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Novel concept of autonomous liquid desiccant-based system for sustainable indoor humidity pumping (A)

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Abstract—A sustainable humidity pump is proposed to manage the indoor humidity levels by directly removing the water vapor from the room air instead of supplying a dried cool air as in the conventional systems. The humidity pump uses liquid desiccant driven by a thermosyphon loop. The system is sized following a systematic sizing approach applicable to any outdoor conditions. The proposed system is simulated for different heat inputs to determine the optimal operating conditions. It was found that the system performance was affected by the outdoor RH levels, where the optimal COP decreased with the increase in the outdoor RH: a maximum COP of 1.54 was reached at low RH (35 °C, 30 %). Furthermore, a higher heat input was needed to operate the system at higher outdoor RH for the same latent load removed.

Keywords— Indoor humidity pump, sustainability, liquid desiccant, water vapor adsorbents

I. INTRODUCTION

The most challenging aspect of the management of the indoor environment is the control of indoor humidity levels [1]. Even though water vapor is not a direct contaminant, its presence at high levels leads to mold growth causing asthmatic reactions to the occupants [2]. In addition, high indoor relative humidity (RH) hinders the body's ability to dissipate heat by transpiration [3], affecting thus the occupants' perceived thermal comfort [4]. Therefore, it is crucial to reduce indoor RH levels to provide occupants with acceptable indoor air quality (IAQ) and hygrothermal comfort [5]. Conventionally, moderate RH levels are provided using ventilation and air-conditioning systems that supply dehumidified and cooled outdoor air [6]. Mechanical air conditioning systems cool the air below its dew-point temperature to dehumidify it, and then the air is reheated to the needed supply temperature [7]. This strategy renders these systems energy intensive, especially for densely occupied spaces in extreme hot and humid climates [8]. Alternatively, desiccant systems have been used to handle the latent load separately, reducing thus the mechanical air conditioning systems' power consumption [9]. Nevertheless, they require high thermal energy for regeneration and their size is typically bulky, which hinders their implementation in residential system [10].

With the rising concerns on the alarming increase rate of global warming [11], it is becoming more crucial to seek **passive alternatives** to sustainably pump indoor humidity directly from the indoor space to the outdoor environment [12, 13]. However, this concept is not well matured to become a standalone fully autonomous system yet [14, 15]: Keniar et al. [16] showed that a membrane-based liquid desiccant was able to pump indoor humidity to the outdoor, but required active regeneration as well as the use of seawater as heat sink to cool the hot regenerated solution [16]. In recent work, Cao et al. [17] and Zhang et al. [18] developed a humidity pump panel consisting of a novel desiccant with high water capacity and kinetics. Nevertheless, the humidity pumping process using such panels is **intermittent**: during adsorption, the desiccant is exposed to the room air and isolated from outdoor conditions using metallic shutters. During desorption, the shutters positions are switched to isolate the desiccant from the room air and expose it to the solar radiation [17, 18]. Thus, there is a need for a sustainable humidity pump with **autonomous and continuous operation**. For this reason, a highly hygroscopic **liquid desiccant** is proposed to circulate in a permeable membrane-based loop, picking the indoor generated moisture, and releasing it to the outdoors. A heat input (from solar radiation, waste heat etc.) is needed to regenerate the liquid desiccant and circulate it between the indoor and outdoor environments via buoyant forces (i.e. thermosyphon) [19]. Since the water vapor absorption raises the solution temperature, an insulation layer is needed to prevent heat gains into the space, without retarding the moisture transfer. Accordingly, a "*breathable*" insulation layer, which is highly water permeable, is used on the indoor side of the liquid desiccant loop [20]. Thus, this system offers a passive humidity pump operating continuously and autonomously. It can be implemented in any outdoor conditions due the use of the liquid desiccant loop, and it is of interest to investigate its effectiveness and performance.

The aim of this work is to assess the feasibility of a passive system constructed from a buoyant-driven liquid desiccant to passively pump the indoor generated humidity to the outdoor environment. For this reason, mathematical models are developed for the heat and mass transfer in the desiccant loop, the thermosyphon and the indoor space. The models are validated with experimental data from literature and used to assess the performance of the proposed system through a case study of a space with high moisture generation rates, at different outdoor humidity conditions. A thermodynamic analysis is conducted to assess the effectiveness of the proposed system compared to conventional systems.

II. System Description

This work considers an occupied space with high internal latent load. The space has a façade exposed to the outdoor environmental conditions as shown in **Fig. 1**. The space is provided with mixing air-conditioning system that supplies cool outdoor air to regulate the space temperature within the comfort range as well as to provide acceptable IAQ. Note that the air-conditioning system does not handle the space latent load. Instead, a passive humidity pump is incorporated within the external wall section to pump the indoor air humidity towards the outdoor environment. The humidity pump is formed of three components: a liquid desiccant loop, a storage tank and a breathable insulation layer as shown in **Fig. 1**.

The inner insulation facilitates the diffusion of the indoor air moisture towards the liquid desiccant solution while creating a barrier to the heat coming from the warm solution. The solution tank is heated to circulate the liquid desiccant in the membrane via buoyant forces. Note that the storage tank is used to avoid fluctuations in the system operation by stabilizing the solution concentration. A check valve (or backflow preventer) is used on the inner side to force the solution direction from the outside towards the room. In the outdoor side of membrane loop, the water vapor pressure level increases beyond that of the outdoor air. This effectively regenerates the desiccant solution, which is then collected in a metallic header to prevent water moisture transfer with the environment. The header is finned to enhance the cooling of the solution with the outdoor air. The warm solution enters thus the loop's inner side to absorb the moisture from the room air before returning back to the tank.

The system performance is evaluated based on the pumped latent load (Q_{latent} (W)) from the indoor space, added sensible load ($Q_{sensible}$ (W)) by the warm solution, as well as its coefficient of performance (COP). The latter is ratio of the latent load to the required heat input (Q_{heat} (W)) to circulate the solution in the desiccant loop $\left(COP = \frac{Q_{latent}}{Q_{heat}}\right)$.

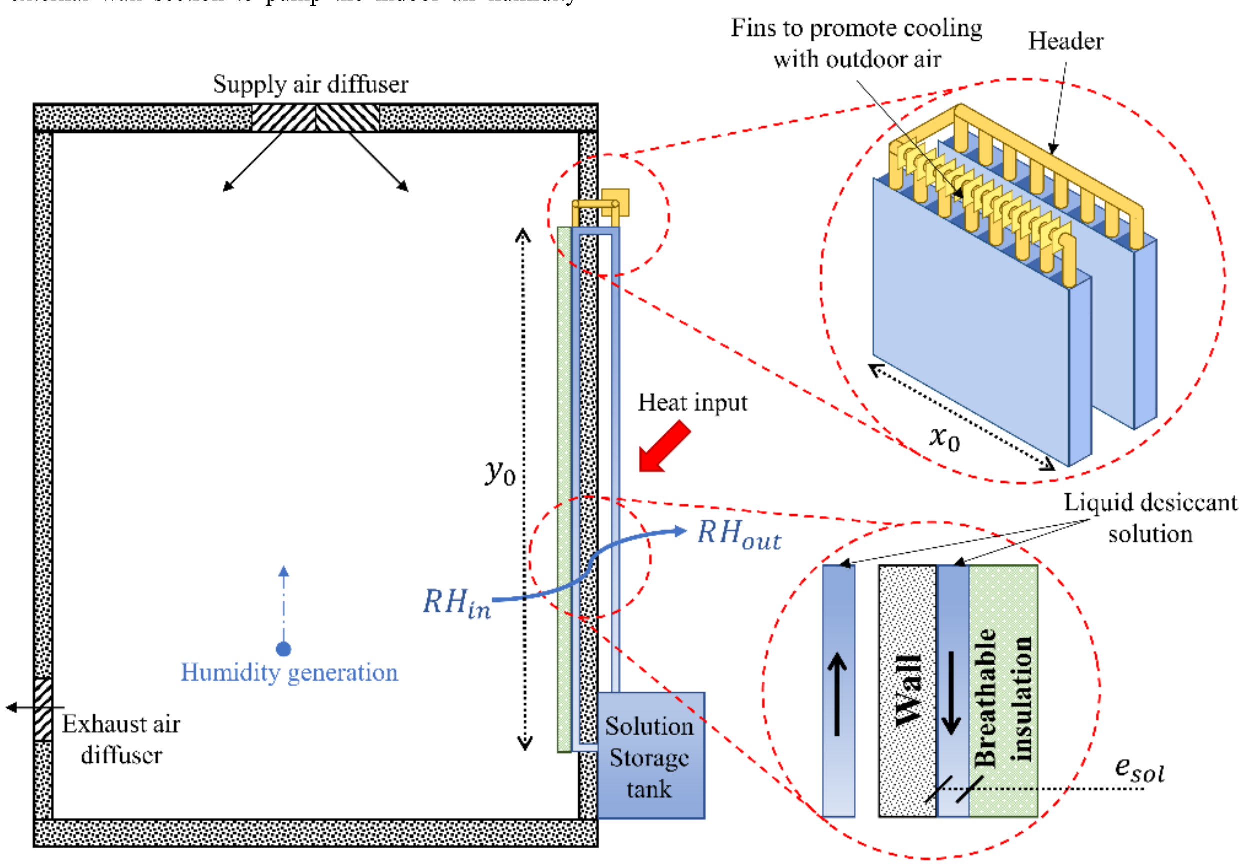

Fig. 1. Schematic of the proposed humidity pump installed in the space façade with close up details for the different subcomponents.

III. Methodology

The performance of the system depends on the effectiveness of the absorption/desorption phases in the desiccant loop. Validated mathematical models are developed for the heat and mass transfer of the sorption processes as well as in the indoor space to enable the optimal sizing of the different humidity pump components. The developed models are applied for a case study of a typical space with high latent load in the hot and humid climate. A thermodynamic analysis is then conducted to evaluate the effectiveness of the proposed system in comparison with the conventional system.

A. Absorption model

The hot solution circulating in the membrane via buoyant forces has a higher water vapor pressure than the outdoor air, which causes the desorption to take place [21, 22]. In the indoor part of the membrane loop, the solution absorbs the moisture from the room air through the adjacent breathable insulation layer, while releasing the heat of absorption. To model the heat and mass transfers taking place inside the desiccant solution, the experimentally validated transient one-dimensional model of Li et al. [23] is adopted. The model assumes that heat and moisture transfer are normal to the membrane surface. The moisture and heat balance on the solution side are given by [23]:

$$\rho_{salt} e_{sol} \frac{\partial X}{\partial t} + \frac{\dot{m}_{salt}}{y_0} \frac{\partial X}{\partial y} - U_m(\omega_g - \omega_{sol}) = 0 \tag{1}$$

$$\rho_{sol} e_{sol} C_{p,sol} \frac{\partial T_{sol}}{\partial t} + C_{p,sol} \frac{\dot{m}_{sol}}{y_0} \frac{\partial T_{sol}}{\partial y} - U(T_g - T_{sol}) - U_m h_{fg} (\omega_g - \omega_{sol}) = 0 \tag{2}$$

The terms of (1) represent the water storage in the liquid desiccant solution, the advective mass flux and the mass flux entrained from the indoor air by diffusion from the membrane and insulation layers, respectively. The terms of (2) represent the heat storage in the solution, the advective heat flux, the convective heat transfer with the room air and the heat gain/loss due to absorption/desorption of water vapor. ω_g (kg/kg) is the specific humidity in the indoor/outdoor air, ρ_{salt} (kg/m^3) and $\dot{m}_{salt}$ (kg/s) are the density and mass flowrate of the desiccant, respectively. ρ_{sol} (kg/m^3), $\dot{m}_{sol}$ (kg/s), $C_{p,sol}$ (J/kg·K), T_{sol} (K) and ω_{sol} (kg/kg) are the solution density, mass flowrate, specific heat capacity, temperature, and specific humidity, respectively. U (W/m^2·K) and U_m (kg/m^2·s) are the overall heat and moisture transfer coefficients between the solution and the air, respectively. h_{fg} (J/kg) is the latent heat of water evaporation. e_{sol} (m) and y_0 (m) are the membrane channel gap and height, respectively. X (-) is the solution mass fraction given by:

$$X = \frac{\dot{m}_{sol}}{\dot{m}_{salt}} - 1 \tag{3}$$

The desiccant solution in the storage tank is heated using a heat source (like solar radiation or waste heat), causing a buoyant driven flow. Assuming homogenous (well mixed) conditions inside the tank, the solution's temperature and desiccant mass fraction are given by:

$$m_{sol} C_{p,sol} \frac{\partial T_{sol}}{\partial t} = \dot{m}_{sol} C_{p,sol} (T_{sol,in} - T_{sol}) + Q_{heat} \tag{4}$$

$$m_{salt} \frac{\partial X}{\partial t} = \dot{m}_{salt} (X_{in} - X) \tag{5}$$

where $T_{sol.in}$ (K) and X_{in} (-) are the solution temperature and desiccant mass fraction entering the storage tank after leaving the indoor side of the membrane loop, respectively. Q_{heat} (W) is the heat supplied to initiate the buoyant driven flow and m_{salt} (kg) and m_{sol} (kg) are the salt and solution mass in the tank.

The solution flowrate ($\dot{m}_{sol}$) is determined from the analytical thermosyphon model adopted from Basu et al. [24] with horizontal heating and cooling segments. Initial and boundary conditions are supplied to the model to complete this set of differential equations. Additionally, the numerical absorption model requires geometrical inputs (membrane characteristic and dimensions), and thermos-physical inputs (absorbent properties and saturation pressure correlations). Based on these inputs, the model yields the adsorbed water vapor by the liquid solution.

B. Space model

A space model is needed to predict the indoor air conditions of temperature and water vapor content. In this study, the validated model of Yassine et al. [25] is adopted, which assumes well-mixed indoor conditions. The zone indoor temperature (T_{in}) is determined from the energy balance on the room air given by:

$$\rho_{in} V_{in} C_{p,in} \frac{dT_{in}}{dt} = \dot{m}_{sup} C_{p,in} (T_{sup} - T_{in}) + Q_{ext} + Q_{int} + U y_0 x_0 (T_{sol} - T_{in}) \tag{6}$$

where ρ_{in} (m^3/kg), V_{in} (m^3) and $C_{p,in}$ (J/kg·K) are the zone air density, volume, and specific heat capacity respectively. T_{sup} (K) is the temperature of the supply air flowrate, Q_{ext} (W) and Q_{int} (W) are the heat gains into the space from the building external envelope and the internal heat generation from the occupants, respectively. The desiccant loop is of dimensions y_0 (m) and x_0 (m).

The zone indoor humidity level is determined from the water vapor mass balance given by:

$$\rho_{in} V_{in} \frac{d\omega_{in}}{dt} = \dot{m}_{sup} (\omega_{sup} - \omega_{in}) + \dot{\omega}_{gen} - U_m y_0 x_0 (\omega_{sol} - \omega_{in}) \tag{7}$$

where ω_{sup} (kg/kg) and ω_{in} (kg/kg) are the air specific humidity in the supply and zone air respectively, while $\dot{\omega}_{gen}$ (kg/s) is water vapor generation rate from the occupants.

The above model requires as input the building geometry, orientation, and envelope material as well as its occupancy schedule and the generation rate of water vapor to solve for the temporal variation of the indoor air conditions as a function of those of the supply air.

C. Numerical solution

The different numerical models are solved using the finite volume method with implicit scheme. First order upwind scheme is used for the discretization of the first order spatial partial derivative. A time-step independence test is performed to determine the time-step that yields accurate results at acceptable computational time. The convergence of the different mass and energy balances is reached when the residuals of the calculated parameters are less than 10^{-6}. These numerical models are integrated among each other through the boundary conditions of mass and heat diffusion between the desiccant loop and the indoor air.

D. Sizing approach

The proper sizing of the different components of the proposed system is vital for its efficient operation. For the membrane loop, there are geometric constraints imposed on the inner side: (i) available area ($x_0 y_0$) for moisture transfer is limited between 30 to 50 % of the wall area [26], (ii) the channel height (y_0) should not cause excessive decrease in the solution concentration, (iii) the channel gap (e_{sol}) is set to impose a velocity between 1 and 2 m/s for effective mass transfer. The thickness of the insulation layer is determined based on the available material in the market, with the consideration of reducing the sensible gain to the space without excessive increase in the water vapor flow. For the outer side of the loop, the same width is maintained, however with a different height – set to ensure complete regeneration of the desiccant solution.

IV. Adopted Case Study

The validated model is applied for a case study of a typical space with a fixed high indoor moisture generation rate. To assess the system performance, three representative weather conditions are considered: hot and humid (35 °C, 70 %) referred to as ***High RH case***, hot and moderate (35 °C, 50 %) referred to as ***Moderate RH case*** and hot and dry (35 °C, 30 %) referred to as ***Low RH case***. This is important to study the proposed humidity pump's performance under all possible outdoor humidity conditions and determine its limitation and applicability ranges.

A. Space characteristics

The adopted space for the case study is chosen as the BESTEST case building proposed by IEA [26]. The space has dimensions of 8 m × 6 m × 2.7 m with exposure to the outdoor environment from the southern façade, while the remaining orientations are considered internal faces adjacent to conditioned spaces. Typical building envelope is adopted, with detailed characteristics presented by Harrouz et al. [27]. Homogeneous conditions are considered in the space, where a temperature of around 24°C is maintained by the mixing ventilation system. The space is operated between *9:00 h – 17:00 h*, where a constant latent load is considered that maintains a high indoor RH level of 85 %.

B. Material selection

The most suitable liquid sorbent, membrane and breathable insulation must be selected to have complementing characteristics and ensure the effective performance of the humidity pump. Potassium formate is the adopted liquid desiccant, which is a weak acid that have recently gained attention: it showed a considerably low regeneration temperature (45 °C – 55 °C) with a lower viscosity compared to conventional absorbents [28, 29]. Such low viscosity is crucial to reduce the required pumping power and enable the buoyant forces to create the needed solution flowrate [19]. To ensure effective operation of the system, a typical concentration of 75 % for the potassium formate solution. As for the membrane, the commercially available PVDF polymeric membrane is used, which is a selective hydrophobic porous layer, permeable to water vapor but impermeable to the liquid solution to prevent carry over [23, 30]. Furthermore, mineral wool is used as a highly breathable insulation layer due to its low thermal conductivity and high water vapor permeability [31].

V. Results and Discussion

The different developed models were validated with published experimental data. The space model of Yassine et al. [25] was validated against a calibrated TRNSYS model and showed a discrepency of ± 5 % on the predicted space temperature between the two model. The adopted absorption model of Li et al. [23] was validated experimentally and the maximum error on the predicted outlet air temperature, humidity, and desiccant temperature were 1.1 %, 1.6 % and 0.9 %, respectiely. These results were reproduced by the current model developed by the authors. Finally, the analytical solution of Basu et al. [24] was validated with publisehd experimental data and used in the applicability range of temperature and heat input as presented in [24].

The proposed system was properly sized and simulated for the three different outdoor humidity conditions. The sizing appraoch was thus applied for the case study, and an area of (1.8 m × 2.7 m) was needed, with a channel height and gap of 1.8 m and 4 cm respectively, for both inner and outer loops. Furthemore, a typical insulation thickness of 50 mm was selected for the mineral wool layer. The sized system was then simulated for the three different cases of outdoor humidity, and the results are presented in **Fig. 2**.

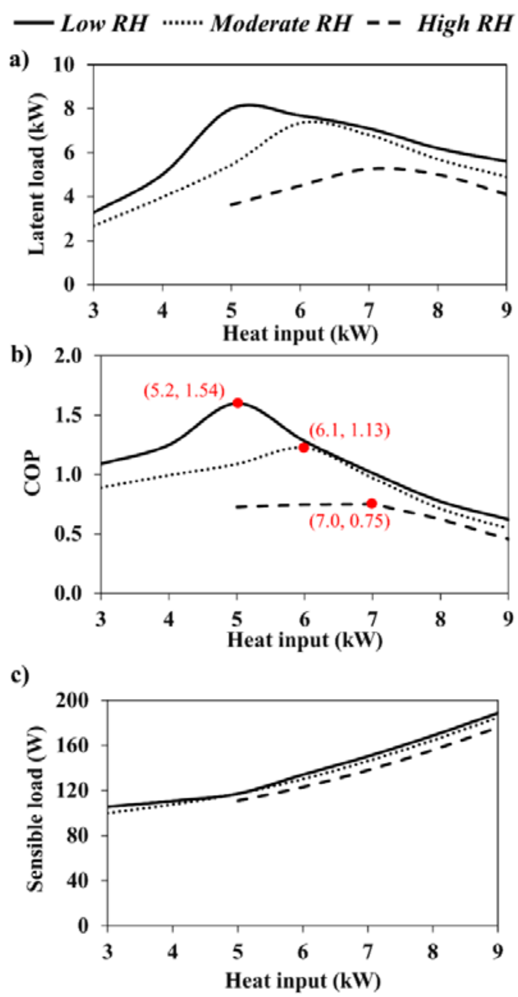

Fig. 2. a) The removed latent load, b) the COP and c) the added sensible load to the space for different heat inputs at the three adopted cases of outdoor RH.

For the ***Low RH case***, the removed latent heat (Q_{latent}) from the space increased with the heat input to the tank until Q_{latent} reached a maximum of 8 kW (**Fig. 2.a**). This is due to the increase in the circulated mass flowrate with the heat input. However, as further heat was supplied to the solution, the pumped latent heat decreased due to two main reasons: i) the decrease in the solution flowrate since the cooling side of the loop is limited by the high outdoor air temperature and the fins effectiveness, ii) the increase in the inlet solution temperature to the room side of the loop increased its equivalent vapor pressure, which reduced the driving gradient for the moisture transfer from the room to the solution. Moreover, heat inputs higher than 9 kW hindered the operation of the system where the vapor pressure was higher than that of the room (due to the high solution temperature), reversing thereby the moisture flow direction. Similar trend was obtained for the cases of ***Moderate*** and ***High RH***, however, with lower removed latent loads. This is due to the reduction in the ability of the solution to be fully regenerated on the outer side of the loop, caused by the reduced gradient of the water vapor between the solution and outdoor air. Note that, for the ***High RH case***, the minimum heat input needed to operate the proposed system was 5 kW, in order to provide the high regeneration temperature required to overcome the high outdoor water vapor pressure.

The resulting COP of the system decreased with the increase in the outdoor RH, and presented a maximal value for a specific heat input to the tank: a COP of 1.54 was reached at low RH for a heat input of 5.2 kW (**Fig. 2.b**). At the moderate RH, a maximum COP of 1.13 was reached for a heat input of 6.5 kW, while at high RH, a heat input of 7 kW was needed to attain the maximum COP of 0.75. A rising shift in the needed heat input was observed with increased outdoor humidity levels.

It is noted that the sensible load is the same for the different outdoor RH levels (**Fig. 2.c**). This is expected since $Q_{sensible}$ mainly depends on the heat input supplied to the solution (i.e. the increase in the solution temperature) rather than the RH levels. However, a small decrease in $Q_{sensible}$ was found at high RH due to the decrease in the latent load removed - i.e. the decrease in the added heat of absorption of water vapor into the solution.

VI. Conclusion

This work proposed a sustainable humidity pump that uses liquid desiccant driven by a thermosyphon loop. A sizing approach was developed and applied for a case study considering three different outdoor humidity conditions. The system was simulated for different heat inputs to determine the optimal operating conditions. It was found that the system performance was affected by the outdoor RH levels:

- The maximum COP decreased with the increase in the RH.
- A higher heat input was needed to operate the system at higher outdoor RH for the same latent load removed.

The system performance can be enhanced by optimizing the different subcomponents' design, especially the breathable insulation to reduce the sensible heat gain without retarding moisture flow. Moreover, the membrane performance can be improved through the impregnation of adsorbents such as metal organic frameworks to reduce its water vapor diffusion resistance and provide it with adsorption properties.

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