Liquid Desiccant Latent Load Handling Simulation for Building HVAC Applications with a DOAS Module

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Abstract

Liquid desiccant dehumidification represents a promising research avenue for HVAC applications. This research presents a case study exploring a novel membrane desiccant absorber that we have characterized extensively at the bench scale in previous work, and in this study we present the simulation to consider the feasibility of scaling up the system to building room scale in terms of pumping costs and air mass exchanger fan cost. As part of an ongoing research pilot building project in Singapore, the simulation examines scaling up the liquid desiccant system to match the loading observed in the solid desiccant wheel in a dedicated outdoor air supply (DOAS) unit in hot and humid Singapore conditions. The liquid desiccant dehumidification system is composed of a novel combination of hydrophilic alkoxylated siloxane liquid desiccant and nonporous, vapour permeable Pebax® membrane. Such a configuration allows cooling with off-coil dehumidification, reducing the need to "over-cool" beyond the dewpoint, saving 40.0% - 61.6% in cooling energy. The corresponding liquid desiccant system would require a 66 x 66 tube array of shell-in-tube style minicontactors.

Introduction

Liquid desiccant dehumidification is a growing research area of interest, with many academic studies coming out in the past couple of years (Ahmed et al., 1998; Lowenstein 2008). The risk-averse building sector will likely slow commercial implementation of such systems, however a promise with liquid desiccant systems over conventional solid desiccant wheels is flexibility of system layout and water mass transport management. By using small, decentralized liquid desiccant dehumidification combined with radiant panels or other low exergy chiller technologies large amounts of energy can be saved (Jeong et al., 2003; Meggers et al., 2012).

This study builds off previous work characterizing a novel liquid desiccant system using a vapor permeable Pebax® membrane in conjunction with an alkoxylated siloxane liquid desiccant (Pantelic et al., 2016). The dynamic viscosity of the neat liquid desiccant at 25 C is 0.031 PaS. This value compares favorably to other liquid desiccants, such as $CaCl_2$ η=0.033 PaS at 51.32 mass percent, and LiCl η=0.00989 PaS, at 41.5 mass percent (Wimby et al., 2014). However, these absorber and desorber apparatuses are often free surface reactors, which opens the air stream to contamination vectors. The system is also often sized for centralized operation and the flow of the viscous desiccant can be large and traverse long distances.

Previous work addresses the chemical viability of the membrane/desiccant pair to produce dehumidified air by leveraging partial pressure differences (Das and Jain 2013; Fazilati et al., 2016; Abdel-Salam et al., 2016; Zhang et al., 2016), however the full scale adaptation including pumping and regeneration costs was still required so a simulation is carried out in this study. Using the data on moisture absorption kinetics and partition coefficients from previous work, this study models the overall energy balance of such a liquid desiccant system over various absorber, desorber, pump, and waste heat recovery system configurations. This is compared to our analysis of the performance of standard solid desiccant wheel systems for both latent energy recovery as well as active desiccant regeneration for dehumidification.

The motivation for this project stems from the desire to develop an improved desiccant dehumidification system for the pilot building research implementation in Singapore called 3-for-2 (Schlueter et al., 2016). In that project we have implemented a dedicated outdoor air system (DOAS) unit in conjunction with a latent heat recovery solid desiccant wheel system that was designed for decentralized integration into the façade. It does not enable direct regeneration of the desiccant and still requires a cold mechanical cooling coil to achieve design humidity conditions in the space.

Based on our initial work with the new membrane and desiccant we are interested to consider its potential as a system for a similar decentralized room operation. This requires analysis of the factors affecting our ability to scale up the current bench scale membrane liquid desiccant system with just one small membrane tube in a shell and tube configuration to a multiple tube system that matches the performance of the system in Singapore.

Background

This paper makes use of research and data associated with the 3for2 Beyond Efficiency research project in Singapore as presented in BS2015 (Rysanek et al. 2015). In that project, a 550 m^2 office space has been outfitted

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with a decentralized ventilation system comprised of 4 dedicated outdoor air systems (DOAS). Each DOAS is equipped with an enthalpy wheel and passive dehumidification wheel (i.e., desiccant wheel) for pre-treatment and off-coil dehumidification of supplied air using return air for energy recovery. The empirical performance of the DOAS was previously characterized by Murray et al. (2015). Using the DOAS performance data as a benchmark, the liquid desiccant absorber system was optimized and functionally compared in a building physics model. Previous studies cite cooling load reductions of 21% with sensible heat recovery (Mumma 2007), and suggest even more of a reduction when the latent load is handled with a solid desiccant wheel, as discussed in previous work on the pilot project in Sinagpore (Murray et al. 2015). However, there are high pressure drops in the air stream associated with each desiccant wheel that can be leveraged by the addition of liquid desiccants to add an intermediate working fluid to aid in the dehumidification of air, offering less power input and high returns since the desiccant allows for off-coil dehumidification.

The authors' previous work with liquid desiccant dehumidification examined fully a shell in tube style mass exchanger composed of a 1 mm ID tube containing liquid desiccant, placed inside a second tube, ID = 3.5mm, through which a humid air supply was pumped. A schematic of the cross section of this tube is shown in Figure 1 (Pantelic, et al. 2016). The tube containing the desiccant was manufactured with Pebax® 1074, a nonporous material with excellent moisture transport properties. This allowed us to determine for a single tube the moisture removal rates per unit surface area of desiccant at different inlet air conditions and flow parameters.

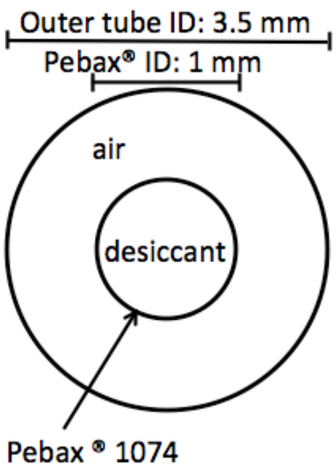

Figure 1: Schematic of cross section of liquid desiccant shell and tube mass exchanger.

The initial study results indicated an optimal length of tube at 10 cm or less, since after this length the mass transfer kinetics slow, indicating a diffusion limiting regime has been approached. This means that the surface of the desiccant very quickly absorbs water, but it doesn't propagate into the center of the laminar fluid flow. Withinn 10cm the uptake slows, but we have designed intermediate mixing stages that allow us to produce a fresh surface layer of desiccant. This allows repeated stages of 10cm to maintain high uptake until the total desiccant has reached a critical mass fraction of water uptake.

Methods

To expand the authors' previous work, a simulation was performed to determine how the liquid desiccant system compares to a state of the art example of solid desiccants in the HVAC industry. Using real performance data from the solid desiccant wheel-equipped dedicated outdoor air supply (DOAS) unit as part of the 3-for-2 pilot project in Singapore as a benchmark, the simulation compares pressure drop in the proposed, scaled up version of the liquid desiccant absorber/desorber unit on both the air and desiccant side to the pressure drop of air within the DOAS unit.

In order to estimate the pressure drop of the desiccant system, certain parameters were chosen to be fixed. These included membrane thickness, desiccant flow rate, and a segment length of 10 cm. The membrane tubes were obtained from a manufacturer with a fixed thickness, which fixed this parameter. Additionally, the desiccant flow rate of 0.012 mL/s was fixed because data (Pantelic et al., 2016) show that for an order of magnitude increase and decrease in the flow rate, only an 11% difference in mass transfer is observed. Therefore, this is not a parameter to which the design would be sensitive. The individual segments are repeatable in series, but the individual segment length was fixed at 10 cm. Again, data by Pantelic et al. show trends in the data that indicate longer tube lengths are not incrementally worth the extra pressure drop. 10 cm was the smallest interval sampled due to physical sensor and connection limitations, however the ideal length may be shorter. The DOAS unit in the Singapore pilot project was capable of maintaining an absolute humidity removal of 13.7 g/kg at peak load. The maximum airflow rate supplied by the unit to the space and its occupants is 522 m^3/hr, 145 L/s. Therefore these values were selected as targets for setting up a multiple tube simulation for operating a scaled up version of our system.

In our previous work, we investigated how shell size and air flow rates affected moisture removal mass transfer kinetics, which resulted in an understanding of the *Re* for the air stream affected mass transfer. Based on the best data points that we had in our previously collected data for air mimicking Singapore conditions of high humidities of 20 g/kg, we choose an air flow rate and shell size that achieves the optimal *Re* from our previous results. Since mass transfer is proportional to a (usually) non-unity power of flow rate, other flow rates than those studied could be used, however the decision was made to restrict to known data since higher flow rates could transition the system to a difusion-rate-limited regime inside the desiccant skewing the affect of the higher *Re*.

This fixed the airflow in each tube that would be assembled in an array to match the building ventilation.

To match the airflow rate, the number of tubes required was determined by dividing the maximum output of the DOAS unit by the individual tube airflow rate. To remove the correct amount of moisture from the air, the tube array was placed in series a number of times sufficient to remove the amount of moisture from the incoming air at the peak design load of 20 g/kg, to supply it at 7.3 g/kg to the occupants In between these stages, it is assumed that a mixing stage is inserted to remove concentrated moisture profiles from the membrane/desiccant interface, and this allows the removal of a total of 13.7 g/kg, the same design as required for the solid desiccant DOAS unit in the pilot project

Next, the pressure drop across each component was determined according to equation 1.

$$\Delta P=8\mu LQ/\pi r^4 \qquad (1)$$

In equation 1, μ is dynamic viscosity given in Pa s, L is the length of the segment in which flow occurs, Q is the volumetric flow rate in m^3/s, and r is the radius of the pipe in m. An additional 10 m of piping was inserted to carry desiccant between absorber and desorber elements, This was calculated for both the desiccant and the air, as we are proposing a shell in tube exchanger. The DOAS unit has a pressure drop across the wheels between 250 and 300 Pa combined, which dictates fan power. Additionally, there are rotors responsible for spinning the wheels that have a parasitic power consumption that must be considered. Therefore, meaningful comparisons can be made between the combined fan power and rotor power for the DOAS unit, and the combined desiccant pumping power and fan power for the proposed desiccant absorber and desorber units.

Results

To begin sizing the absorber unit, it was established that the liquid desiccant system must be capable of removing 13.7 g/kg of moisture from the air at 145 L/s maximum air supply rate. Based on previous work, we examined data and chose a 2000 mL/min or 0.033 L/s air supply per tube point that removed 3 g/kg per 10 cm section of desiccant tube length. Dividing 145 L/s by 0.033 yields 4,350 shell and tube sections that must be incorporated in the final absorber unit to achieve the maximum required airflow rate. This would result in a 66 by 66 square tube matrix in cross section. Achieving this array would require a cross-sectional area of around 0.5m by 0.5m, which is similar to the existing unit in Singapore.

As indicated in the methods, this 10 cm section must be repeated to achieve the required dehumidification of 13.7 g/kg, or approximately 5 times in series. This is the final size of our system, a 66 by 66 tube matrix with shell and tube sections of 10 cm, repeated 5 times in series to achieve the maximum allowable air flow and the required dehumidification. Each tube has an outer diameter of approximately 7 mm, which results in an array of 0.46 m x 0.46m in height and width. These dimensions could be reduced by using either a 3D printed or pre-existing shell structure that eliminates the need to use individual tubes. Length is a minimum of 0.5 m, but in reality would likely be closer to 0.6m when accounting for mixing stages. Figure 2 is a mockup of a 2x3 element in the 66x66 array. Final designs could have higher packing densities, or take advantage of interstitial spaces.

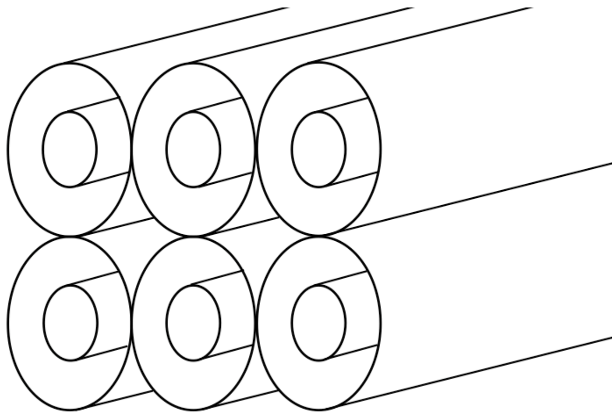

Figure 2: Diagram of stacked array of tubes.

Following the sizing of the unit, the pressure drop across each of the elements was calculated. For a single 10 cm long, 1 mm ID Pebax® tube, the desiccant inside has a dynamic viscosity of 0.031 PaS, a density, ρ, of 1031 kg/m^3, and is moving at a flow rate of 0.021 mL/s or 1.2×10^{-8} m^3/s. Simple pressure drop for an incompressible fluid is given in equation 1.

This corresponds to a pressure drop of 7600 Pa across a single tube. However, due to the parallel arrangement, the pressure drop across all 4,350 tubes is equivalent to the pressure drop across one 10 cm tube. Taking the required pumping power as the pressure drop times the total flow rate, this corresponds to a pumping power of 0.4 W, increasing to 0.8 W at 50% pump efficiency for all five 10 cm lengths. Doubling this to account for both the absorber and desorber, we arrive at 1.6 W of required pumping power. Adding an additional 10m of length of 2.5 cm ID piping added less than a tenth of a Watt. The final check for the desiccant is its ability to hold the amount of water required to be removed in total from the air side. Based on the removal of the 13.7 g/kg, the desiccant would need to absorb about 5% by weight of water. This is a bit higher than the 3% we anticipate being possible with relatively good kinetics, so for the very high humidity removal conditions the desiccant may need to be circulated slightly faster. A doubling of the flow rate decreases the final concentration to 2.5% and increases the desiccant pumping to 5 Watts. In order to stay below 1% by weight, which would ensure fast kinetics in the desiccant uptake through the length of the system operation, the pumping would need to be 5 times faster and the pump power would be about 30 W. Still, these are not unreasonable values for pumping and could be managed by the system with a variable speed pump to minimize overall pumping costs for various humidity removal needs.

The air side experiences more pressure drop, as the 4,350 shells for the air to flow in have a significant volumetric flow rate. Specifically, the air in each tube flows at 2000 mL/min, or 0.033 L/s, orders of magnitude larger than the desiccant flow rate. The pressure drop across a single tube is 16.7 Pa, scaling up to 83.5 Pa for all 5 segments, and doubled for the desorber is 167 Pa total. These numbers are less than the pressure drop for the solid desiccant and enthalpy wheels. However, compared to the 250-300 Pa pressure associated with both wheels in the DOAS unit which corresponds to a 575W fan power, there is a favorable comparison.

Discussion

Many of the fixed design parameters were chosen reflecting the large dataset accumulated in Pantelic et al. (2016). However, many deeper relationships were uncovered that could form the basis of future simulation and optimization. For instance, shown in Figure 3 is a standard trend in heat and mass transfer, namely mass transfer in terms of *Re* to raised to a power less than 1. The continuous curve here represents an example of how the data could be parameterized for a full optimization in the future. Ideally the 10cm length and the actual airflow rates can be explored more precisely in the large system. The relationship shown in Figure 3 should help optimize the operation such that the point at which maximum air loss of water vapor by transport into the desiccant can be matched with the fastest kinetics of uptake by the desiccant, further optimizing the size and geometry.

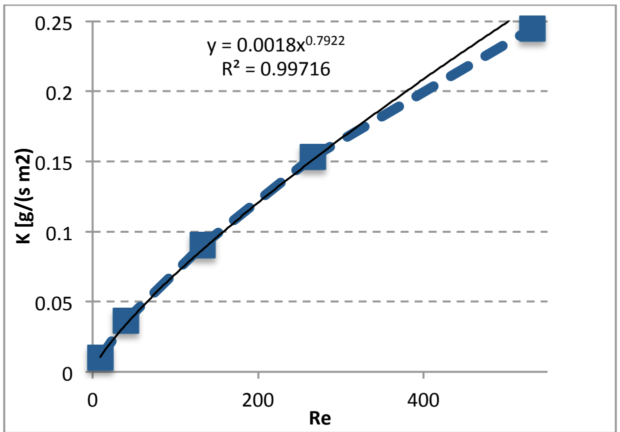

Figure 3: Mass transfer versus Re.

The liquid desiccant technology presents a methodology for off-coil dehumidification, one of the most promising aspects of liquid desiccant technology. Off-coil dehumidification eliminates the need to cool air below the dew point, an energy-intensive step that is excessive in comparison to the supply temperature, which is typically much higher than the dewpoint. For instance, the coil temperature in the DOAS unit is 6.8 °C for a supply air temperature of 18 °C. From a simple energy balance, there is a 61.1% reduction in the overall cooling power when taking the outdoor air just from 21.1 °C to 18°C rather than 6.8°C. This reduction does not account for additional heat inputs form the heat of condensation of water into the desiccant, nor does it take into account chiller COP, a result of the added exergy needed to get to cooler temperatures, which represents a significant energy savings (Meggers, Ritter, et al. 2012). When combined with the favorable comparison presented in the results section when comparing pumping and fan power between the DOAS and the proposed liquid desiccant ventilation system, it appears this combination of liquid desiccant and Pebax® membrane is a promising advancement at scale.

Future work will involve the fabrication of the large-scale system using 3D printed manifolds and mixing volumes between the 10cm sections. The simulation will then be further refined and serve as a check for validating the performance observed in the system.

Conclusions

We analyzed the feasibility of scaling up an experimental combination of membrane and desiccant for building dehumidification based on a comparison to an existing system that is part of a pilot building installation we are researching. It demonstrates feasibility for use at the scale of a system being used for several office spaces in Singapore.

The system can be scaled up to roughly the size of a 0.5m per side cube, but would probably be longer in its entirety to house fans, filters and the tubing connections. The desiccant pumping costs appear to be manageable for flow rates studied and also potentially for larger flow rates if needed for reduced demand on mass fraction of water absorbed by the desiccant. The airside results also were comparable to the operation of the existing solid desiccant system, and there is also room to explore variations in geometry and spacing to further minimize pressure drop while maintaining good water removal.

In conclusion, the simulation supports the further development of a larger building-scale experimental prototype. There is great potential for desiccants to reduce the energy needed for cooling systems, especially if they can be regenerated with low-grade heat, something humid places generally have in excess. Liquid desiccants combined with membranes provide the opportunity to achieve that performance while addressing current technological challenges. We will continue the development of this system to increase its feasibility in building ventilation applications.

References

Abdel-Salam, Mohamed R. H., Robert W. Besant, and Carey J. Simonson. 2016. "Performance Testing of a Novel 3-Fluid Liquid-to-Air Membrane Energy Exchanger (3-Fluid LAMEE) under Desiccant Solution Regeneration Operating Conditions." *International Journal of Heat and Mass Transfer* 95 (April): 773–86. doi:10.1016/j.ijheatmasstransfer.2015.10.065.

Ahmed, S. Younus, P. Gandhidasan, and A. A. Al-Farayedhi. 1998. "Thermodynamic Analysis of Liquid Desiccants." *Solar Energy* 62 (1): 11–18. doi:10.1016/S0038-092X(97)00087-X.

Das, Rajat Subhra, and Sanjeev Jain. 2013. "Experimental Performance of Indirect Air–liquid Membrane Contactors for Liquid Desiccant Cooling Systems." *Energy* 57 (August): 319–25. doi:10.1016/j.energy.2013.05.013.

Fazilati, Mohammad Ali, Ahmad Sedaghat, and Ali Akbar Alemrajabi. 2016. "Natural Induced Flow due to Concentration Gradient in a Liquid Desiccant Air Dehumidifier." *Applied Thermal Engineering* 105 (July): 105–17. doi:10.1016/j.applthermaleng.2016.05.135.

Jeong, Jae-Weon, Stanley A. Mumma, and William P. Bahnfleth. 2003. "Energy Conservation Benefits of a Dedicated Outdoor Air System with Parallel Sensible Cooling by Ceiling Radiant Panels." *ASHRAE Transactions* 109 (2): 627–36.

Lowenstein, Andrew. 2008. "Review of Liquid Desiccant Technology for HVAC Applications." *HVAC&R Research* 14 (6): 819–39. doi:10.1080/10789669.2008.10391042.

Meggers, Forrest, Luca Baldini, Marcel Bruelisauer, and Hansjürg Leibundgut. 2012. "Air Conditioning without so Much Air – Low Exergy Decentralized Ventilation and Radiant Cooling Systems." In *Proceedings of the 5th IBPC: The Role of Building Physics in Resolving Carbon Reduction Challenge and Promoting Human Health in Buildings*, edited by The 5th IBPC organizing committee, 529–36. Kyoto, Japan. message:%3CCAD6278A.3B59%25meggers@arch.ethz.ch%3E.

Meggers, Forrest, Volker Ritter, Philippe Goffin, Marc Baetschmann, and Hansjürg Leibundgut. 2012. "Low Exergy Building Systems Implementation." *Energy* 41 (1): 48–55. doi:10.1016/j.energy.2011.07.031.

Mumma, S. A. (2007). DOAS & desiccants. *Engineered Systems*, *24*(8), 37-38.

Murray, Portia, Adam M. Rysanek, Jovan Pantelic, Matthias Mast, and Arno Schlueter. 2015. "On Decentralized Air-Conditioning for Hot and Humid Climates: Performance Characterization of a Small Capacity Dedicated Outdoor Air System with Built-in Sensible and Latent Energy Recovery Wheels." In *Energy Procedia*, edited by Marco Perino and Vincenzo Corrado, 78:3471–76. doi:10.1016/j.egypro.2015.12.332.

Pantelic, Jovan, Eric Teitelbaum, and Soran Kim, Hongshan Guo, Arno Schleuter, and Forrest Meggers. 2016. "Air Dehumidification with Novel Liquid Desiccant System." Expanding Boundaries: Systems Thinking for the Built Environment. Conference Proceedings.

Rysanek, A., Murray, P., Pantelic, J., Mast, M., & Schlüter, A. Simulation Analysis of a Low-Exergy Decentralized Air-Conditioning System for Hot and Humid Climates: Towards a Pilot Implementation in Singapore. Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association, Hyderabad, India, Dec. 7-9, 2015.

Schlueter, Arno, Adam Rysanek, Clayton Miller, Jovan Pantelic, Forrest Meggers, Matthias Mast, Marcel Bruelisauer, and Kian Wee Chen. 2016. "3for2: Realizing Spatial, Material, and Energy Savings through Integrated Design." *CTBUH Journal*, no. II. http://global.ctbuh.org/paper/2783.

Wimby, J. M., & Berntsson, T. S. (1994). Viscosity and density of aqueous-solutions of LiBr, LiCl, ZnBr2, CaCl2, and LiNO3. 1. single salt-solutions. *Journal of Chemical and Engineering Data*, *39*(1), 68-72.

Zhang, Ning, Li-Zhi Zhang, and Jian-Chang Xu. 2016. "A Heat Pump Driven and Hollow Fiber Membrane-Based Liquid Desiccant Air Dehumidification System: A Transient Performance Study." *International Journal of Refrigeration* 67 (July): 143–56. doi:10.1016/j.ijrefrig.2016.01.001.