A pilot system for the characterization of hydrophobic membrane contactor modules to be used in air handling processes

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Abstract— **Thermal comfort control in electrical vehicles calls for air conditioning systems with a low energetic demand. The paper describes a pilot system developed in the frame of the "Xeric" EU project in order to study the effect of different operating variables (e.g. desiccant temperature, air velocity) on the performance of hydrophobic membrane based on desiccant air humidification/dehumidification. The overall vapour mass transfer coefficient was estimated in different conditions. By evaluating the membrane mass transfer resistance of the membrane through a modified desiccant inverted cup method, the experimental estimation of the mass transfer resistances in the fluid phases was done. The data obtained through the pilot system are of great interest for the development of air condition systems based on membrane contactors to be used in vehicles cabins.**

Keywords— ***Car cabin environmental conditions; humidity; membrane contactor; hydrophobic membrane; resistance mass transfer model.***

I. INTRODUCTION

Thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment" [1]. Although such mind condition is subjective, several studies attempted to define some ranges of environmental conditions which can provide a wider acceptable thermal comfort sensation in different situations (e.g. inside buildings or in automotive cabins).

The control of the thermal comfort in car cabins is accomplished by the Air Conditioning (AC) unit. The use of the conventional AC units can increase the fuel consumption up 20-30%. Therefore the development of more energy efficient systems to control the thermal comfort in vehicle cabins represents a challenge especially for their application in electric vehicles based on battery or fuel cells.

The thermal comfort in car cabins is affected by several factors which can be either subjective (e.g. clothing insulation and activity level) or measurable (e.g. air velocity and temperature, relative humidity, radiant temperature) [2]. Among them, humidity is one of the most important factors influencing the thermal comfort. The level of relative humidity which provides a comfort sensation depends on the air temperature and in turn on the season (e.g. winter and summer).

The EU project "XERIC - Innovative climate-control system to extend the range of electric vehicles and improve comfort" aims to develop an energy-friendly climate-control system capable of reducing at least 50% the energy used for passenger comfort throughout the year (i.e., heating, cooling and dehumidifying) [3]. In the frame of the Xeric project, a novel system based on the concept of the membrane contactor and the use of a desiccant solution is under development for the humidity control in car cabins.

The concept of humidity control by contacting a desiccant solution with air through an hydrophobic membrane can be more energy efficient than the traditional systems based on air cooling cycles. Membrane contactors combined with liquid desiccant cooling systems have been already used as alternative to the conventional vapour compression cooling systems [4-7], but they have never been used to control climate on vehicles.

The vapour mass transfer takes place through an hydrophobic membranes which acts as a well-defined interface between air and a desiccant solution (Fig.1) [6]. Since humidity can be changed independently from the temperature an energy saving is in principle expected.

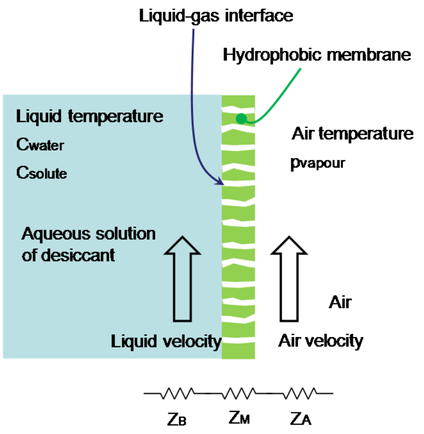

Fig. 1: Schematic representation of the mass transfer resistances in membrane-based liquid desiccant air conditioning.

Although the humidification/dehumidification operation is a process which involves both mass and heat transfer in a lump theoretical model, the driving force for the mass vapour flux, g_v (kg_{water} m^{-2} s^{-1}), is given by the difference between the mass transfer potential in the air, ψ_a (Pa), and the mass transfer potential in the desiccant solution, ψdesiccant (Pa) [6].

$$g_v = K_v(\psi_{air} - \psi_{desiccant}) \qquad (1)$$

The overall mass transfer coefficient, K_v, is related to the mass transfer resistance offered by the membrane, Z_m, and to the vapour mass transfer resistances on the air-side, Z_a, and on the liquid-side, Z_d.

$$K_v = \frac{1}{Z_a + Z_m + Z_d} \qquad (2)$$

In the frame of the XERIC project, a pilot system has been developed aimed to characterize the behaviour of different membranes and desiccant solutions with different air inlet temperature and relative humidity conditions. In this work the effect of some experimental conditions, as well as air velocity and the desiccant temperature, on the vapour mass transfer rate by using a commercial polypropylene membrane and lithium chloride in the desiccant solution will be shown.

II. Materials and Methods

A. Experimental set-up for testing vapour mass transfer in dynamic conditions

Fig.2 shows the experimental set-up developed for testing membrane modules. It consists of an air loop and a desiccant loop. Ambient air is humidified at some set conditions (e.g. air temperature and relative humidity). The fan speed can be controlled to deliver different air flow rates in the range 0.4-3.5 m^3/h. A proper design of both inlet and outlet channels was adopted in order to control the fluid dynamics of the air entering the membrane module. The air channels were realized in polyvinyl chloride (PVC). The air velocity was measured by using an air calibrated rotameter. Humidity and temperature probes and a differential pressure transducer connected to a data recording software were placed on the air side at the inlet and the outlet of the membrane module.

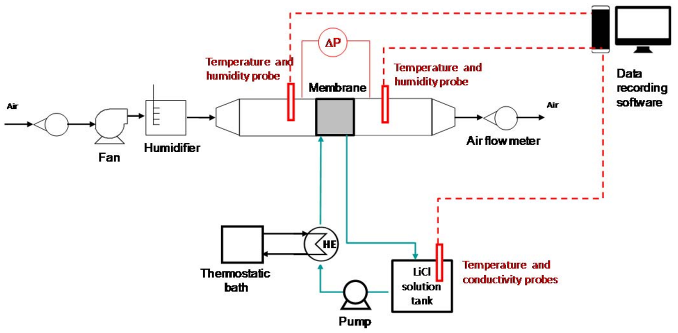

Fig. 2: Experimental set-up for membrane module testing.

As desiccant a lithium chloride solution was used. The initial concentration of the desiccant solution in each experimental run was 35% wt. The desiccant solution was re-circulated to the membrane module with a gear pump which can deliver a flow rate in the range 0-100 l/h. Before to enter in the membrane module the temperature of the desiccant solution was adjusted by circulating cold or warm water in a heat exchanger (HE). After each run the desiccant solution was regenerated to the initial concentration by checking both its conductivity (a correlation between conductivity and concentration was developed) and density. In all the experiments the increase or decrease of the desiccant concentration was less than 1% for each test.

The flat-sheet module (Fig. 3) was made of transparent polyvinyl chloride (PVC) and it held two membrane sheets with effective exchange area of about 0.014 m^2 per membrane sheet for a total membrane area of 0.0028 m^2. Air flows in the middle channel between the two membrane foils separated by a spacer. The desiccant solution was re-circulated to the two liquid-side compartments of the flat-sheet module.

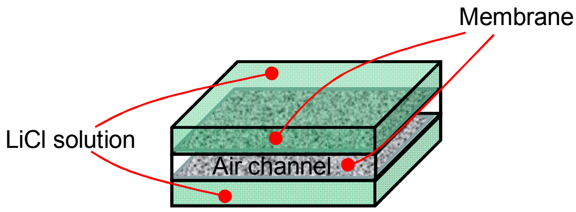

Fig. 3: Flat-sheet module and fluids configuration.

For the experimental tests it was used an Accurel PP1E membrane supplied by Membrana GmbH. The PP1E membrane is an hydrophobic flat membrane made of polypropylene with a thickness of about 100 μm and a pore size of about 0.1 μm. A non-woven layer (Viledon FO 2431, Freudenberg, Germany) was placed between the membrane and the liquid in order to offer a better mechanical support for the polypropylene membrane.

The mass vapour flux, g_v (kg_{water} m^{-2} s^{-1}), was calculated from the mass balance on the air-side loop.

$$g_v = \frac{G_a(x_{out}-x_{in})}{A_m} \qquad (3)$$

where

G_a= mass flow rate of dry air ($kg_{dry\ air}$/s)

x_{in}= inlet humidity ratio (kg_{water}/$kg_{dry\ air}$)

x_{in}= outlet humidity ratio (kg_{water}/$kg_{dry\ air}$)

The overall vapour mass transfer coefficient, K_v, was estimated from g_v by assuming the mass transfer potential ψ_a equal to the partial vapour pressure in the air and in analogy with the heat exchanger practice the driving force was expressed in terms of "vapour pressure mean-logarithmic difference".

$$g_v = K_v \Delta P_{lm} = K_v \frac{(p_{in}-p_v^*)-(p_{out}-p_v^*)}{\ln\frac{(p_{in}-p_v^*)}{(p_{out}-p_v^*)}} \qquad (4)$$

where the vapour pressure in equilibrium with the desiccant solution p_v^* (Pa) was calculated from the activity of the desiccant solution and the saturated vapour pressure of water at the desiccant solution temperature:

$$p_v^* = a_w\, p_s \qquad (5)$$

B. Membrane mass transfer resistance estimation

The membrane mass transfer resistance was estimated using an adapted version of the ASTM E96 test for the Resistance to Evaporative heat Transfer (RET) [8]. The polypropylene membrane was placed between two polytetrafluoroethylene membranes (PTFE, 3μm nominal pore diameter, Goretex, W. L. Gore & Associates, USA) sealed to the bottom of the cup. The bottom PTFE membrane was put into contact with distilled water while the cup was partially filled with a saturated lithium chloride solution. The weight of the cup was measured at defined time intervals. A "blank" test was initially performed only with the PTFE membranes without the polypropylene membrane sample. The RET tests were carried out in isothermal conditions.

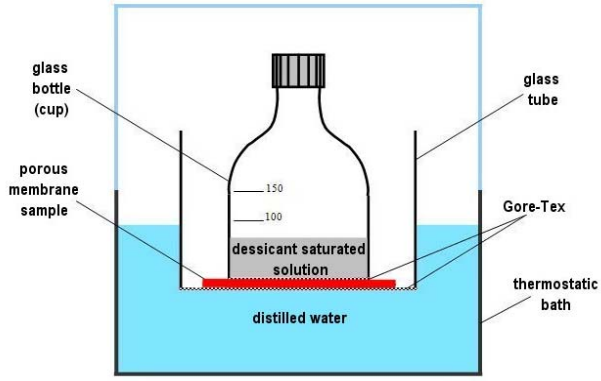

Fig.4: Desiccant inverted cup method for RET measurements

III. Results and Discussion

An example of an experimental run is presented in Fig. 5. The time to achieve steady conditions was usually about 10-15 min for a desiccant temperature between 10 and 35°C and then steady vapour flux were obtained. In any case when a vapour mass flow rate changing with the time was observed the effect of the change of concentration of the desiccant solution was taken into account for the calculation of the driving force.

Fig. 6 shows the effect of the temperature of the desiccant solution for two different air inlet conditions. Positive vapour fluxes corresponds to air humidification while negative fluxes are related to air dehumidification. Considering the air humidification region the vapour flux through the membrane increases by increasing the desiccant temperature since increases the driving force of the humidification process. Similarly in the dehumidification region a lowering of the desiccant temperature again corresponds to an increase of the driving force.

Fig. 7 shows the influence of the air velocity on the vapour mass flux in different conditions of inlet humidity and temperature and at various temperatures of the desiccant solution. Considering the absolute values of the vapour fluxes it is evident that by increasing the air velocity higher vapour mass fluxes were obtained.

For example considering the tests carried out with a temperature of the desiccant solution of 35°C, the overall vapour mass transfer coefficient, K_v, was about 7.6 x10^{-8} kg Pa^{-1} s^{-1} m^{-2} for an air velocity of 0,17 m/s and 1.6 x 10^{-7} kg Pa^{-1} s^{-1} m^{-2} for an air velocity of 0.33 m/s.

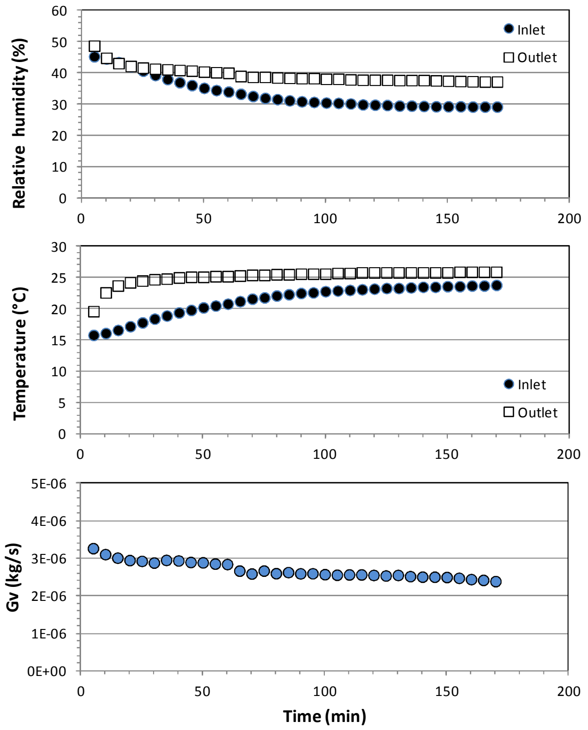

Fig. 5: Inlet and outlet relative humidity and temperature and vapour mass flow rate as a function of the operating time. Air velocity 1 m/s, the initial LiCl solution concentration 35% LiCl, desiccant temperature = 40°C, liquid-side flowrate = 38 kg/h.

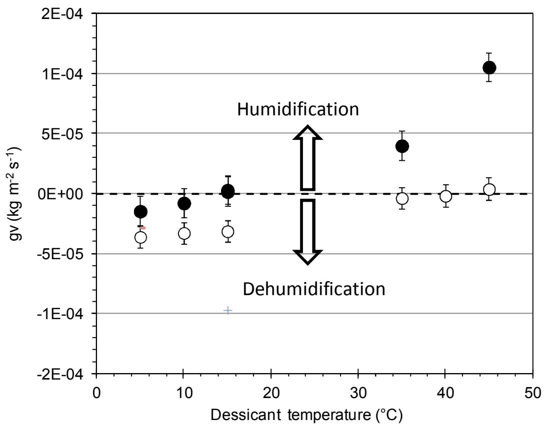

Fig. 6: Effect of the desiccant temperature. (•) Inlet temperature=25-28°C, inlet RH= 27-28%, air velocity =1 m/s; (o) Inlet temperature=18-19°C, inlet RH= 80-90%, air velocity = 0.17 m/s. In both the test the initial LiCl solution concentration was 35% wt; liquid-side flowrate = 38 kg/h.

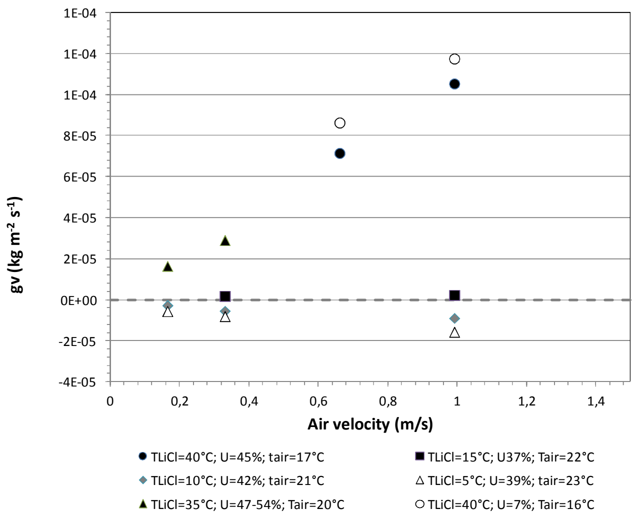

Fig. 7: Effect of air velocity Initial LiCl solution concentration =s 35%wt; liquid-side flowrate = 38 kg/h.

In order the estimate only the membrane resistance RET measurements with the polypropylene membrane were carried out. Fig. 8 shows the vapour flux measured through the Accurel PP1E membrane sandwiched between the two PTFE membranes. Since the vapour flux obtained in the blank test is higher than the ones obtained with the PP membrane, the mass transfer resistance of the PTFE membranes is lower but not negligible. By calculating the driving force for the vapour flux either with or without the PP membrane, the Accurel PP1E membrane mass vapour resistance at 35°C was found to be Z_m= 2.08 x 10^6 Pa s m^2 kg^{-1}.

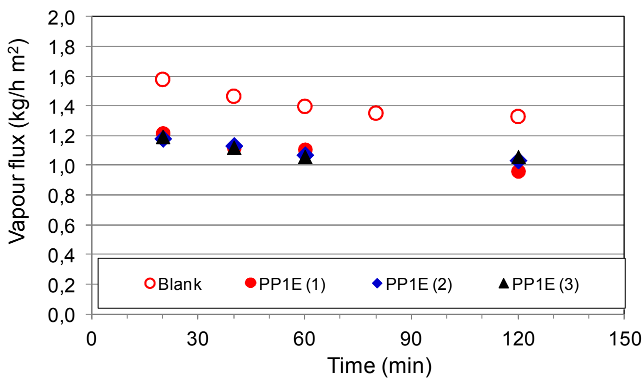

Fig. 8: Vapour flux obtained during RET measurements with three different samples of the Accurel PP1E membrane sandwiched between two Goretex membranes. The blank test refers to the vapour flux measure only with the two Goretex membranes.

By taking in consideration the membrane resistance with respect of the overall membrane resistance that can be calculated from the overall mass vapour transfer coefficient, K_v, the contribution of the membrane resistance was estimated to be between 15% and 25%. In this particular run a large mass transfer resistance is located in the fluid phases. Experimental tests are still on-going to evaluate the contribution of the fluid dynamics in the air-side and liquid-side on the overall mass transfer resistance. In any case the strong influence of the air velocity on the membrane contactor performance suggests a large influence of the mass transfer resistance in air-side.

IV. CONCLUSIONS

A pilot system for the acquisition of air humidification/dehumidification data by using a membrane contactor fed with a desiccant solution was developed in order to investigate the influence of some operating conditions as well as air velocity and desiccant temperature. The pilot system can host different membrane contactor modules.

In the present work the influence of the temperature of a lithium chloride solution and the influence of the air velocity on the mass vapour flux of a 0.1 µm polypropylene commercial membrane was investigated.

By changing the desiccant temperature either humidification or dehumidification of the inlet air stream can be obtained. The desiccant temperature where the behaviour switches from dehumidification to humidification depends on the relative humidity and temperature of the inlet air. In fact the inversion temperature corresponds to a driving force equal to zero.

The air velocity influences the overall mass vapour transfer coefficient indicating the presence of a not negligible resistance on the air-side of the membrane.

The RET measurements allowed for an estimation of the membrane resistance contribution to the overall mass vapour resistance.

The evaluation of each resistance contribution is of great importance for the development of an energy friendly climate control system to be used in the electric vehicles (EVs), in order to extend their range capability in all weather conditions.

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