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ENC-2022-0369 TRANSIENT ASSESSMENT OF LOW-GWP FLUIDS IN A TWO-STAGE REFRIGERATION SYSTEM

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Abstract. *Efficient thermal management is particularly needed in electric vehicles because it can substantially increase the range and lifespan of the battery. An engineering approach to address this issue is using numerical analysis. In this study, a transient model was proposed for the refrigeration system of the battery and cabin of an electric vehicle using MATLAB and REFPROP. The refrigeration cycle is based on vapour compression of the refrigerant. The refrigerant fluids considered in the analysis are R-134a, R-1234ze, R-1234yf, and R-32. It was considered the volumetric refrigerant effect for each fluid, in order to make a reasonable comparison between them. The system consists of a compressor, condenser, expansion valve, and evaporator with a heat exchanger between the exit of the condenser and the exit of the evaporator. There is one evaporator for both the cabin and battery. The psychrometric properties of humid air were used to evaluate the thermodynamic properties and calculate mass diffusion. The thermodynamic properties of the fluid were calculated using REFPROP linked with MATLAB. The results provide a relevant computing code for the evaluation of vapour compression cycles and compares the performance of different refrigerant fluids.*

Keywords: *vapour compression refrigeration system, electric vehicle, automotive air-conditioning, automotive air-conditioning system.*

1. INTRODUCTION

Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) have long been presented as a viable substitute of conventional internal combustion vehicles (Safdari et al, 2022). Since their launch, one main concern regarding their utilization is range: it is necessary to make sure the vehicle can travel a long distance before depleting its battery charge. In this aspect, it is important to notice that the lack of good thermal management may lead to significant performance loss. Therefore, a suitable Battery Thermal Management System (BTMS) is mandatory for EVs. Thakur et al (2020) have presented a state-of-art review of cooling techniques for EVs, which includes air-cooled, heat pipe cooled and liquid-cooled BTMSs, where the current work falls under the direct refrigerant cooling category.

Refrigerant fluids have also experienced a change over the years. The most recent ones tend to have lower environmental impact, as described by Vuppaladadiyama et al. (2022), seeking characteristics such as low global warming potential (GWP), being non-toxic, non-flammable, and having zero-ozone depletion potential (ODP), while still offering good thermophysical properties. R-134a has been the most used refrigerant in vehicle air conditioning since 1994, according to the United States Environmental Agency - EPA (2022), and, starting from 2021, all newly-manufactured domestic vehicles in the USA will no longer use R-134a. Although it has low ODP, R-134a still has high GWP and since the 2010's, car companies have started to transition to other refrigerant fluids, more environment-friendly, such as R-1234yf, R-1234ze and R-32.

On pair with the up-to-date needs of the industry, this work presents a numerical model for a HEV refrigeration cycle, which conjugates both the cabin refrigeration, for air-conditioning cooling for the passengers of the vehicle, as well as the battery refrigeration. The model proposed consists of a compressor, a condenser, an expansion valve and two evaporators working at the same pressure. The condenser and the evaporators and studied in their transient phase, while the compressor and expansion valve are assumed to start working in steady state since the start of the cycle. All calculations were performed using MATLAB, linked with REFPROP, so that all fluid properties could be calculated at each instant of the cycle.

Finally, this article provides plots for both condenser and evaporator temperatures over time for each of the refrigerant fluids considered.

2. METHODOLOGY

A numerical approach is presented. A vapour-compression system consisting of compressor, evaporator, expansion device and two evaporators was modeled. The computational code was written for MATLAB 2022 Academic Version, and the thermophysical properties of each refrigerant fluid was determined using REFPROP. A tool was used to link MATLAB and REFPROP, so that all properties could be adequately evaluated at each step of the solution. The Figure 1, as seen in Vegini (2022), is a good representation of the refrigeration cycle employed in the current work.

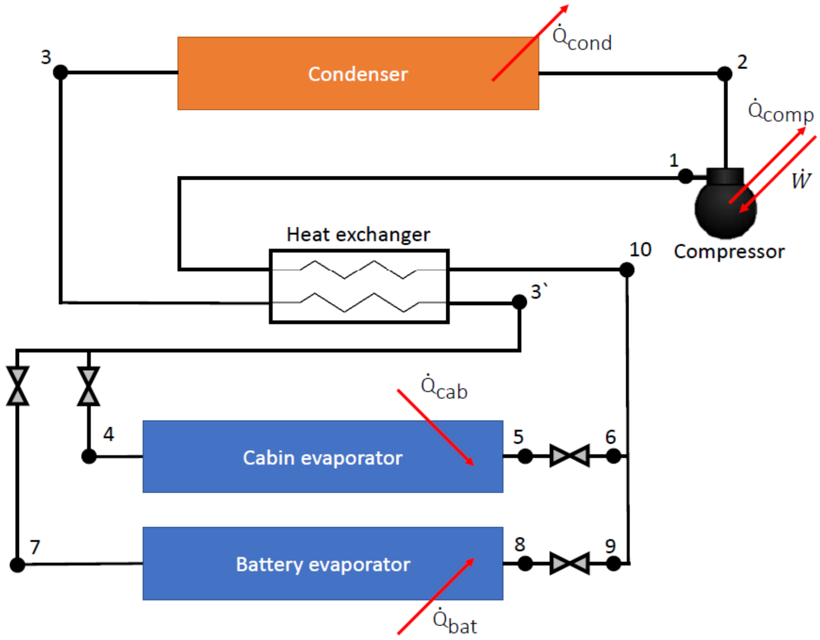

Figure 1. The refrigeration cycle used to control the temperature of the cabin and the battery at the same time, as seen in Vegini (2022).

It is important to notice that the pressure difference between evaporators will not provide excellent performance, as shown in Vegini (2022). Therefore, the present work only studies the case in which both evaporators work at the same pressure. One evaporator corresponds to the passenger comfort, being employed in the cabin, while the other one cools down the battery. It is also worth noticing that point 4 will have the same specific enthalpy as point 7, while point 5 will have the same specific enthalpy as point 8.

The heat exchangers, i.e., condenser and both evaporators, were modeled in their transient phase, whereas the compressor and the expansion valve transient stages were assumed to be so short compared to the transient stage observed in the heat exchangers that they were neglected. The heat transfer between compressor and environment was considered in the calculations.

In this work, the compressor volume was updated accordingly to each fluid, as to maintain the same volumetric refrigerant effect in all cases, as described in Vegini (2022). It was necessary to change the compressor's volume so that one could compare the results with different refrigerant fluids.

The calculation process was represented in Fig. 2. It is required to determine the condensation and the evaporation temperature of the refrigerant fluid over time. The solution is found with an initial guess for both condensation and evaporation temperatures. Since both evaporators are running at the same pressure, they also share the same temperature and the same specific enthalpy at the entrance and exit of each device. An iterative solution is required to determine the correct mass flow in each evaporator. The bisection method was deemed suitable for this purpose. Finally, an explicit energy balance is proposed to calculate the temperature at the next time step.

2.1 Governing mathematical equations

There is a thermostatic valve at the end of the condenser, to ensure a decrease temperature past condensation. There is also an internal heat exchanger. With an initial guess of T_C and T_E, it is possible to determine the following quantities, one by one. In the equations displayed here, T represents temperature, while the subscripts *1, 3, 5, sub* and *sup* represent compressor inlet, condenser outlet, evaporator outlet, subcooling and superheating, while *c* represents condenser, *e* represents evaporator and *IntHX* represents the efficiency of the internal heat exchanger:

$$T_3 = T_C - T_{SUB} \tag{1}$$

$$T_5 = T_E + T_{SUP} \tag{2}$$

$$T_1 = T_5 + IntHX(T_3 - T_5) \tag{3}$$

Those temperatures were used to evaluate the thermophysical properties of each fluid, at specific values of condensation and evaporation pressure.

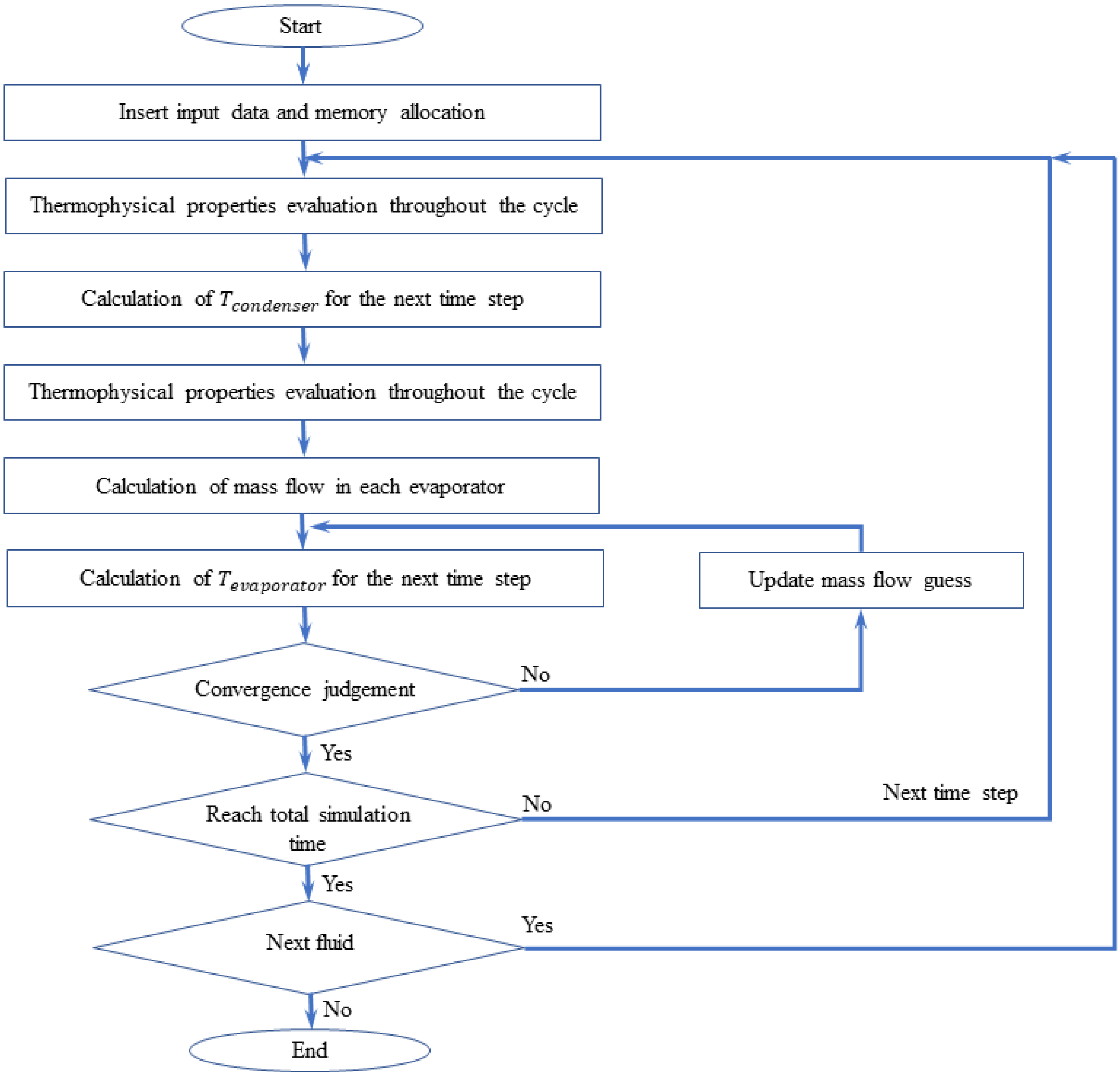

Figure 2. Calculation flowchart for the transient model proposed

The mass flow rate was modeled based on Borges (2015), as:

$$\dot{m} = {ROT * \eta_V * V_{eq}}/{v} \tag{4}$$

Where $\dot{m}$ is the fluid mass flow rate, ROT is the rotational speed, η_G is the volumetric efficiency, v is the specific volume and V_{eq} is the equivalent volume, which is calculated according to the following relation, for each refrigerant fluid:

$$V_{eq} = V_{R-134a} \, {}^{VRE_{R-134a}}/_{VRE} \quad (5)$$

The variables used in equation (5) mean, respectively: V_{R-134a}, the volume of the compressor for a standard refrigerant fluid, in this work chosen as R-134a; VRE_{R-134a} is the volumetric refrigerant effect for R-134a, the standard refrigerant fluid; and VRE, the volumetric refrigerant effect of each fluid, which will lead to the refrigerant's equivalent volume.

As for the compressor, it was modeled according to the following equations, as seen in Borges (2015), to find the enthalpy at the compressor discharge:

$$POT = {}^{\dot{m}(h_{2s} - h_1)}/_{\eta_G} \quad (6)$$

Where POT means the compressor power, h_1 is the specific enthalpy at the compressor inlet, h_{2s} is the specific enthalpy at the compressor discharge in an isentropic process going from h_1 at evaporator pressure to h_2 at condenser pressure, and η_G represents the global efficiency of the compressor.

$$h_{2s} = h_1 + {}^{POT}/_{\dot{m}} \quad (7)$$

The subscript a means that the enthalpy found at this step is the adiabatic enthalpy.

$$\dot{Q}_{comp} = UA_{comp}(T_{2a} - T_{2a}) \quad (8)$$

$\dot{Q}_{comp}$ is the rate of heat transfer, from the compressor to the environment, while UA_{comp} is the conductance of the compressor and T_{2a} is the ambient temperature.

$$h_2 = h_1 + {}^{(POT - \dot{Q}_{comp})}/_{\dot{m}} \quad (9)$$

With an initial guess for condenser and evaporator temperature at time $t = 0$, one can calculate the temperature in the next time step utilizing an energy balance on the condenser, for a given T_C, an energy balance on both evaporators, followed by a refrigerant mass flow balance. For the condenser, the temperature of the next time step may be found using the following equation:

$$C_C(T_{C-new} - T_{C-current})/_{dt} = \dot{m}(h_2 - h_3) + UA_C(T_{C-current} - T_{amb}) \quad (10)$$

Where C is the heat capacity. Similarly, for each evaporator, the energy balance is given by

$$C_{cab}(T_{ECN} - T_{ECC})/_{dt} = \dot{m}_{cab}(h_3 - h_1) + UA_{cab}(T_{cab} - T_E) \quad (11)$$

$$C_{bat}(T_{EBN} - T_{ECC})/_{dt} = (\dot{m} - \dot{m}_{cab})(h_3 - h_1) + UA_{bat}(T_{bat} - T_E) \quad (12)$$

Where $\dot{m}$ is the total refrigerant mass flow rate, while $\dot{m}_{cab}$ is the refrigerant flow rate passing through the cabin's evaporator. It is important to notice that the evaporator temperature of the next time step T_E should be the same for both cabin (T_{ECN}) and battery (T_{EBN}), since they are working at the same pressure. To make this statement true, it is necessary to calibrate $\dot{m}_{cab}$, until both T_{ECN} and T_{EBN} have an acceptable agreement, which was done in this work using the bisector method. T_{cab} and T_{bat} means the cabin and the battery temperature, respectively.

The heat capacities of both heat exchangers were considered for the analysis. Therefore, it was not necessary to assess the heat capacity of the refrigerant fluid because the object of analysis in Equations 10, 11 and 12 was the heat exchangers themselves and not the fluid running through them. This means that C_C, C_{cab} and C_{bat} represent the heat capacities of the equipment instead of the fluid.

The calculations were performed for all refrigeration fluids studied in this work: R-134a, R-1234ze, R-1234yf and R-32. Both condensation, evaporation and mass flow rate obtained by this process were used to analyze the system behavior over time.

3. RESULTS AND DISCUSSION

The data input was obtained mostly by tests carried with a Battery Electric Vehicle (BEV), the only exception being the heat capacity for the condenser, the battery pack and the cabin, which were determined by making an analogy with the values presented by Andrade (2013), with a refrigerator. It was considered that the ratio heat capacity to heat conductance was approximately constant in both Andrade's (2013) work and Vegini's (2022) work, making it possible to determine the heat capacity for both cabin and battery pack in the present work. For the condenser, the ratio was multiplied by 2, as an attempt to make up for the presence of forced convection in the car condenser, because the work described by Andrade (2013) considered only natural convection. The values are shown in Tab. 1.

Figure 3 shows that R-32 requires the least mass flow rate for the specified system, while R-1234ze has a mass flow rate change over time very similar to that observed with R-134a, while R-1234yf required the most mass flow rate. Taking R-134a as a reference, upon reaching steady state, the mass flow rate of R-1234ze, R-1234yf and R-32 correspond to the values shown on Tab. 2.

It can be seen from Fig. 4 that there is an overall convergence for condenser and evaporator fluid temperature once the system reaches steady state, regardless of the fluid. However, R-32 does so noticeably faster than its counterparts, R-134a, R-1234yf and R-1234ze. This result was expected, since both R-1234ze and R-1234yf were created to substitute R-134a, under the premise to provide thermophysical properties similar to those of the R-134a, while being less aggressive to the environment. They also have the same behavior, with a temperature overshoot that peaks at about 15 minutes after the start and diminishes until reaching the equilibrium.

The steady state temperature for R-134a, R-1234ze, R-1234yf and R-32 are, respectively, 44.02 ºC, 44.12 ºC, 44.23 ºC and 43.90 ºC for condensation, and 14 ºC, 13.98 ºC, 13.96 ºC and 13.91 ºC for evaporation, which means that there was not a noticeable difference in condensation temperature between refrigerants at steady state.

From Fig. 4, both R-134a, R-1234ze and R-1234yf reach steady state roughly at 1 hour and 10 minutes after the cycle starts, and all of them have display a temperature overshooting of about 2 ºC, with exception of R-32, whose highest temperature was 45.53 ºC, thus being 1.63 ºC above steady state temperature.

Table 1. Input data for the mathematical model

Input name	Symbol	Value	Unit
External Temperature	T_{amb}	32	[ºC]
Cabin Temperature	T_{cab}	27	[ºC]
Battery Temperature	T_{bat}	30	[ºC]
Reference volume	V_{ref}	27E-6	[m³]
Compressor rotation	Rot	120	[Hz]
Volumetric efficiency	η_V	0.7	[-]
Global efficiency	η_G	0.6	[-]
Sub cooling	Sub	5	[ºC]
Super heating	Sup	5	[ºC]
Internal HX efficiency	IntHX	0.9	[-]
Compressor conductance	UA_{comp}	0.5	[W/K]
Condenser conductance	UA_{cond}	700	[W/K]
Cabin conductance	UA_{cab}	500	[W/K]
Battery pack conductance	UA_{bat}	100	[W/K]
Condenser heat capacity	C_c	430000	[J/K]
Cabin heat capacity	C_{cab}	688700	[J/K]
Battery heat capacity	C_{bat}	133000	[J/K]

Table 2: correspondence between mass flow for each refrigerant and its value relative to R-134a.

Refrigerant	Mass flow, steady state [kg/h]	Relative to R-134a [%]
R-134a	167.4	100
R-1234ze	180	107.5
R-1234yf	207	123.6
R-32	107.3	64.1

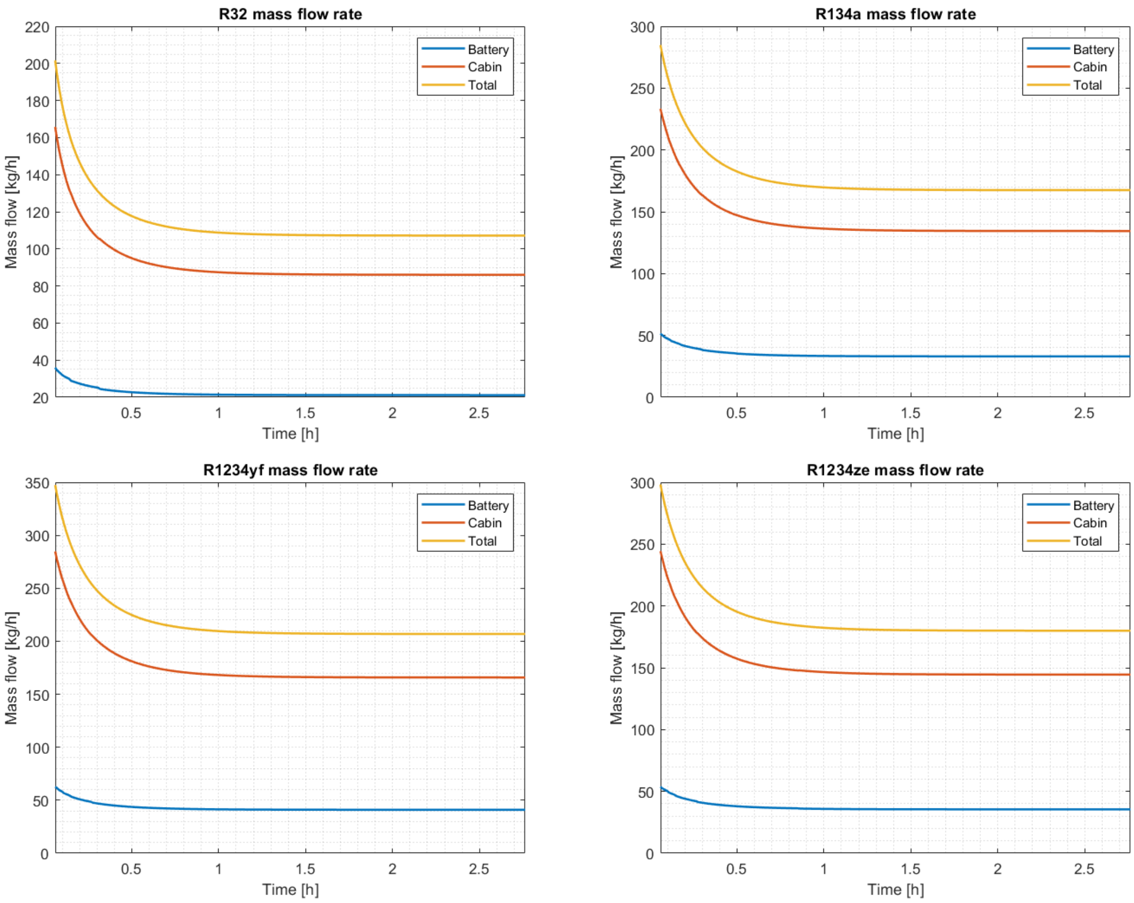

Figure 3: mass flow rate over time for each refrigerant fluid considered in this analysis. From top left to bottom right, R-32, R-134a. R-1234yf and R-1234ze.

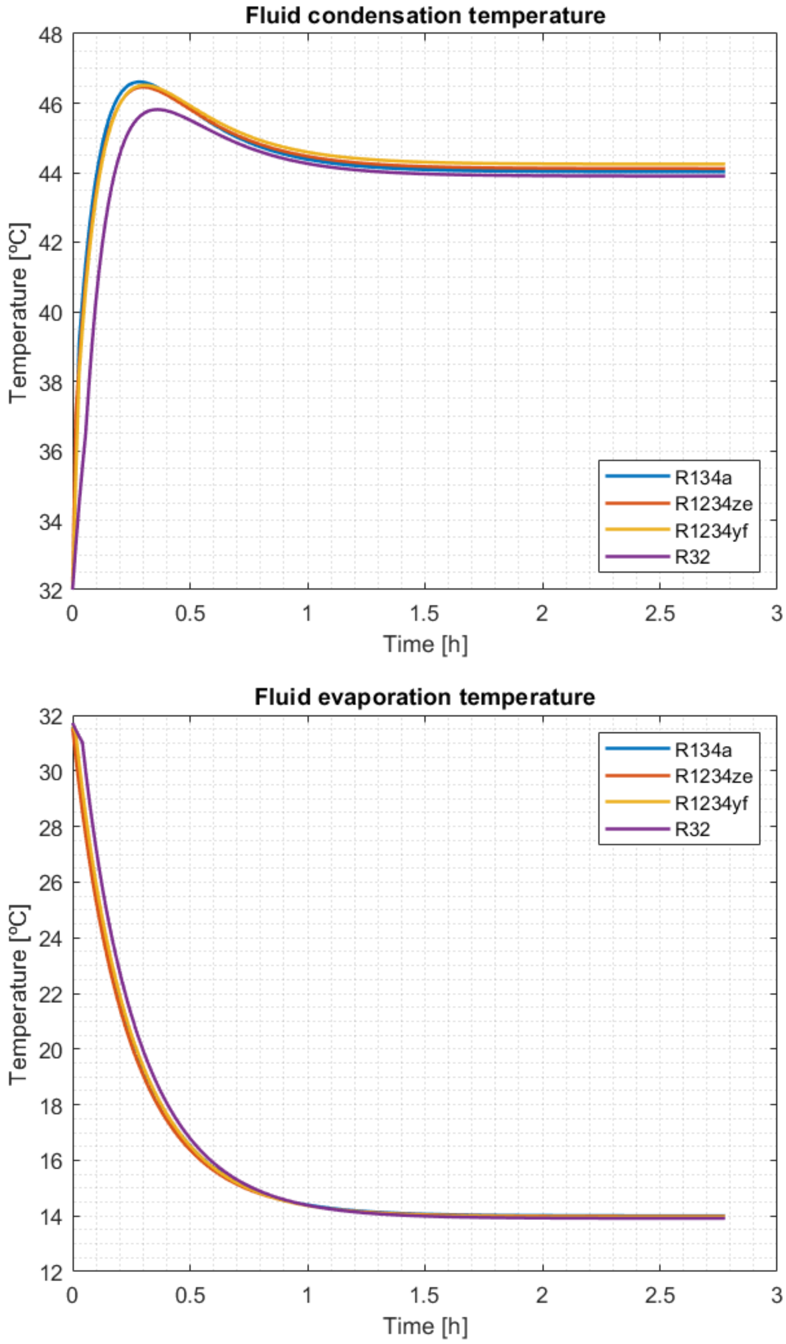

Figure 3: condensation (top) and evaporation (bottom) temperature over time, for each refrigerant.

4. CONCLUSION AND FURTHER WORKS

This work presented a numerical analysis of an EV air-conditioning refrigeration cycle, working under vapour-compression condition, with different refrigerant fluids. The mathematical model employed was also described, with emphasis on the fact that this model is composed by two evaporators: one for the cabin and another one for the battery pack. This works shows that the refrigerant fluids suggested to take R-134a's place in the car refrigeration industry can, indeed, substitute their predecessor, while being far more environment-friendly, posing as good alternatives to R-134a.

The time necessary to reach a steady state is about 70 minutes, what means that knowing the transient solution of such system plays a key role in determining how the system itself works. Considering that EV are mostly used in urban areas, for periods of time shorter than 40 minutes, it is reasonable to assume that the refrigeration system in EV are governed mainly by the transient solution.

Future works could implement a more detailed model for both condenser and evaporator, considering the latent heat transfer existent on the cabin evaporator, since an air-conditioning system is also expected to change the ambient humidity.

5. ACKNOWLEDGEMENTS

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