ANALYSIS OF A FABRIC/DESICCANT WINDOW CAVITY DEHUMIDIFIER

by

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ABSTRACT

This paper presents the results of an exploratory study of a fabric/desiccant window cavity dehumidifier system for possible use in commercial buildings. The objective was to evaluate fabrics commonly used in buildings, and system concepts that employ these fabrics, which can be used to dehumidify room air. We developed a first-order energy/mass balance model to determine the performance of a window cavity dehumidifier that uses silica gel encapsulated in a fabric matrix rotating on a belt alternately through dehumidification and regeneration chambers; the modeling effort was supplemented by environmental chamber measurements of the moisture absorption characteristics of 16 fabric/desiccant combinations.

We ran the model for a typical office building module, for outside air design conditions characteristic of the most difficult humidity regime in Texas. Two flow configurations, outside air and return air, were evaluated to determine the capability of such a system to dehumidify the air streams under consideration. Issues addressed included the physical limitations on the amount of desiccant that can be included in this configuration and the degree of dehumidification achievable.

INTRODUCTION

A recent Florida Solar Energy Center study has shown that moisture absorption/desorption in building materials, especially fabrics, can have significant effects on cooling/dehumidification system energy use in the hot and humid climates characteristic of major portions of Texas [2]. The results showed that fabrics in building furnishings can store up to nine times the moisture capacity of the room air, suggesting that building fabrics might be used as dehumidification devices. Thus, the intent of the present study was to develop preliminary concepts in which fabric/desiccant combinations are used as dehumidification devices.

The objective of this study was to evaluate fabrics—for shades, curtains, wall coverings, or other interior furnishings—and system concepts that employ these fabrics, which absorb and desorb water vapor so as to dehumidify room air. A conceptual design of such a system was developed and modeled to determine its performance under typical load and weather conditions. The design includes a moving fabric/desiccant belt installed in a window cavity, coupled with a regenerative heat exchanger, which serves to dehumidify either outside air (ventilation mode) or return air (recirculation mode), in a commercial building environment. The conceptual approach is similar to that proposed by Miller [5], who describes a system consisting of moving cellulose yarn belts in a window cavity, in which the desiccant (the cellulose yarn) is regenerated by solar or other heating methods [6, 7]. Miller's results indicate that yarn speed has a significant effect on the final relative humidity of the dehumidified air; the slower the yarn moves, the greater the moisture that is removed.

Our system is also quite similar to the one analyzed by Schultz and others [9], in which a rotating belt is coated with a desiccant material (silica gel microbeads) in the configuration of a counterflow rotary dehumidifier, and the desiccant is regenerated by solar energy. In contrast, our approach includes a solid desiccant embedded in a fabric matrix that moves through the window cavity. The fabric in which the solid desiccant is embedded may also be coated with a desiccant material, such as polyglycol. As in both the Miller and Schultz approaches, we propose that the fabric/desiccant move alternately through a dehumidification channel on the inside of the window cavity, and then through a regeneration cavity in an outer channel. Similar to Schultz, we assume that the desiccant is exposed to solar radiation, which provides direct regeneration heating. Our system differs from Miller's in that we examine the effect of additional finishes and/or solid desiccants embedded in the fabric system.

A first-order, quasi-steady-state, energy and mass balance model (with local equilibrium assumed) of the proposed system was developed, based on the work of Schultz and others [9], but it is not as rigorous as is their model. More rigorous and detailed models of similar desiccant dehumidification systems are available, such as that developed by Haves [3], but these are beyond the scope of this conceptual study. The model was run for a typical office building module configuration, but for outside air design conditions characteristic of the most difficult humidity regime in Texas. Outside and return air flow configurations were evaluated to determine the key design parameters of such a system, and the system's ability to dehumidify the air streams. Issues addressed include the moisture removal capacity of this system and the degree of dehumidification that can be achieved in each of the configurations proposed.

In addition, experiments were conducted in an environmental chamber to determine the fundamental properties of selected fabrics encapsulating a solid desiccant (silica gel) or treated with a polyglycol finish, and the combination of desiccant and finish. The rate of moisture uptake and the effectiveness of the fabric/desiccant combinations were measured when the samples were exposed to relative humidity environments of 40% and 60%. Details of both the simulation model and experimental studies are documented in Hunn and Grasso [4].

PROPOSED DEHUMIDIFIER

The system under consideration is situated in a window (or opaque wall) cavity having two chambers separated by a partition, with the fabric/desiccant matrix on a rotary belt passing alternately through each chamber in a counterflow arrangement, as shown in Fig. 1. Dehumidification of the air being processed is accomplished in the inner chamber and regeneration of the desiccant in the outer chamber. Regeneration heat is provided by solar energy, but could be supplied by an auxiliary source. A regenerative heat exchanger extracts heat from the hot exhaust of the dehumidification channel and preheats the incoming regeneration air stream. This system can be configured to process two different air flow amounts: outside (ventilation) air only or building return air only.

The proposed system is only conceptual at this preliminary stage. Whether it is situated in a window cavity or an opaque wall cavity is not important to its function. In addition to the potential dehumidification accomplished, there are other practical considerations such as the large air volumes required to flow in a narrow cavity, and the resultant pressure drop, or the view obstruction that may result. Although these other matters may be of critical importance to the feasibility of such a design, we do not address them in this study; we focus strictly on the dehumidification/regeneration performance of the proposed system.

In the *outside air* configuration (Fig. 1), only ventilation air is passed through the dehumidification

1. Outside Air
2. Return Air
3. Air (Entry to Dehumidification Chamber)
4. Air (Exit from Dehumidification Chamber)
5. Entry to Regeneration Chamber
6. Exhaust from Regeneration Chamber

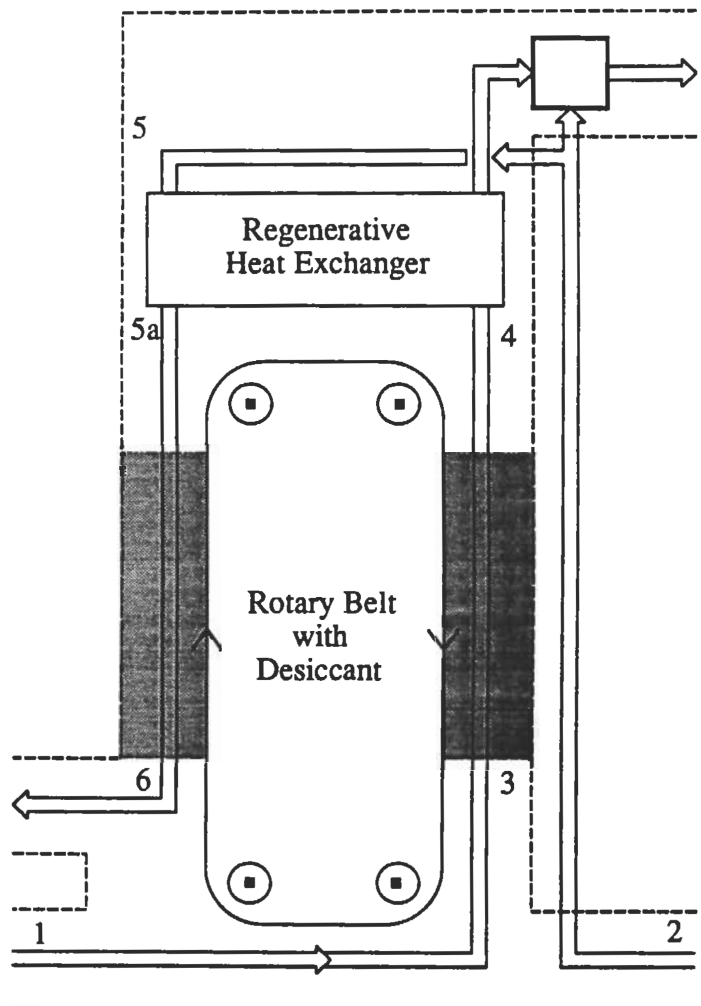

Fig. 1. Window Cavity Dehumidifier
Outside Air Configuration

chamber and is then mixed with return air in the supply air duct system. An equal amount of exhaust air is extracted from the return air stream and is passed through the regeneration chamber and then exhausted. In the *return air* configuration (Fig. 2), a portion of the return air stream equal to the supply air volume is passed through the dehumidification chamber; outside air is added downstream of the chamber. The remainder of the return air stream, equal to the outside air volume, is passed through the regeneration chamber.

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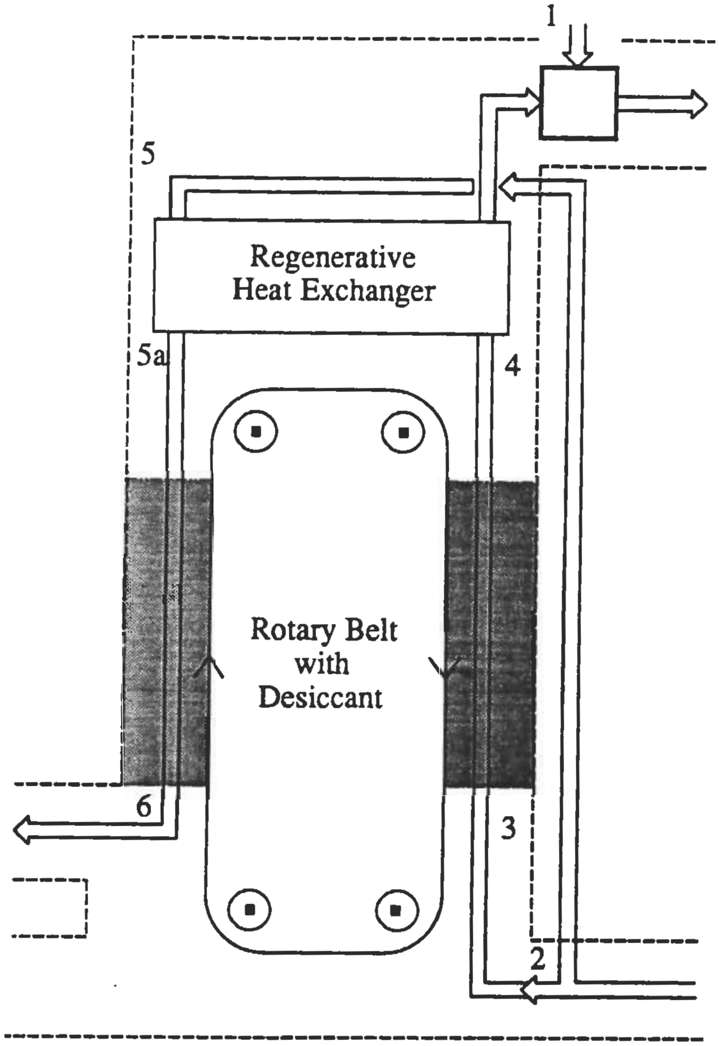

Fig. 2. Window Cavity Dehumidifier
Return Air Configuration

Thus, in both configurations the air enters the regeneration chamber at return air conditions and at a flow rate equal to the outside air flow rate. However, for the dehumidification chamber the entering conditions and flow volumes differ in the two cases. In the return configuration the ratio of the dehumidification-to-regeneration air flow rates is on the order of 10, whereas for the outside air configuration it is 1.

DEHUMIDIFIER MODEL

Model Formulation

For each configuration the model satisfies global mass and energy balances on the dehumidification and regeneration moist air streams, as is documented by Vadlamani [10]. We assume that the fabric/desiccant belt moves slowly through the chambers so that ample time is available for steady-state conditions to be achieved. The rigorous numerical model of Schultz and others indicates that the optimum belt rotation period is in the 600–900 second range, depending on the amount of desiccant involved in the process. There are transients as the desiccant leaving the regeneration chamber is heated to the inlet conditions of the dehumidification chamber, and vice versa, but these are neglected in the energy balances.

We use the parameters and results of the Schultz analysis to establish reasonable exiting conditions for both chambers. Thus we assume a regenerative heat exchanger effectiveness of 0.9 and an absorbed solar radiation flux of 450 m^2 in the regeneration channel. The loss coefficient for the outside channel is assumed to be at a design value of 0.88 Btu/h-ft-°F (5.0 W/m^2-°C), and that for the inside channel at 0.58 Btu/h-ft-°F (3.3 W/m^2-°C). Heat capacitance effects are included by assuming that the combined desiccant and belt has a specific heat of 0.34 Btu/h-ft-°F (1.42 kJ/kg-°C) [3], and that the desiccant/belt is heated or cooled from inlet to exit state over the period of belt rotation. The belt period is such that the ratio of desiccant "flow rate" to process air flow rate is maintained at an optimal 0.2.

The Schultz and others model satisfies the equilibrium moisture loading conditions at each point on the belt; they then calculate the dehumidification and regeneration chamber exit conditions under design conditions. Because we match the dehumidification and regeneration chamber exit states determined from the rigorous Schultz model, the rate of moisture transport to the desiccant and the moisture sorption capacity (desiccant loading) are assumed to be sufficient to achieve the moisture removal amounts specified as input to our model. In a later section we report a measured moisture removal capacity of such a fabric/desiccant system and compare it to that necessary to achieve the specified dehumidification.

The variables to be considered are defined as follows:

Outside Air

$\dot{m}_{ra}$ is the flow rate of outside air (on a dry basis), and ω_{oa}, h_{ra}, and t_{oa} are the humidity ratio, enthalpy, and temperature at hot and humid design

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conditions for an office building (90°F db, 79°F wb) (32°/26°C), or a specific humidity of 0.0188.

Return Air

$\dot{m}_{ra}$ is the return air flow rate (on a dry basis), and ω_{ra}, h_{ra}, and t_{ra} are the humidity ratio, enthalpy, and temperature at typical design conditions for an office building (75°F, 50% RH) (24°C, specific humidity = 0.00925). However, for the return air configuration a 60% RH (specific humidity = 0.0110) is assumed.

Here we consider a typical 15 ft x 20 ft office module having a window area of 16 ft x 4 ft. (64 ft^2 or 5.95 m^2). Assuming a supply air flow rate of 1.0 cfm/ft^2 (0.0062 kg/s–m^2) of floor space, we get a total supply air flow of 300 cfm (0.172 kg/s) at standard temperature and pressure. If the outside air flow is set at 20 cfm/person (0.012 kg/s–m^2), based on an occupancy of two persons for this office module, the total outside air flow is 40 cfm (0.023 kg/s), for an outside air fraction of 13%. However, in general the outside air fraction (α) is set as an input parameter, ranging from 0 to 20%.

Outside Air Configuration

Because there is no mixing upstream of the dehumidification chamber, the inlet conditions are identical to the outside air conditions. Thus, at Point 3

$$\dot{m}_{3a} = \dot{m}_{oa} \quad t_5 = t_{ra} \quad \omega_3 = \omega_{oa} \quad h_3 = h_{oa} \qquad \text{Eq. (1)}$$

For the *dehumidification process* we define

• Moisture absorption capacity rate of the desiccant bed, per unit bed length = k lb/s-ft (kg/s-m), where k is averaged over the bed length. Thus, for a bed of length = δ ft (m), the moisture absorption rate of the full bed = kδ lb/s (kg/s)

• Heat of sorption = L = 1,200 Btu/lb (2,796 kJ/kg)

Thus, the sorption heat release rate = Lkδ Btu/s (kJ/s)

A mass balance for the air and water in the dehumidification process gives

$$\omega_4 = \omega_{oa} - \frac{k\delta}{\dot{m}_{oa}} \qquad \text{Eq. (2)}$$

With the heat release rate from the absorption of water vapor equal to Lkδ, and assuming steady-state conditions, an energy balance on the dehumidification air stream gives

$$\dot{m}_{3a}h_3 + Lk\delta + \left(M_d\, c_{pd} / \Delta\tau\right)(t_6 - t_4) = \dot{m}_{4a}h_4 + h_{l,d}\, A_g\left(\bar{t}_d - t_{ra}\right) \qquad \text{Eq. (3)}$$

where M_d is the combined desiccant/belt mass, c_{pd} is the combined desiccant/belt specific heat (0.34 Btu/lb °F = 1.42 kJ/kg °C), $\Delta\tau$ is the belt rotation period, and $\bar{t}_d$ is the average dehumidification chamber temperature. With the desiccant "flow rate" ($M_d/\Delta\tau$) to process air flow rate ($\dot{m}_{oa}$) ratio equal to 0.2, and the heat loss coefficient of 3.3 W/m^2°C applied to an area of 5.95 m^2, the energy balance becomes

$$\frac{Lk\delta}{\dot{m}_{oa}} = h_4 - h_3 - (0.2)(1.42)(t_6 - t_4) + \frac{(0.020)}{\dot{m}_{oa}}\left(\frac{t_4 + t_3}{2} - t_{ra}\right) \qquad \text{Eq. (4)}$$

where each term is expressed in kJ/kg.

With the humidity ratio at the exit of the dehumidification chamber (Point 4) determined from Eq. 2, the air temperature at Point 4 is given by the standard enthalpy-temperature relationship for air-water vapor mixtures [1] as

$$h_4 = t_4 + \omega_4 (2501 + 1.805 t_4) \text{ kj/k} \qquad \text{Eq. (5)}$$

where t_4 is in °C. Thus, Eq. 4 can be solved for the exit temperature, t_4, in terms of known values and the regeneration exit temperature, t_6.

For the *regeneration process* the inlet conditions are the same as those of the return air, and the air flow rate is equal to the outside air flow rate:

$$\dot{m}_{5a} = \dot{m}_{6a} = \dot{m}_{oa} \quad t_5 = t_{ra}, \quad \omega_5 = \omega_{ra}, \quad h_5 = h_{ra} \qquad \text{Eq. (6)}$$

A mass balance on the water during regeneration gives:

$$\omega_6 = \omega_{ra} + \frac{k\delta}{\dot{m}_{oa}} \qquad \text{Eq. (7)}$$

because for steady-state operation the water absorbed by the desiccant in the dehumidification chamber must equal that released in the regeneration chamber. Observing that energy must be supplied to desorb the water from the desiccant in the regeneration air stream at a rate of Lkδ, and denoting the external energy supplied (assumed to be solar) to the regeneration chamber as $\dot{Q}_{ext}$, an energy balance gives:

$$\frac{\dot{Q}_{ext}}{\dot{m}_{oa}} = h_6 - h_{5'} + \frac{Lk\delta}{\dot{m}_{oa}} + (0.2)(1.42)(t_6 - t_4) + \frac{(0.0298)}{\dot{m}_{oa}}\left(\frac{t_4 + t_6}{2} - t_{oa}\right) \qquad \text{Eq. (8)}$$

where the average regeneration chamber temperature is $(t_4 + t_6)/2$, the heat loss coefficient from the regeneration chamber to the ambient air (5.0 $W/m^2{}^\circ C$) is applied to an area of 5.95 m^2, and the desiccant/belt heat capacitance is the same as for the dehumidification chamber.

Combining Eqs. (2) and (7) relates the humidity conditions at the chamber exits

$$\omega_6 = \omega_{oa} + \omega_{ra} - \omega_4 \qquad \text{Eq. (9)}$$

Noting that $\omega_{5'} = \omega_5 + \omega_{ra}$, that $\dot{Q}_{ext} = 0.45$ kJ/s-m^2, and that

$$h_6 = t_6 + \omega_6 (2501 + 1.805\, t_6)(\text{kJ/kg}) \qquad \text{Eq. (10)}$$

Equations (4) and (8) can be combined to solve for t_4 and t_6.

Return Air Configuration

With reference to Figure 2, the conditions at Points 1 and 2 are the same as for the outside air configuration. However, the dehumidification inlet condition (Point 3) is given by

$$\dot{m}_{3a} = \dot{m}_{ra}, \quad t_3 = t_{ra}, \quad \omega_3 = \omega_{ra}, \quad h_3 = h_{ra} \qquad \text{Eq. (11)}$$

The mass balance equations for both chambers are identical to those for the outside air configuration, except for the dehumidification inlet state and air flow rate given above. Similarly, the regeneration inlet condition is identical to that for the outside air configuration. In this case,

$$\omega_4 = \omega_{ra} - \left(\frac{\alpha}{1-\alpha}\right)\frac{k\delta}{\dot{m}_{oa}} \qquad \text{Eq. (12)}$$

where α is the OA fraction. Combining the mass balance equations for dehumidification and regeneration yields the regeneration exit humidity:

$$\omega_6 = \frac{\omega_{ra} - (1-\alpha)\omega_4}{\alpha} \qquad \text{Eq. (13)}$$

Likewise, the dehumidification chamber energy balance becomes

$$\frac{Lk\delta}{\dot{m}_{oa}} = \left(\frac{a}{1-a}\right)(h_4 - h_3) - (0.2)(1.42)(t_6 - t_4) + \frac{(0.020)}{\dot{m}_{oa}}\left\langle\frac{t_4 + t_3}{2} - t_{ra}\right\rangle \qquad \text{Eq. (14)}$$

Because the flow rate through the regenerator is the same as for the outside air case, Eq. (8) is the applicable energy balance equation.

Solution Approach

In the above sets of equations, the moisture absorption rate of the bed, $k\delta$, is unknown and will depend on the effective dehumidification capacitance of the desiccant in the bed, the air flow rate, and the coupling between the desiccant and the air. A rigorous determination of the moisture absorption rate requires solution of the above mass and energy balance equations simultaneously with the desiccant loading curve (desiccant moisture loading versus relative humidity of process air), such as is solved by Haves [3] and by Schultz and others [9]. We take a simpler approach, solving the quasi-steady-state energy and mass balance equations, but using the Schultz results to determine the validity of the dehumidification and regeneration chamber exit conditions and appropriate values for the various parameters. We assume a given level of moisture removal, expressed as the moisture removal fraction (mrf). Experimental data presented below confirm this assumption.

For the outside air configuration the *relative* moisture removal fraction (rmrf) is defined as the fraction of the moisture removal required to bring the dehumidified air to the space air specific humidity conditions. Thus,

$$(\text{mrf})_{rel} = \frac{\omega_3 - \omega_4}{\omega_3 - \omega_5} = \frac{\omega_{o\alpha} - \omega_4}{\omega_{o\alpha} - \omega_{ra}} \qquad \text{Eq. (15)}$$

For the return air case, we assume a slightly higher space humidity and define the rmrf as the fraction of the moisture removal required to bring the dehumidified return air to the space air reference level of 50% RH (ω_{ref} = 0.00925). Thus,

$$\text{mrf} = \frac{\omega_3 - \omega_4}{\omega_3 - \omega_{ref}} = \frac{\omega_{r\alpha} - \omega_4}{\omega_{r\alpha} - \omega_{ref}} = \frac{0.0110 - \omega_4}{0.0110 - 0.00925} \qquad \text{Eq. (16)}$$

Thus, the model is used to determine the dehumidification end state (State 4) and the regeneration end state (State 6), consistent with the assumed solar energy absorption rate and the amount of moisture removed.

ANALYTICAL RESULTS

The basic question to be addressed is, can a sufficient mass of desiccant be placed in the window cavity to dehumidify the process air to specified levels in the two proposed configurations? The desired levels of dehumidification are those that allow the air to enter the space, without further dehumidification, at a specific humidity that is neutral to the space conditions, corresponding to a relative moisture removal fraction of 1.0.

Outside Air Configuration

We first present results for the *outside air configuration*. Solution of the mass and energy balance equations, with the relative moisture removal fraction specified as an input parameter and with an outside air ratio of 0.10, results in the dehumidifier and regenerator exit states shown by the succession of dots on the psychrometric chart in Fig. 3; States 4 and 6 represent an rmrf of 1.0. Note that as the rmrf is varied from 0.10 to 1.0 and more moisture is

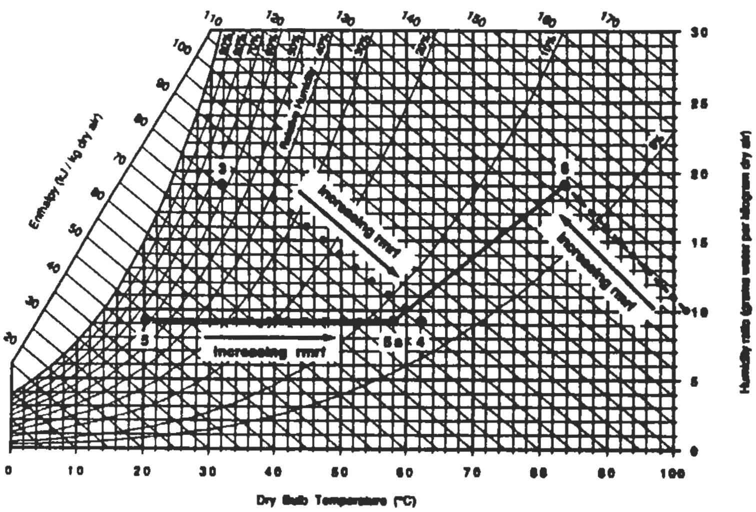

Fig. 3. Process Representation on Psychometric Chart for Outside Air Configuration with Outside Air Ratio of 0.10, Outside Air Conditions are 90°F/79°F (32°C/26°C). Corresponding to a Specific Humidity of 0.0188, Net Solar Energy Input = 0.45W/m^2, [The State Points Shown Identify the Relative Moisture Removal Fractions Considered.]

removed in the dehumidifier channel, the dehumidifier exit temperature increases and the regenerator temperature decreases. If enough moisture is removed to bring the specific humidity to the space condition (rmrf of 1.0), the operating point is quite similar to that determined by Schultz and others [8, 9].

For the outside air configuration, Fig. 4 shows that the range of expected water removal rates is 1.6 to 32.9 x 10^{-5} kg/s for outside air fractions ranging from 0.1 to 0.2. These water removal rates are compared below with experimental values.

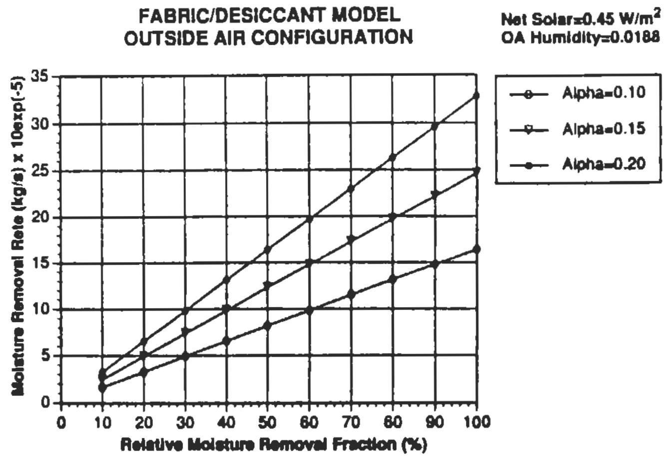

Fig. 4. Fabric/Desiccant Model Results for Outside Air Configuration, Moisture Removal Rate as a Function of Relative Moisture Removal Fraction {Net Solar Energy Input = 0,45 W/m^2, Outside Air Humidity = 0.0188, for Outside Air Ratios of 0.1, 0.15, and 0.2.]

It is also significant to compare the predicted moisture removal capacity of the outside air configuration with the amount of desiccant that could be placed in the dehumidification channel. The moisture that must be removed in a bed rotation period (approximately 600 s) to achieve an rmrf of 1.0 is given by a mass balance on the air side as

$$\dot{m}_{oa}\,(\omega_3 - \omega_4)\,\Delta\tau = (0.0172\ \text{kg/s})\,(0.0188 - 0.00925)\,(600\ \text{s}) = 0.0986\ \text{kg water} \qquad \text{Eq. (17)}$$

Taking the desiccant to be in equilibrium with the air at the dehumidifier exit, the moisture removal capacity is given by the difference in desiccant moisture loading between the wettest (State Point 3)

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and the driest (State Point 6) bed conditions. Thus, if the bed is fully saturated (which it is not), the implied moisture transfer in a bed rotation period would be

$$M_d\,(X_3 - X_6) = M_d\,(0.35 - 0.03)\ \text{kg}\ H_2O \qquad \text{Eq. (18)}$$

where M_d is the effective desiccant mass and X is the equilibrium moisture loading for silica gel, taken from Fig. 5 at a State 3 of 32°C, RH = 62.5% and a State 6 of 84°C, RH = 7% (rmrf of 1.0).

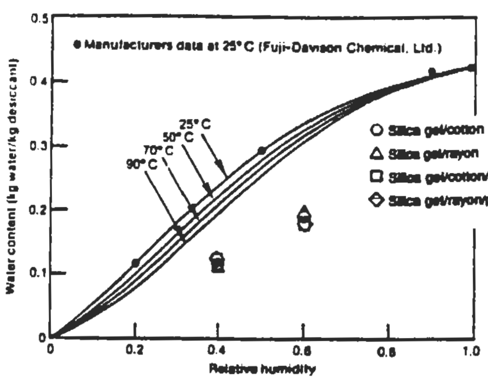

Fig. 5. Microbead Silica-Gel Isotherms at Several Temperatures (8) Including Data Measured at The University of Texas at Austin for Fabric-Encapsulated Silica Gel at 60°F (15.6°C)

Equating the desiccant side and air side moisture capacity, we find that 0.31 kg of desiccant are needed. However, because the bed will only be from 20–50% saturated, the required desiccant amount will be in the range of 0.62–1.55 kg. For a dehumidification channel width of 0.5 in. (1.27 cm), an available area of 64 ft^2 (5.95 m^2), a silica gel density of 70 lb/ft^3 (1130 kg/m^3) [8], and a void volume of 50%, the maximum amount of desiccant would be 94.1 lb (42.7 kg). Thus, even if only a fraction of this desiccant is effective in moisture removal, enough desiccant mass could be placed in this dehumidifier for it to operate with sufficient capacity in the outside air configuration.

In Fig. 6 the dehumidification efficiency (moisture removal rate normalized by the solar regeneration heat rate) is given as a function of the rmrf, for outside air fractions ranging from 0.10 to

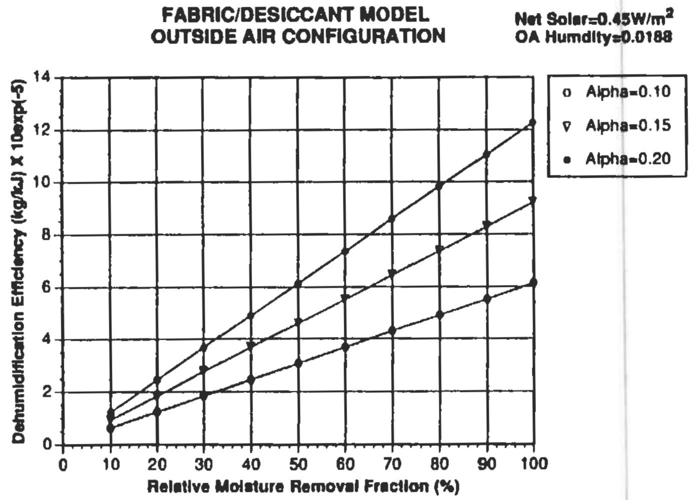

Fig. 6. Fabric/Desiccant Model Results for Outside Air Configuration, Dehumidification Efficiency as a Function of Relative Moisture Removal Fraction. [Net Solar Energy Input = 0.45 W/m^2, Outside Air Specific Humidity = 0.0188, for Outside Air Ratios of 0.1, 0.15, and 0.2.]

0.20. The dehumidification efficiency is shown to increase linearly with increasing moisture removal fraction, and with the outside air fraction. Thus, high moisture removal fractions are desirable.

Return Air Configuration

For the *return air configuration*, the resulting dehumidifier and regenerator exit states are shown in Fig. 7. As in the outside air case, as the rmrf is varied from 0.10 to 1.0 and more moisture is removed in the dehumidifier channel, the dehumidifier exit temperature increases and the regenerator temperature decreases.

Figure 8 shows that the range of expected water removal rates is 2.4 to 27.1 x 10^{-5} kg/s for outside air fractions ranging from 0.1 to 0.2. These rates are only slightly less than those for the outside air configuration because although the specific humidity range is considerably smaller, the process air flow rate is increased by a factor of from 5 to 10. Furthermore, because an increasing outside air fraction shifts air from the dehumidification chamber to the regeneration chamber, the moisture removal rate decreases with increasing outside air fraction. Moreover, the sensitivity to outside air fraction is considerably lower than for the outside air configuration (see Fig. 4).

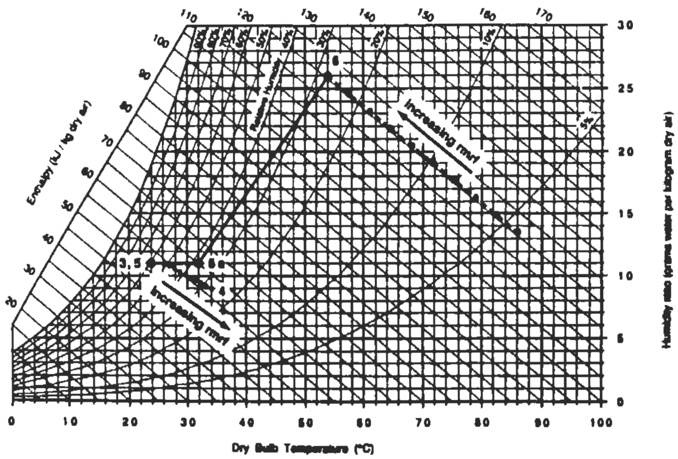

Fig. 7. Process Representation on Psychometric Chart for Return Air Configuration with Outside Air Ratio of 0.10, Return Air Humidity = 0.0110, Net Solar Energy Input = 0.45 W/m^2, [The State Points Shown Identify the Relative Moisture Removal Fractions Considered.]

To determine the mass of desiccant required to achieve an rmrf of 1.0 for the return air case, we again equate the moisture removed from the air to that absorbed by the desiccant. In the dehumidifier channel the air side moisture removal is

$$\dot{m}_{ra} (\omega_3 - \omega_4) \Delta\tau = (0.1548 \text{ kg/s}) (0.0110 - 0.00925) (600 \text{ s}) = 0.1625 \text{ kg water} \quad \text{Eq. (19)}$$

Assuming the desiccant to be in equilibrium with the air at the dehumidifier exit, the moisture removal capacity is given by

$$M_d (X_3 - X_6) = M_d (0.34 - 0.17) \text{ kg water} \quad \text{Eq. (20)}$$

where the equilibrium moisture loading for silica gel is from Fig. 5 at a State 3 of 24°C, RH = 60% and a State 6 of 52°C, RH = 30% (see Fig. 7). Equating the two expressions and assuming that the bed is only 20–50% saturated, then 1.92–4.80 kg are needed. This is still considerably less than the estimated maximum amount of silica gel (42.7 kg) that could be placed in the dehumidification channel.

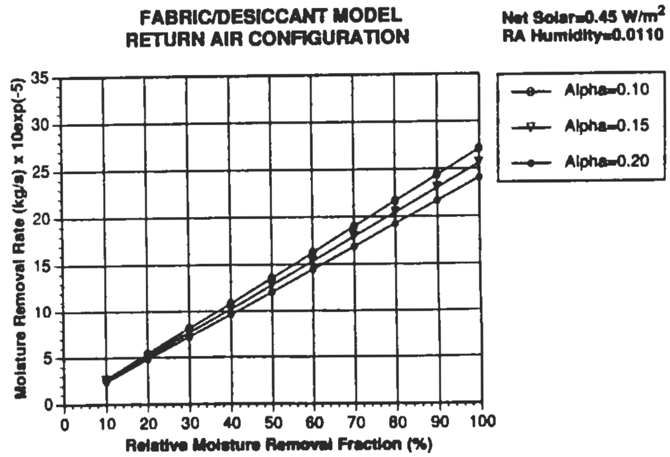

Fig. 8. Fabric/Desiccant Model Results for Return Air Configuration, Moisture Removal Rate as a Function of Relative Moisture Removal Fraction. [Net Solar Energy Input = 0.45 W/m^2, Return Air Humidity = 0.0110, for Outside Air Ratios of 0.1, 0.15, and 0.2.]

Similarly, because of the 5–to–10 ratio of dehumidifier to regenerator air flow rates, the dehumidification efficiency is much less influenced by the outside air ratio than it is in the outside air configuration (Fig. 9). Whereas the dehumidification efficiency increases with outside air ratio for the outside air case, it decreases with outside air ratio for the return air case. Again, the reason is that as the outside air ratio increases, air flow is shifted from the dehumidifier to the regenerator.

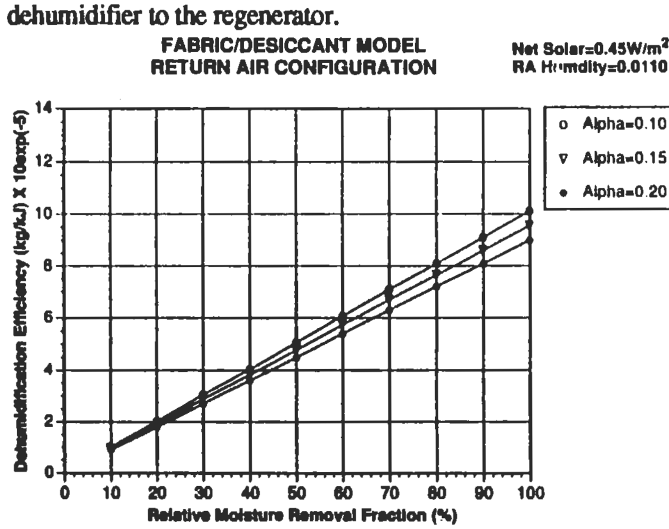

Fig. 9. Fabric/Desiccant Model Results for Return Air Configuration, Dehumidification Efficiency as a Function of Relative Moisture Removal Fraction. [Net Solar Energy Input = 0.45 W/m^2, Return Air Humidity = 0.0110, for Outside Air Ratios of 0.1, 0.15, and 0.2.]

EXPERIMENTAL APPROACH

Laboratory experiments were conducted to a) determine a suitable fabric/desiccant combination for use in the window cavity dehumidifier, and b) to estimate the moisture absorption (regain) capacity of the candidate fabric/desiccant combinations. After examining the properties of various solid desiccants, we determined that silica gel beads, encapsulated in a fabric pouch, would be the best approach.

Thus, we measured the moisture regain characteristics of several fabrics used to encapsulate silica gel beads. These included cotton (a natural fiber) and rayon (a synthetic fiber), both with and without a polyglycol coating; a polyglycol coating has been shown to have good hygroscopic properties [11]. The samples of the various combinations were tested in a walk-in environmental chamber, which exposed the samples to an environment of constant temperature and relative humidity.

Description of the Apparatus

The experimental apparatus consists of an electronic analytical balance located inside an environmental chamber. Operating conditions in the chamber are controlled by a host computer through a data acquisition and control unit. The analytical balance has an associated infrared dryer that is used to dry the fabric/desiccant samples before they are tested. Sample weights before, during, and after each experiment are recorded. Details of the communication linkages among the components are given by Vadlamani [10].

In addition to using the temperature and relative humidity sensors built in to the environmental chamber control system, these quantities were measured independently using a combined resistance temperature sensor and thin-film capacitive humidity sensor.

Experimental Procedure

Moisture absorption tests were conducted for two sets of samples. The first set included only the encapsulating fabric, treated and untreated with a polyglycol finish, as follows:

- 100% cotton
- 100% rayon
- Cotton coated with polyglycol finish
- Rayon coated with polyglycol finish

The fabrics were coated with polyglycol at the U.S. Department of Agriculture, Southern Regional Research Center in New Orleans, Louisiana. The purpose of this first set of tests was to determine the effect of the encapsulating fabric, and the associated polyglycol finish, on the moisture regain rate and equilibrium value. In the second set we included these same fabrics sewn into a fine net structure, forming pouches about 3.0 in.(7.6 cm) square, encapsulating approximately 0.013 lb (6 g) of silica gel beads each.

For each sample the moisture regain (equilibrium amount of water gained, starting from a dry sample) was determined when exposed to constant relative humidities of 40% and 60% (except for the plain, uncoated cotton which was exposed at 40% and 54%) at a constant temperature of 15.6°C (60°F). Initially each sample was dried in the infrared dryer for about 75 min. to assure essentially zero moisture content at the beginning of each test. Then the sample was weighed to determine its dry weight. It was then placed on the electronic balance in the environmental chamber that had been preset at the desired humidity condition, and was weighed at four-min. intervals until the sample reached saturation.

A fan in the chamber gently circulated air over the fabric/desiccant pouch. Therefore, the air flow pattern differs from the matrix air flow that would be expected in a window cavity configuration. Here the air generally circulates over but not through the sample. Hence the effective contact area between air and desiccant is not as great as with the window cavity configuration; this arrangement will reduce the moisture regain rate and the equilibrium moisture content of the saturated sample.

RESULTS

Moisture Regain Characteristics

For each test a time series plot of the sample weight is recorded. The results of four representative tests of the 16 conducted are presented in Figs. 10–13, and are summarized in Table 1; the full set of 16 time series plots of the results is documented in Hunn and Grasso [4]. It is seen that the silica gel encapsulated in rayon, exposed to the 60% relative humidity environment, has the highest moisture regain of 19.3%. This follows the general trend that the higher the relative humidity, the higher the moisture regain fraction. However, all four of the silica gel cases at a 60% relative humidity are about the same, having moisture regains of 17.9% to 19.3%. The results for the uncoated cotton and rayon fabrics alone show that rayon is more hygroscopic than is cotton. However, when polyglycol is added to the plain fabric, the moisture regain appears to be reduced; this is illustrated by the fact that the polyglycol-coated cotton has the lowest moisture regain at 3.1%. Moreover, when the polyglycol-coated fabrics are combined with the silica gel, no trends are evident with respect to the coating as in two cases the regain increases, and in two cases it decreases. Clearly the silica gel acts as a significant desiccant,

Proceedings of the Ninth Symposium on Improving Building Systems in Hot and Humid Climates, Arlington, TX, May 19-20, 1994

approximately doubling the moisture regain, from the 5–10% range to the 10–20% range.

As is shown in Fig. 5, the encapsulated desiccant results fall below the desiccant loading curves for microbead silica gel [8]. The reason is probably the restricted contact area resulting from the encapsulation and the air circulation configuration.

In Table 1 the average and maximum moisture regain rates (under dry sample conditions) are given, as determined from the slopes of the curves in Figs. 10–13 at zero moisture content, where the average has been calculated over the period required to reach saturation. Although no general trends are evident as to the effect of relative humidity or polyglycol coating on either the average or maximum moisture regain rate, the rayon consistently results in higher average regain rates compared to the cotton.

It is interesting to note that the time required to reach saturation is considerably lower for the plain and coated fabrics, as compared to the encapsulated silica gel samples. This is likely a result of the greater surface area to volume ratio of the fibers as compared to the spherical silica gel beads. Moreover, the lowest saturation periods are obtained for the polyglycol-coated fabrics, indicating that the polyglycol serves to enhance the rate of moisture absorption, if not the total moisture regain.

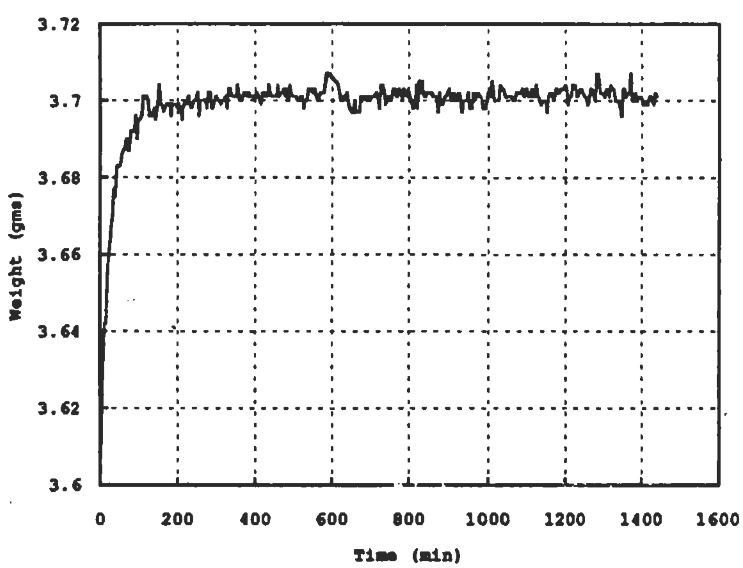

Fig. 10. Moisture Regain Time Series: 100% Cotton Sample at 40% Relative Humidity

For the window cavity dehumidifier we seek a fabric/desiccant combination that has a high moisture regain, as well as a high moisture regain rate. The experimental results shown here indicate that the silica gel encapsulated in polyglycol-coated rayon provides the best performance as it combines a high moisture regain with a modest moisture regain rate.

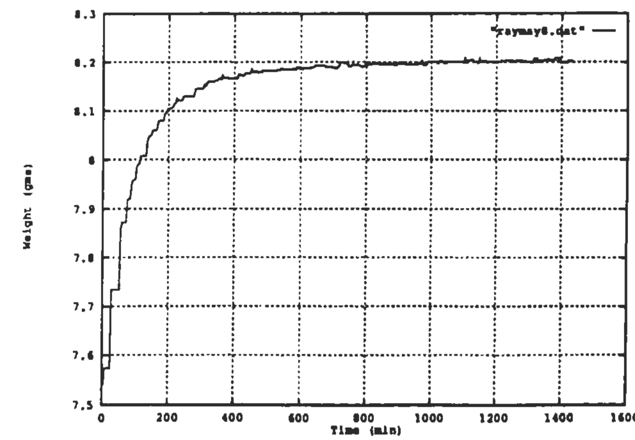

Fig. 11. Moisture Regain Time Series: 100% Rayon Sample at 60% Relative Humidity

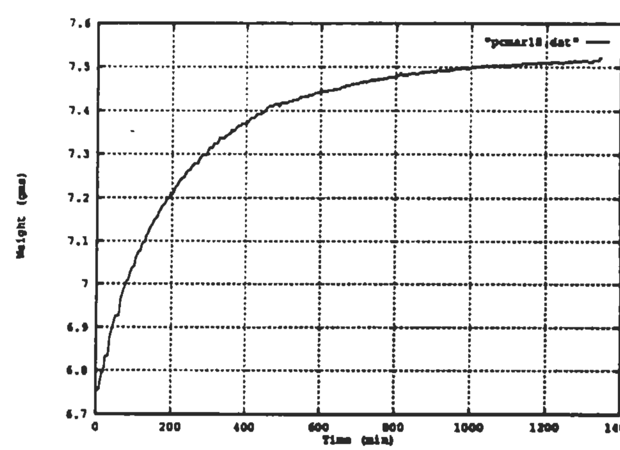

Fig. 12. Moisture Regain Time Series: Polyglycol-Coated Cotton With Silica Gel at 40% Relative Humidity

Potential Dehumidification Capacity

A key issue is whether a sufficient amount of desiccant can be placed in the dehumidification and regeneration chambers of the window cavity dehumidifier described herein. Figures 4 and 8 show that for an outside air fraction of 0.10, the moisture removal rate predicted by the model at a relative moisture removal fraction of 1.0 is on the order of 20 x 10^{-5}kg/s, for the configurations considered. From Table 1 we see that the average moisture regain rate for the silica gel encapsulated in polyglycol-coated rayon is 2.7 x 10^{-5} g/s for a sample of 6.85 g. Therefore, the moisture removal rate obtained in our experiments is 0.39 x 10^{-5} kg/s per kg of desiccant, if the initially dry desiccant is taken to saturation conditions. Scaling this up to a moisture removal

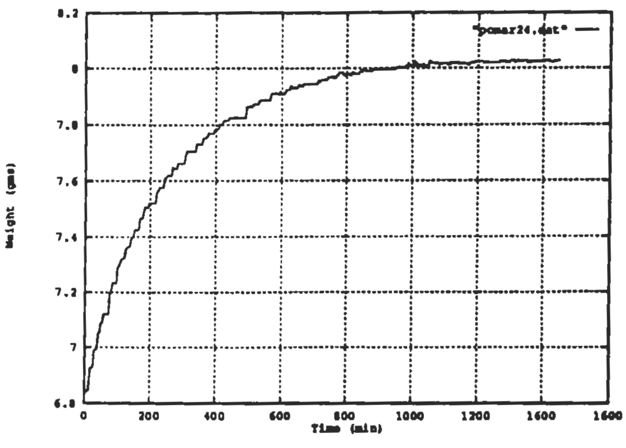

Fig. 13. Moisture Regain Time Series: Polyglycol-Coated Cotton With Silica Gel at 60% Relative Humidity

Table 1
EXPERIMENTAL OBSERVATIONS OF FABRIC/DESICCANT MOISTURE REGAIN

Sample	Relative Humidity (%)	Initial Dry Weight (g)	Absolute Moisture Gain (g)	Moisture Gain (%)	Time to Reach Saturation (min)	Average Regain Rate (g/s x 10^{-5})	Maximum Regain Rate (g/s X 10^{-5})
Cotton	40	3.60	0.102	2.83	300	0.57	6.8
Cotton	54	4.02	0.215	5.35	500	0.72	5.1
Rayon	40	6.45	0.42	6.51	600	1.2	10.0
Rayon	60	7.54	0.66	8.75	700	1.6	11.0
Cotton/Polyglycol	40	1.065	0.033	3.10	110	0.50	2.2
Cotton/Polyglycol	60	1.07	0.048	4.49	500	0.16	3.2
Rayon/Polyglycol	40	1.28	0.073	5.70	150	0.81	4.6
Rayon/Polyglycol	60	1.28	0.123	9.61	100	2.1	5.1
Silica Gel/Cotton/Polyglycol	40	6.7	0.80	11.94	1000	1.3	13.3
Silica Gel/Cotton/Polyglycol	60	6.8	1.22	17.94	1000	2.0	14.5
Silica Gel/Rayon/Polyglycol	40	6.82	0.82	12.02	900	1.5	7.8
Silica Gel/Rayon/Polyglycol	60	6.85	1.3	18.98	800	2.7	10.8
Silica Gel/Cotton	40	6.5	0.75	11.54	1200	1.0	6.9
Silica Gel/Cotton	60	6.55	1.20	18.32	1400	1.4	5.9
Silica Gel/Rayon	40	5.86	0.65	11.09	1400	0.77	6.0
Silica Gel/Rayon	60	5.87	1.13	19.25	1400	1.3	8.2

rate of 20 x 10^{-5} kg/s results in a required desiccant mass of 51.2 kg. Thus the experimental data indicate that the required amount of desiccant is a bit more (20%) than the 42.7 kg that can be accommodated in the potential space available in the window cavity dehumidifier.

However, note that the required desiccant mass determined from the experiments is about an order of magnitude higher than that predicted by the quasi-steady-state model. One reason for this discrepancy is that the air flow pattern in the environmental chamber experiments produces dehumidification rates considerably lower than would be the case for air flowing through a fabric-desiccant matrix.

CONCLUSIONS

Based on the results of a highly simplified, fabric/desiccant dehumidifier model applied to worst-case humidity conditions in Texas, and experimental measurements of the adsorption characteristics of fabric-encapsulated silica gel, we draw the following conclusions.

1. Based on the model results, the proposed fabric/desiccant window cavity dehumidifier exhibits satisfactory dehumidification performance in either the outside air or return air configuration. For both configurations an amply sufficient mass of desiccant (from 27 to 9 times the amount required, respectively) can be placed in the dehumidification channel to dry the supply air to a humidity state that is neutral to the space conditions. However, despite the lower moisture removal requirements of the return air configuration, because the process air flow is considerably greater (by a factor of five to ten) in the return air configuration, the required amount of desiccant is three times that required for the outside air configuration.

2. Absolute moisture removal rates indicated by the model range from 2 to 33 kg/s x 10^{-5} for the outside air configuration, to 2 to 27 kg/s x 10^{-5} for the return air configuration.

3. For a relative moisture removal fraction of 1.0, the dehumidification efficiency (mass of moisture removed per unit of solar regeneration energy required) ranges from 6 to 12 kJ/kg for the outside air configuration, and from 9 to 10 kJ/kg for the return air configuration.

4. Silica gel beads encapsulated in a rayon pouch and exposed to a relative humidity of 60% had a moisture regain (starting from a fully dried sample) of nearly 20%, the highest of the samples tested. The type of encapsulating fabric (cotton or rayon), and the presence of a polyglycol coating on this fabric, had no distinguishable effect on the moisture regain; the results were all in the 17.9–19.3% regain range.

5. The experimental data indicate that the required amount of desiccant is about (20%) more than the mass that can be accommodated in the space available in the window cavity dehumidifier. However, the required desiccant mass determined from the experiments is about an order of magnitude higher than that predicted by the model. One reason for this discrepancy is that

the air flow pattern in the environmental chamber experiments produces dehumidification rates considerably lower than would be the case for air flowing through a fabric-desiccant matrix.

ACKNOWLEDGMENTS

The authors wish to thank Dennis Waugaman of Texas A&M University and Kenneth Schultz of the Trane Company, LaCross, Wisconsin, for their valuable comments and suggestions. This research was funded by the Texas Energy Research in Applications Program, Project No. 206.

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