Starch Particles, Energy Harvesting, and the “Goldilocks Effect”

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ABSTRACT: This study reports on the unique water vapor adsorption properties of biomass-derived starch particles (SPs). SPs offer an alternative desiccant for air-to-air energy exchangers in heating, ventilation, and air conditioning systems because of their remarkable adsorption–desorption performance. SP15 has a particle diameter (d_p) of 15 μm with a surface area (SA) of 2.89 m²/g and a pore width (P_w) of 80 Å. Microporous starch particles (SP15) were compared with high amyllose starch (HAS15; SA = 0.56 m²/g, d_p = 15 μm, P_w = 46 Å) and silica gel (SG13; SA = 478 m²/g, d_p = 13 μm, P_w = 62 Å). Transient water vapor tests were performed using a customized small-scale energy exchanger coated with SP15, HAS15, and SG13. The water swelling (%) for SP15 was ca. 2 orders of magnitude greater with markedly higher (ca. three- and sixfold) water vapor uptake compared to HAS15 and SG13, respectively. At similar desiccant coating levels on the energy exchanger, the latent effectiveness of the SP15 system was much improved (4–31%) over the HAS15 and SG13 systems at controlled operating conditions. SP15 is a unique desiccant material with high affinity for water vapor and superior adsorption properties where ca. 98% regeneration was achieved under mild conditions. Therefore, SPs display unique adsorption–desorption properties, herein referred to as the “Goldilocks effect”. This contribution reports on the utility of SPs as promising desiccant coatings in air-to-air energy exchangers for ventilation systems or as advanced materials for potential water/energy harvesting applications.

INTRODUCTION

The demand for energy-efficient buildings is rising because the heating/cooling of commercial, residential, and industrial housing accounts for ca. 30–50% of energy consumption and greenhouse gas emissions in Canada¹ and in the EU.² In particular, the demand for cooling is expected to increase almost exponentially (by ~30-fold over this century) because of climate change and increased energy needs for developing countries.³ Several researchers⁴,⁵ have noted that heating, ventilation, and air conditioning (HVAC) systems equipped with air-to-air energy exchangers (AAEEs) can mitigate the problems associated with massive energy intake. AAEE systems may use an energy wheel that is a rotating wheel coated with a solid desiccant. This type is the most common heat and moisture exchanger in HVAC systems that constitute about 75% of the market. Although there are numerous potential desiccants for energy wheels, only about 10 different desiccants have been used commercially. The design of energy wheels allows the transfer of a large portion of sensible (heat) and latent (moisture) energy from the exhaust airstream.

The performance of energy wheels is determined by its latent effectiveness, which is the actual rate of moisture transfer between the supply and exhaust airstreams as a function of the maximum possible rate of transfer between streams.⁶ Extensive experimental modeling and simulation data are available which outline the performance and effectiveness of desiccant-coated wheels at variable operating conditions.⁷−¹³ Few studies, as those reported by Simonson and Besant¹⁴−¹⁶ and others,¹⁷ have considered the role of desiccant adsorption–desorption properties on the performance of mineral-based desiccant-coated energy wheels. However, studies related to the structure–function (adsorption–desorption) relationship for desiccant materials relevant to AAEE applications are scarce and contribute to a limited understanding of the performance of such desiccant-coated wheels. The desiccant adsorption capacity, along with the rate and the regeneration temperature play key roles in the recovery of latent energy for hygroscopic wheels. Consequently, recent research has focused on the development of sustainable desiccants with enhanced properties such as adsorption capacity, regeneration ability, and long-term stability. Starch-based adsorbents have suitable properties as potential coatings for energy wheels owing to their low cost, bioavailability, biodegradability, mechanical stability, and easy disposal.¹⁷ Furthermore, starch materials possess unique...
adsorption properties with high affinity for water and organics in the liquid and gas phase. In general, studies on the performance of desiccants have traditionally been carried out at equilibrium conditions, whereas moisture uptake/removal for energy wheels is a transient process. More recently, Fathieh et al. compared the performance of high amylose starch (HAS15)- and silica gel (SG13)-coated wheels by performing transient tests using a small-scale energy exchanger with comparable matrix geometry and coating configuration. Conventional full-scale steady-state latent effectiveness test methods on coated wheels are known but are often limited because of time and financial constraints. The use of small-scale transient testing methods addresses the difficulty and challenges associated with the full-scale protocols while ensuring reliable results.

In this paper, carnation-based starch particles (SPs), hereafter referred to as SP15, are introduced as a unique alternative desiccant for energy wheel applications and are compared with results for HAS15 and SG13 desiccants. Several objectives are pursued in the current study (1) to introduce a modified desiccant coating technique with sieving, (2) to compare the performance of SP15 with other desiccants (HAS15 and SG13) onto coated wheels, and (3) to further understand the structure–function relationship of the desiccant systems. The surface and textural properties of the desiccant materials were characterized by various techniques: spectroscopy, microscopy, N2 adsorption isotherms, and particle size distribution analysis. The adsorption–desorption properties and latex effectiveness of the materials were further investigated by swelling tests in water and vapor sorption/desorption with a small-scale energy exchanger. This study presents a novel starch-based desiccant (SP15) with unique vapor adsorption (dehumidification) and desorption (regeneration) properties. SP15 has favorable affinity with water vapor and greater uptake with a 98% regeneration during the vapor desorption process. The interplay of adsorption–desorption properties of the SP15 desiccant confers a unique “Goldilocks effect” for energy wheel applications. The phenomena refers to the unique adsorption–desorption properties of the desiccant that are optimal or “just right” for AAEE systems and other water harvesting applications in arid environments.

## RESULTS AND DISCUSSION

**Physicochemical Properties of the Desiccants.** The structure of the SP15 was characterized using Fourier transform infrared (FT-IR) and a particle size analyzer and compared with HAS15 and SG13 shown in Figure 1. In Figure 1a, the FT-IR spectra of the starch materials (SP15 and HAS15) show similar spectral bands at ca. 1081 cm$^{-1}$ (C–H deformation), 1660 cm$^{-1}$ (C–C stretching), 2940 cm$^{-1}$ (C–H stretching), and 3390 cm$^{-1}$ (O–H stretching), which is in agreement with another report. SP15 has a relatively narrow O–H stretching band compared with HAS15, which may relate to crystallinity differences due to greater amylpectin content (cf. Table S1). The IR band at ca. 1540 cm$^{-1}$ for SP15 may be due to lipid and protein constituents reported elsewhere that result in minor spectral variations. For SG13, two major peaks are shown at ca. 1109 and 810 cm$^{-1}$ related to the Si–O–Si asymmetric stretching and −O–H bending vibrations. The broader signal at ca. 3000–3600 cm$^{-1}$ was assigned to the stretching vibrations of the silanol (Si–OH) groups.

The laser particle size analysis in Figure 1b shows the volume distribution of the samples with respect to the particle size, where the average particle diameters ($d_{p}$) for the three materials are similar (13–15 μm; cf. Table 2). The bimodal distribution for SP15 and SG13 at a greater particle size (≥2100 μm) is accounted for by particle aggregation via electrostatic interactions due to their greater particle size distribution.

Experimental adsorption isotherms using gaseous N2 in Figure 2 were used to estimate the surface area (SA) and the average pore structure (diameter and volume). The data are listed in Table 2. The isotherms of the starch (SP15 and HAS15) and silica (SG13) differ markedly by the profile of the adsorbed–desorbed N2. The starch and silica materials generally display a type II behavior, according to the IUPAC classification system. The N2 gas uptake for SP15 and HAS15 are low at each relative pressure ($p/p_o$) that concurs with a low porosity and SA. In contrast, greater uptake of N2 occurs for SG13 where saturation is attained at $p/p_o \approx 0.8$. The greater pore volume and SA of the mesoporous SG13 material relate to its rigid structure, and the steep increase in N2 uptake ($p/p_o > 0.6$) by capillary condensation is consistent with its mesoporous structure. The rigid nature of SG13 is contrasted against flexible starch materials that possess a reduced SA and pore structure. The limited uptake of starch occurs mainly on the outer surface of the powder grains at higher $p/p_o (\approx 0.9)$ because of its lower SA and reduced porosity. This is in contrast to SG13 and other porous materials such as metal–organic frameworks (MOFs).

The textural properties and accessible surface functional groups of porous materials can be assessed using different adsorptive probes (N2/H2O). Polysaccharides that contain polar functional groups may undergo swelling in water, which is in contrast to the absence of such effects for N2 adsorption

![Figure 1](image_url)
isotherm results. The relative swelling for SP15 and HAS15 was compared where the SP15 granules are ca. 2 orders of magnitude greater than HAS15 (cf. Table 2). The difference relates to the flexible and polar nature of SP15 and its ability to undergo significant conformational change upon uptake of water. Although SG13 has a greater accessible SA and pore structure over SP15, its rigid structure limits the ability to undergo extensive swelling of the rigid Si network relative to starch.

The SEM images of SP15, HAS15, and SG13 coated onto the Al-plates are shown in Figure 3. The SEM images reveal a uniform particle size distribution for HAS15 (Figure 3b). SP15 (Figure 3a, spherical particles with smooth edges) and SG13 (Figure 3c, amorphous particles with sharp edges) are characterized by a range of sizes because of potential aggregation, which is in agreement with the particle size distribution analysis. The SEM images of SP15-coated plate (sieving) and the HAS15/SG13-coated plates (spray-coating) can be compared for the two types of coating methods. In general, the sieving and spray-coating techniques have advantages over conventional methods for the HVAC industry: (1) uniform coating is achieved, (2) the coating is monolayer, and (3) the desiccant particles are surface-bound onto the acrylic adhesive substrate. The minor effect of the particle bonding agent (see section S1.3) allows for maximum accessible desiccant adsorptive interactions. In particular, the modified sieving method affords complete surface coverage of the plate without any voids, which is in accordance with the SEM results (cf. Figure 3a).

**Transient Test Results.** The transient response of the small-scale coated exchangers is presented using a normalized humidity ratio ($W$), as defined by eq 1. $W$ is defined as the difference in the exchanger outlet humidity ratio at any time ($t$) during the experiment divided by its maximum difference during the step test.

$$W(t) = \frac{\nu_{out,t} - \nu_{out,t=0}}{\nu_{out,final} - \nu_{out,t=0}}$$

where ($\nu_{water,vapor}/kg_{dry,air}$) in eq 1 is the air humidity ratio (or air moisture content). Detailed equations and models used to calculate the air humidity ratio are presented in the supplementary data (section S2). The relative humidity (RH) and temperature variation at the outlet of the small-scale exchanger during the humidification (adsorption) and regeneration (desorption) tests is also presented (Figure S2). For each exchanger, the breakthrough response curves were obtained by normalizing the humidity ratios over the testing period (cf. eq 1). The breakthrough curves for small-scale exchangers coated with SP15, HAS15, and SG13 are shown in Figure 4 for the adsorption–desorption cycles. Note that the transient responses for the humidity sensor and the noncoated plates (Al substrate and the acrylic adhesive agent) for the small-scale exchanger were previously reported (cf. Figure 9 ref 30) by use of the hollow test cell after its step-wise humidity changes as reported by Wang et al.31 The findings of the control test demonstrated that the transient response for both

**Figure 2.** $N_2$ gas adsorption isotherms (at 77 K) for SP15, HAS15, and SG13.20 The insets show the schematic of the structures of the materials.

**Figure 3.** Scanning electron microscopy (SEM) images of the coated aluminum substrate for (a) starch particles (SP15), (b) high amylose starch (HAS15), and (c) silica gel (SG13) at two magnification levels; 50X (top) and 250X (bottom). Images (b,c) are reproduced from ref 20 with permission.
Figure 4. Breakthrough response curves for small-scale exchangers for (a) dehumidification (adsorption) and (b) regeneration (desorption) cycles, at the operating conditions listed in Table S3.

Table 1. Dehumidification/Adsorption ($\Omega_{ads}$) and Regeneration/Dehumidification ($\Omega_{des}$) Capacity Values in mg Water Vapor/mg Desiccant for the Various Desiccant Materials

|                  | SP15 | HAS15 | SG13 | $\Omega_{ads}$ (SP15)/$\Omega_{ads}$ (SG13) | $\Omega_{des}$ (SP15)/$\Omega_{des}$ (HAS15) |
|------------------|------|-------|------|---------------------------------------------|---------------------------------------------|
| $\Omega_{ads}$   | 0.152| 0.052 | 0.026| 5.84                                        | 2.92                                        |
| $\Omega_{des}$   | 0.149| 0.041 | 0.020| 7.45                                        | 3.63                                        |

the bare Al-sheets and acrylic adhesive was nearly identical to the humidity sensor and indicate that the aluminum (Al) plates and adhesive have negligible water vapor sorption. Figure 4 shows that the air humidity ratio ($W$) gradually increases/decreases during the adsorption–desorption cycles, until it reaches the humidity ratio of the inlet air. At the initial stages of the test, the desiccant can adsorb–desorb all water vapor in the airflow, where no apparent changes in the normalized humidity are observed. This effect is more pronounced for the SP15 exchanger during the dehumidification cycle (cf. Figure 4a), indicating that more moisture is adsorbed by this material. Hence, better dehumidification is expected for the SP15 particles over HAS15 and SG13 accordingly. By contrast, the regeneration process is rapid and occurs within a few seconds for the three exchangers with the HAS15- and SG13-coated desiccants showing improved performance (Figure 4b).

On the basis of the dehumidification profile, the SP15 exchanger likely has greater relative moisture recovery among the desiccants studied. A better comparison of the adsorption–desorption performance of the three exchangers is possible on a specific basis (per unit mass of the desiccant) analysis among the various materials.

Dehumidification and Regeneration Results. The desiccant mass-based adsorption ($\Omega_{ads}$)–desorption ($\Omega_{des}$) results were analyzed as detailed in the Supporting Information (section 2.4.2). The isotherms representing the adsorption/dehumidification ($\Omega_{ads}$) and desorption/regeneration ($\Omega_{des}$; mg water vapor/mg desiccant) of the three exchangers are shown in Figure S3 and Table 1. The adsorption kinetics are relatively fast, and equilibrium is attained within minutes, where saturation occurs after the active sites become occupied. The $\Omega_{ads}$ for SP15 (0.152 mg$_{wv}$/mg$_{des}$) shows ca. three- and six-fold greater moisture removal over HAS15 (0.052 mg$_{wv}$/mg$_{des}$) and SG13 (0.026 mg$_{wv}$/mg$_{des}$) materials. Similarly, the desorption level ($\Omega_{des}$) increased by up to seven-fold for the SP15 exchanger (cf. Table 1). Despite the lower N$_2$ gas uptake for the starch materials, greater moisture uptake is observed, especially for SP15. The variable moisture uptake/removal cannot be explained because of the textural (pore and SA) properties of the materials solely. While SG13 has greater SA/pore volume over the starches, the greater moisture uptake for the starch-based desiccants relates to favored hydrogen bonding of adsorbed H$_2$O with the polar functional groups (–OH) of starch and the ability of SP15 to undergo conformational changes upon adsorption of water vapor. Although silica gels have greater SA (up to 800 m$^2$/g) imparted by the mesoporous framework, the lower adsorption capacity relates to less abundant –OH groups and rigidity of the Si framework. Water vapor adsorption capacity values (~0.25 mg water/mg MOF) were reported by Wang and Yaghi et al. for zirconium-based MOFs at 20% RH and 25 °C. The pore structure ($d_p \approx 0.0007 \mu$m, $P_i \approx 0.45$ cm$^3$/g) and the permanent SA ($\approx 1000$ m$^2$/g) of the Zr-MOFs account for the high water uptake. Seo et al. reported greater values of 1.5–1.7 mg water/mg MOFs (SA $\approx 4150$ m$^2$/g) at 30–40 °C, while the regeneration occurred at 70–80 °C and may not be practical for energy wheels. Despite the limited textual properties and the absence of the permanent SA for the microporous SPs reported herein, the abundant accessible surface –OH groups account for the favorable adsorption. In addition, more active sites and surface defects improve moisture adsorption upon expansion of the SP15 network because of notable swelling for such materials. It is noteworthy that the measured water adsorption capacities for the samples herein may be underestimated, as the materials were not fully evacuated at the start of the transient adsorption cycle. For the sorption of SP15 versus HAS15, greater water swelling of SP15 has been reported. The swelling results are consistent with the enhanced moisture uptake of SP15 compared to HAS15. In addition, the modified coating method via sieving may contribute to improved moisture adsorption of the SP15 desiccant. The coating method influences the particle textural properties and accessibility of sorption sites because of the presence of fine versus coarse particle grains. The favorable water vapor uptake of SP15 concurs with the FT-IR and SEM results, along with the pore filling theory, where micropore domains have greater affinity with water over mesopore adsorption sites.

The regeneration performance of a desiccant relates to its utility in hygroscopic wheels because of the multiple adsorption–desorption processes required for energy wheels. SP15 has the highest regeneration capacity (98%) compared to...
HAS$_{15}$ (79\%) and SG$_{13}$ (77\%), as shown in Table 1 and Figure S3. A reduced regeneration performance of SG$_{13}$ at 4\% RH, 22.5 °C, and the specified flow rate relates to capillary condensation within the pore network (Table S3). By comparison, the reduced pore structure and the hydrophilic nature of HAS$_{15}$ account for its reduced desorption relative to SP$_{15}$. Li et al. reported that the activation energy of SP$_{15}$ is ca. 50\% and 10-fold smaller than the corresponding values for SP$_{15}$. We conclude that the regeneration effectiveness of SP$_{15}$ qualifies the material as a very promising desiccant for energy wheels because less energy is required for regeneration, which is in accordance with the hydration-driven allosterism of the SP$_{15}$ desiccant material. In the current study, the heat of adsorption ($\Delta H_{\text{ads}}$ 44.2 ± 6.1 kJ/mol)/desorption ($\Delta H_{\text{des}}$ 47.8 ± 7.9 kJ/mol) was quantified (Table S4 and section S2.4.3). Whereas values of $\Delta H < 50$ kJ/mol indicate a physisorption process, values of $\Delta H_{\text{ads}}$ are slightly higher than $\Delta H_{\text{des}}$, which is consistent with the effects of capillary condensation and/or cooperative effects. The given enthalpy of adsorption is not too high and not too low but just right. As expected, the moisture recovery (latent effectiveness) of the SP$_{15}$ desiccant is significantly high, and this phenomenon is likened to the “Goldilocks effect”.

**Latent Effectiveness.** The latent effectiveness (moisture recovery ratio) of an energy wheel that would be constructed with the desiccant-coated plates is determined from the breakthrough curves (Figure 4). The method involves fitting a double exponential model to the breakthrough curves and predicting the number of mass transfer units (NTU$_{\text{m}}$) and effectiveness, as described by Fathieh et al. and also in section S2.4.4. The latent effectiveness of the coated wheels was predicted for the adsorption–desorption cycles at a flow rate of 15 L/min and a face velocity of 0.05 m/s ($Re = 26.2$), and variable angular speeds are shown in Figure 5. It is evident from Figure 5 that for the entire range of wheel angular speed $\omega$, the estimated latent effectiveness for the SP$_{15}$-coated exchanger is generally higher relative to the latent effectiveness of HAS$_{15}$- and SG$_{13}$-coated exchangers.

The increase of the latent effectiveness of the SP$_{15}$ over HAS$_{15}$ and SG$_{13}$ (Figure S4a,b) reveals that the SP$_{15}$-coated exchanger outperformed the other exchangers at each angular speed ($\omega$). At the typical wheel speed ($\omega \approx 0.1$–0.5 rpm), the dehumidification effectiveness of the SP$_{15}$-coated exchanger was greater relative to the other coated exchangers by ca. 18.9\% (HAS$_{15}$) and 31.3\% (SP$_{15}$). This clearly shows that SP$_{15}$ can be used as an alternative desiccant for dehumidifier or desiccant wheels with significantly improved performance. Similarly, at angular speeds $\omega > 10$, the effectiveness of SP$_{15}$-coated exchangers was as high as 4.3 and 6.8\% (dehumidification) and 4.2 and 5.7\% (regeneration), as compared with HAS$_{15}$- and SG$_{13}$-coated exchangers, respectively. The difference in latent effectiveness of the SP$_{15}$ exchanger during the dehumidification and regeneration processes with corresponding uncertainties was evaluated (Figure S4c). At low angular speeds ($\omega \approx 0.5$ rpm), the difference in latent effectiveness is large at 3.8\% with an uncertainty of 3.4\%. For energy wheels with angular speeds $\omega > 1.0$ rpm, the difference in latent effectiveness was reduced (ca. 2.6\%) and was within the experimental uncertainty (ca. 3.0\%) estimated for the SP$_{15}$-coated exchanger. The small difference in latent effectiveness during the regeneration cycle at low angular speeds may suggest that capillary condensation makes a partial contribution to the adsorption of water at certain RH and temperature conditions as described previously.

**CONCLUSIONS**

The current study reports on the unique water vapor adsorption–desorption for a biomass-derived starch particle (SP$_{15}$) from the seed of the Prairie carnation. This starch-based alternative desiccant has significant potential as a sustainable coating in AAEE systems. The surface and textural properties of the carnation-based starch particles (SP$_{15}$) in the dry state were comparable to high amylose starch (HAS$_{15}$) and silica gel (SG$_{13}$). The desiccant performance was characterized by using a small-scale AAEE coated with desiccants to measure transient water vapor tests. The moisture recovery (latent effectiveness) of the exchanger was used to evaluate the desiccant performance for energy wheels. Despite the similar textural properties for SG$_{13}$ and SP$_{15}$ by nitrogen adsorption results, the water vapor adsorption capacity of SG$_{13}$ was lower ($6.1 \text{ mg/mg}_{\text{des}}$) relative to SP$_{15}$ ($0.152 \text{ mg/mg}_{\text{des}}$) and HAS$_{15}$ ($0.052 \text{ mg/mg}_{\text{des}}$).

The SP$_{15}$-coated exchanger had ca. six-fold greater water vapor adsorption over SG$_{13}$. SP$_{15}$ showed impressive regeneration performance (98\% at 24 °C) versus 79\% (HAS$_{15}$) and 77\% (SG$_{13}$). The significantly greater sorption performance of the SP$_{15}$-coated desiccant is related to the accessible and abundant –OH active adsorption sites, unique water swelling properties, and its particle morphology. The estimated latent effectiveness for the SP$_{15}$-coated exchanger was found to be notably greater relative to the latent effectiveness for HAS$_{15}$- and SG$_{13}$-coated systems. The low energy required to regenerate the SP$_{15}$ desiccant material favors its use as an alternative desiccant for energy wheel applications in HVAC systems with greater performance over commercial silica materials. The impressive regeneration performance for the adsorption–desorption of water vapor for the SP materials is...
Table 2. Physicochemical Properties of the Desiccants

| sample ID | material description | particle diameter $d_{50}$ ($\mu$m) | average pore width PW$^c$ (Å) | accessible SA$^a$ (m$^2$/g) | pore volume$^b$ (cm$^3$/g) | H$_2$O swelling (%)$^c$ |
|-----------|----------------------|-------------------------------------|-----------------------------|-----------------------------|-----------------------------|------------------------|
| SP$_{15}$ | SPs                  | 15                                  | 80.6                        | 2.89                        | 0.0065                     | 4521                   |
| HAS$_{15}$ | high amylose starch | 15                                  | 46                          | 0.56                        | 0.0006                     | 63                     |
| SG$_{13}$ | silica gel           | 13                                  | 62                          | 478                         | 0.7409                     | not reported           |

$^a$Laser particle size analysis. $^b$N$_2$ gas adsorption. $^c$Gravimetric solvent swelling. Data for HAS$_{15}$ and SG$_{13}$ are presented from ref 20 with permission.

Table 3. Coating Techniques and Coated Mass of SP$_{15}$, HAS$_{15}$, and SG$_{13}$ Particles on Small-Scale Exchangers

| sample | coating technique | total coated mass (g) | coated mass (mg/cm$^2$) | coated-to-matrix mass (%) | ref     |
|--------|-------------------|-----------------------|------------------------|--------------------------|---------|
| SP$_{15}$ | sieving          | 3.43 ± 0.02         | 0.714 ± 0.005         | 0.7                      | this work |
| HAS$_{15}$ | spraying        | 3.20 ± 0.02         | 0.667 ± 0.004         | 0.6                      | 20      |
| SG$_{13}$ | spraying        | 3.12 ± 0.02         | 0.650 ± 0.004         | 0.6                      |         |

A unique sieving method was modified from a previously reported spray coating technique to cover the SP$_{15}$ desiccant onto the Al-substrate. The sieving method avoids the use of a high-pressure pneumatic spray gun that led to nonuniform dispersion of SP$_{15}$ particles because of sticking and aggregation. The coating method has several stages: (1) a thin layer of aerosol adhesive (3M super 77) was evenly sprayed over the metal plate, (2) a thin (0.035 mm) annealed Al-foil tape (3M 3381) backing with a thin acrylic adhesive was attached to the substrate from the nonadhesive side. The Al-foil tape creates a barrier against extreme moisture conditions: −23 to 49 °C and 0–95% RH, (3) the solid desiccant was sieved over the exposed adhesive side of the foil using a series 120 mesh screen, and the coating was gently pressed to enable surface binding, and (4) the loosely bound particles were removed using pressurized dry air to achieve a coating thickness and level listed in Table 3. The mass of coated desiccant per unit plate area is (mg/cm$^2$) for the three small-scale exchangers is within the acceptable industry level range. The coating methods are detailed in the Supporting Information (section S1.3).

Transient Test Facility. A lab-scale transient test facility (Figure S1) was developed to allow the stationary desiccant-coated energy exchangers to sudden changes in the inlet humidity. The small-scale coated exchanger was placed vertically into the test cell within the transient test facility, as detailed in the Supporting Information (section S2.2). To perform the single-step transient tests, dry and humid airstreams were introduced, as listed in Table S3, and a step-wise procedure was followed (section S2.3). The first step was preconditioning, where dry air (~2% RH) at ∼24 °C (Table S3) was passed through the exchanger to dry the desiccant before each adsorption cycle. Similar preconditioning with humid air (~43% RH) at 24 °C occurred before each desorption cycle. Further details of the transient test facility are presented in section S2.
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ADDITIONAL NOTE

The context of the term “Goldilocks effect” refers to the favorable balance of adsorption and desorption properties of the starch particles with water vapor using a small-scale energy exchanger under transient test conditions, as reported herein.

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