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Predictive model that seeks to optimize the use of energy necessary for thermal comfort in electric vehicles

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ABSTRACT Thermal Management in electric vehicles is being a real nightmare. The range of these vehicles is closely related with the temperature of the batteries and the electric consumption of the HVAC system. All the heat generated by the batteries, passengers and the electric engine has to be dissipated in order to keep the temperature within the optimal range. Internal combustion engines can withstand higher temperatures and by burning fuel there is an almost limitless source of heat. The vehicles that use petrol and diesel have a higher range and that is one of the reasons why electric vehicles manufacturers are improving the batteries and the use of energy, to try to compete in the automotive market. On the other hand, the world is becoming greener every day, and the principal manufacturers are trying to reduce polluting emissions. Refrigerants were one of the most polluting parts of the cars so new laws are appearing against the worst ones. The solution proposed in this article is to explore new possibilities for the refrigerant used in the HVAC and try to develop a prototype of the software used in Predictive Thermal Management. This software is about optimizing the use of the HVAC avoiding energy peaks and maintaining a constant minimum consumption. Thanks to the software, the HVAC system can maintain the temperature on its optimum consuming the minimum amount of energy.

INDEX TERMS Thermal Management, Electric vehicles, xEVs, Predictive Thermal Management, HVAC, Refrigerant, GWP, ODC, PTC, Compressors, Two-stage cycle, Closed Intercooler, Open Intercooler

I. INTRODUCTION

The world is changing, it is becoming more and more respectful with the environment trying to reduce all kinds of harmful emissions. One of the most polluting sectors is the automotive. New alternatives are appearing to reduce the use of internal combustion engines. Hybrid vehicles were the first step to a new concept of mobility.

With the development of full electric vehicles and the restrictions that governments are imposing to the most polluting cars, the investment in green mobility is increasing. This investment is intended to improve electric vehicles. The main problem is the range of the vehicle and the recharging time. There are many options to increase the limited range that EVs have, for example, new kinds of batteries or PCM (phase change materials). Those are new ways of storing electric and thermal energy.

The aim of this project has been to design a new refrigeration cycle using a fluid that is environmentally friendly (R290) and implant all the calculations in a software.

Otherwise, GA is not a battery or HVAC manufacturer, so we studied other possibilities. There is a concept called Predictive Thermal Management that reduces the electric consumption of the HVAC by using it wisely. The main purpose of the Predictive Thermal Management is to develop a software that can decide when to cool the cabin and when to heat it. Just like the GPS plans the trip, the software can collect weather information of several points and prepare the car to cool or heat in advance avoiding the peaks of consumption.

On the other hand, as long-distance trips are becoming more frequent, planes, trains and cars are trying to turn them into a new user experience. The seats are more comfortable, there is entertainment for every passenger and thermal comfort is guaranteed.

Regarding both problems, cars manufacturers are increasing the comfort of the passengers and reducing the waste of energy. The objective of the project is to ensure thermal comfort during the whole trip but taking into account that the range is highly reduced when the HVAC requires too much cooling or heating.

There are several technologies that can complement traditional HVAC. For example, electric heaters or PTCs (Positive Temperature Coefficient) are used in extreme conditions (when temperature is below -10ºC) where traditional heat pumps do not work.

Besides, we decided to explore and analyze the world of thermal sensations. There are many experiments that prove that human beings perceive a temperature different that the ambience depending on the lightning. That means that if the lights are warm, the passengers will have the sensation of being in a warmer cabin.

The Predictive Thermal Management software collects all the calculation of the refrigeration cycle, the heat created inside and outside the cabin and the implication of lightning in the inside of the vehicle. For the development of the software, we decided to use Python because is free code and it has many libraries about Big Data and Machine Learning in case of future developments.

II. DESIGN OF THE HVAC

The first step is to select the refrigerant that is going to be used. There are many determinant factors to design the compression cycle. The first one is the selection of the refrigerant. It was really common to use ammonia or other fluorinated gases. But in 2014 a new regulation limited its use. There two ratings that indicate how bad a refrigerant is. They are GWP (Global Warming Potential) and ODP (Ozone Destruction Potential). They are calculated based on the value of the CO_2. There are some refrigerants with goods thermal properties that fit the needs of the cycle. For example, CO_2 trans-critical system can be used in the areas where the temperature goes below -10ºC. But the circuit becomes really complex, and it occupies a lot of space. We considered to use R290 due to its low GWP index and the good thermal properties that it has.

The next step is to design the compression cycle. The simplest one has only four components. It is the standard compression cycle it the components are a compressor, a condenser, a thermal expansion valve and an evaporator. The compressor receives the low-pressure gas and puts it under pressure and forces it out to the condenser. Compressors can not compress liquids so it can only receive gas. The condenser is basically a radiator. The flow of air absorbs the heat of the refrigerant, so it goes from gas to liquid. Now the refrigerant is a high-pressure liquid.

Normally, there is a fifth element that goes right after condenser called the receiver-dryer. It contains desiccant that remove any water that has entered the system to prevent the formation of ice crystals that can damage the compressor. Then the refrigerant goes to the thermal expansion valve. The system changes from high pressure to low pressure. The liquid refrigerant is expanded so its pressure is reduced. The valve is connected to the evaporator to regulate the flow of refrigerant. Finally, once the liquid has decreased its pressure, it goes through the evaporator. This is usually the part that goes in the cabin. The refrigerant enters as a cold low-pressure liquid and comes out as a low-pressure gas. It absorbs all the heat that must be extracted from the cabin.

There are two other cycles that were studied. They were two-stage cycles with open and closed intercooler. These cycles are commonly use in industrial applications and, even the efficiency was better, they were too complex for the purpose of the study and bigger and heavier than the simple one. We decided to design the simple cycle with R290 as the refrigerant.

In order to calculate the cold generated by the standard cycle it is necessary to know that heat sources are in the vehicle. There are two types of heat sources, external and internal. The external sources are the ones generated by radiation, convection, and conduction. The sun transfers heat to the surface of the car and it conducts the heat to the interior. Radiation goes also through the windows and rises the temperature of the cabin.

To calculate the amount of heat that penetrates in the cabin by the sun, it is necessary to know where the vehicle is and its geometric characteristics. For the radiation that goes through the windows there are stipulated values that needs to be fixed with some coefficients, for example, the coefficient for windows with iron frames or the one that describes how the glass absorbs part of the heat.

For the convection and conduction heat, we used a method called Cooling Load Temperature Method (CLTD). It consists of an equivalent temperature difference used for calculating the instantaneous external cooling load across a wall or a roof. Then, we calculated the global coefficient of transmission of the wall. Depending on the materials of the wall and the isolating material used, the walls and the roof of the car will transfer more or less heat.

$$Q = K * S * \Delta t_{eq}$$

Q is used for the heat transferred in Watts; K is the global coefficient of transmission is Watts per square meter and ºC; S is the surface of the compound wall in square meters; Δt_{eq} in ºC. In the example that we calculated the vehicle was in the city of Madrid in July. That means that the latitude is 40º north and the ambient temperature is 34ºC.

The global coefficient of transmission depends on the characteristics of the wall. In this case, we choose a 1 mm layer of steel and an isolating layer whose coefficients of conduction and convection are measurables.

$$\frac{1}{K} = \frac{1}{h_e} + \frac{1}{h_i} + \frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2} + \cdots$$

L1 and L2 are the thicknesses of the layers; he and hi are the coefficients of convection of the exterior and interior layer; λ1 and λ2 are the conductivity coefficients of each layer.

This process had to be done for the four sides of the vehicle. We considered the size of the windows, the orientation, and the slope of the windshield.

The interior thermal loads have different sources. On the one hand, the passengers generate two types of heat, latent and sensible. There are tables with the amount of heat generated depending on the temperature of the cabin. On the other hand, the engine and the batteries generate heat depending on the power that the engine is giving. In order to develop a reliable software, we decided to simulate the engine operation taking into account the speed of the vehicle, the slope of the road and the coefficients of performance of the engine and the transmission. For that calculation of the power required from the vehicle, we needed to calculate the three forces that brake the car. These forces are due to the resistance with the air, to the slope of the road and to the coefficient of friction with the asphalt.

$$F_{rodadura} = Coef_{rodadura} * P * g * \cos(Pend)\ [N]$$

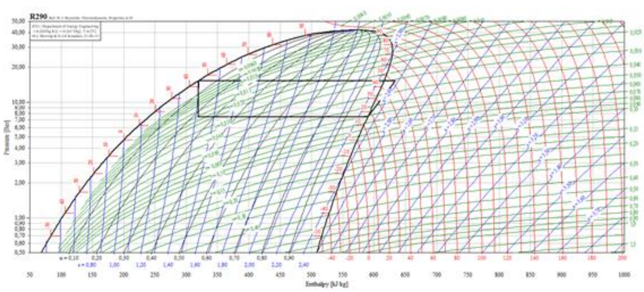
$$F_{aero} = \frac{1}{2} * S * \rho_{aire} * \frac{v^2}{3.6^2}\ [N]$$

$$F_{pendiente} = P * g * seno\,(Pend)$$

The resultant force multiplied by the speed of the vehicle and by the coefficients of performance gave us the total power that the engine dissipates as heat.

Once all the loads are calculated, it is possible to know how much heat or cold the HVAC must give. In order to be able to calculate all the points of the compression cycle, it is necessary to know the thermal characteristics of the R290 refrigerant such as the temperature, pressure, or enthalpy when the refrigerant is saturated liquid, saturated vapor and when it is a mix of gas and liquid, two phase refrigerant.

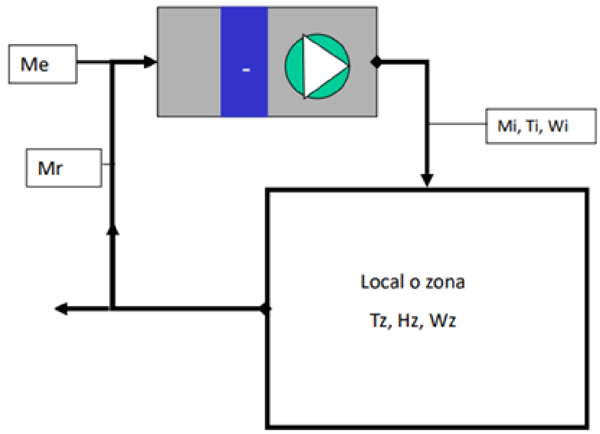
The software Coolpack was used to design the compression cycle and to know the characteristics of each point, for example, when the refrigerant is at the evaporator and is absorbing heat.



Having defined the four important points of the cycle, the work done by the compression, the amount of heat dissipated, and the refrigerant power given by the cycle are easy to calculate.

III. VENTILATION SYSTEM

The HVAC system is the part of the ventilation system that heats up or cools down the air that is coming to the cabin. This mass of air is a mix between exterior air and recirculated air from the cabin. The temperature in the cabin has to be between 23ºC and 25ºC in summer and the relative humidity around 50%. The scheme of the installation is the following:



We decided to divide the circuit into to parts. The first one is where the external and recirculated air meet. It is a normal mix of two different currents of air, each one with its characteristics of temperature and specific humidity. Therefore, we did a mass and humidity balance to calculate the characteristics of the mixture depending on the quantity of exterior air added to the blend. This quantity is defined in the rules of the RITE and is 115,2 m^3/h.

$$\dot{m}_i = \dot{m}_e + \dot{m}_r$$

$$\dot{m}_i * h_m = \dot{m}_e * h_e + \dot{m}_r * h_r$$

$$\dot{m}_i * W_m = \dot{m}_e * W_e + \dot{m}_r * W_z$$

Being *h* the enthalpy of the exterior, recirculated and mix air; *W* the specific humidity; *m* the specific flow of the three air currents.

The second part of the circuit is the entrance of the air in the heat exchanger (evaporator) where the heat is absorbed, and it is blow inside the cabin. In order to avoid the formation of dew, the temperature of the evaporator was stablished above 16ºC. Then, the heat exchanger does not change the amount of water in the air, it only changes the temperature.

IV. ALTERNATIVE TECHNOLOGIES

As the system wanted must be reliable, we explored different technologies that could represent an alternative or complement the HVAC system already designed.

Firstly, the PTC surfaces were analyzed. They are commonly use in extreme conditions (less than -10ºC) where is necessary a previous warm up to use the engine. They are also used in the seats of the passengers to heat some strategic parts of the body and create a comfortable sensation on the passenger even when the cabin is still cold. Nevertheless, this technology is not really efficient, it consumes a lot of energy from the batteries but is used because sometimes there is no other alternative.

The opposite effect is called the Peltier effect. Some materials absorb heat when subjected to some potential difference. They were used in some specific areas to cool down faster than the HVAC. The results were not very promising, the consumption was high comparing it to the HVAC and the reaction time was not much better either.

Secondly, we studied the repercussion of the lightning in the thermal sensation. The Polytechnique of Lausanne made an experiment with males and females from 18 to 50 years old where they analyzed the effect of the intensity of the light in the thermal perception. They conclude that changes in the intensity or in the tonality of the light (warmer or colder) provoked a false perception of the temperature of the room. When the light was warmer and the temperature colder, the people of the experiment were comfortable even if the standards of comfort say the should not. This difference between the real temperature and the perceived one was around ±2ºC.

All this information was taken into account in the design of the Predictive Thermal Management software. Before the study of the thermal perception, the interval of acceptable temperatures was 23-25ºC but with the effect of lightning this interval is now 21-27ºC.

Finally, we studied other opportunities such as lighter materials or the possibility to include solar panels. These options were quickly ruled out. But there was a project in development at the University of Purdue about the whitest paint in the world. This paint rejected 98,1% of the light that reached it. In the future, it could be interesting to improve the insulation of the vehicle.

V. PREDICTIVE THERMAL MANAGEMENT

The Predictive Thermal Management software tries to reduce the consumption of energy by the HVAC. This consumption limits the range of the vehicle. Normally, the extra energy that the HVAC requires is due the human error. Humans do not anticipate the changes of temperature, radiation, or humidity on the exterior and when the cabin is already hot, they react.

With this software the idea is to divide the trip in several points and store their climatological data to take advantage of the cold zones and reduce the temperature of the cabin so when the hot ones come, the HVAC has less work to do refrigerating the cabin.

The data must be provided by a company that measures the climatological conditions of different points in Spain, for example AEMET. They normally measure the temperature, humidity, or radiation but to know what heat loads are coming to the vehicle it is necessary to integrate all the calculations in the software. Python is the programming language selected. Grupo Antolin wanted a free-code language that will accept applications like Big Data or Machine Learning in the future and that is why Python was chosen.

As the code developed is just a prototype, we chose a trip between Madrid and Vigo and selected four different points. When the software is used in a real application, the number of points has to be determined depending on the characteristics of the trip. If the climatological conditions of the trip vary too much, the number of points should be increased. For this example, we stored the data of the four different points in vectors and arrays.

```
Radiaciones_matrix = [
          [126.77,126.77,541.96],
          [102.5,110.7,407.4],
          [138.92,131.63,470.38],
          [111.48,105.6,436.27]

]
rad_m = np.array(Radiaciones_matrix)
```

It was necessary to use some libraries existing in Python, for example *numpy*. The data showed is the one that was used for the example. It corresponds to the radiation received on the back, the side, and the front of the car for each one of the four points in which the trip was divided.

Once the external loads were integrated, we also developed a simulation for the engine. We defined a function that receives the speed of the vehicle, the slope of the road and some geometrical characteristics of the car like the surface of the front.

In addition, the loads generated by the passengers depend on the temperature of the cabin. For this example, we assume that the temperature inside the cabin can only be 21ºC, 24ºC or 27ºC because those are the values that the RITE has in its tables. To store this data, we used a dictionary where the *key* is the temperature of the cabin, and the *value* is the heat generated depending on if the human is the driver or a normal passenger.

```
Carga_sensible_cond = {27.0:50.0,
24.0:60.0, 21.0:70.0}

if(N_pers <= 1):

C_s = Carga_sensible_cond[Temp_local]
C_l = Carga_latente_cond[Temp_local]
Carga = [C_s, C_l]
```

As it is shown in the code above, we calculated both heat loads. They are not necessary for the purpose of the example but just in case some future extension would need it we calculate it separately.

Once the calculation of the heat loads is integrated in the code, it is necessary to calculate the compression cycle to determine how much power does it consume. As the cycle works with R290 refrigerant, the properties of saturated vapor and liquid must be stored. As we did not have a database with all the values, we store the values that we needed and their “neighbors” just in case we need them in another example. The characteristics that we needed from each point of the cycle were the temperature, the pressure, the enthalpy, the entropy, and the specific volume. So, we define a vector with five different positions which restarts every time we need to do the calculations.

```
Punto_1 = [0, 0, 0, 0, 0]

matriz_aux = [
[16.0,7.475,0.06146,590.03,2.3509],
```

```
[18.0,7.89,0.05823,592.02,2.3492],
[20.0,8.322,0.0552,593.99,2.3476],

    ]
    m = np.array(matriz_aux)
```

The array has the value for saturated vapor at 16ºC, 18ºC and 20ºC. As we said before, the temperature at the evaporator has to be 16ºC or more to avoid the formation of dew. The same was done with the values of saturated liquid from 38ºC to 52ºC. The temperature at the condenser has to be at least 10ºC greater than the ambient to ensure the exchange of heat.

Finally, once the loads are calculated and the cycle is design, in the main function of the code we called again all the functions and repeat the process for the next point.

We design an intelligence that decide if the temperature of the cabin is the lowest one of the interval, the medium or the highest one depending on the characteristics of the trip.

In addition, we decided to take advantage of the research made by the Polytechnique of Lausanne and change the lightning at the inside of the car to make the trip more comfortable. When the temperature outside is extremely hot and the compressor needs to save energy, the vehicle turns on the appropriate lightning to change the perception of the passengers.

	Consumo del compresor (W)
Tramo 1	686,70
Tramo 2	2.184,63
Tramo 3	1.526,63
Tramo 4	699,70

In the table above the consumption of the compressor is shown. As it was said before, the trip was divided into four parts, each one with its own characteristics. The second and third parts of the trips were the ones with higher temperatures and with the steepest slope. The principal advantage of the software is that the consumption varies depending on the requirements of the cabin, so it is always the minimum.

As the lightning is part of the software, we stablished that the variable that represents it would take the value 0 when the lights should be turned off; the value 1 when it has to be warm; and the value 2 when the temperature is too high, and the light has to reduce that perception.

$$Iluminación = [0, 1, 2, 1]$$

Thanks to the lightning the power required from the compressor decreased.

VII. CONCLUSION

Due to GA's business interests and the intention to design the worst-case HVAC system, it was decided that all calculations of thermal loads (internal and external) and the compression circuit designed would be performed for summer conditions that occur in a Mediterranean city like Madrid. Therefore, the data of temperature, relative humidity and radiation indexes are the corresponding ones for the said city in the month of July.

The calculation of the thermal loads revealed how important it is to have an efficient cooling system. It has not only sought to overcome the thermal loads of the cabin, but also those generated by elements such as the engine or the batteries. The objective is to increase the range of the vehicle and for this the temperature of the electrical elements must be kept within a certain range. In this way its proper functioning is ensured, and its useful life is lengthened.

All this was included in a software developed in Python. The choice of the programming language was relatively straightforward. An open-source language was needed that would support future extensions in the fields of Big Data and Machine Learning.

In this way, it was tried to compartmentalize each of the parts of the project to the maximum to facilitate the work of future engineers or developers who want to expand, update, or improve any of the parts.

The result of using the software has been really satisfactory. Taking into account that it is especially useful on long journeys or journeys with changes in temperature, radiation, and speed, hence the journey analyzed is a Madrid – Vigo journey. Despite having divided the route into just four sections, the optimization of consumption is clearly appreciated. It is clear that there are travel sections in which consumption has little room for optimization, for example, when the outside temperature is very high, and the vehicle is traveling at high speed on a steep slope. However, its main action points are the changes between sections. Humans are notably slower than software in accepting and responding quickly to span-to-span changes.

VIII. FUTUR PROJECTS

The project developed throughout this report is by no means perfect or invariant. There are numerous extensions, updates and improvements that can be made.

On the one hand, the characteristics of the refrigerant fluid have not been included for all conditions, that is, the date necessary for the study have been included. However, a future extension would be to store the values for the temperature, pressure, enthalpy, entropy, and specific volume of the fluid as saturated vapor, saturated liquid, and liquid-vapor mixture for as many temperatures and pressures as possible.

In addition, temperature, humidity, and CO_2 level meters could be included inside the cabin to feed back the system, establishing some type of control (P, PI, PD or PID) to constantly calculate the thermal requirements of the cabin.

On the other hand, taking advantage of the way the code has been written, any update in the world of air conditioning could be included. For example, the design of more efficient refrigeration cycles, the discovery of a new less polluting refrigerant with better properties or even new calculation techniques for both internal and external thermal loads.

Also, not all calculations are perfect. There are several simplifications, which have been discussed in chapter 3, necessary to be able to calculate the loads efficiently and accepting a certain margin of error. However, it is possible to further refine these calculations by including all the variables that are desired.

Leaving aside the possible extensions of the software or the improvements and updates that can be included in the HVAC system, the world of Industry 4.0 can bring interesting innovations.

At first, the digitization of the manufacturing process of any system, and in particular the one designed in this project, would have a very positive impact when calculating profits versus costs. The manufacturing and production system would be optimized by shortening times and reducing the number of defective products.

Together with digitization, a world of possibilities opens up if the option of including manufacturing processes with 3D printing is studied. This type of manufacturing is very versatile and allows different configurations to be designed for each vehicle, making the most of the available space and adapting to the different distributions of the same that can be given in each model.

With the idea of using the data collected by predictive software to design new routes, the Big Dara option arises. Once a lot of data from the same trip or similar trips is stored, consumption predictions could be made indicating the minimum level of charge necessary for the batteries.

Continuing with the previous idea, this type of process would not have to be carried out in the vehicle. They normally require computing power that a normal car cannot cope with. All these classifications and calculations could be done in the cloud. It would simply be necessary to send the data, perform the calculations with more powerful data processing equipment and receive it back to know how to deal with each situation. For this, it should collaborate with companies that develop Cloud Computing such as Amazon, Google, or IBM.

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