

Design of Efficient Air-Conditioning Systems for Electric Vehicles

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ABSTRACT

Among all the auxiliary components in conventional and electric vehicles, air-conditioning (AC) systems present the highest energy consumption. In fully electrical vehicles (FEVs), the heating of the cabin becomes an additional challenge as there is less waste heat available. Therefore, a careful design of the air-conditioning system and of the operation strategies is necessary to reach a reasonable FEV autonomy without compromising the thermal comfort.

This paper presents a tool for the design, analysis and optimization of an efficient air-conditioning system for an electric minibus. It consists of dynamic models of each component of the system that have been developed and fully validated individually. Finally, they have been coupled together to simulate the overall vehicle performance of the vehicle in MATLAB-SIMULINK.

The core of the system is a water-to-water reversible heat pump with a variable speed compressor. The internal water loop connects the heat pump to the air-coolers inside the cabin while the external water loop is integrated within the heat rejection system of the power electronics. An automatic control system regulates the speed of the compressor, the blowers and the circulation pumps to reach thermal comfort.

The power consumption has been analysed under different working conditions and control settings using the overall vehicle model. The latter is a powerful tool not only to design and select MAC equipment, but also to find the most efficient operation strategies.

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INTRODUCTION

The recent trend in the automotive industry is to progressively increase the number of electric vehicles, as they are being strongly promoted due to the greenhouse emission reduction and pollution reduction policies. However, to achieve a real success, it is necessary to reach similar comfort and performance levels to those of conventional vehicles.

In thermal engine powered vehicles, the thermal management of the cabin is relatively simple given the fact that there is waste heat available from the engine. A heater core is integrated in the engine cooling system and helps to heat up the air. Heater cores are generally sized to deliver from 5 to 10 kW of heating power.

In summer, a mechanically powered chiller usually provides cold air to the cabin. Typical installed cooling power ranges from 3 to 5 kW. The temperature control is usually done by mixing hot and cold air, since the chiller runs at the speed imposed by the engine [1].

However, the engine in electric vehicles has completely different characteristics and it is hereby necessary to re-

design the air conditioning system. Since the electric engine turns off when the car stops, electrically powered components are used to allow a continuous operation. Furthermore, the electric engine produces limited waste heat, around 2kW at 40°C, which is not enough to warm the cabin in winter. Therefore, the problem of climate control in winter, which does not exist with thermal engines, must be solved. An efficient solution is the use of reversible heat pumps, which provide both cooling power and heating power [2].

In any case, the air conditioning system is the largest auxiliary load on a vehicle by nearly an order of magnitude and it has a significant influence on the overall energy balance. In fact, it can increase the fuel consumption up to a 20% during a standard driving cycle in summer [3]. In FEVs, state-of-art efficient heat pumps reduce autonomy by 8% in winter [4-5], but the use of less efficient technologies such as thermal resistances can lead up to 24% autonomy losses [5].

The impact of the AC can be minimized with an accurate sizing and design, as well as by selecting the most efficient technologies and control strategies. In order to do so, it is

necessary to dispose of a simulation tool including dynamic models of all the components, hence allowing for the evaluation of the vehicle performance under any operating condition.

The aim of this work is to present a dynamic model which has been developed to simulate a complete AC system of vehicles, including not only a reversible heat pump but also the complete distribution system and a thermal model of the cabin. In this paper, the main characteristics of the model are firstly outlined, including a brief description of each component. Then, a sample of the simulation results is analyzed for both cooling and heating modes. Finally, some examples are shown on how the overall model can help in design tasks of the AC systems in vehicles.

This work has been developed in the frame of the European ICE project [6] which is funded by the EC under FP7. The ICE project aims to develop an efficient MAC system for an EV based on the magnetocaloric heat pump technology and on an innovative design and control strategies of the thermal power distribution loop. This system will be installed on a demonstrator vehicle, the Daily Electric minibus from IVECO-ALTRA, which is already commercialized. The overall model of the thermal systems of the demonstrator vehicle is one of the outcomes of the project.

MODELLING

An overall transient model of the new air conditioning system that will be installed in the Daily Electric minibus during the ICE project has been developed and validated. In this work, the magnetocaloric heat pump, which is the main outcome of the ICE project, has been replaced by a conventional vapor compression heat pump. [Figure 1](#) is a scheme of the system and its main components.

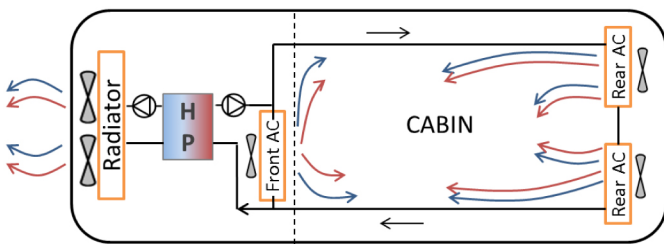


Figure 1. Daily Electric minibus MAC system layout

The purpose of the model is to become a useful tool to design not only the ICE project MAC system, but also others. Taking this into account, a description of the model is outlined below.

- **Modular.** The overall model is the result of the integration of single models of each component. The model of each component has been previously validated against experimental measurements. This modular concept enables an easy modification of the components if another vehicle has to be modelled.

- **Dynamic.** Models inside the overall model are completely dynamic. This allows performing simulations under transient conditions.

- **Flexible.** The models proposed are based on general equations and/or experimental data. Similar systems can be simulated by changing only the characteristics of the components.

- **Comprehensive.** The fundamental parameters that influence MAC operation have been taken into account, for instance the air recirculation, the heat pump performance under variable temperature conditions, etc.

- **Low computational cost.** In order to reach a compromise between a low computation time and a good accuracy, 0D models and performance based components have been introduced. The 0D-models are based on energy and mass balance differential equations. The state variables change with time but there is no spatial discretization. Hence, the integration in the whole system and the interaction between all the components can be analyzed at a low computational cost.

- **Accurate.** The models have been validated with experimental results. They have shown enough accuracy for assessing on overall system performance [5].

The model has been built in MALTAB-SIMULINK [7]. The main inputs are the ambient conditions, the car speed and the control settings. The interaction between the different subsystems is shown in [Figure 2](#). The overall model calculates the temperature of the working fluid along the loops given the properties of the air inside the car and the performance data of each component. These results are essential to make an accurate design and selection of components for MAC systems.

In the next paragraphs, the main characteristics of the different subsystems are summarized. This simulation tool can also be extended for other MAC systems provided that there is sufficient data in order to validate the models. For instance, the present model has been validated against heating and cooling tests of the cabin, and the model of the chiller has been compared with experimental performance data. In principle, the model can reach a similar accuracy for any MAC system provided that the experimental data is fully available. A comprehensive description of the data required by the cabin model and the heat pump model can be found in [8], while the hydraulic loops and heat exchangers were described in [5].

Cabin

The cabin model simulates the thermal behavior of the cabin and calculates the mean relative humidity and temperature inside the vehicle. It includes two new features regarding former literature [9,10]. On the one hand, the thermal inertia of both the vehicle body and the internal masses (such as seats, curtains, etc.) has been included. On the other hand, it differentiates between the temperature of

the air in the driver's and the passengers' region. This helps to create different comfort criteria depending on the occupation of the passenger region. For each thermal zone, the model considers the thermal loads due to occupation, ventilation, auxiliaries and solar irradiation. It also takes into account the air circulation between zones.

The model is based on differential equations which represent energy and mass balances [5, 8]. The heat transfer mechanisms are modelled using the conductance method including the thermal inertia of the masses (car body, cabin air and internal masses). These parameters were calculated given the dimensions and characteristics of the vehicle. The model has been validated with an experimental warm-up and cool-down test, as shown in Figure 3. The experimental temperature which is shown is the mean value of different thermocouples placed in several points of the minibus, all at head level. The mean deviation with respect to the measurements is 2%. Further details on the experimental tests can be found in recent literature [5, 8].

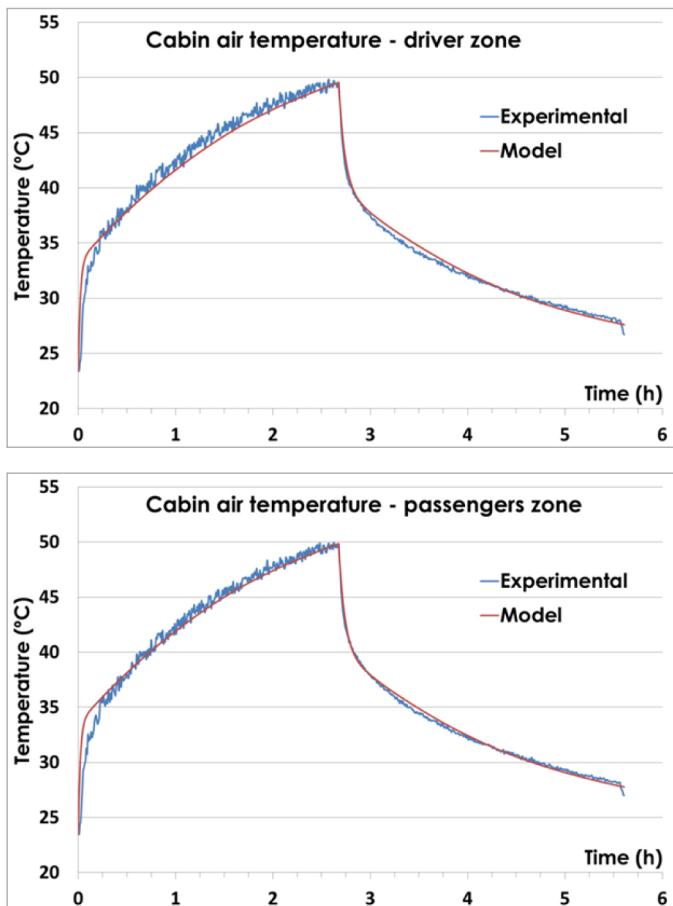


Figure 3. Validation of the cabin model during a warm-up and a cool-down test [5]

Heat Pump

A model of a water-to-water heat pump with variable speed compressor (Figure 4) has been developed in two stages.

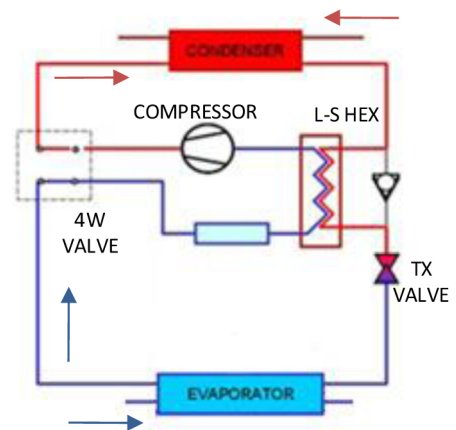


Figure 4. Scheme of a water-to-water heat pump, which consists of a 4-way valve (4W valve), a compressor, a thermostatic valve (TX valve), two refrigerant-to-water heat exchangers (evaporator and condenser) and a liquid-to-suction heat exchanger (L-S HEX) which only works in cooling mode)

In a first stage, detailed models of the components of the Daily's current heat pump, which is currently evaporated by air, were developed and validated [5, 8] using IMST-ART [11]. IMST-ART is a software tool which enables the simulation of refrigeration equipment. It includes physical-based models of heat exchangers and performance based models of compressors. Figure 5 shows the validation of the Daily's current heat pump in heating mode. A maximum deviation of 3.3% is obtained with respect to the measurements. Further details and results for the cooling mode can be found in literature [5, 8].

In the present work, the models of the Daily's current heat pump components were assembled in order to simulate a new water-to-water heat pump. In order to do so, the refrigerant-to-air heat exchanger of the cabin side was replaced, and a refrigerant-to-water heat exchanger was used instead.

The inputs from the system to the heat pump are the return temperature and flow rate of the secondary fluid and also the compressor speed determined by the automatic control. The outputs of the heat pump needed by the system are the supply temperature of the secondary fluid at each side, the corresponding pressure drop and the power input to the compressor. Therefore, in a second step the heat pump model was simulated in IMST-ART by varying in small steps the input variables. The results obtained for each of the outputs listed were then implemented in Matlab as a look-up table. In this way, the overall model counts with a fast and accurate model of the heat pump.

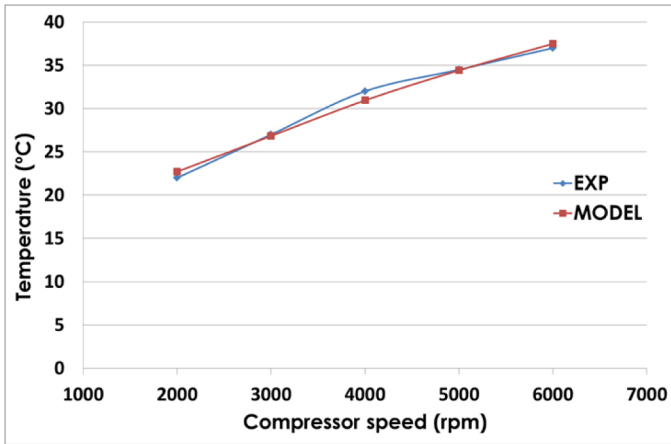


Figure 5. Temperature of air at the air-conditioning outlets in heating mode (IVECO Daily Electric's heat pump) [5]

Hydraulic Loops and Heat Exchangers

The hydraulic loops and the heat exchangers communicate each side of the heat pump with the outside and with the cabin (Figure 6). In the external loop, the radiator transfers heat with the ambient. In the internal loop, the air-coolers warm up or cool down the air inside the cabin depending on the season. The heat transfer fluid is a 50% ethylene-glycol solution.

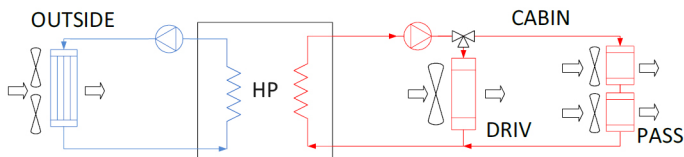


Figure 6. Scheme of the hydraulic loops

The model of the loops determines the supply and return temperatures of the heat pump by means of energy balances [5]. The inertia and heat losses in the pipes have been considered. The thermal power of each heat exchanger ($\dot{Q}$) is calculated in Eq. (1) by means of its effectiveness (ε), considering that air is the fluid with the minimum heat capacity.

$$\dot{Q} = \dot{m}_{air} \cdot \varepsilon \cdot (h_{air,in} - h_{sat,in}) \quad (1)$$

In Eq. (1), $\dot{m}_{air}$ is the air mass flow rate, $h_{air,in}$ is the specific enthalpy of air at the inlet and $h_{sat,in}$ is the specific enthalpy of saturated air at inlet temperature. The enthalpy has been used in Eq. (1) instead of the temperature in order to take into account both latent and sensible changes in the air side.

The model of the heat exchangers is based on the global heat transfer coefficient. This approach is convenient for

design purposes since it allows scaling up and down heat exchangers and therefore optimizing its performance. Considering the geometry of the heat exchangers in the minibus, the global heat transfer coefficient has been related to the effectiveness by means of correlations [12]. The effectiveness of a heat exchanger depends on its characteristics and on the temperatures and mass flow rates of the fluids through it. Thus, experimental data is required. The data was obtained from a series of tests on the radiator of the minibus [5].

Auxiliaries

The main auxiliaries in a MAC system based on a water-to-water heat pump are the circulation pumps in the hydraulic loops, the fan of the radiator and the blowers of the cabin air-coolers. The control of these elements is an essential part of the MAC system given their high power consumption.

The circulation pumps of the ICE project MAC system are variable frequency pumps. They were integrated into the overall model by means of catalogue curves [13], which determine its performance depending on the flow rate set and the pressure drop along the system.

The radiator of the Daily minibus has two fans. Its performance (air flow through the radiator and power input) was experimentally measured and the data obtained was included in the overall model (Table 1).

Table 1. Fans of the radiator

Number of fans	Air flow (m ³ /h)	Power input (W)
1	1254	109.7
2	2188	234.63

The HVAC module in the front of the Daily minibus can handle fresh air or recirculated air. The blower inside has six distribution modes and four fixed speeds (positions) that determine the air flow and the energy consumption. The corresponding data was provided by the manufacturer and was directly included in the model (Table 2).

Table 2. Blower characteristics in the front HVAC module (summary)

Position	Air flow (m ³ /h) 100% Floor distribution	Air flow (m ³ /h) 100% Head distribution	Power input (W)
1	60	88	48.0
2	96	137	102.0
3	146	195	171.6
4	264	311	290.4

The HVAC modules installed at the rear part of the minibus for the ICE project will only recirculate air. Each of them includes a blower with three fixed speeds. Its performance has been also added in the model (Table 3).