating	7^oC	Evaporator fan mass flow	300kg/h	Condenser fan mass flow	1200kg/h
Subcooling	5^oC	Evaporator air inlet temperature	35^oC	Condenser air inlet temperature	45^oC
Rotational speed	1800 rpm	Condenser pump mass flow	300kg/h	Condenser pump power	100W

The effectiveness of the air-cooled condenser was obtained adjusting the EQ. 15 to the performance data given by the manufacturer with coefficient of determination (R^2) of 99.5%.

$$\varepsilon_e = 0.9309 - 0.01351(T_3 - T_{ci}) \tag{15}$$

The model of water-cooled condenser is similar of or air cooled condenser but the thermodynamic properties of water instead of air and effectiveness that is given by:

$$\varepsilon_e = 0.91 - 0.01494(T_3 - T_{ci}) \tag{16}$$

This equation was adjusted to the performance data given by the manufacturer with coefficient of determination (R^2) of 98.4%.

2.4 Numerical procedure

In fact, the pressure of the refrigerant in the evaporator and condenser is not known and cannot be obtained from of the equations present so far. An algorithm explaining how these pressures are obtained is shown in Appendix A. The secant method mentioned in Appendix A is described in detail by Chapra and Canale (2008) and the errors E_e and E_c, in percent, is given by:

$$E_{eo} = \left| \frac{\dot{Q}_{ae} - \dot{Q}_{re}}{\dot{Q}_{re}} \right| \cdot 100 \tag{17}$$

$$E_e = \left| \frac{\xi_{ea} - \xi_{eb}}{\xi_{ea}} \right| \cdot 100 \tag{18}$$

$$E_c = \left| \frac{\xi_{ca} - \xi_{cb}}{\xi_{ca}} \right| \cdot 100 \tag{19}$$

The coefficient of performance (COP) is defined as follow:

$$COP = \frac{\dot{Q}_e}{\dot{W}_{cp} + \dot{W}_{aux}} \tag{20}$$

where $\dot{W}_{aux}$ is the fan and/or pump power consumption. A list of the main parameters used in the following simulations is presented in Tab. 1.

3. RESULTS

A comparison of COP for different rotations speed using the air-cooled and water cooled condensers, R134a and R1234yf is shown in FIG. 3. The COP reduces with the increase of the rotation speed for all systems. If the the rotation speed increases, the refrigerant mass flow also increases (EQ. 1 and 2), therefore the heat transfer heat in the evaporator and condenser also increase. Although, the analysis of the correlations of Shah (2017) for boiling and Shah (2016) for condensation shows that the increase of refrigerant mass flow increases the convective heat transfer coefficient, is expected that the difference of temperate between the secondary fluid and the refrigerant also increases leading to a increase in the condensing pressure and and to a reduction of evaporation pressure, and increasing the the power consumption of compressor. These variation of pressure is shown the FIG. 4 for R134a.

This tendency of reducing the COP with the increase of rotation speed was also presented by Daviran *et al.* (2017) for air-cooled condenser. The difference of COP for an R134a air-cooled condenser in the results of Daviran *et al.* (2017) at 1800 rpm and the results in FIG. 3 is approximately 7%. The simulations shown that the COP of R1234yf is 18% to 22% lower than R134a for air-cooled condenser and 18% to 28% lower for water-cooled condenser. Many works have reported a lower COP of R1234yf than R134a, Lee and Jung (2012) detected a 0.8 to 5% lower COP, Daviran *et al.* (2017) noticed

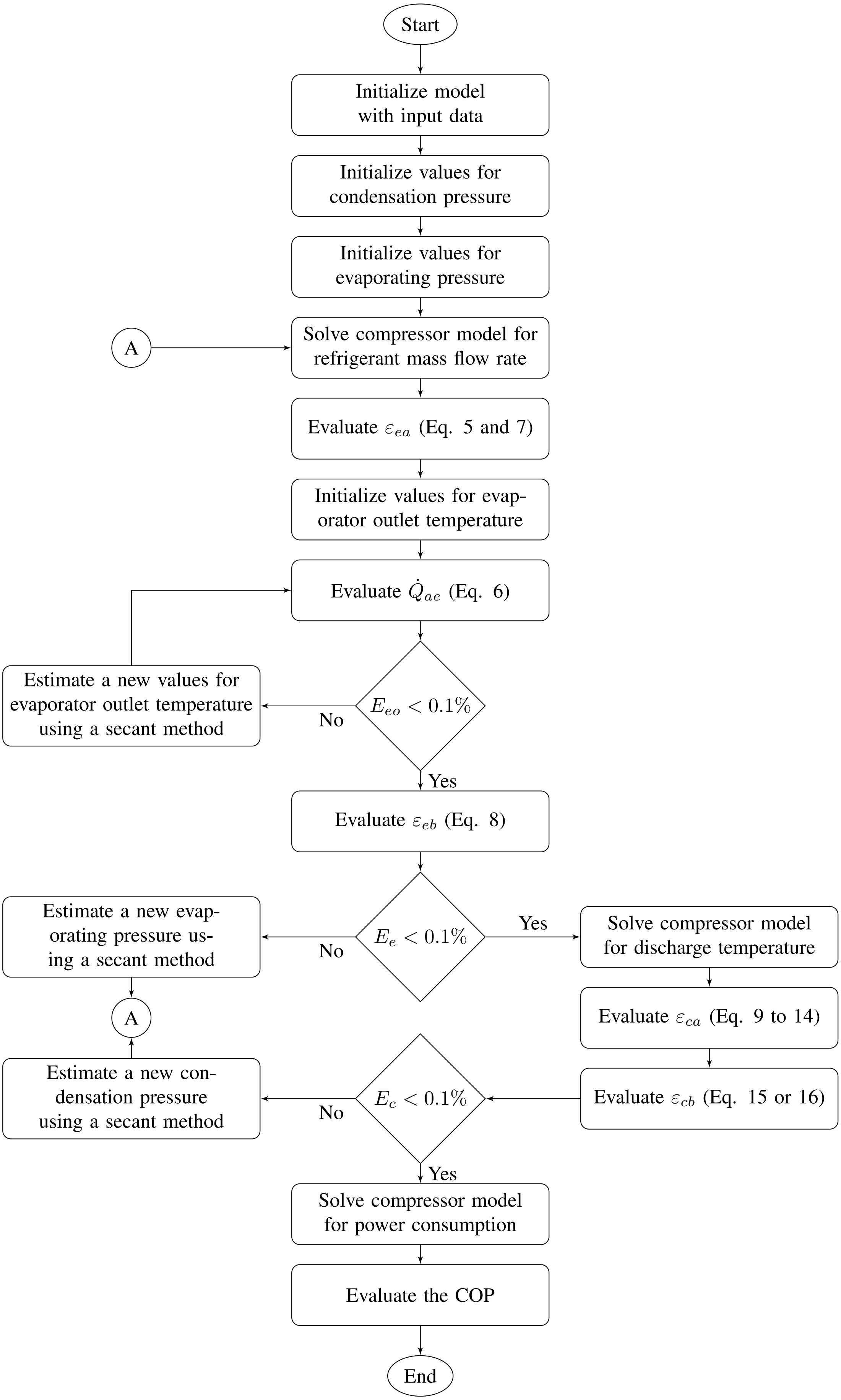

Figure 2. Algorithm used to solve the equations of the model

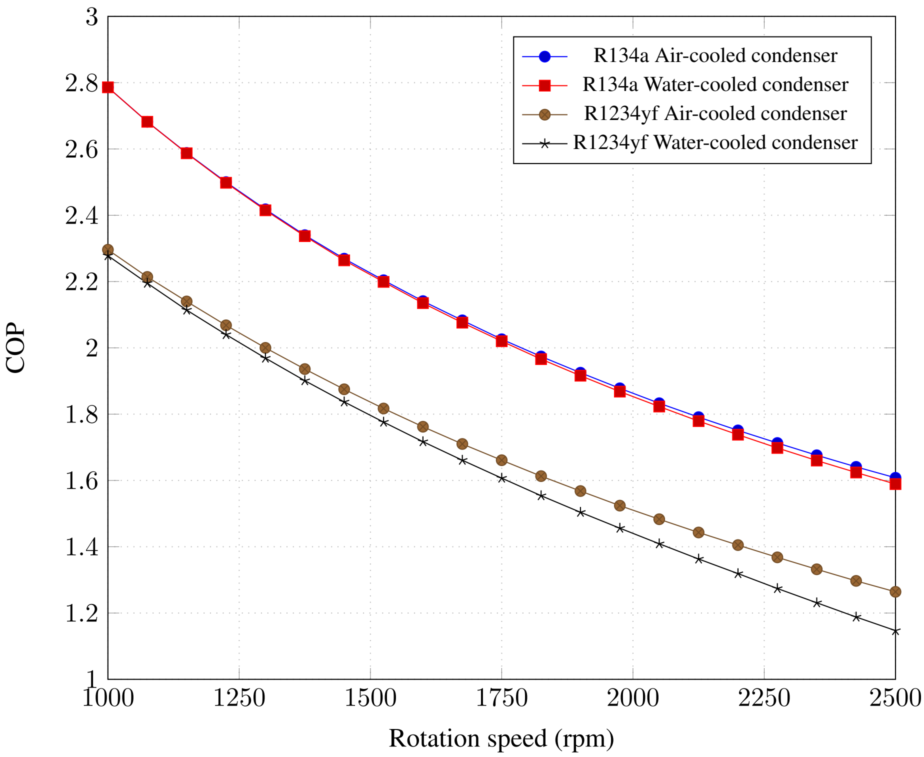

Figure 3. Variation of COP in function of the rotation speed..

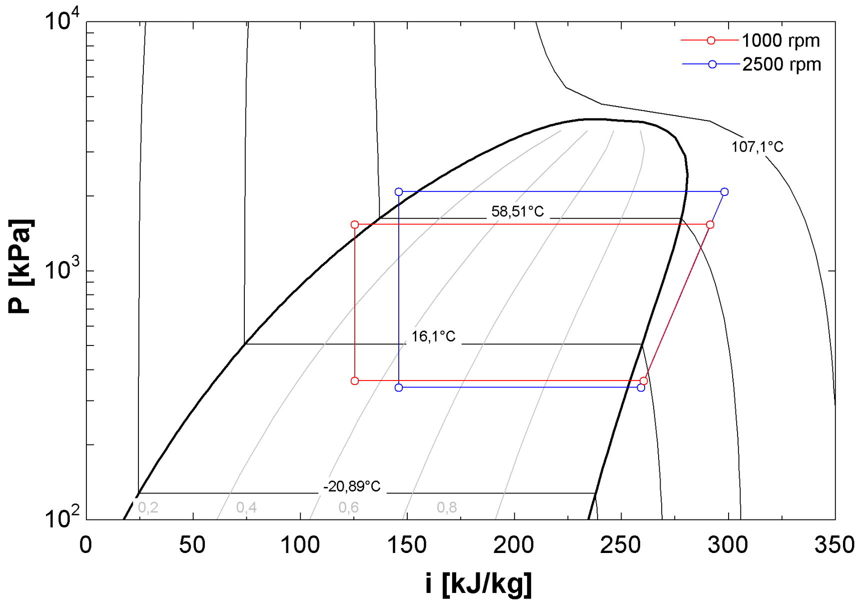

Figure 4. Diagram pressure versus specific enthalpy for rotations speed of 1000 rpm and 2500 rpm using air-cooled condenser.

a 1.3 to 5% lower COP, Duarte *et al.* (2019a) reported a 20 to 21% lower COP, Illán-Gómez and García-Cascales (2019) noticed a COP around 25% lower, de Paula *et al.* (2020) detected a COP 14% lower.

A comparison of cooling capacity for different rotations speed using the air-cooled and water cooled condensers is shown in FIG. 5. Since the simulation made for this figure assume a fixed mass flow rate of secondary fluid at the evaporator and condenser, for higher rotational speed the cooling capacity is higher if the air-cooled condenser is used. A higher cooling capacity for R134a than R1234yf was also presented by Daviran *et al.* (2017) for air-cooled condenser.

The comparisons of cooling capacity and COP for different condenser inlet temperature are shown in FIG. 6 and 7. The COP decrease with temperature of condenser inlet, except for R1234yf with water-cooled condenser that have a maximum

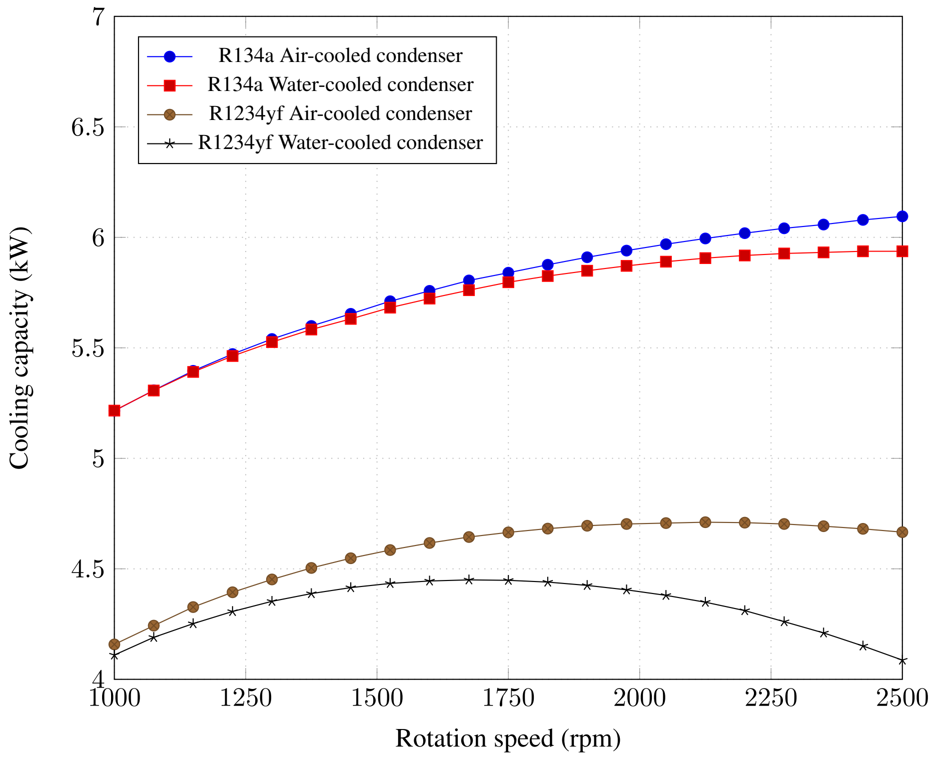

Figure 5. Variation of cooling capacity in function of the rotation speed.

point around 43^{o}C. In the range of 35 to 43^{o}C the effectiveness of R1234yf water-cooled condenser is decreasing with the decrease of the condenser inlet temperatures, increasing the condensing pressure that reduces the COP and the cooling capacity.

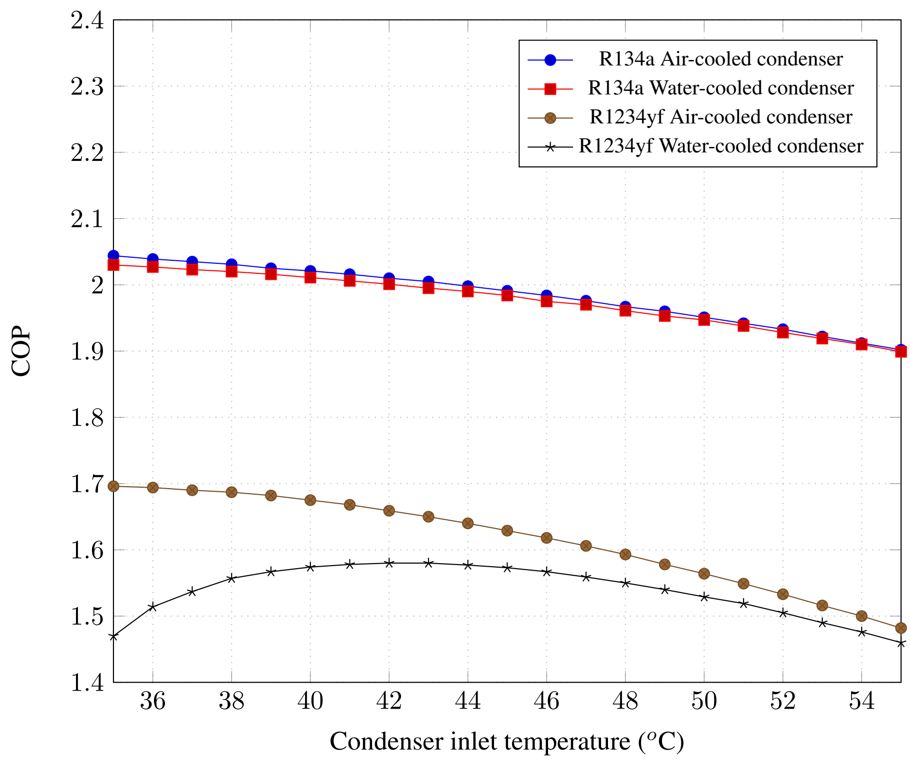

Figure 6. Variation of COP in function of the condenser inlet temperature.

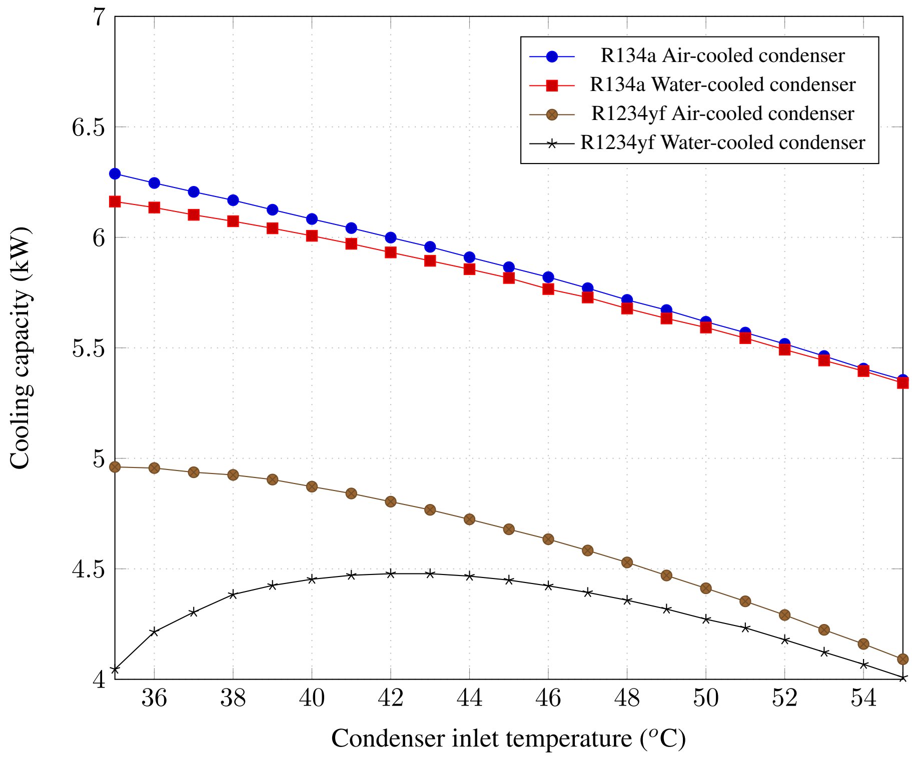

Figure 7. Variation of cooling capacity in in function of the condenser inlet temperature.

4. CONCLUSIONS

In this work presents a mathematical model of the AC system, conceived to represent specific operating conditions of the mobile units. This study presented a comparative analysis of AC system with an air and water condenser. And also, two refrigerants R134a and R1234yf. Based upon the simulation results, following conclusion can be drawn.

- COP reduces with the increase of the rotation speed for all systems.
- The COP of R1234yf is 18% to 22% lower than R134a for air-cooled condenser and 18% to 28% lower for water-cooled condenser.
- The cooling capacity increases with the increase rotation, except for R1234yf with water-cooled condenser that have a maximum point around 1750rpm.
- COP decrease with higher temperature of condenser inlet, except for R1234yf with water-cooled condenser that have a maximum point around 43^{o}C.
- The Cooling Capacity of R1234yf is lower than R134a.

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