Development of moisture absorber based on hydrophilic nonporous membrane mass exchanger and alkoxylated siloxane liquid desiccant

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ABSTRACT

In order to deal with corrosion, crossover and desiccant utilization issues encountered in commercially available liquid desiccant systems, we develop and characterize the performance of a hydrophilic nonporous membrane-based liquid desiccant absorber. The liquid desiccant is an alkoxylated siloxane mixture, a modified silicone oil for enhanced moisture absorption. Performance is characterized for a shell and tube configuration by measuring air temperature and relative humidity at the inlet and outlet of the absorber. We determine the characteristics of counter and parallel flow configurations, various air and liquid desiccant flow rates and several contact lengths within the membrane absorber. The absorption was weakly increased by liquid desiccant flow rate. Results for counterflow configuration show that the humidity ratio of the air entering the membrane system can be reduced by up to 15.7 g/kg at maximum air flow Re number and longest contact length. Desiccant utilization in the system ranged up to 0.012 g of water per gram of desiccant. The highest desiccant utilization does not correspond to the highest mass flux rate, suggesting that the most effective system does not depend on on the quantity of removal, but rather the rate. Bulk diffusion of moisture into the desiccant is the rate limiting step for moisture absorption, with with five times faster absorption in the first 10 cm of contact length, guiding us toward future system design.

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1. Introduction

Cooling buildings is a technical feat that while only being achieved a century ago, has now become ubiquitous. Effective cooling of a building requires in particular proper handling of moisture level, and many of the largest developing cities are located in hot and humid tropical climates. Humidity in indoor environments has an impact on thermal comfort [16], productivity [25] and occupant health [3]. Apart from regions with desert climates, annual latent ventilation loads are several times greater than sensible loads for HVAC [9]. Due to these high latent loads, effective and efficient dehumidification of ventilation air is very important from an energy perspective. The most frequently used method for dehumidification is on-coil condensation that wastes cooling potential

[14], and often requires reheating the air after cooling it below the dew point to mechanically remove moisture. With plenty of refrigeration capacity and cheap energy, mechanical condensation of water on cooling-coils became the defacto the method to condition air to comfortable humidity levels. Nowadays, we face energy and climate challenges that drive us to better control and reduce the energy and refrigeration use in buildings.

Desiccants offer a chemical alternative to mechanical condensation by using thermodynamically spontaneous absorption as a means to dehumidify supply air, and heat to release the chemically absorbed moisture to exhaust air, and therefore avoid extra cold condensing temperatures. Desiccant chemicals may be employed in either solid or liquid forms. Each form of desiccant is known to have drawbacks such as: physical transport limitations in solids, risk of corrosion, and evaporation in liquids [13]. Solid desiccant wheels are an efficient dehumidification alternative [12], where the electrical energy used in conventional chillers to generate subcooling for condensation can be replaced with heat or recovered dry exhaust air to regenerate a solid desiccant wheel that can absorb

moisture. On the other hand, we have recently shown that liquid desiccants have the potential to allow decentralized dehumidification in buildings [14]. Liquid desiccants that must be in direct contact with air streams are commercially available, but due to their intrinsic properties, they are less popular than solid desiccant wheel systems. Liquid desiccants are commonly divided into two categories: halide salts and glycols. Halide salts are very strong desiccants, but also corrosive to most metals, hence corrosion-resistant parts, e.g. titanium, have to be used [13]. Glycols are not corrosive but highly volatile, therefore, glycol-based setups require frequent maintenance to compensate for losses. Additionally, the ability to absorb water vapor from the airstream is reduced [1] at elevated temperatures. This has important consequences for dehumidification, since the regeneration of the liquid desiccant requires additional energy in the form of heat to increase desiccant temperature, so that it can desorb water.

Current modes of humidity absorber configurations involve direct contact of liquid desiccant with the air supplied to the indoor environment. This can cause carryover of liquid droplets into the airstream [10], and can have harmful consequences to occupant health, building structure and materials [10]. Recently, membrane based desiccant systems have been developed to physically segregate the liquid desiccant and the gas phase, and ultimately overcome carryover problems [10]. Polymeric membranes provide resistance to water vapor transport from the air–liquid desiccant interface. Thus, current research is directed towards developing membranes that can minimize resistance to mass transfer, while preventing droplet carryover. The efficiencies of hydrophobic [4–6,11,28] and hydrophilic [12,21,22,30] microporous membranes have been studied in the literature, and it has been demonstrated that they do not provide complete separation between desiccant and air, if the partial pressure difference between the two streams is not well controlled. Consequently, some crossover may still take place in such a system [27]. In order to achieve complete phase separation, a nonporous membrane must be used.

In this study, we investigate a novel liquid desiccant system combined with a nonporous vapor transport membrane that minimizes contamination risks. We address the major challenges mentioned above simultaneously, namely the problems associated with diffusion of water vapor through the membrane, carryover, and corrosion. We develop a novel membrane-based liquid desiccant absorber that uses a hydrophilic nonporous membrane and an alkoxylated siloxane liquid desiccant [2] that is not corrosive nor highly volatile. We test the basic desiccant kinetics, compare the membrane/desiccant water removal rates, and analyze their interactions. We characterize the humidity control potential of this system in a variety of desiccant and airflow configurations for a single shell and tube configuration. Finally, we perform a variety of tests with different tube geometries, flow rates, and humidity levels for both shell and tube mass exchanger setups. The results suggest potential development into a larger multi-tube dehumidification system.

Using a system such as a liquid desiccant dehumidification allows for separate treatment of latent and sensible loads, as the two loads are conventionally linked due to the nature of mechanical on-coil condensation for latent load handling. By separating the loads, more flexible navigation of the psychrometric chart is possible, and cold temperatures can be used at a high temperature for radiant cooling, rather than for low temperature air cooling and dehumidification. Dehumidification technology is if cooling is handled primarily with radiant or passive chilled beams, as dried air is essential for avoiding condensation. Desiccant technology therefore enables high temperature systems for the most effective low exergy cooling strategy.

2. Materials and methods

In order to simultaneously address the limitations mentioned above, we combine a hydrophilic nonporous membrane and an alkoxylated siloxane type III liquid desiccant [2,15]. The study contains two sections, as shown in Fig. 1. Testing of the component characteristics, namely the kinetics of the liquid desiccant and the membrane was the initial characterization work [18]. Once the first part was completed, water removal rates from air flowing along a small membrane tube containing flowing desiccant were studied to understand the system dynamics. As shown in Fig. 1, the different system configurations include geometry, flow rate, and humidity ratio modulation.

2.1. Instrumentation

The weight of desiccant and other compounds were measured using a Denver Instrument S-4002 type scale (accuracy of ± 0.01 g). Air temperature (T) and relative humidity (%RH) were measured using a Sensirion SHT75 type sensor. T and %RH were measured every 5 s, with accuracies of $\pm 0.3\,°C$ and $\pm 1.8\%RH$, respectively. Airflow was measured using a Sensirion SFM 4100 type gas flow meter, with an accuracy of 0.15% of full scale or 3% of reading, whichever is dominant. Sensors were connected to an Arduino Uno board and data were recorded on a computer through the Sensirion software and a serial monitor.

Various air T and %RH combination experiments were conditioned in a cubic box with dimensions of 1 m³. One side of the box was made of acrylic, and the rest out of plywood. Air T was regulated with an electrical heater placed inside the box and %RH with an ultrasonic humidifier (Tao Tronic) with built-in water purifier and control sensor. A fan was used to mix the air in the box. The ultrasonic humidifier had cyclic operations, and output RH was cycled by 5%. The temperature in the box reached steady state within an hour, after which air was used in experiments.

2.2. Liquid desiccant

The liquid desiccant is an alkoxylated siloxane (Dow Corning XX-8810) with a significantly reduced vapor pressure dependence on temperature. We experimentally determined the volatile content to be approximately 1–3 wt%, by drying a known amount in a vacuum-oven for 6 h under vacuum of 100 kPa and temperature of $50\,°C$. These alkoxylated siloxanes have good affinity for water, with the equilibrium saturation ranging between 1 and 3 wt% for 20–80 %RH in a wide range of temperatures. While this is a modest equilibrium concentration range compared to other desiccants, the range lends itself well to a mass concentration based desorption process, with minimal enthalpic input. As provided by the manufacturer, the dynamic zero shear viscosity of the neat liquid desiccant at $25\,°C$ is 0.031 Pa s. This value compares favorably to other aqueous liquid desiccants, such as $CaCl_2$ η=0.033 Pa s at 51.32 wt%, and LiCl η=0.00989 Pa s at 41.5 wt% [26]. Additional physical properties of the alkoxylated siloxane are available in the Supplemental Material file.

2.3. Hydrophilic nonporous membrane

The shell portion of the mass and heat exchanger is a high permeability Pebax® 1074 membrane. In the following, we will refer to it as "Pebax®". The membrane material, developed by Arkema and manufactured into 1.5 mm outer diameter tubes by Foster Corporation, is a polyether block amide copolymer elastomer. The water vapor transport rate in Pebax® is controlled by the relative composition of the polyether and polyamide elements. The contact angle with the raw polymer and liquid water is about 70°, and