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Liquid Desiccant-Polymeric Membrane Dehumidification System for Improved Cooling Efficiency in Built Environments

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ABSTRACT

We have recently demonstrated a new type of moisture absorber using a silicone-based liquid desiccant and a nonporous hydrophilic membrane. The setup consists of a core-shell structure where the desiccant flows inside the hydrophilic membrane (core) surrounded with humid air and confined inside a larger diameter tube (shell). In this work, we propose to extend the capabilities of this moisture absorber prototype by addressing two additional characteristics in order to fully validate its capabilities in the built environment. In the first section of this study, we developed a new setup to demonstrate the regeneration process of the liquid desiccant. The regeneration process takes into account the following parameters: (i) air temperature and relative humidity level, (ii) desiccant temperature and water saturation amount, (iii) air/desiccant contact length, (iv) air and liquid desiccant flow rates. In the second part of this paper, we extend our earlier work with this absorber and propose to further improve its performance. We investigate in detail the water absorption kinetics to favor water access to the bulk liquid desiccant surface through efficient mixing inside a confined volume.

KEYWORDS
Liquid desiccant; hydrophilic nonporous membrane; dehumidification; absorption/desorption kinetics.

INTRODUCTION
The global demand for air conditioning is expected to increase drastically over the next 30 years according to recent studies conducted (Shah et al., 2015). This is predominantly attributed to the rapid economical growth of developing countries in Latin America (e.g. Brazil, Mexico), and Asia (e.g. China, India), which are located in hot and humid climate zones (Shah et al., 2015). To effectively cool buildings using existing Heating, Ventilation, and Air Conditioning (HVAC) systems, a major requisite is controlling the humidity level, commonly known as latent loads. In highly-populated geographical zones, excluding desert climates, latent loads require several times larger energy amounts than sensible loads (Harriman et al., 1997). Nevertheless, conventional HVAC technologies address both loads within the same system using a sub dew point vapor compression air conditioner (Meggers et al. 2013). Overall, this process is energy intensive, and better suited for climates with high latent loads. A promising alternative for dehumidification in the built environment is the use of liquid desiccant technologies which present several advantages over traditional solid desiccant wheel systems available on the market (Lowenstein, 2008; Pantelic et al., 2018). Due to their physical and chemical properties, liquid desiccants have the unique capability of being adaptable to the host environment, and can therefore be easily deployed. Another

important characteristics of liquid desiccant is their ability to be regenerated at a different location from where dehumidification takes place.

In a recent study, we have demonstrated the capabilities and advantages of a liquid desiccant absorber prototype where the two key components are: (i) a noncorrosive alkoxylated siloxane liquid desiccant, (ii) a nonporous hydrophilic membrane to contain the desiccant (Ahn et al., 2013; Pantelic et al., 2018). We have demonstrated that such a system can effectively remove moisture from the air, while also solving carryover problems and eliminating the need for noble metal parts. However, we also pointed out the need to investigate the direct regeneration capabilities of the desiccant after exposure to moisture. In addition, we have mentioned the possibility to further improve the kinetics of water absorption into the desiccant by analyzing the different diffusion mechanisms taking place in the system.

In this work, our objective is to address these two remaining aspects that are required for a successful and complete implementation of this new generation of liquid desiccant absorber. In the first part of this paper, we demonstrate preliminary experimental results that support the regeneration potential of the liquid desiccant under easily achievable experimental conditions. Then, we discuss the remaining improvements and future work required to determine the ideal parameters for the water desorption process. In the second part of this manuscript, we describe a new manifold concept that will be tested to improve the kinetics of water absorption into the desiccant, and improve the dehumidification performances of the device.

METHODS

The liquid desiccant regeneration setup shown in Fig. 1 consists of the following main components: (i) alkoxylated siloxane liquid desiccant, XX-8810 (Dow), (ii) commercially available nonporous hydrophilic tube, Pebax® 1074 (noted Pebax in the following sections) (Foster Corporation) with 1.50 mm outer diameter, (iii) clear Polyvinyl Chloride (PVC) tube (Advanced Technology Products) with 6.35 mm outer diameter, and inside which the Pebax tube is located.
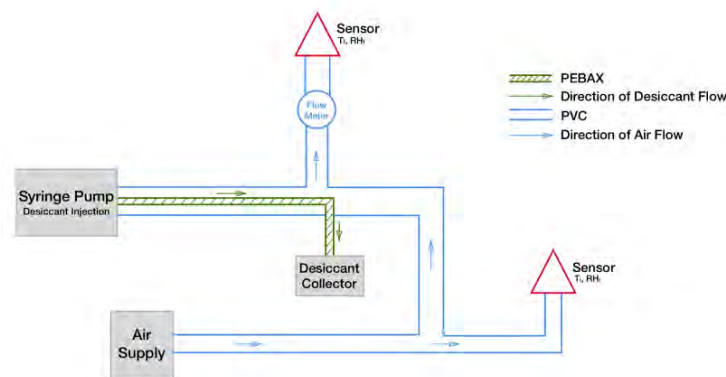

Figure 1. Diagram of the experimental setup used for the desiccant regeneration.

The liquid desiccant was fed through the Pebax membrane at controllable flow rates using a syringe pump (Harvard Apparatus). The air flow was measured with a gas flow meter (Sensirion SFM 4100), and the temperature (T), relative humidity (RH) of the air were acquired with Sensirion SHT75 type sensors. All raw data were recorded through an Arduino Uno board interface for subsequent analysis.

The desiccant regeneration experiments were carried out by feeding supply air around the Pebax tube which was confined inside a PVC tubes (Fig. 1). The liquid desiccant at room temperature, and saturated with 3 wt.% deionized water was flowing inside the Pebax at various flow rates. The supply air was directly taken from the in-house laboratory system and

subsequently heated through a hot water bath prior to contacting the Pebax membrane. During the desiccant regeneration experiments, we recorded the T and RH of the air before (T_i, RH_i) and after (T_f, RH_f) contacting the Pebax membrane across a defined contact length. For all experiments, the supply air and desiccant flows were in counter flow configuration. We let at least about a 15 minute gap between each experiment to ensure that the system was at equilibrium. The air flow rates were determined such that they would be within the range of rates previously used for dehumidification (Pantelic et al., 2018). Two air/desiccant contact lengths of 10 and 30 cm were studied. All experiments were carried out inside a fume hood where the T was near 20 °C and RH fluctuating between 2 and 6%.

RESULTS & DISCUSSIONS

Desiccant regeneration experiment with 10 cm air/desiccant contact length
In Table 1, we summarize the first series of the results collected using the setup described in Fig. 1. Experiment A corresponds to the baseline T and RH measurements in the absence of air and desiccant flow. The high humidity value of RH_f is simply due to the location of the sensor inside the fume hood, i.e. closer to the higher RH indoor environment of the laboratory. In experiment B, no change in RH_f is observed after running the desiccant (with 3 wt.% water) through the Pebax tube, and in the presence of air flow around it. This clearly indicates no desorption of the water (absorbed in the desiccant) through the hydrophilic membrane. Therefore, in the subsequent experiments, B-E, the liquid desiccant flow rate was progressively decreased by a factor of 2, while maintaining the air flow constant. Despite lower desiccant flow rates, experiments B-E do not result in any obvious water desorption. Therefore, in experiments F and G, we further increased the air flow rate by a factor of 2 to reach higher Reynolds numbers. Yet, higher air flow rates combined with low desiccant flow rates do not result in a water desorption mechanism. All results obtained with 10 cm contact length appear to indicate that the region of air/desiccant contact is insufficient to allow the desorption process to take place.

Table 1. Summary of experiments for 10 cm air/desiccant contact length.

Experiment	Desiccant Flow Rate (L/s)	Air Flow Rate (L/s)	T_i (°C)	RH_i (%)	Desiccant Injection Time (s)	T_f (°C)	RH_f (%)	Duration of Experiment (s)
A	0	0	20.98	2.40	N/A	20.88	6.48	5
B	$1.30 \ 10^{-5}$	16.67	43.99	1.66	105	22.24	0.83	260
C	$0.65 \ 10^{-5}$	16.67	43.47	1.64	105	22.33	0.90	250
D	$1.67 \ 10^{-6}$	16.67	43.49	1.64	105	22.33	1.04	215
E	$0.84 \ 10^{-6}$	16.67	43.32	1.63	105	22.35	1.13	220
F	$0.65 \ 10^{-5}$	33.40	43.75	1.56	105	21.67	0.27	380
G	$0.84 \ 10^{-6}$	33.40	45.15	1.53	105	21.5	0.15	330

Desiccant regeneration experiment with 30 cm air/desiccant contact length
In these series of experiments, we maintained the desiccant flow rate as low as $0.84 \ 10^{-6}$ L/s and studied the effect of 33.40 and 16.67 L/s air flow rates. The Reynolds number corresponding to the flow rates of 33.40 and 16.67 L/s are $4.3 \ 10^5$ and $8.6 \ 10^5$, respectively. These results are shown in Fig. 2. When the air flow rate is as low as 16.67 L/s, there is a possible water desorption process taken place, as confirmed by the higher RH_f values. In this case, the increase in absolute humidity is about 23.10 mg/m^3. Although the difference between RH_i and RH_f is about 10%, we acknowledge that this RH range is within the domain where readings from the sensor can reach up to 4% error. Nevertheless, in all experiments,

including the first series with 10 cm contact length, we have obtained consistent and reproducible data. Therefore, we expect the results obtained with 30 cm contact length to support an effective water desorption process which tends to support the possible regeneration of the alkoxylated siloxane desiccant.

In the next series of ongoing experiments, we plan to investigate the effect of larger air/desiccant contact lengths to confirm these preliminary results. In addition, we will also increase the RH value of the air to reach 10% or more RH. This will ensure that we are in the range where the sensors are the most accurate.
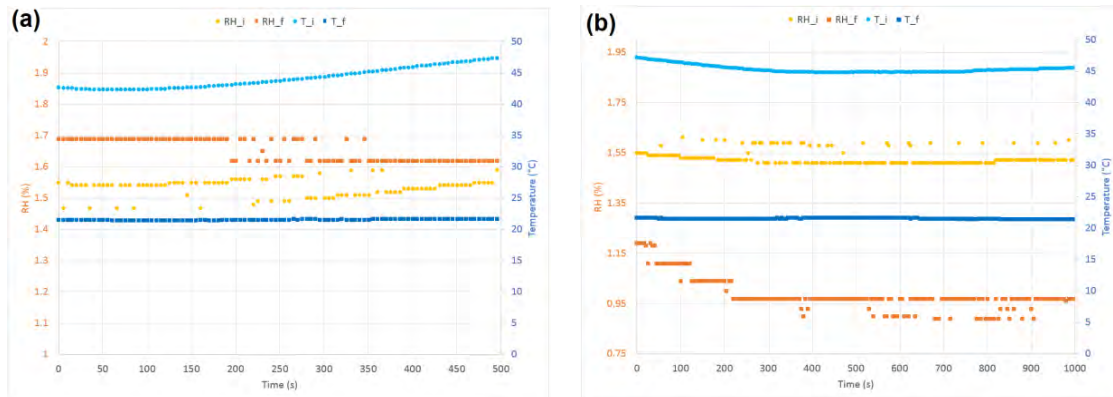

Figure 2. Water desorption experiments for 30 cm air/desiccant contact length. Air flow rate of (a) 16.67 L/s, and (b) 33.40 L/s.

Improving the performance of the dehumidification prototype

In parallel to the desiccant regeneration experiments, we are currently exploring solutions to enhance the overall performance of the dehumidification system described in our previous study (Pantelic et al., 2018). To achieve this goal, we propose to improve the kinetics of water absorption into the desiccant by designing a chamber to enhance the mixing of the desiccant, and thus to effectively use its total volume for water absorption. The new desiccant mixing chamber is represented in Fig. 3. This initial design includes four inlets for the Pebax and PVC tubes. In our ongoing experiments, our objective is to test the dehumidification performance of the absorber under similar conditions to our earlier study (Pantelic et al., 2018), and directly evaluate the anticipated advantages of the mixing chamber.
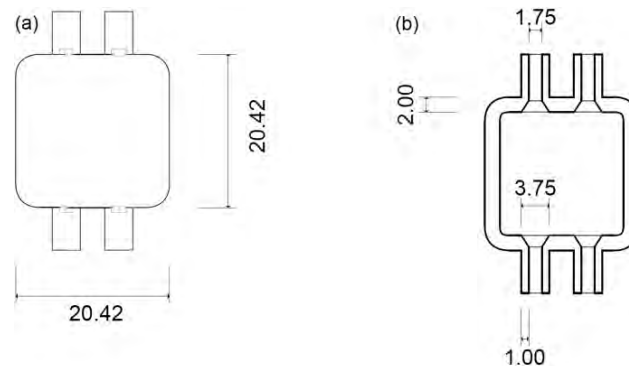

Figure 3. Technical drawing of the 3D printed manifold, with dimensions in mm. (a) Top view, (b) Cross-sectional view of the chamber showing the 1.75 mm inlets for the Pebax tubes.

CONCLUSIONS

In this study, we have covered two fundamental characteristics of the liquid desiccant-based dehumidification prototype. In the first part, we have demonstrated preliminary and ongoing experiments to investigate the regeneration process of the alkoxylated siloxane liquid desiccant in the presence of 3 wt.% water. The preliminary results appear to confirm that at least a 30 cm air/desiccant contact length is necessary to effectively evidence the water desorption. We are currently in the process of evaluating the effect of larger contact lengths on the water desorption from the desiccant.

In the second part of this work, we presented the potential of a new mixing chamber for the liquid desiccant. This chamber is expected to improve the water absorption kinetics by favoring water access to the bulk liquid desiccant surface through mixing. The initial results presented in this paper are still the subject of ongoing research. We expect to complete the two research directions described here and successfully demonstrate the dehumidification and regeneration capabilities of this new generation of liquid desiccant prototype.

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