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Experimental validation of an isothermal dehumidifier with stepwise sorption characteristics at different humidity loads

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ABSTRACT

Today's dehumidification technologies of compressor-based condensation and desiccant wheel both handle latent heat loads via sensible heat transformation, requiring complex mechanical components and, therefore, not friendly to the humidity regulation in volume-limited space. In this work, we demonstrated a highly performant humidity regulator by separately handle the sensible and latent loads via Peltier coolers and vapor adsorbent. The whole-solid components enable the miniaturization of the mechanical system. The direct path of isothermal dehumidification is practical in climates with high latent loads. We used aluminum-based MOFs with stepwise sorption isotherm for the proof-of-concept. It shows the ability of this humidity regulator to precisely control the supply air states with a single operation that merits further exploitation in variable industrial scenarios.

Keywords: Humidity regulation, miniaturization, Peltier cooler, desiccant, MOFs, stepwise isotherm

NONMENCLATURE

Abbreviations	
MOF	Metal-organic frameworks
SG	Silica Gel
HEx	Heat exchanger
TEC	Thermoelectric cooler (Peltier cooler)
RH	Relative humidity
Symbols	
W	Electricity work input(J)
H_{ev}	Evaporation Enthalpy($J.g^{-1}$)

1. INTRODUCTION

The air-conditioning system accounts for 30% of the total energy requirement in buildings [1]. The Vapor-compression refrigeration system is commonly used for indoor temperature and humidity regulation in summer. As the latent heat takes up for 20-40% of the operation loads in this regulation process [2], the removal of moisture via dewing is not an energy-efficient path, and the overcooled supply air impairs occupants' comfort. Research efforts have been growingly dedicated to the separate treatment of sensible and latent loads, due to the generally high efficiency of these systems and the potential to utilize waste heat [3]. A proper embodiment is sorption technologies, including desiccant cooling systems, which stock and transport the water molecules via sorbents to enable energy transfer. Typical sorption-based humidity regulation systems for buildings consist of at least one sorber, a combination of the core sorbent and adjacent support structure. In applications, the moisture is firstly taken in from the indoor space and then released to the environment, usually powered by thermal energy input. The key to improving the performance of the sensible load handling part is to avoid overcooling [4] by decoupling from the moisture treatment (Fig 1).

Solid sorbents [5] and liquid desiccant [6] are both commercialized choices of effective means to employ low-temperature heat from waste or renewable sources. Unfortunately, the sorption systems often outsize the compression systems, thus are not suitable for small space applications. Research interests have been focused on optimizing the thermodynamic cycles for a range of sorbents. However, the improvement in energy density, as well as miniaturization, is marginal and the

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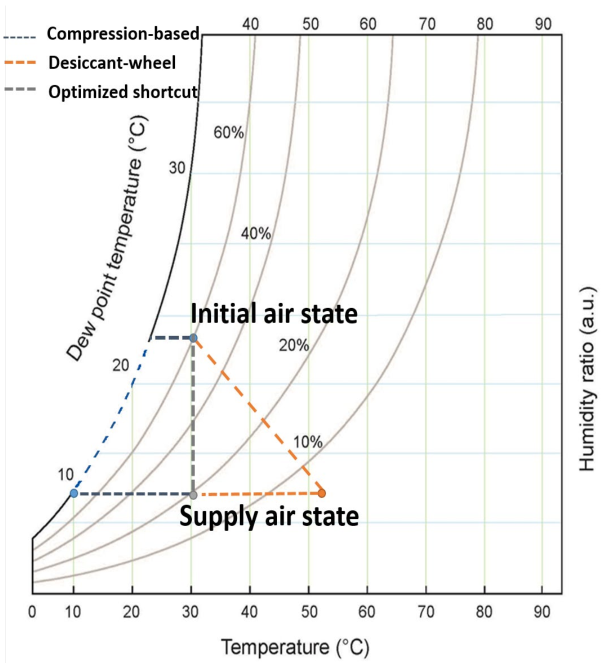

Fig 1. Optimized dehumidification with direct path of air processing

systems are not friendly to many niche segments of indoor humidity regulation, such as museums, galleries, cold chain logistics, electrical appliances space, etc.[7-11] The number of studies publically available focused on highly compact systems is limited, among which solid-state refrigeration is often employed[12-14].

This work focuses on the development of a compact dehumidifier, which combines solid-state refrigeration and sorption cycle. The dehumidifier is suitable for indoor air humidity control in variable volume-limited scenarios where the latent loads are dominant. Two aluminum MOFs with stepwise sorption curves have been used as advanced sorbents for the transfer of moisture [15]. The aim of the study is twofold. I) Validate the water vapor transport mechanism in the sorber based on aluminum MOFs, which serve for optimizing the mechanic design to improve efficiency and compactness. II) Illustrate the potential in the humidity control process of the stepwise water sorption curves.

2. MATERIAL AND METHODS

The dehumidifier aimed to dry air to a certain relative humidity via a shortcut path on the psychrometric diagram. We employed the hybrid porous material MOFs. MOFs are an emerging class of advanced hybrid solid water adsorbents with large pore volumes and tunable hydrophilic characteristics, and were recently used for adsorbing moisture from atmosphere [16-17]. Their S-shape water sorption isotherms can facilely allow the precise control of the final state of supply air. Sorbents of CAU-10 (Aluminium-isophthalate) and MIL-53-FA (Aluminium-Fumarate) were chosen as examples to demonstrate the idea thanks to their step-wise isotherms. (Table 1)

Table 1. Sorption properties of the selected Al-MOFs

MOFs	Formula	Water uptake ($g \cdot g^{-1}$)			
		10%RH	25%RH	40%RH	90%RH
CAU-10	$Al(OH)(C_8H_4O_4)$	0.001	0.255	0.273	0.312
Al-Fum	$Al(OH)(C_4H_2O_4)$	0.025	0.053	0.343	0.422

The water uptake capacity of the sorbents is mainly determined by the environmental relative humidity (RH) for a given stepwise isotherm, so as their adsorption rates. The adsorption rates with RH situated on the left of the sorption step are supposed to be much lower and on the right to be higher (Fig 2). As a result, the dehumidification of the environment will be active as long as the humidity is higher than the sorption step, and will be shut off autonomously once the RH drops below it. This sorption characteristic allow a dehumidifier to achieve one-step precise humidity control without air mixing process used in a conventional air-handling unit, which avoid the complex mechanical components and can be adapted to variable space-limited applications.

A proof-of-concept was fabricated, as shown in Fig 3,

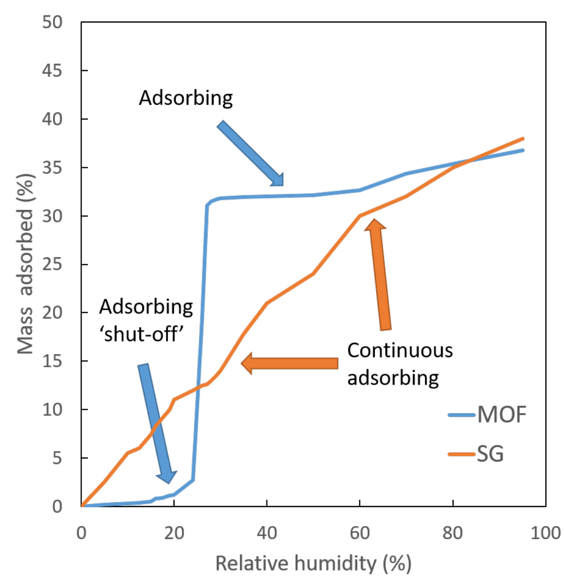

Fig 2. Realization of precise humidity regulation

composed of two acrylic boxes of 300×60×130 mm^3 with apertures on both ends. The boxes served as air ducts, each containing a fin-type Al heat exchanger. The

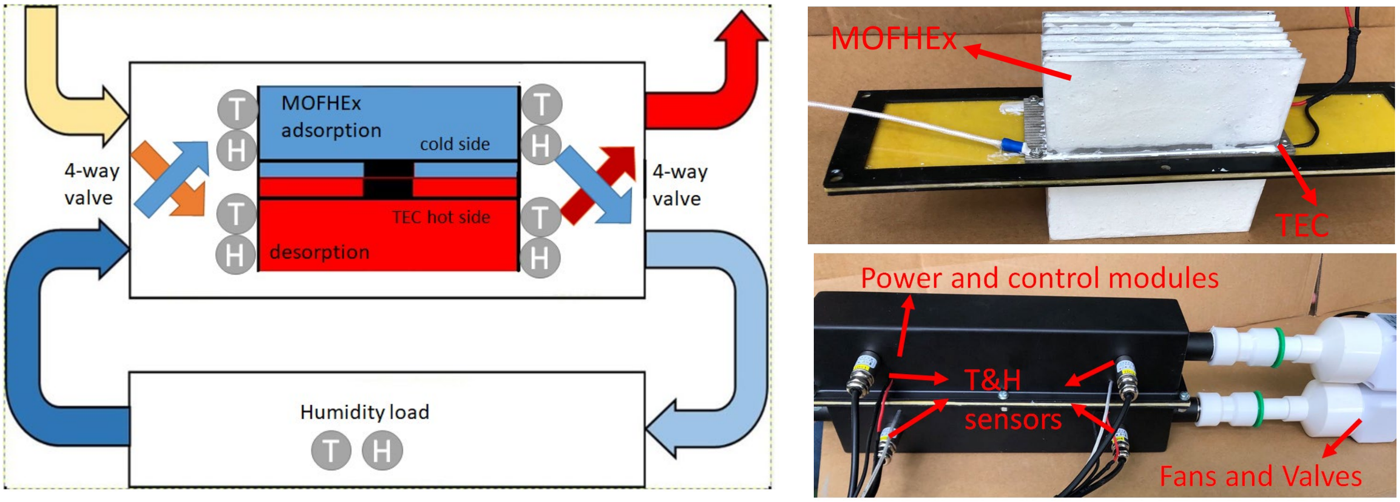

Fig 3 Schematic illustration and photo of the isothermal dehumidifier

attached longitude side of the boxes was hollowed out, and two Peltier coolers were inserted. The two heat exchangers were each attached to one side of the Peltier cooler of type 12708 with thermal conductive grease. The periphery of the heat exchangers was scribbled with hot melt adhesive to ensure airtightness. Both heat exchangers were coated with sorbents before plugged-in (MOFHEx). The procedure of shaping to combine the sorbents and the metal support can refer to [14].

The two ducts of the dehumidifier were connected to indoor and outdoor environments, respectively. When dehumidification of indoor air initiated, the Peltier cooler was activated, and two fans at the end of the ducts started to work. As the airflow from indoor passed over the dry MOFHEx, the moisture was absorbed by the sorbent, and the adsorption heat was compensated by the cooler. The outdoor airflow brought away the moisture previously captured by the MOFHEx on the hot side of the Peltier cooler due to regeneration at a higher temperature. The two flows were conducted back to indoor and outdoor. After a set time, while adsorption and desorption processes on each MOFHEx accomplished, the connection to indoor and outdoor was switched by 4-way valves. The coated CAU-10 and Al-Fum were 49.2g for the HEx, which renders an average layer thickness of 280µm.

Digital hygro-sensors measured the temperature (±0.1°C) and humidity (±2% RH) of inlet and outlet air in each air duct, as well in the space of humidity load. Power consumption of the Peltier cooler and the fan were adjusted and recorded during the test (Data acquisition instrument ±0.001%).

3. RESULTS AND DISCUSSION

Large-pressure-jump sorption tests were conducted on small samples of the coated sorbent layer with a DVS Vacuum system [18-19]. The water vapor sorption properties of the coated MOFHEx under constant relative humidity were shown in Fig 4.

The inflection points of CAU-10 and AF were 18% and 30% RH, respectively, at this temperature. When the environment humidity was at a lower level than their sorption steps, both the sorption capacity and sorption rate were negligible, as the blue lines. When the environment humidity increased to the right of the inflection point (30%RH), both the coating layers adsorbed vapor with 25% of the dry mass, which equated to 85% of the maximum capacity. The sorption kinetics of the coated layers demonstrated similar profiles to different working conditions.

The sorption rate increased to the peak value of 10.8 $mg.g^{-1}.min^{-1}$ for CAU-10 at 30%RH and slowly decreased in 40 minutes within 85% of the sorption time, then dropped sharply to zero at the end-stage. When the environment humidity is much higher than the location of the isotherm step (60% and 90%RH), the sorption rates were found to reach a peak of 30 $mg.g^{-1}.min^{-1}$ in a shorter time. The sorption behaviors indicated an interlayer-resistance controlled mass transfer mechanism, which means the sorbent amount or thickness determined the dehumidification capacity but not the drying power.

The dehumidification tests to validate the concept were conducted under laboratory conditions. A Plexiglas box with a volume of 0.5 m^3 providing humidity loads, was sealed and thermally insulated then connected to the air ducts. The initial indoor air conditions were set to be 30°C with variable humidity loads (40%, 60%, 90%RH).

The RH of the confined space decreased from the initial set humidity loads to final states within 30 min while the indoor temperature increased for less than 2 degrees. Despite different initial humidity loads, the final air states were regulated to a certain level for both types of adsorbents, which was close to their inflection points.

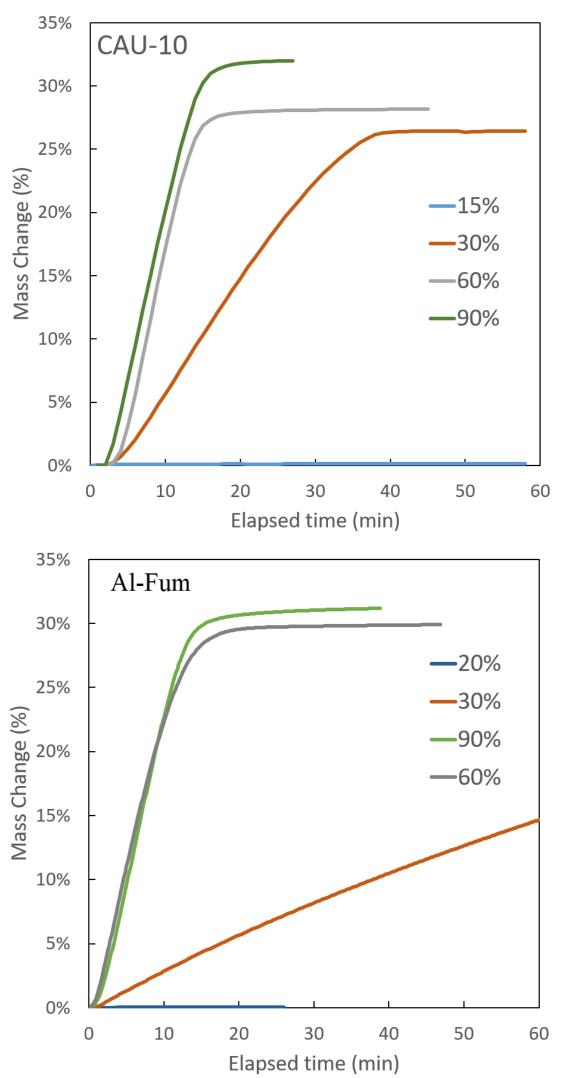

Fig 4. Adsorption mass profiles of the MOFs CAU-10 and Al-Fum under variable relative humidity at 30°C

The overall system efficiency can be roughly estimated as

$$COP = \frac{W_{TEC} + W_{Fan}}{m \cdot H_{ev}} \quad (1)$$

The electricity work of the TEC was read from the voltage-current controller as 57.6W, two fans contributed to 6.4W. The energy efficiency was calculated for time to achieve a 90% drying effect in each test (t_{90}). The COP for CAU-10 and Al-Fum of initial humidity loads 90%, 60%, 40% were 0.73, 0.20, 0.55 and 0.49, 0.13, 0.04, respectively. The error analysis is calculated as in equation (2) and the maximum uncertainty during the measurement is 5.1%.

$$\lambda_{COP} = \sqrt{\left(\frac{\sigma_T}{T}\right)^2 + \left(\frac{\sigma_{RH}}{RH}\right)^2 + \left(2\sigma_{DAQ}\right)^2} \quad (2)$$

These results were compounded from two effects, the thermal efficiency of the sorption cycle and the figure-of-merit of the TEC. Since the adsorption heat was closed to the evaporation enthalpy under the working conditions for CAU-10 and Al-Fum, both around 0.8, the primary constraint of the present system is the low performance of the Peltier effect, compared to compression-based dehumidification. However, the solution is still interesting for specific scenarios with high compactness demand.

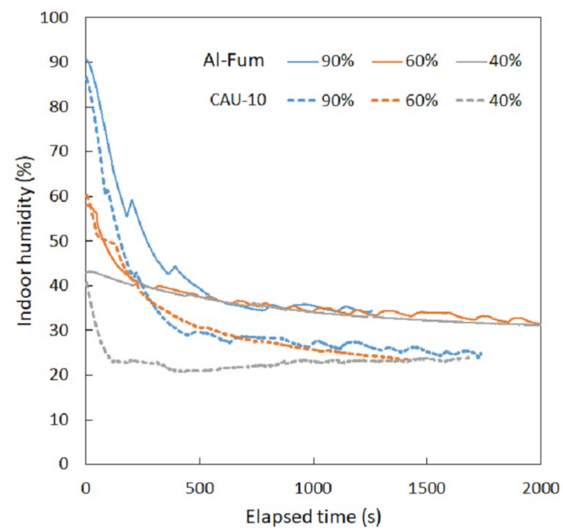

Fig 5. Drying and precise humidity control for confined indoor environment

When the inlet humidity approached the inflection point, the energy efficiency dropped along with the sorption kinetics. It means that the fine regulation of the humidity is more energy costly, and the advanced sorbents are particularly useful to deal with heavy humidity loads. Conventional sorbents such as SG do not possess a performance plateau as MOFs. However, their vapor sorption ability is weakened quickly when the environment humidity decreases. This shortage limited the final air humidity after drying to a relatively high level.

MOFs' affability to water and superior kinetics enabled the possibility of fast dehumidification. Since the cost of the sorbents is the most substantial investment in such systems, economizing the amount of the material used is essential for general acceptance. The whole set-up was placed in an air-conditioned room to maintain the environment as the initial indoor conditions during the tests. However, unlike the compression-based system, which is strongly impacted by the temperature and humidity, the drying ability of the present dehumidifier was almost independent of the exterior moisture. Because of the fine-tuned hydrophilicity of CAU-10 and Al-Fum, a 30°C temperature ramping of the TEC can regenerate most of the adsorbents in the open system.

There is much space for the optimization of such devices in the aspects of energy efficiency and mechanical deployment. If a high-performant solid refrigerator is used, the system can compete with the compression-based dehumidification process in broader applications. Efforts can also be made to the optimizing design of the MOFHEx, the control strategy regarding the electricity input, the sorption kinetics, and working loads.

4. CONCLUSIONS

In this study, we demonstrated the concept of a novel precise humidity regulator. A compact design to combine solid refrigerator and vapor adsorbents enabled the fine control of the target drying effect, which is particularly attractive to confined space applications with heavy latent loads. As examples, we achieved one-step dehumidification to 40%RH and 25%RH, respectively, with two MOFs Al-Fum and CAU-10 that possess S-shape isotherms. The new concept offers opportunities to realize compact air-conditioning paradigm aims with reasonable energy efficiency in many scenarios with particular humidity demand in practice, including museum and fine-art conservation, bio-pharmaceutical storage, library and archival preservation, electronic appliances space, etc.

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