New climate-control units for more energy-efficient electric vehicles: system architecture

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***Abstract*— The paper presents the architecture of a new climate-control system that is under development in the XERIC project, funded within the Horizon 2020 EU program, that aims to increase Battery Electric Vehicles (BEV) autonomy by reducing more than 50% the energy used all over the year for passenger comfort in all weather conditions. The system combines a traditional Vapor Compression Cycle (VCC) with a liquid desiccant cycle, by taking advantage of an innovative component, called Three-Fluids Combined Membrane Contactor (3F-CMC). The approaches that can be adopted by the XERIC system to face the different seasonal needs are shown. Moreover, numerical models developed in the Matlab/Simulink environment and used to predict the system performance are presented. Finally, first results regarding the experimental campaign performed to link the VCC and the liquid desiccant cycle are discussed.**

*Keywords— **XERIC project; Hybrid systems for air dehumidification; liquid desiccant; membrane contactors; energy-efficient electric vehicles; AC mobile system.***

I. INTRODUCTION

As known, the air dehumidification can be realised by means of a liquid desiccant (for instance, aqueous solution of LiCl, $CaCl_2$, etc.) avoiding to cool the air itself down to dew point [1]. Moreover, the usage of a liquid desiccant can be advantageous since it allows to control air humidity and air temperature independently [1-3].

Hybrid Air Conditioning systems, using a desiccant cycle to face the latent heat (air dehumification) and a Vapour Compression Cycle (VCC) to face the sensible heat (air cooling), are nowadays object of great attention worldwide as shown by technical papers available in the literature [4-6].

Hybrid systems can save energy up to 35 - 40% in comparison with traditional AC systems because the refrigeration cycle can operate at a higher evaporation temperature and at a lower condensation temperature [4-7].

Up to now, liquid desiccants have been used mainly for industrial applications in direct-contact air-liquid desiccant plants [1,2]; indeed, these systems usually require a high volume, present issues given by desiccant droplets carryover in the process air and are not suitable to be used in mobile applications (inertial effects and vibrations).

Membrane contactors equipped with hydrophobic membranes only permeable to the vapour phase and not to the liquid phase [8-11], avoiding the direct contact between the air and the desiccant, enable hybrid systems to be considered also for mobile AC applications since also a high compactness of such components can be reached.

Aim of the XERIC project, funded by EU Horizon 2020, is to develop an innovative climate-control system that is able to increase Electric Vehicle (EV) autonomy while preserving passengers' comfort, in all weather conditions. The core of the XERIC approach is the new component called Three Fluid Combined Membrane Contactor (3F-CMC) whose concept is covered by patents [12-15].

II. XERIC SYSTEM ARCHITECTURE

The XERIC system architecture refers to a hybrid system where the desiccant cycle plays a very important role. Figure 1 shows a sketch of the desiccant cycle studied which consists of two membrane contactors (3F-CMC1, 3F-CMC2) crossed by three fluids (air, desiccant, refrigerant) and a heat recuperator (HE). Both the 3F-CMCs are simultaneously crossed by air. In detail, 3F-CMC1 is used to dehumidify and to cool the outside air before sending it to the passenger's cabin: the dehumidification is obtained by means of the desiccant

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solution, while the temperature is controlled by the evaporating refrigerant. On the other hand, 3F-CMC2 acts as a regenerator to re-concentrate the weak solution coming from the 3F-CMC1, by releasing vapour to an external air flow. The desiccant regeneration process, taking place in the 3F-CMC2, is realized by exploiting the thermal energy given up by refrigerant (first in the cooling of its overheated vapour and then in the condensing process).

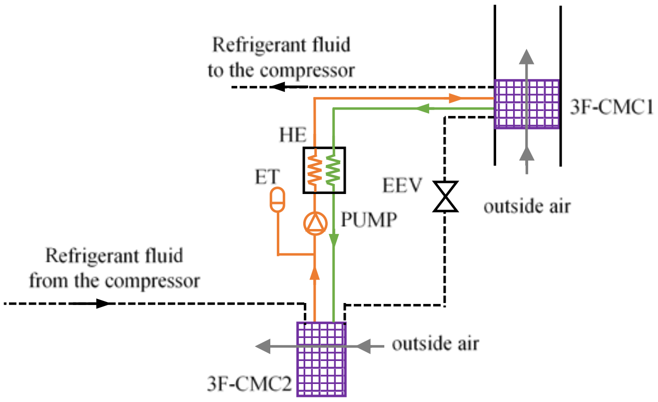

Fig. 1: Sketch of the desiccant loop that uses two 3F-CMCs.

The heat and vapour exchanges with the process air crossing the two components are opposed one to the other: in 3F-CMC1 the vapour is absorbed from the air while in the 3F-CMC2 is discharged to the external air flow.

Since the desiccant temperature in these two components is controlled by the internal heat exchanges with the refrigerant, only a small desiccant flow rate is needed through 3F-CMC1 and 3F-CMC2. In order to reduce parasitic heat transfers from 3F-CMC2 to 3F-CMC1, the economizer (HE) works between warm and concentrated desiccant flow from 3F-CMC2 and the diluted cold one from 3F-CMC1.

Figure 2 shows how the desiccant loop is integrated with a VCC to obtain the innovative and original XERIC climate control-system architecture (Patent pending [16]).

The 3F-CMC1, set on the renewal air path, handles this air flow before it mixes with the recirculated air flow from the cabin (see the recycle door set before the ventilator, in Fig.2).

The air flow through the 3F-CMC1 can be excluded by a second door when the desiccant cycle does not work. As shown in the sketch, downstream the fan the air flow can be partially or totally conveyed to the heat exchanger HE1 through a third door, whereas further doors may address the air flow to cabin vent, to glass defrost and to cabin floor.

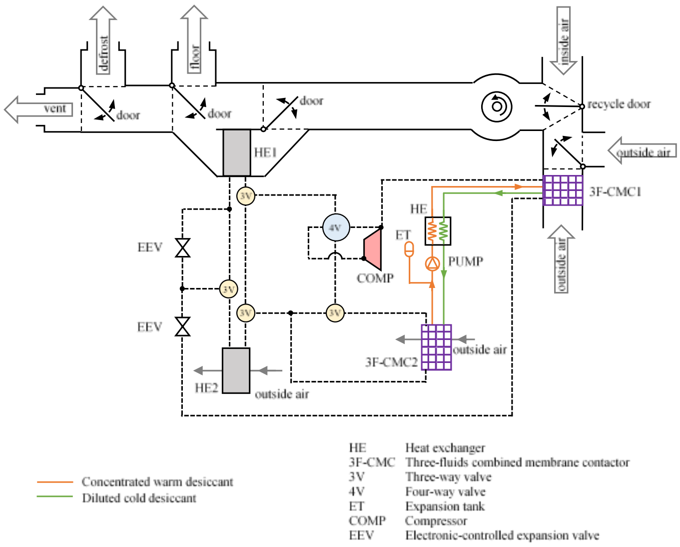

Fig. 2: XERIC climate-control system architecture.

The XERIC system architecture depicted in Fig. 2 allows to grant passengers' comfort in all weather conditions, i.e. in summer cooling & dehumidification, in winter heating and also in the intermediate seasons where only dehumidification or dehumidification coupled to air heating is needed. The following paragraphs give details on how these actions can be carried out by the XERIC system.

A. Cooling & dehumidification action

Air cooling & dehumidification is obtained by setting 4V (four-way valve) and 3V (three-way valve) valves to get the refrigerant paths shown in Fig. 3. It is worth noticing that at the compressor inlet (lower pressure section) the refrigerant flow is fed by two parallel circuits, i.e. from the evaporator HE1 and from 3F-CMC1. The refrigerant mass flow rate in each circuit is independently adjusted thanks to the actions of two Electronic Controlled Expansion Valves (EEVs). They assure that the thermodynamic conditions of the refrigerant coming from HE1 and from 3F-CMC1 are identical (i.e., same overheating temperature and same pressure for the two refrigerant vapour flows). At the compressor outlet (high pressure section of the system), the regeneration contactor 3F-CMC2 and the heat exchanger H2 (condenser of the VCC) are set in series so that they are crossed by the whole refrigerant flow discharged by the compressor.

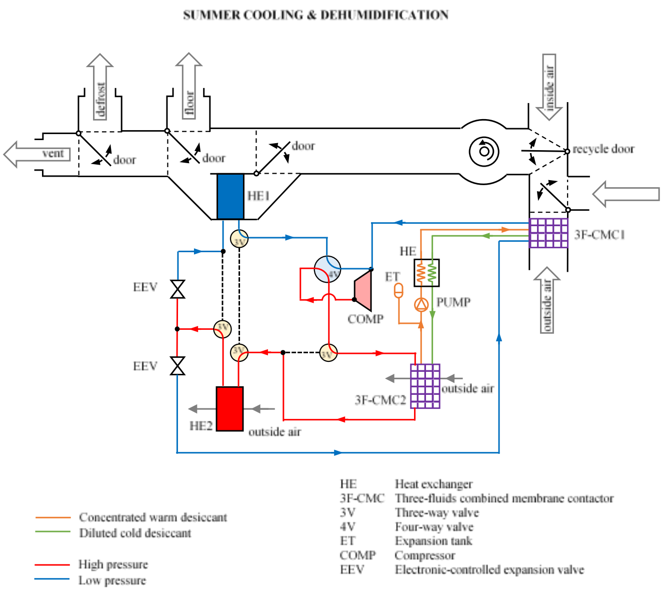

Fig. 3: Summer cooling & dehumidification action.

B. *Heating action*

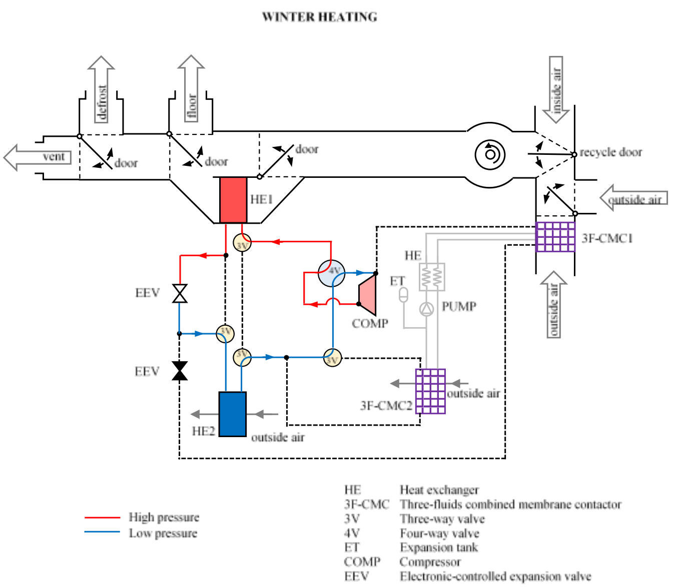

Fig. 4: Winter air heating.

In winter, air heating is obtained by setting 4V and 3V valves to get the refrigerant paths shown in Fig. 4. The renewal air flow does not cross the 3F-CMC1 and refrigerant circulation in the desiccant cycle is excluded. The 4V has been turned to reverse the refrigerant flow in the VCC cycle: in these conditions the heat exchanger HE1 becomes the condenser and the HE2 the evaporator. The heat released by HE1 is used to heat the air flow sent to the passengers' cabin.

C. *Dehumidification action*

In intermediate season or in raining days when fogging on the glass should be prevented, air dehumidification is often the only need. In this case, as shown in Fig. 5, the XERIC system works as in summer (air cooling & dehumidification action) but with the HE2 instead of the HE1 which is now excluded from refrigerant path; also the air path to it can be fully closed by the door shown in the Fig. 5. The outside air dehumidification process upstream the recycle door is carried out by the 3F-CMC1 component.

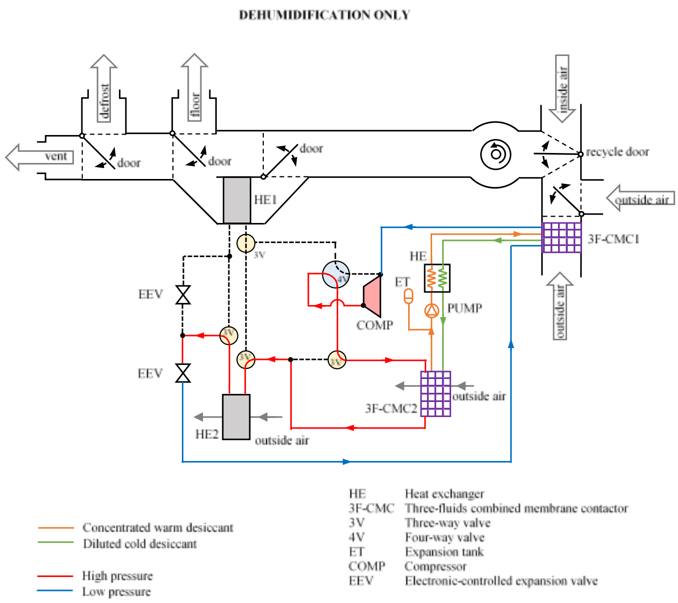

Fig. 5: Air dehumidification.

D. *Heating & dehumidification action*

Sometimes, depending on the considered climatic region, in intermediate seasons or in raining days, when dehumidification only is not sufficient to achieve thermal comfort conditions to the passengers , the XERIC system can work as in the dehumidification action but with air heating, i.e. with the path to the heat exchanger HE1 open and the path to HE2 closed, as shown in (Fig. 6). In this way, the heat released by HE1 is used to heat the dehumidified air flow sent to the cabin.

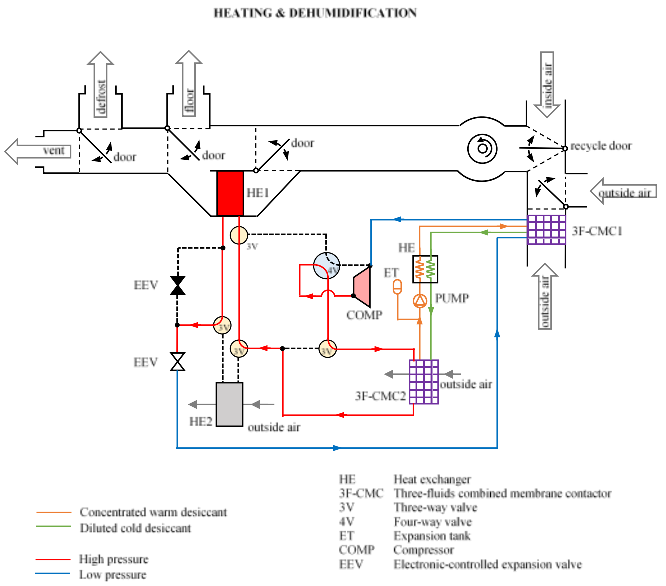

Fig. 6: Air dehumidification & heating.

III. XERIC SYSTEM ARCHITECTURE

The steady state mathematical model of 3F-CMC is described in [17], where some theoretical results are also presented. These results, together with the experimental activity planned within the Project, will be essential to address not only the 3F-CMCs design evolution but also the architecture of the climate-control system. Indeed, to simulate the whole XERIC system it is mandatory to develop software codes that describe the behavior of the all components, i.e. compressor, condenser, evaporator, expansion valve, 3F-CMC. First, each component of the XERIC system must be individually simulated and expressed in the form of a Simulink block (MatLab© environment). Thereafter, all the blocks describing the XERIC components will be linked together to obtain the complete simulation code that can be used to describe the whole system and to forecast its energy performance. Figure 7 shows the 3F-CMC1 and 3F-CMC2 Simulink blocks obtained by converting the FORTRAN code developed in [17] in two MatLab-S functions. In the example shown in Fig.7, the 3F-CMC1 allows the process air flow to be dehumidified and cooled while the 3F-CMC2 acts to restore the LiCl concentration.

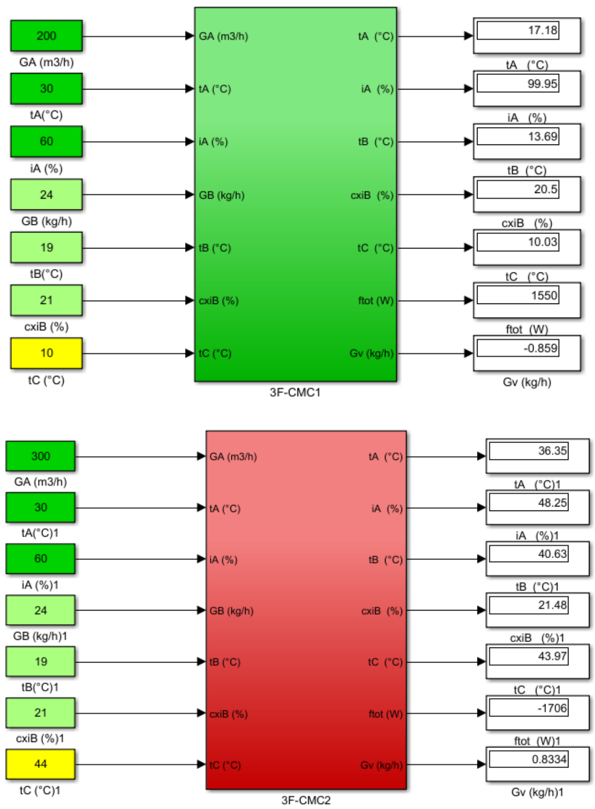

Fig. 7: Simulink blocks representing the 3F-CMCs behaviour.

The left side of each block shows the input data: in green, the considered air inlet conditions (volumetric air flow rate, temperature and relative humidity R.H.); in light green, the desiccant inlet conditions (mass flow rate, temperature and mass composition); in yellow, the refrigerant temperature.

The right side of each block shows the computed outputs: from the top to the bottom, air outlet conditions (volumetric air flow rate, temperature and R.H.); the desiccant outlet conditions (mass flow rate, temperature and mass composition); the refrigerant outlet temperature, the total (sensible + latent) heat flux exchanged and finally the vapour flow rate absorbed.

Figure 8 shows the Simulink scheme of the dehumidification loop: the warm and concentrated desiccant solution from 3F-CMC2 exchanges heat with the diluted and the cold one from 3F-CMC1. In the loop is inserted the counter-flow heat exchanger which works between the warm, concentrated desiccant from 3F-CMC2 and the diluted, cold one from 3F-CMC1.

Inputs that are common to the 3F-CMCs (orange blocks) are the parameters defining the external air conditions. Input to 3F-CMC1 is the refrigerant evaporation temperature Tevap while input to 3F-CMC2 is the condensation temperature Tcond.

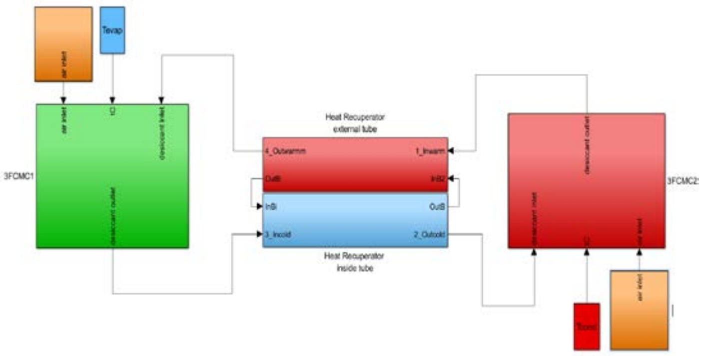

Fig. 8: Simulink scheme representing the desiccant loop.

IV. EXPERIMENTAL TESTS

A vapor compression cycle has been implemented at the Frigomar laboratory in order to evaluate the working conditions when the two expansion valves are operating in parallel: indeed, in the XERIC system one ECEV works on the traditional VCC and the other one works at the inlet of 3F-CMC1. Waiting for the prototypes of the 3F-CMCs to be assembled within the Project, a new evaporator made by U shaped minitubes having the same inlet diameter of those used in the 3F-CMCs has been setup in Frigomar laboratory [16]. Frigomar has manufactured this heat exchanger by welding 80 copper mini tubes to two drilled manifolds. A stainless-steel shell has been designed and manufactured for housing the mini tubes and ensuring the outside flow of the water, which exchanges heat with the refrigerant fluid. The shell has been completed with a stainless steel cover equipped with gaskets in order to avoid water leakages. The overall outside heat transfer surface is 0.466 m^2. Figure 9 shows the scheme of this new heat exchanger with its main geometric characteristics, the frame and an enlarged view of the connection of the mini tubes to the manifold.

This minitubes evaporator has been connected to the testing refrigeration system consisting of the following components:

- Condenser brazed plates with exchanging surface 0.75 m^2;
- Electronic expansion valve ECEV with 1 step accuracy in the range 20 (closed) – 480 (open);
- Hermetic type compressor.

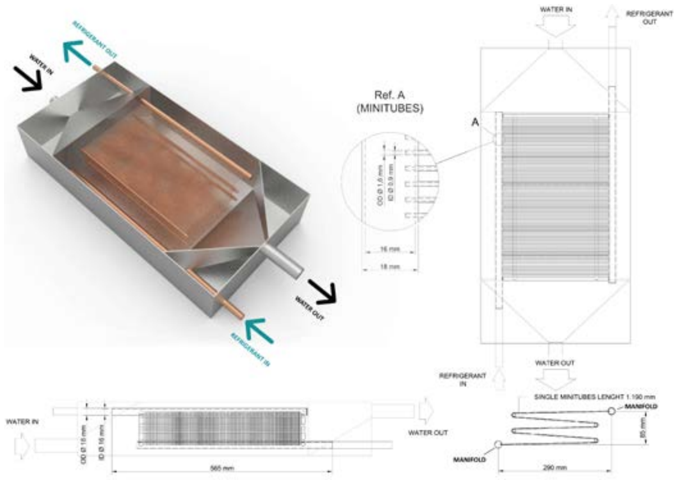

Fig. 9: Schematic view of the mini tubes heat exchanger.

For each component, temperature and pressure of the refrigerant can be measured at the inlet and at the outlet sections; moreover, two 2-way valves installed upstream and downstream of each evaporator allow to carry out tests with only one or both of these two components working.

Figure 10 shows the traditional and minitubes evaporators in parallel and the two electronic expansion valves, ECEV1 and ECEV2, which control the overheating for each evaporator.

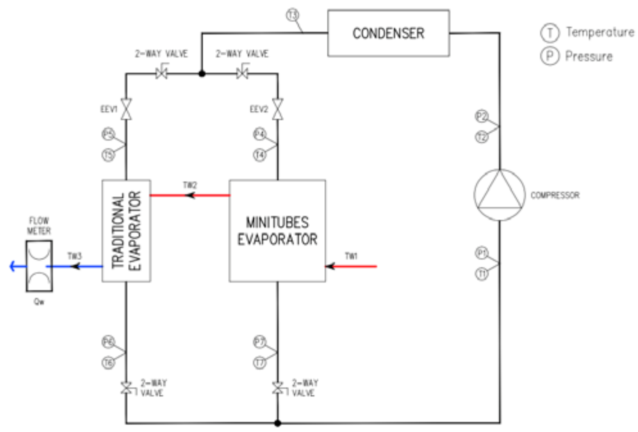

Fig. 10: Scheme of the refrigeration testing cycle.

A set of experimental tests using the refrigeration cycle shown in Fig. 10 have been carried out in order to verify the correct control on the overheating temperature, set equal to 5°C, by the EEVs over time.

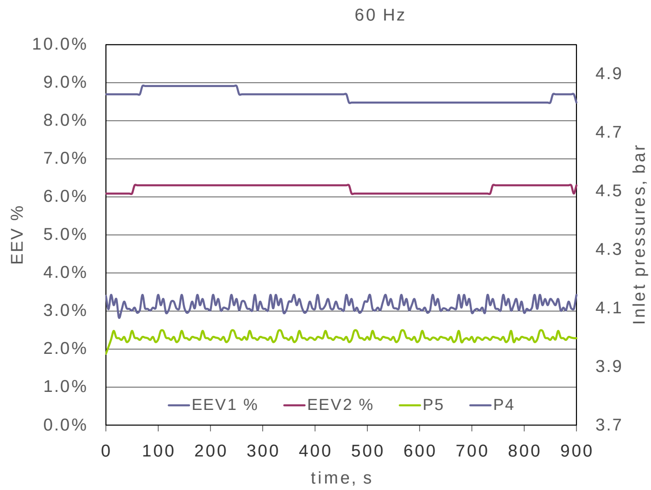

Fig. 11: Experimental results on electronic expansion valves working in parallel: 60 Hz.

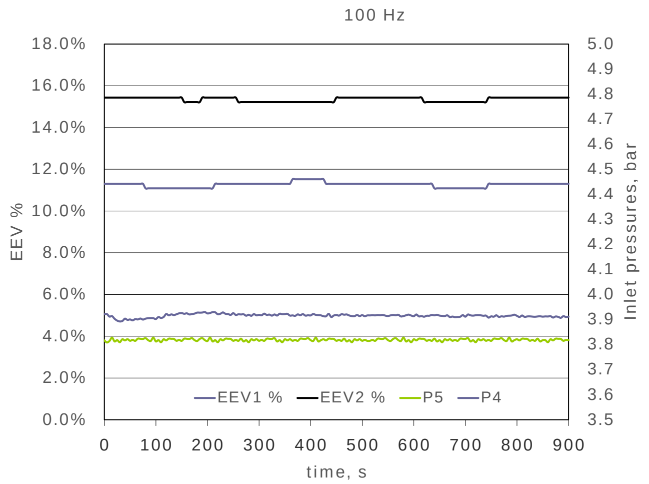

Fig. 12: Experimental results on electronic expansion valves working in parallel: 100 Hz.

Results are depicted in Figures 11 and 12 for two different values of the electric frequency motor: 60 Hz and 100 Hz, respectively. The ordinate indicates the percentage of free passage area of the EEV while the abscissa refers to the testing time. Both Figs 11 and 12 show that the refrigerant pressure downstream the EEVs is almost constant as well as the opening of the EEVs; it follows that the refrigerant flow rate through the traditional evaporator and through mini tubes is constant and stable during time.

V. CONCLUSION

In the present paper, the architecture of a new hybrid climate-control system is presented and commented, by considering the several different working conditions that can be faced. Moreover, the code developed in the Matlab/Simulink environment and used to predict the system performance is presented. Finally, the experimental tests performed in the laboratory to test the proper working of the electronic expansion valves that have to be connected in parallel in the system are shown and commented.

Summarizing, at the present development state, the XERIC climate-control system promises to be capable to satisfy the proposal requirements granting passengers' comfort, in all weather conditions. Its architecture has a very high ductility since the following air handling actions can be performed: in summer, cooling & dehumidification; in winter, heating; in intermediate seasons, air dehumidification only or air heating & dehumidification. Moreover, the preliminary experimental results show a stable operation of the two evaporators working in parallel.

ACKNOWLEDGMENT

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