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On the experimental study of a hybrid dehumidifier comprising membrane and composite desiccants☆

K.J. Chua*, S.K. Chou, M.R. Islam

Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore

HIGHLIGHTS

- Development of a hybrid air dehumidification technology that reduces energy use.
- Hybrid system comprised of membranes and composite desiccants working in tandem.
- The synthesized membrane has an outstanding selectivity of water vapor over air ratio.
- Compared to silica-gel, composite desiccants realized a two-fold moisture removal improvement.

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ABSTRACT

The paper describes the development of a hybrid solution that improves air dehumidification. It comprises the integration of a composite desiccant and a nano-woven membrane for air dehumidification. The solution compliments any building HVAC project where the removing moisture from the air via an energy-efficient means is a concern. Longer sustainable performance of the desiccant is achieved as the non-regenerative membrane assists in partial air dehumidification. Accordingly, the hybrid system requires a lower regenerating temperature while producing air of very low humidity. In sum, the proposed hybrid solution involves the composite desiccant and membrane to work hand-in-hand in order to achieve enhanced moisture removal efficiency and improved energy efficiency by up to 40% compared to the best grade commercial silica-gel desiccant.

1. Introduction

In tropic countries, air conditioning (AC) is widely used to control temperature and humidity to maintain human thermal comfort conditions and also a hospitable environment for equipment such as computers and perishables. In Singapore alone, the total energy consumed by the air conditioning system comprises up to about 50% of a commercial building's total energy consumption. About 90% of the space cooling comes from the employment of vapour compressor systems. Additionally, the efficiency of air conditioning decreases significantly when it is required to remove increasing amount of moisture from the air. Therefore, there is a need to remove moisture efficiently before cooling the air. Conventionally, desiccant is employed in AC system. As the air stream passes through the desiccant, it efficiently absorbs the water vapour. However, the water vapour absorption process induces a side effect of increasing temperature of the air [1]. Additionally, to maintain a sustainable working condition, the desiccant needs to be periodically regenerated. Although the desiccant cooling system realizes better efficiency than the conventional vapour compression system, its overall efficiency is still considered low, because of its low moisture adsorption capacity and high thermal heat to regenerate [2].

Currently, desiccant used for air conditioning can be classified into two types, liquid and solid [3,4]. Liquid desiccant is comparatively better as it creates less resistance to air, which gives less pressure drop and less regeneration temperature [3]. Liquid desiccant also performs better in terms of water adsorption capacity when compared to solid desiccant. Nonetheless, liquid desiccant has its drawbacks, such as corrosiveness and toxicity [3]. Solid desiccant, however, has less toxicity and corrosion problems [4]. Silica gel is widely used in commercial air conditioning system even though its water adsorption capacity is comparatively not high [4]. Hence, a combination of existing and new dehumidification technologies should be studied.

Recently, O'Connor et al. [5] re-designed the traditional honeycomb matrix structure of rotary desiccant wheels in order to achieve a low pressure drop value of below 2 Pa so that passive ventilation can be effectively carried out. Additionally, their revised design also led to

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* Corresponding author.
E-mail address: mpeckje@nus.edu.sg (K.J. Chua).

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lower regenerative air temperature for desiccant desorption while achieving a reduction in relative humidity of the air by up to 55%. Fu et al. [6] developed a dual-scale modeling approach specifically tailored to study the performance of a desiccant wheel with a novel organic–inorganic hybrid adsorbent material. Employing their dual-scale model, the effects of the micro physical–chemical properties of desiccant materials and macro structure of the wheels, as well as the operating parameters on system performance were systematically investigated. Key findings indicated an improved moisture adsorption capacity of the material of about two times higher than that of silica gel B. As a result, the sensible and latent effectiveness were found to improve by 12% and 30%, respectively [6].

Giovanni et al. [7] conducted an experimental analysis on a desiccant system, with key emphasis given to the variation of its performance as a function of the process and regeneration air flow rates. The desiccant material is regenerated using low-temperature thermal energy (about 65 °C) from a micro-cogenerator. Key results highlighted the positive impact of process air humidity ratio and regeneration temperature on the desiccant wheel performance compared to the process air temperature. Recently, Rambhad et al. [8] conducted a review on different solid desiccant dehumidification and their regeneration methods. In their review paper, they discussed the functioning of dehumidification, cooling and air-conditioning systems using various solid desiccants targeting the use of solar energy for humid air dehumidification and regeneration of solid desiccant wheel. In another review paper on solid desiccant, Zheng et al. [9] summarizes the key research that have been conducted on new desiccating materials including composite desiccants, nanoporous inorganic materials and polymeric desiccants. For these materials, the adsorption isotherms were studied and compared. Contrasting the performance of these desiccating materials, it was inferred that a judicious selection of the host matrix, immersed salts and composite desiccants impacts on the desiccant's moisture adsorption capacity and regenerative process. These are existing challenges that ongoing research works aspire to overcome [10]. Also, an optimal trade-off can be reached between regeneration and adsorption capacity by calibrating the textural properties of nanoporous inorganic materials.

Thus far, there are limited studies found in the literature on polymeric membrane development specifically tailored for air dehumidification. Qi et al. [11] developed and investigated an electrochemical air dehumidification system with polymer electrolyte membrane (PEM). Results have shown that the novel system was able to dehumidify air flow with a humidity of 90% RH (inlet) to less than 30% RH (outlet) simply by using a 3 V electric field. When the air humidity dropped from 70 to 90%, the dehumidification rate improved about 1.5–2 times. But only 30% of the total power input was utilized for dehumidification resulting in a relatively low system COP of 0.33. Indeed, there exists limitations to the PEM dehumidifier. Keniar et al. [12] conducted an investigation on the feasibility of employing a solar regenerated liquid desiccant membrane system to remove humidity from an office space. Via a validated model, they demonstrated that only a decrease of 10% in indoor relative humidity is obtained when the system was operating under hot and humid climate in Beirut. Kim et al. [13] produced a polyamideimide defect-free hollow fiber membranes to investigate its water vapour removal efficiency under high pressure and high temperature. Their study observed improved water vapour removal efficiency from 54% to 90% at 120 °C operating condition primary due to enhanced water vapour flux movement.

Zaw et al. [14] analysed a cross-flow membrane based air-dehumidification system which is driven by the water vapour concentration gradient between the incoming outdoor air and the outgoing exhaust air. Experimental results highlighted that moisture reductions between 4 g and 8 g per kg of moist air is possible for high humidity ambient air conditions spanning 16–20 g/kg. Indeed, to achieve a supply air with moisture content of below 13 g/kg of moist air based on membrane dehumidification is a highly challenging task. Very recently, Omar et al. [14], in their recent study, have emphasized that the membrane-based cooling system stand-alone design with vacuum pump remains impractical largely due to the associated high compression ratios. However, by simply employing a two-stage pumping configuration with condenser notably improved performance. The development of high performing and cost-effective membranes that possess high water vapour permeability and water vapour/air selectivity characteristic is a key challenge to mitigate that is chiefly connected to the materials used and the synthesis method employed [15,16].

Based on the literature survey of papers published recently, experimental works to address some of the key challenges of realizing efficient membrane dehumidification are limited. To achieve high dehumidification performance, the membrane should meet the following requirements: (1) the synthesized membrane has to be highly permeable so that the partial pressure gradient of water vapour across the membrane is kept small to enable energy-efficient water vapour sieving; (2) the membrane is highly selective towards water vapour over air; (3) the membrane has to be robust to resist air contaminations, and mechanical corrosion in the duct; and (4) the membrane synthesizing process has to be easy, cheap, and environmental friendly (does not require high heat) to produce nor requires any thermal regeneration.

While significant progress continues to be made in the area of new composite desiccants and their performance under varying thermal conditions, a broader impact study of their performance in conjunction with non-regenerative membrane dehumidification has been missing in the literature. The evolution of such a study on hybrid dehumidification will bring about further insights into conventional versus new hybrid dehumidification and cooling process.

Dehumidifiers incorporating a desiccant wheel alone, or in combination with heat exchangers are abundantly available in the literature. However, these systems usually relate to the control or optimization of cooling and dehumidification; none of the disclosed systems utilized a membrane module for assisted dehumidification and prolonging desiccant performance. In some membrane systems employ compressed air, the compression can cause the water vapour to oversaturate and condense to liquid water [15]. The filters discussed in such prior art typically used to remove this excess liquid water, rather than water vapour, from the air. In addition, the energy to compress the humid air can be comparable or substantially higher when compared to refrigerant compressors. As such, the development of the hybrid dehumidification system combining composite desiccant and membranes not only enables lower humidity air to be achieved but also enable the dehumidification process to be conducted in a more energy efficient manner.

Having conducted a detailed theoretical analysis and comparison on desiccant and membrane-based dehumidification and cooling, Omar et al. [17] proposed combining membrane with desiccant-based cooling to improve energy efficiency. The objective of this work is, therefore, to experimentally study the potential of a hybrid membrane/composite desiccant dehumidification system to markedly promote moisture removal from the humid air as well as to reduce energy consumption for air dehumidification. Key findings from this work is expected to have great impacts on the design and operation of next-generation HVAC technologies and shed light on potential new avenues to achieve higher efficiencies in dehumidification applications.

2. Materials and methods

2.1. Composite desiccant synthesis

Composite desiccants with different compositions are prepared from silica gel, lithium chloride, calcium chloride, bentonite and activated carbon. To evolve a good performing composite desiccant, different combinations of these ingredients are used.

For silica gel preparation, the procedure is relatively