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New Climate-Control Units for More Energy-Efficient Electric Vehicles: the Innovative Three-Fluids Combined Membrane Contactor

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Abstract— **This paper describes the work in progress in the XERIC project, funded within the Horizon 2020 EU program, that is aimed at building and testing a new climate-control system. The latter integrates a vapour compression cycle with a liquid desiccant cycle to increase Battery Electric Vehicles autonomy thanks to its increased energy efficiency. Modeling activity carried out on the design of an innovative Three-Fluids Combined Membrane Contactor (3F-CMC) and on the development of a lumped-parameters model to predict the 3F-CMC performance is described. The physical assumptions considered in the lumped-parameters model are presented. Results of 2D and 3D numerical heat and mass transfer simulations are used to get input data for the lumped code. The effect of air spacer geometry design on the overall component performance is presented.**

*Keywords— **XERIC project; Three-Fluids Combined Membrane Contactors; hybrid AC systems, mobile air conditioning; liquid desiccant air handling.***

I. INTRODUCTION

XERIC project, funded within the Horizon 2020 EU program, is aimed at developing a new climate-control system able to increase Battery Electric Vehicles (BEV) autonomy thanks to its better energy efficiency in comparison with traditional air conditioning systems. The climate-control system should be able to grant passengers' comfort, in all weather conditions. The core of the system are innovative Three Fluid Combined Membrane Contactors (3F-CMCs) that simultaneously are crossed by air (to be sent to passengers vane), an aqueous desiccant solution (to dehumidify air) and a refrigerant (to control the desiccant temperature and partly to cool the air). The desiccant is a salt aqueous solution (e.g. LiCl, $CaCl_2$). Sensible and latent heat transfers between the air and the desiccant take place through a hydrophobic membrane which is permeable only to the vapour phase, while the refrigerant undergoes phase changes. The heat exchanges with the refrigerant allows to control the desiccant temperature maintaining throught the whole membrane surface an higher gradient of the mass transfer potential Figure 1 shows the desiccant cycle with two 3F-CMCs. A first contactor, 3F-CMC1, is used to dehumidify and to cool the process air, while another (3F-CMC2) acts as a regenerator to re-concentrate the weak solution from 3F-CMC1 by means of solution exchanges between these components. An economizer (HE), between the cold and the warm solution, reduces the parasitic heat transfer. As shown in the figure, the desiccant loop is linked to a Vapour Compression Cycles (VCC). As known, AC hybrid cycles integrating Vapour Compression Cycles (VCC) with Liquid Desiccant Cycles (LDC) are advantageous in comparison with traditional ones since they can operate at a higher evaporation temperature (it is not necessary to cool the air below the dew-point temperature in order to dehumidify it) and also with a lower condensation temperature. As detailed in [1,2], theoretical mechanical power savings up to 35-40 % become possible.

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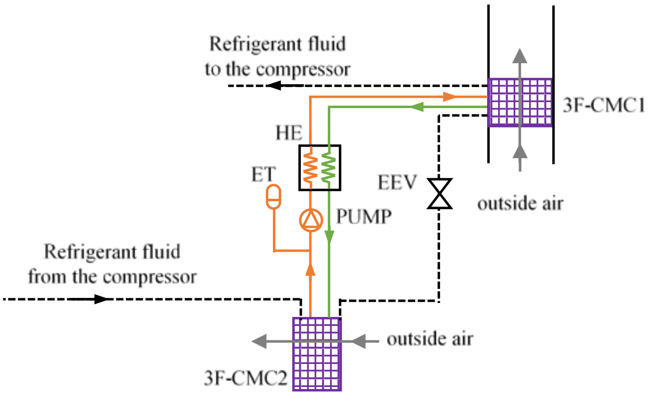


Fig. 1: The desiccant loop with two 3F-CMCs.

II. THE 3F-CMC CONTACTOR

Figure 2 presents the actual 3D design of the 3F-CMC contactor under development, which shows the inlet gaps through which the air flow takes place (white arrow) The other two fluids (desiccant and refrigerant) flow in cocurrent/counter current, in the direction trasversal to the air stream. As depicted in Figure 3, the refrigerant flows inside the lumina of metal minitubes (blue arrows). The desiccant flows outside the minitubes in a domain confined by two membrane sheets (not shown in the figure), according to orange arrows. The minitubes are U-shaped and made of copper/copper-alloys treated to be corrosion resistant. Figure 3 shows also how U-shaped minitubes are arranged in the plastic frame constituting one module. Such a shape of minitubes (Patent pending [3]) has been developed in order to reduce the thermal stresses that affect the 3F-CMC in working conditions.

With reference to Fig. 4, in order to mechanically support the membrane sheets (in blue) that are attached to the frames (one in yellow, one in red), as well as in order to enhance the heat and mass transfer on the air side, a spacer (in green) is placed between two adjacent membranes on the air path. The spacer is made by longitudinal beams that support the membrane, which are connected by elliptical transversal rods to increase the heat and mass transfer coefficients, by periodically breaking the boundary layer.

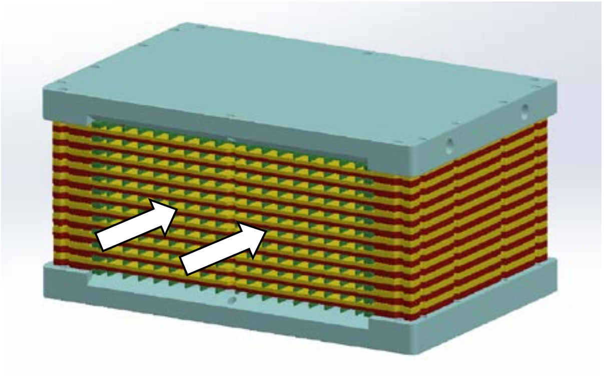


Fig.2: CAD design of the 3F-CMC prototype.

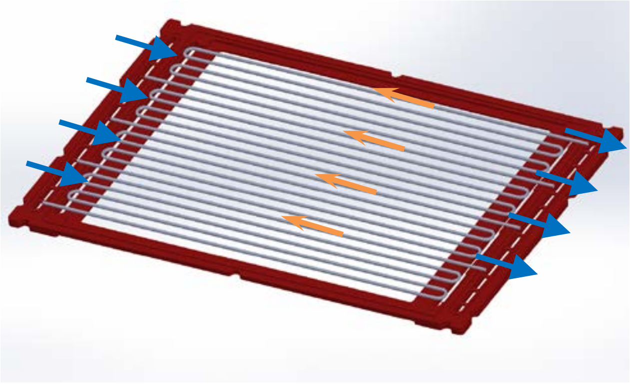


Fig.3: Copper minitubes to ensure internal cooling/heating I 3F-CMCs; U-shaped minitubes arrangement in a module frame.

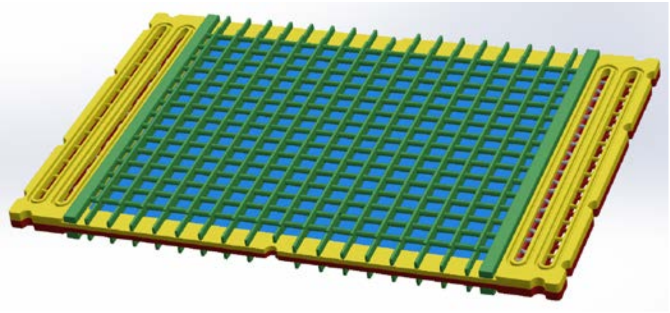


Fig.4: The spacer on the air path supporting the membrane sheets.

III. MODELING ACTIVITY

In XERIC project intense modeling activity is planned to develop mathematical tools to predict the 3F-CMCs behavior as a fundamental step to get full simulation tools of the whole system.

In the 3F-CMC, heat and mass transfers occur simultaneously according to temperature gradients at the two membrane sides and to the different partial vapour pressures between air and liquid desiccant [4,5]. The physical model governing the vapour mass transfer is fully described in [6]. The water vapour absorbed/desorbed by the desiccant brings about thermal effects such as latent/dilution heats which are faced by the heat transfer with an evaporating/condensing refrigerant fluid flowing through the 3F-CMC. The following assumptions have been made:

- steady state conditions;
- unidirectional and fully developed flow for each fluid;
- all fluids are not compressible;

The refrigerant phase changes (evaporation/condensation processes) that take place in the 3F-CMCs are simulated by assuming a very high value of the refrigerant specific heat so that the related heat capacity rate keeps nearly constant the refrigerant temperature.

The mathematical model is based on the mass and energy conservation equations applied to each fluid, i.e. the moist air, the desiccant solution and the refrigerant. The refrigerant flow is assumed to be in cocurrent/counter-current to the desiccant flow.

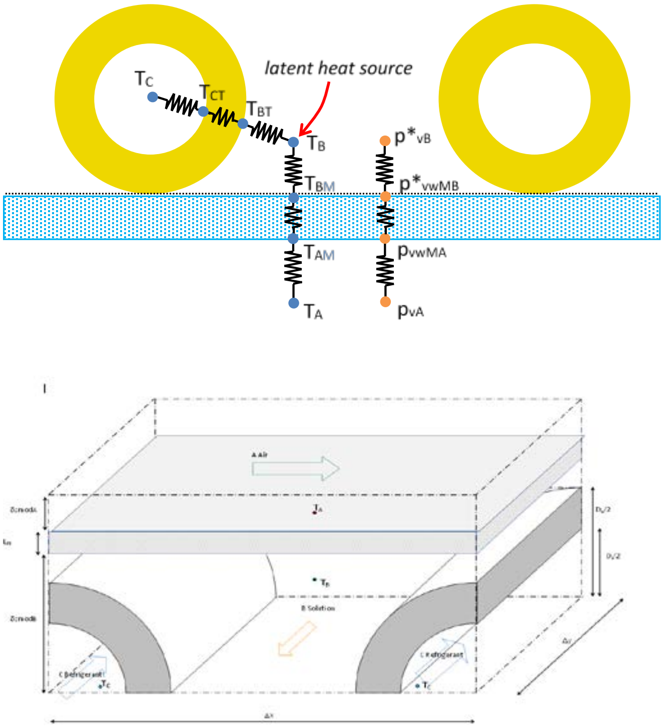


Fig. 5 Sketch of the heat and mass transfer resistances and the 3F-CMC elemental cell.

In Fig.5, a sketch of the heat and mass transfer resistances controlling the 3F-CMC behaviour and the elemental cell (a half air channel and half solution/refrigerant channels) used in the numerical model. Fig. 6 shows some results obtained by means of the lumped-parameter numerical model developed. Reference is made to an air dehumidification process carried out in the following conditions: 20 % mass LiCl solution as desiccant; membrane vapour mass transfer resistance 3.7 $\cdot 10^6$ m/s (i.e. latent heat flux per unit partial vapour difference RET = 1.5 m^2Pa/W); copper/copper-alloys minitubes with an external diameter 1.6 mm and internal diameter 0.9 mm. The linear density of minitubes in the direction perpendicular to the air flow (X direction) is 133 minitubes/m. The 3F-CMC, equipped with 68 modular frames, is crossed by 200 m^3/h air flow rate at 30 °C with a R.H. 60 %, the inlet desiccant mass flow rate is 24 kg/h at 19 °C. The refrigerant temperature is set at 10 °C. In detail, Fig. 6a and 6b show air and desiccant temperature distributions. The exit air temperature is nearly uniform (about 18-19 °C) along the Y direction. The solution temperature is controlled by the refrigerant in the temperature range 13 – 16 °C on more than 90 % of the membrane surface, so that its distribution is nearly uniform. Fig. 6c shows the specific vapour mass flow rate distribution which, again results quite uniform, i.e. there are not dead zones.

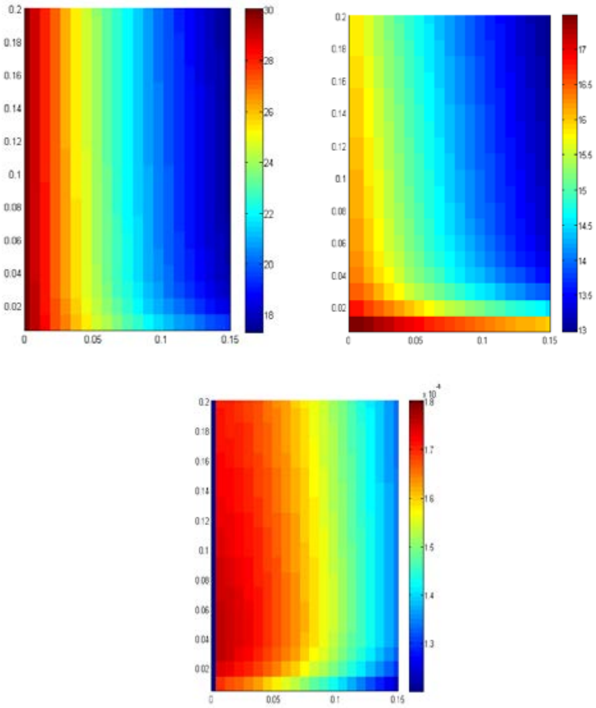


Fig. 6: a) Air temperature b) Desiccant temperature c) Specific mass flow rate absorbed

The heat and mass transfer coefficients adopted in the lumped-parameter numerical model have been determined by means of accurate 3D CFD simulations made by means of two commercial software, i.e. COMSOL Multiphysics (© COMSOL, Inc.) and Fluent (© ANSYS, Inc.). Simulations have been devoted to fulfil the requirement chosen for the maximum allowed air pressure drop (100 Pa) while maximizing the heat and mass transfer coefficients on the air side of the membrane. For instance, Fig. 7 shows some results about air pressure drop given by spacer and air flow velocity distribution.

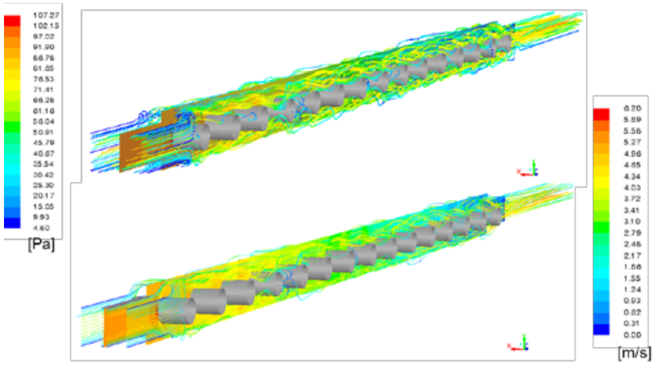
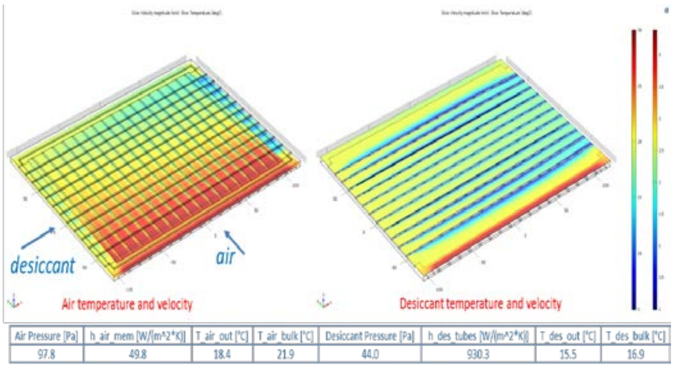


Fig. 7: Air pressure and velocity distributions for an investigated spacer geometry.

Figure 8 shows the results obtained by CFD simulations for the whole repetitive element of the 3F-CMC in order to taking into account the heat and mass transfer processes between air, desiccant solution and also refrigerant. The table at the bottom reports the computed values for the main quantities of interest. The heat and mass transfer intensification at the membrane air side by means of circular/elliptical rods inserted in the space between two opposite membranes.



Air Pressure [Pa]	h_air_mem [W/(m^2*K)]	T_air_out [°C]	T_air_bulk [°C]	Desiccant Pressure [Pa]	h_des_tubes [W/(m^2*K)]	T_des_out [°C]	T_des_bulk [°C]
97.8	49.8	18.4	21.9	44.0	930.3	15.5	16.9

Fig. 8: CFD fluid dynamics computations on the repetitive element constituting the 3F-CMC.

These 3F-CMC1 simulations carried out at the University of Genova (Italy) and at the Fraunhofer Institute for Industrial Mathematics (Germany) demonstrate that the heat transfer coefficients and the coupled mass transfer coefficients can be increased up to 100% while respecting the constraint of a maximum air pressure drop of 100 Pa.

The lumped code allows to study easily the 3F-CMCs behavior giving information on the impact of main 3F-CMCs characteristics on its performance, for instance, by making reference to its enthalpy effectiveness, ε_h defined as follows [6]:

$$\varepsilon_h = \frac{\text{moist air enthalpy variation through 3F-CMC1}}{\text{moist air enthalpy variation for an infinite counter-current 3F-CMC1 surface}}$$

The impact of varying the air side heat transfer coefficient on the computed enthalpy efficiency of the 3F-CMC1 (same input data of Fig. 6) is shown in Fig. 9.

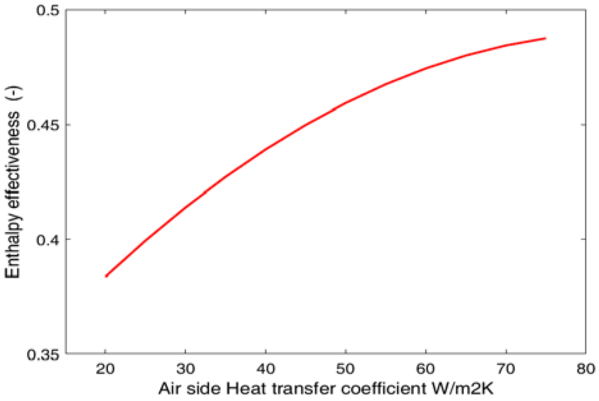


Fig. 9: Computed enthalpy efficiency of 3F-CMC1: effect of increasing the air side heat transfer coefficient.

The curve shown in Fig. 9 has been determined by considering a heat transfer coefficient on both the external tube surface and on the desiccant-side membrane surface equal to 1200 W/(m^2 K). Indeed, this value can derived according to [7], with reference to a rectangular channel having the same aspect ratio of the desiccant flow domain. Preliminary 3D CFD simulations made on the actual desiccant flow domain are in progress, and substantially confirm this order of magnitude for the heat transfer coefficient. Figure 10 shows the desiccant velocity distributions computed for two different aspect ratio of the desiccant flow domain.

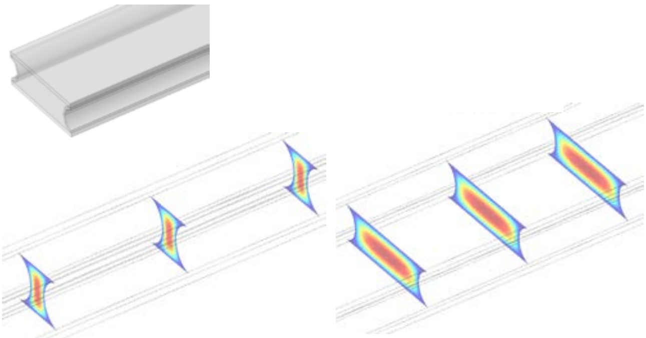


Fig.10: 3D CFD simulations for two aspect ratio of the desiccant flow domain: slices showing the velocity distribution.

IV. CONCLUSION

In the present paper, an innovative component, called Three-Fluid Combined Membrane Contactor (3F-CMC), is presented. It is the core of a new climate-control unit 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 design of the 3F-CMC is described, together with the wide numerical modeling activity needed to predict its performance. In detail, the 3F-CMC is given by the superposition of a repetitive module, thus allowing for an easy scalability of the component to the desidered performance. Both 2D and 3D CFD simulations have been done to investigate the heat and mass transfer processes that occur within the 3F-CMC. The results have helped in both designing the 3F-CMC and in writing a lumped-parameters Fortran code that can be easily and quickly adopted to evaluate the 3F-CMC performance. In detail, the code can be used to determine the air temperature distribution, the desiccant temperature distribution, the water vapor absorption and the enthalpy effectiveness of the 3F-CMC.

Finally, the effect of air spacer geometry design on the 3F-CMC performance is presented.

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