# INNOVATIVE AIR-CONDITIONING SYSTEMS FOR CONVENTIONAL AND ELECTRIC VEHICLES

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## ABSTRACT

The heating and cooling systems are a major challenge in the development of electric vehicles (EVs). In combustion engines, the residual heat is largely sufficient to cover the heating load of the vehicles. Nevertheless, in EVs, the use of non-efficient heating and cooling systems may reduce substantially the vehicle range.

The European Project ICE started in November 2010 and aims to develop an efficient air-conditioning system for EVs. An innovative magnetocaloric reversible heat pump is used. Such systems are expected to be much more efficient than conventional chillers. In this paper, the first results of the project and the target performance are discussed.

*Keywords*: Electric vehicles, heating, cooling, Magnetic refrigeration, performance

## 1. INTRODUCTION

Due to the increasing concern about environmental and energy issues, the automobile industry started to develop electric vehicles (EVs), hybrid electric vehicles (HEVs) and fuel-cell electric vehicles (FCEVs) in the first half of the 1990s. Nowadays, many manufacturers are starting to offer electric vehicles (Chevrolet, Honda, IVECO...). In Spain, the government aims to have 1 million electric cars on the roads by 2014.

Regardless of the type of vehicle, the air-conditioning systems present the highest power consumption of the auxiliary components. From EU estimations, mobile air-conditioning (MAC) in conventional vehicles can increase the fuel consumption in up to 20% in a standard urban driving cycle in summer. In the case of EVs, the energy consumption for air-conditioning becomes an additional challenge as there is no waste heat available in the engine. In EVs, the sole energy which is available is the electricity stored in the battery, so any additional power consumption implies a reduction of the vehicle range.

Given the actual state of the art, electrically driven compressors are the most feasible solution, but at present they present several drawbacks in terms of size, weight and cost. Consequently, they have been produced only in small quantities for electric vehicles and are not yet in widespread use.

Two recent European projects aim to develop innovative air-conditioning systems for vehicles. During the TOPMACS project, which finished in 2009, sorption cooling systems were installed in a FIAT car and an IVECO truck. Such systems were driven by the waste heat from the engine instead of a conventional chiller. The air-conditioning systems used zeolite and silica-gel-based adsorption chillers [1]. Other technologies were also developed and tested, such as ammonia-water chillers or metal hydride cooling systems [2]. However, the project showed that it is possible to recover the heat from the engine, but the volume, weight and costs are too high to make this solution feasible on a commercial level.

Very recently, another European project has started (ICE - MagnetoCaloric Refrigeration for Efficient Electric Air-Conditioning [3]) with the aim to develop an innovative magnetocaloric air-conditioner for electric vehicles. In this paper, the ICE project is described and some preliminary results are presented.

## 2. ICE PROJECT DESCRIPTION

The ICE project started in November 2010 and aims to develop an efficient air-conditioning and heating system for electric vehicles. The air-conditioning system is based on a magnetocaloric reversible heat pump and on an innovative design of the system architecture and operation strategies. This system can be applied in both electric and conventional vehicles.

In any vehicle, the heating system is required not only to cover the heating demand of the cabin, but also to assure the window de-icing and defogging. In an EV, the available heat is rather limited and usually has a low temperature (around 40ºC). Thus, an electrical heating and cooling system is required. Typical heating requirements range between 5 kW and 10 kW depending on the vehicle characteristics.

In summer, the cooling system has to reduce the temperature and dehumidify the air moisture. In conventional systems, a mechanical vapour-compression chiller is used. Typical installed cooling powers range between 3 kW and 5 kW.

The Daily electric minibus from IVECO-ALTRA is powered by 3 ZEBRA batteries providing a total capacity of 63.6 kWh. With this stored energy, the vehicle has a range of around 100 km. If a conventional 5 kW chiller with a COP of 2.5 is used, this implies an electric consumption of 20 kWh during a 10 h drive. Under these conditions in summer, the range would then be reduced from 100 km down to 69 km. During the ICE project, a magnetic air-conditioning system will be specially designed for the vehicle. Theoretically, such a system can double the performance of a conventional chiller. If a COP of around 5 is achieved, this will lead to a vehicle range of around 84 km.

The optimisation of the air-conditioning and heating system is a key issue, otherwise the vehicle range can be substantially decreased. The ICE project aims to develop a new magnetocaloric heat pump and to redesign the cabin air-conditioning based on efficient control strategies offering both high comfort and safety solutions (de-fogging and de-icing).

The magnetocaloric system will be developed by the company COOLTECH applications with the support from the University INSA Strasbourg who will assist in the design and performance tests. The prototype will be installed in the Daily electric minibus from IVECO-ALTRA.

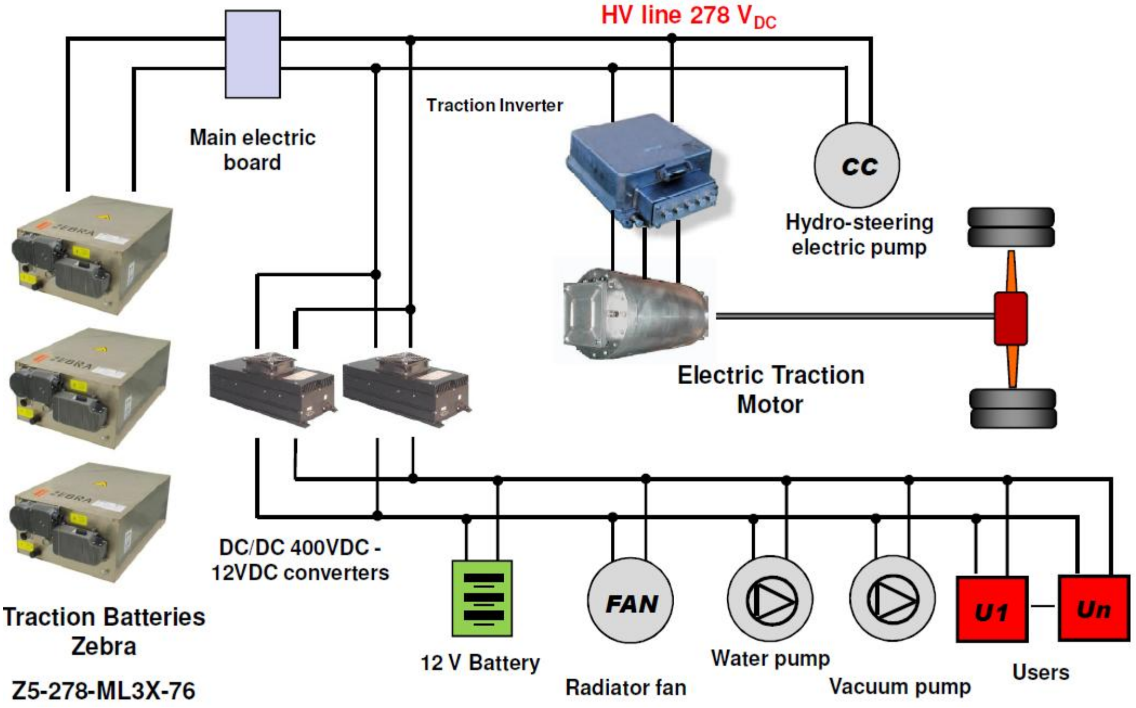


**Figure 1. Electric scheme of the Daily Electric Minibus**

Fig. 1 represents a scheme of the electric equipment of the vehicle. The electric power generated by the 3 ZEBRA batteries is used directly to power the electric traction motor and the hydro-steering pump. The rest of the equipment requires the use of 400 VDC-12VDC converters. The converters power a 12 V battery, the radiator fan, water pumps and the vacuum pump which is necessary for the brakes.

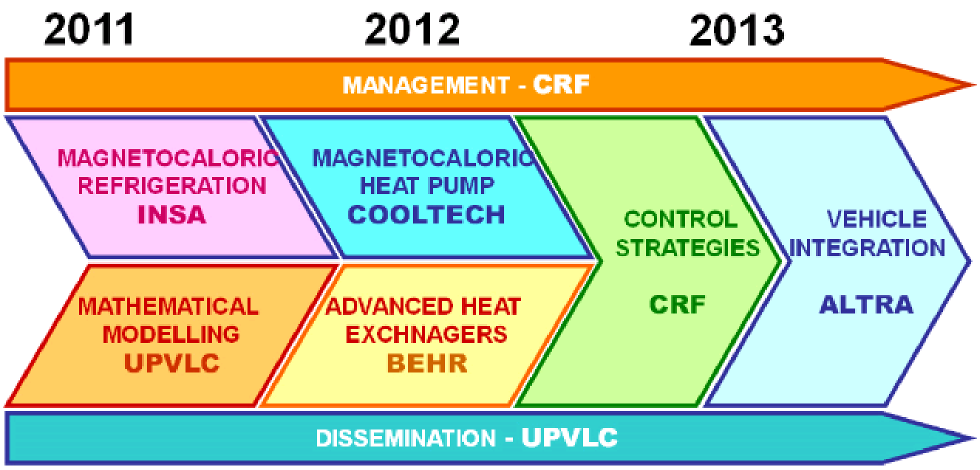


**Figure 2. ICE project planning**

Fig. 2 shows the planning of the project and the role of each partner. BEHR will provide advanced heat exchangers required for the prototype. The Polytechnic University of Valencia (UPVLC) will develop dynamic models of the complete vehicle including a thermal model of the cabin, the magnetocaloric heat pump and the distribution system. One key issue in such a system is the operation strategy. The latter will be studied by CRF and optimized by UPVLC by means of the overall model.

The project mayor objectives are:

- **Efficient electrical heat pump** (COP > 5 in cooling mode) based on the magnetocaloric effect using high efficiency magnetic materials, a smart design and specific micro channelled heat exchangers.
- **Redesign of the vehicle thermal systems** to distribute locally the thermal power and to regulate the batteries and the temperature of the electronics.
- **Microclimate control system** based on the thermal comfort and able to limit the thermal power generation only to the strictly required power and to adapt the system to the occupants' number.
- **Sustainable cost** thanks to the innovative technical solutions that will be adopted to develop the heat pump, to the thermal systems resize and their integration.

## 3. MAGNETIC AIR-CONDITIONING

The fundamental principal of magnetic cooling was discovered at the end of the 19th century and several systems were then built and tested in the 20th century. During the last 40 years particularly, different prototypes have been developed, although generally more on a research phase. Today, magnetocaloric refrigeration systems can already be found in the market. For instance, COOLTECH [4] is considered as one of the worldwide leaders and pioneers in this efficient technology.

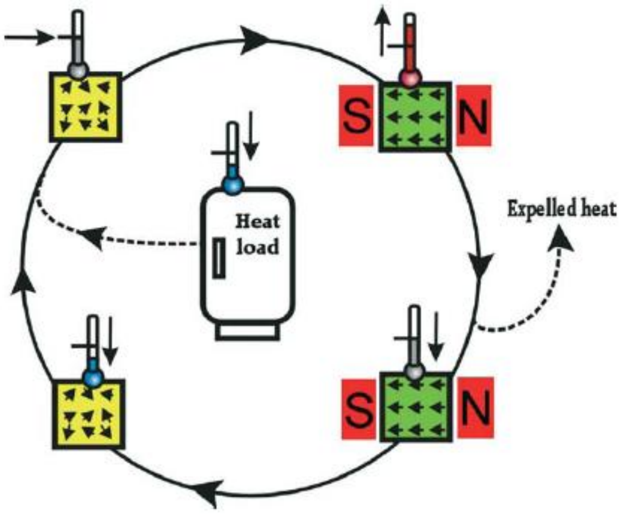


**Figure 3. Schematic representation of a magnetic-refrigeration cycle [4]**

Magnetic refrigeration is based on the magnetocaloric effect (MCE) [5-6] and is represented schematically in Fig. 3. If a magnetic material is exposed to a magnetic field, then the initially randomly-oriented magnetic moments will align. This reaction is exothermic and the heat can be released to the ambient. If the magnetic field is then removed, this process is endothermic and the temperature of the material will reduce as the magnetic moments randomize. Heat from the system to be cooled can then be extracted using a heat-transfer medium like water or air.

As magnetic refrigeration does not require any polluting refrigerants, it is an environmentally friendly technology. Additionally, magnetic cooling systems are more efficient than conventional chillers. The higher the energy efficiency, the lower the $CO_2$ emissions and the consequent green house effect.

One disadvantage of magnetic cooling is that high efficiencies are realized when high magnetic fields are applied (≈5 T). Recent research aims at new magnetic materials displaying larger MCEs, which then can be operated in lower fields (≈ 2 T) that can be generated by permanent magnets.

In active magnetic regenerators (AMR), the magnetic refrigerant also acts as a heat storage medium and participates in the cycle like a regenerator. Gadolinium is a well-studied material that produces a relatively large MCE.

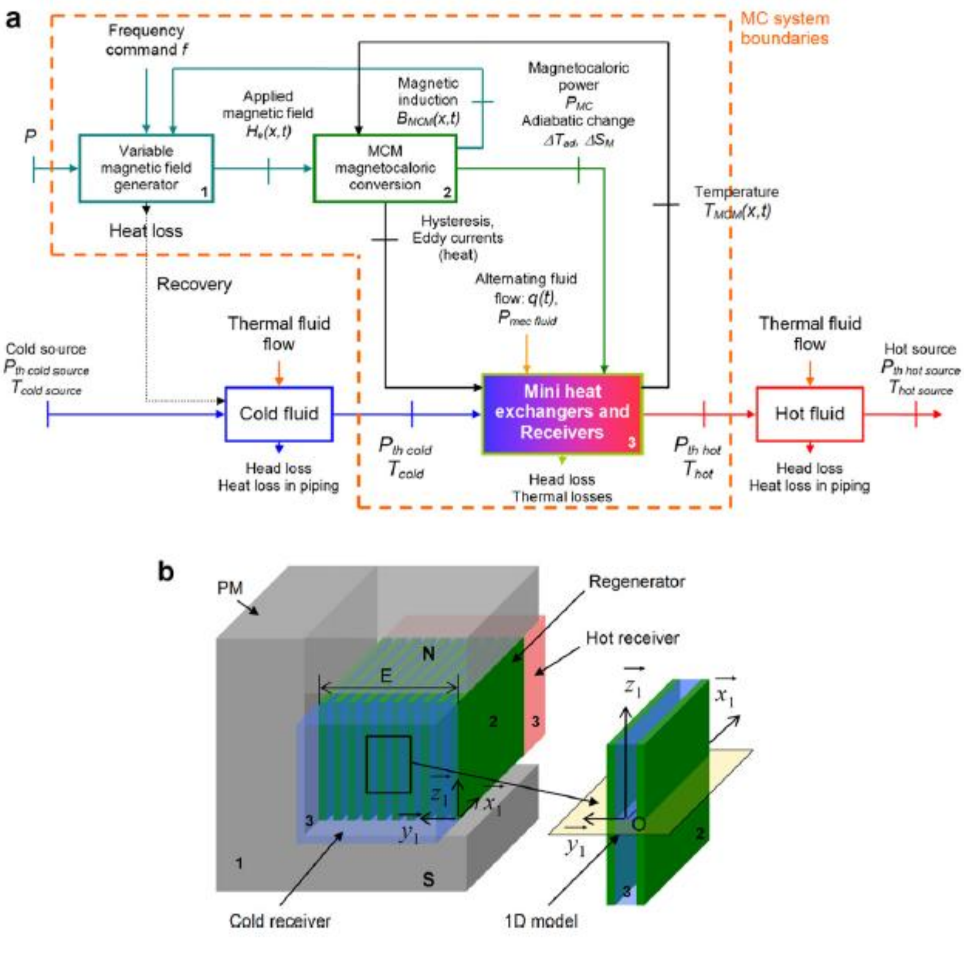


**Figure 4. Schematic representation of a magnetic refrigeration cycle [7]**

A magnetocaloric refrigeration system with an AMR cycle may be broken down into different sub-systems: magnetic, mechanical and thermal-fluidic. These sub-systems, which are represented in Fig. 4, fulfil different functions such as generating the variable magnetic field in relation to the MCM, transferring thermal energy, moving the heat transfer fluid etc. The final coefficient of performance of the system is a combination of the performance of each of these parts. The aim of Fig. 4a is to show the analytic working parameters, the variables and theirs interactions through the studied system. The boundary of this system is presented as dashed line. In Fig. 4b the schematic view of the same MC system, with the 3 sub-systems, is presented in order to realise a comprehensive parallel between this geometrical view and the analytic view of Fig. 4a. The regenerator is made up of sheets of MCM separated by rectangular mini channels of heat transfer fluid arranged parallel to the magnetic field as shown in Fig. 4b. This parallel orientation allows a decrease of the demagnetizing field and a decrease of the reluctance of the regenerator and thus, an increase of the MCE.

# 4. METHODOLOGY

In order to size the MAC system, it is necessary to calculate the thermal load inside the cabin. An accurate calculation is especially important for EVs, since an oversized system working out of its optimal design point can shorten the vehicle range substantially. To fulfill this purpose, the following transient thermal model of the cabin of the IVECO Daily minibus has been developed and validated.

## CABIN MODEL

The cabin model diagram is shown in Fig. 5. Given the use of the minibus (e.g. shuttle), the occupation in the passenger area is very variable. Thus, it is interesting to make a special design of the air-conditioning system in order to have different comfort levels in both the driver and passenger region. For these reasons, the cabin model has been structured in two nodes, one for the driver region and one for the passenger zone.

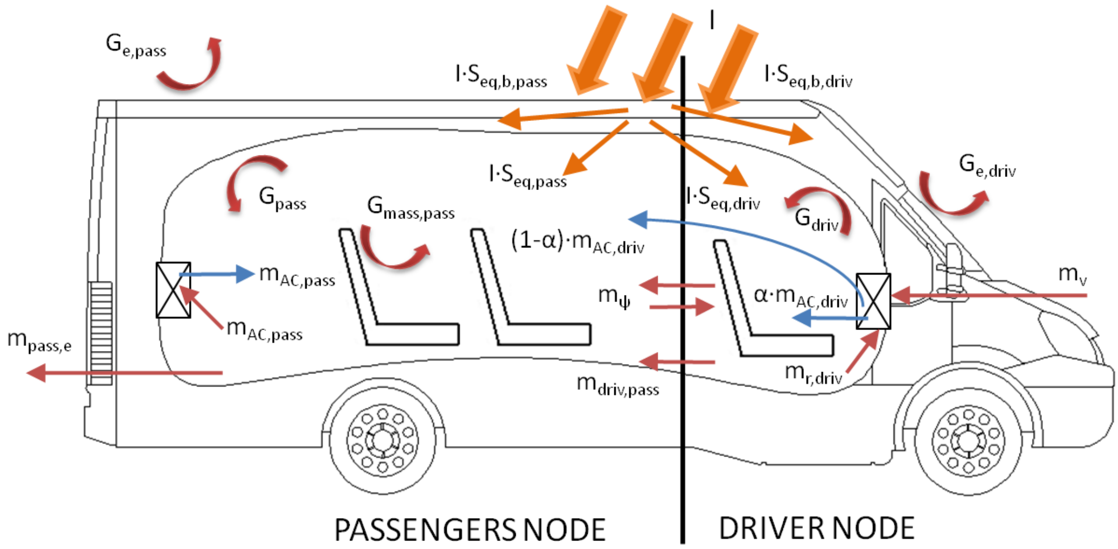

**Figure 5. Cabin energy flow diagram**

The model considers, for each area, the heat transfer between the external environment and the car body ($G_e$), between the body and the air inside the cabin (G) and between the cabin air and the interior masses such as the seats ($G_{mass}$). Thermal loads due to solar irradiation (I), people ($Q_p$) and stack effect ($m_\Psi$) are also included.

In order to overcome these loads, two air-conditioning systems supply air to the cabin with a mass flow rate $m_{AC}$. The air conditioning system in the driver area can work in 0-100% recirculation mode. The system in the passenger area acts just as a support and works only in 100% recirculation mode. By means of a mass balance, the air flow across the cabin can be expressed as a function of the recirculation ratio β and the flow at the air-conditioning outlets.

As in former studies [8], the model assumes that the properties of the air, internal masses and car body are spatially uniform. Sensible and latent loads are treated separately. In the driver area, equations 1, 2 and 3 refer to the energy balance of the vehicle body, of the cabin air sensible heat and of the interior mass, respectively. Equation 4 represents the humidity mass balance of the cabin air. The equations for the passenger area are similar.

$$C_{b,driv} \cdot \frac{dT_{b,driv}}{dt} = G_{driv} \cdot \left(T_{driv} - T_{b,driv}\right) - G_{e,driv} \cdot \left(T_{b,driv} - T_e\right) + I \cdot S_{eq,b,driv} \tag{1}$$

$$C_{driv} \cdot \frac{dT_{driv}}{dt} = \dot{V}_{AC,driv} \cdot \rho \cdot c_p \cdot (\alpha \cdot T_{AC,driv} - \beta \cdot T_{driv} - (\alpha - \beta) \cdot T^*) - G_{driv} \cdot \left(T_{driv} - T_{b,driv}\right) + G_{mass,driv} \cdot \left(T_{mass,driv} - T_{driv}\right) + Q_{p,s} + \psi \cdot \left(T_{pass} - T_{driv}\right) \tag{2}$$

$$C_{mass,driv} \cdot \frac{dT_{mass,driv}}{dt} = I \cdot S_{eq,driv} - G_{mass,driv} \cdot \left(T_{mass,driv} - T_{driv}\right) \tag{3}$$

$$V_{driv} \cdot \rho \cdot \frac{dW_{driv}}{dt} = \dot{V}_{AC,driv} \cdot \rho \cdot (\alpha \cdot W_{AC,driv} - \beta \cdot W_{driv} - (\alpha - \beta) \cdot W^*) + \frac{Q_{p,l}}{\Delta h_{fg}} + \dot{m}_\psi \cdot \left(W_{pass} - W_{driv}\right) \tag{4}$$

The heat transfer mechanisms are modeled using the conductance method (G) including the thermal inertia of the masses (C). These parameters were calculated given the dimensions and characteristics of the vehicle. The model was validated with and experimental warm-up and cold-down test, as shown in Fig.6. The thermal model of the cabin reproduces very well the transient behavior of the cabin.

## THERMAL LOAD CALCULATION

Once the parameters of the model are adjusted, the thermal load in the steady-state is calculated replacing in the model equations the design conditions.

In order to perform transient calculations, an evaporator/condenser model based on wet air properties was attached to the cabin model. The evaporator/condenser model takes as an input the inlet air conditions, which depend on the recirculation ratio. The supply air conditions are then calculated and provided as inputs to the cabin model. The power of the device is set constant, so the thermal load is the value of the power that helps to reach the target conditions in a given time. The results for the IVECO Daily minibus are shown in Table 1. De-fogging and de-icing have not been considered in the calculation of the heating demand.

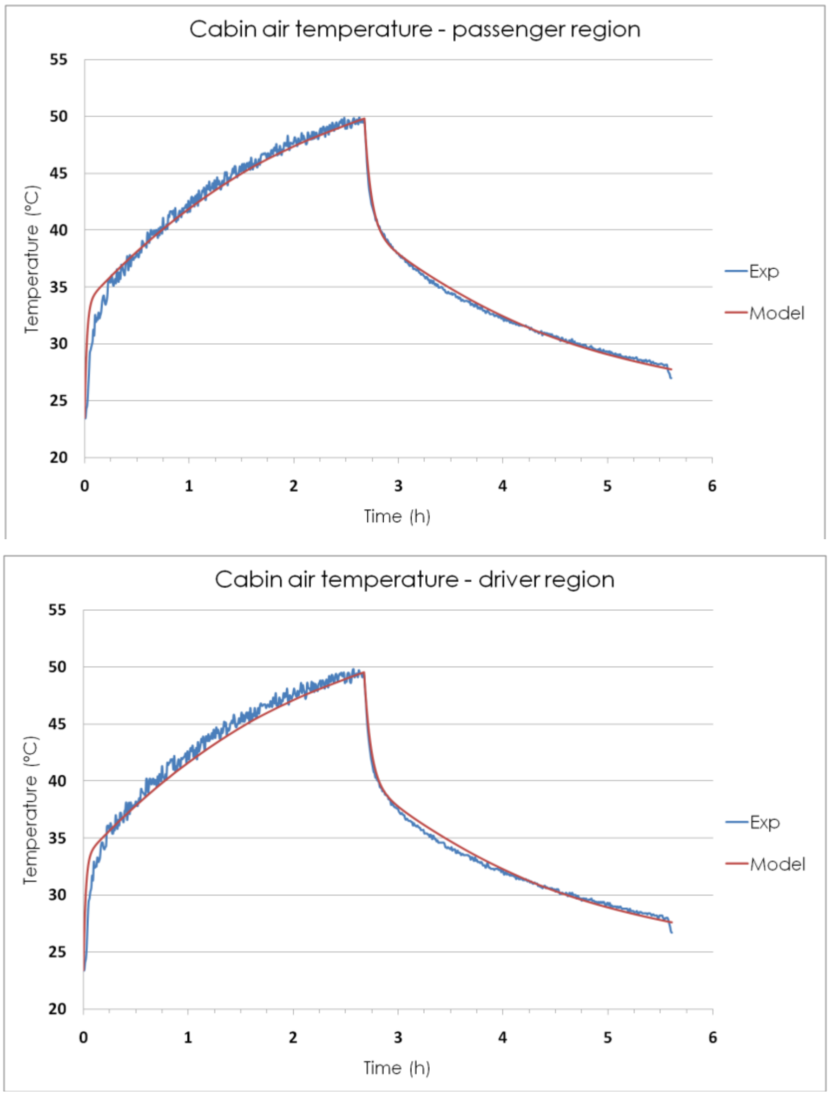


**Figure 6. Validation of the cabin thermal model**

| **LOAD (kW)** | **SUMMER MODE**<br>- Outside = 35ºC, 60%, I=0<br>- Comfort = 25ºC, 50%<br>- 7 passengers + driver<br>- Full recirculation mode | | | | **WINTER MODE**<br>- Outside = 0ºC, I=0<br>- Comfort = 20ºC<br>- 7 passengers + driver<br>- Fresh air mode (only driver) | | | |
|---|---|---|---|---|---|---|---|---|
| | **STEADY** | | **COOL DOWN 1h** | | **STEADY** | | **WARM UP 1h** | |
| | Driver | Pass. | Driver | Pass. | Driver | Pass. | Driver | Pass. |
| SENSIBLE | 0.33 | 0.99 | 0.47 | 1.58 | 2.78 | 0.45 | 3.05 | 0.75 |
| LATENT | 0.04 | 0.24 | | | 0 | 0 | | |
| **TOTAL** | **1.60** | | **2.05** | | **3.23** | | **3.80** | |

**Table 1. Thermal load calculation for the IVECO Daily minibus**

## 5. CONCLUSIONS

The heating and cooling systems of EVs are a key issue in their development within the next years. Non-efficient systems can lead to a significant reduction of the vehicle range. In the European ICE project, an efficient magnetocaloric air-conditioning system is being developed. Such systems can almost double the efficiency of conventional air-conditioners.

During the next 3 years, a prototype will be built and installed in an electric minibus from IVECO-ALTRA. If this high performance is proved, magnetocaloric air-contioners can be a major breakthrough not only in the automotive sector, but also in domestic and industrial applications.

## ACKNOWLEDGEMENTS

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