Characteristics of Desiccant Polymers for Air Conditioning Systems

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ABSTRACT

Controlling temperature and humidity within a conditioned space is important for a wide variety of applications. One dimensional numerical model was developed for the performance studies of a rotary wheel total enthalpy exchanger. After an initial experimental study of several candidate materials, it was decided that polyvinyl alcohol is the best and met the predetermined selection criteria. Various polyvinyl alcohol materials were modeled as operating desiccants in a rotary wheel total enthalpy exchanger. Finite difference equations and differential equations were developed for the rotary wheel total enthalpy exchanger model through the use of the control volume technique. Using the principals of conservation of energy and conservation of mass, governing equations were derived.

Keywords: Desiccant polymer, Heat transfer, Mass transfer, Air conditioning, Simulation

INTRODUCTION

Since Pennington¹ obtained the first patent of desiccant cooling system in 1955 and Dunkle² constructed a solid desiccant dehumidification and cooling rotary wheel in 1965, much research on the solid desiccant dehumidifiers has been accomplished, and many effective mathematical models to predict the heat and mass transfer process in such dehumidifiers have emerged³-⁶.

Chlorofluorocarbon emissions have been reported to destroy the stratospheric ozone layer due to the chemical interactions in the stratosphere. Industry has begun to look for refrigeration systems with increased energy efficiency that may use alternative processes that are less likely to affect the
environment. Due to these and other reasons, desiccant based cooling systems are proving to be an attractive alternative to traditional chlorofluorocarbon based air conditioning7-9.

The major advantages of desiccant cooling are that no limitation on the dew-point temperature, no condensation water, having significant potential for energy savings, and reduced consumption of fossil fuels. The electrical energy requirement can be very low comparing with conventional refrigeration systems. The source of thermal energy can be diverse (i.e., solar, waste heat, natural gas)10, 11. Having low coefficient of performance (COP) can be considered as the main disadvantage for desiccant cooling systems. COP values of 0.8-1 are commonly predicted for this cycle. Since the introduction of this technology, much research on the solid desiccant dehumidifiers has been accomplished12-17.

Desiccant cooling is based on an open cycle where the cooling is done directly in the air by changing its humidity, instead of being cooled through evaporators as in the other systems. A desiccant is a synthetic or natural hygroscopic material that is able to absorb or release the humidity of the surrounding air. The humidity absorption is followed by an increase of the air temperature because of the latent heat released by the condensing water. In an opposite way, the humidity absorbed by the desiccant can be released to the air by heating the desiccant to a sufficiently high temperature. This results in a decrease of the surrounding air temperature, because of the water evaporation18. The most important advantage by using desiccant cooling is that both air temperature and humidity can be simultaneously controlled (World Health Organization recommends a maximum humidity of 7 g/kg for healthy indoor air). For human comfort, the relative humidity must be within a specified range19. Applications like laboratory, museum, computer room, taps archives, library, etc. require not only low temperature but also low humidity. It is estimated that when room dry bulb temperature is lowered by 5.5 K, the life of the paper will double20. A low relative humidity of 35-45% and temperature of 20-24 °C have been recommended for library and museum applications.

A considerable amount of research21-30 have been conducted in recent years with a purpose of modeling the simultaneous heat and mass transfer processes that occur in rotary dehumidifiers and analyzing effects of different parameters on their performance. The desiccant systems are characterized by
constraints to the load that they can satisfy, through the trade-off between the dehumidification cooling capacity and the latent load of the conditioned space. Situation is burdened by the climatic conditions, especially referring to hot and humid conditions.

The wide acceptance of desiccant technology, coupled with the expanding markets for these materials have created a competitive production environment. The air conditioning industry is continually looking for an improved desiccant material. Specifically, research within the field of air conditioning technology has focused upon the development of new desiccant materials capable of removing both sensible and latent energy within a single process. A vast number of desiccant applications currently in operation use desiccant technology in tandem with a heat exchanger; in this situation sensible and latent energy are processed at different stages within the air conditioning cycle. The development and validation of an improved desiccant for use in various total enthalpy exchangers is the goal of this research.

**DESICCANT COOLING PRINCIPALS**

Desiccant cooling consists of dehumidifying the incoming air stream by forcing it through a desiccant material and then drying the air to the desired indoor temperature. In order to make the system working continually, water vapor adsorbed/absorbed must be driven out of the desiccant material (regeneration) so that it can be dried enough to adsorb water vapor in the next cycle. This is done by heating the material desiccant to its temperature of regeneration which is dependent upon the nature of the desiccant used. A desiccant cooling system comprises principally three components, namely the regeneration heat source, the dehumidifier (desiccant material), and cooling unit as shown in Fig. 1.

The desiccant wheel is a rotary cylindrical wheel that consists of a large number of parallel channels. The channel walls can be coated or impregnated with a desiccant material. The process air stream, which is supplied to a conditioned space after being dehumidified and cooled, passes through adsorption side of the side of the desiccant wheel. The regeneration air, heated by an external heat source, passes through the regeneration side of desiccant wheel and regenerates the desiccant. Within the desiccant wheel, heat and mass transfer processes take place between the two air streams and the desiccant wheel.
Fig. 1. Principle of desiccant cooling.

**DESICCANT MATERIAL STUDIES**

The search for desiccant materials with improved sorption capacity has a great attention of researchers\(^ {31-40} \). Several solid desiccant materials can be found, such as silica gel, carbon, etc. The working principals of both solid and liquid desiccant systems are similar; however there are some differences in the equipment design. For example, in a cooler using liquid desiccant, the desiccant wheel is replaced by a spray chamber. This is an important advantage, since desiccant wheels are generally large in size in order to enhance heat and mass transfer, but makes them relatively expensive. Liu et al.\(^ {41} \) developed a composite material obtained by impregnation silica gel with calcium chloride and obtained a composite adsorbent which was subsequently used to extract water from atmospheric air. Aristov et al.\(^ {42} \) developed hybrid materials by impregnating a host porous material (silica gel, vermiculite) with hygroscopic salt (calcium chloride, lithium chloride). The obtained product has a sorption capacity which can triple that of pure host material.

It was decided that the candidate desiccant to best meet the predetermined selection criteria would be chosen as the material to be incorporated into the total energy exchanger designs. Initially, the selection criteria concerns such as equilibrium moisture capacity, quick moisture absorption rates, and ability to desorb quickly at ambient temperatures. Commercial availability, low toxicity, and safety hazards were also considered\(^ {43-48} \).
EXPERIMENTAL RESULTS

It is important when analyzing the adsorption rate/equilibrium moisture content experiment results to keep the time rate of the desiccant application in mind. That is, it was imperative to consider how long the desiccant would be expected to adsorb moisture. Not only was the equilibrium moisture content important, but the time required for each material to reach its equilibrium moisture content is equally significant.

The dimensionless water vapor absorption ratio \((W/W_o)\) for three different desiccant materials was measured at the same conditions as a function of time as shown in Fig. 2. These initial experiments were conducted for comparative purposes only. The results indicate that the activated alumina absorb more humidity compared with the other studied materials up to 180 minutes, after that polyvinyl alcohol (PVA) is the best for absorption process. The desiccant material desorption rates were also observed. The results of this test are presented in Fig. 3. After this experimental study of several candidate materials, it was decided that polyvinyl alcohol is the best and met the pre-determined selection criteria.

![Desiccant material uptake curves.](image-url)
THEORETICAL ANALYSIS

The dehumidifier is rotating cylindrical wheels with small channels are adhered with an adsorbent such as polyvinyl alcohol. For simplicity it is divided into two equal sections: the adsorbing section and the regeneration section. The regeneration and adsorption air steams are in a counter flow arrangement. The schematic of a balanced rotary dehumidifier is illustrated in Fig. 4.
Four equations concerning water content balance and energy conservation are used to describe the complicated heat and mass transfer occurring in moisture adsorption and regeneration. The numerical analysis is based on the following assumptions:

- All ducts are assumed to be adiabatic.
- Heat and mass transfer coefficients of the wheel are constant.
- Heat and mass transfer axially by diffusion along the length of the dehumidifier is negligible.
- The air channel height in such a wheel is so minimal that no substantial gradient would exist within the height of the air stream.
- The thermodynamic properties of dry air, vapor and desiccant are constants.

Based on the above assumptions, the model used in this analysis is transient and one-dimensional.

Conservation equations for the absorbing rotary wheel system:

\[
\frac{\partial H_a}{\partial x} = \frac{PK_y H_v}{\rho V_a A_c} (W - Y_a) + \frac{Ph}{\rho V_a A_c} (T_w - T_a) \tag{1}
\]

\[
\frac{\partial H_w}{\partial t} = \frac{PK_y H_v D_w}{M_w} (Y_a - W) + \frac{Ph D_w}{M_w} (T_a - T_w) \tag{2}
\]

\[
\frac{\partial Y_a}{\partial x} = \frac{PK_y}{\rho V_a A_c} (W - Y_a) \tag{3}
\]

\[
\frac{\partial W}{\partial t} = \frac{PK_y D_w}{fM_w} (Y_a - W) \tag{4}
\]

where,

\[W^* = \frac{W(x,t)}{W_{\text{max}}}, \quad Y_a^* = \frac{Y_a(x,t)}{Y_{a_{\text{max}}}}.
\]

\[W_{\text{max}}: \text{maximum moisture loading of desiccant material.}
\]

\[Y_{a_{\text{max}}}: \text{moisture content of air at 100\% relative humidity.}
\]

Conservation equations for the adsorbing rotary wheel system:

\[
\frac{\partial H_a}{\partial x} = \frac{PK_y H_v}{\rho V_a A_c} (Y_a - Y_{a_0}) + \frac{Ph}{\rho V_a A_c} (T_w - T_a) \tag{5}
\]
The latent efficiency can be defined as the ability of the system to remove moisture from one air stream and transfer it to another and is given by:

\[ \eta_l = \frac{(Y_{a1} - Y_{a2})}{(Y_{a1} - Y_{a3})} \]  

(9)

The total efficiency can also be defined as the ability of the system to remove total sensible and latent energy from one air stream and transfer it to another and is given by:

\[ \eta_{tot} = \frac{cd_a (T_{a1} - T_{a2}) + (Y_{a1} h_{g1} - Y_{a2} h_{g2})}{cd_a (T_{a1} - T_{a3}) + (Y_{a1} h_{g1} - Y_{a3} h_{g3})} \]  

(10)

The governing differential equations for the one-dimensional rotary wheel total enthalpy exchanger model were derived using a control volume technique. Simultaneously, using the theories of conservation of energy and conservation of mass, finite difference equations were derived. A differential element with length \(dx\), was chosen and analyzed with respect to the principles of conservation of energy and conservation of mass.

The method employed to develop the finite difference equations for the model consisted of a quasi-central-difference formulation. These difference equations were evaluated in time and space according to the techniques introduced by Zheng and Worek\(^{49}\). This method was implemented into the rotary wheel performance solutions. By using pre-determined information at time step \(k\) and node \(n\), a series of equations was generated for each system. The solution of unknowns at \(k+1\) and \(n+1\) was then accomplished via substitution.

The supply air boundary conditions:

\( T_{a} (0, t) = T_{abs} \)
\[ Y_a(0,t) = Y_{abs} \]

\[ T_a(x,t) = T_{abe} \]

\[ Y_a(x,t) = Y_{abe} \]

The initial conditions:
\[ W(x,0) = W_{ic} \]

\[ T_n(x,0) = T_{nic} \]

Due to its performance in the initial uptake test examined experimentally, polyvinyl alcohol was believed to be the most promising polymer desiccant coating. Three different forms of polyvinyl alcohol were studied and compared with silica gel and molecular sieves. The materials properties are summarized in Table 1.

**Table 1. The studied materials properties.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Density (kg/m(^3))</th>
<th>Specific heat (J/kg.K)</th>
<th>Mass diffusivity (m(^2)/s)</th>
<th>Max. moisture content (kg(_w)/kg(_d))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyvinyl Alcohol Film</td>
<td></td>
<td>1310</td>
<td>1500</td>
<td>2.0 \times 10^{-13}</td>
<td>0.156</td>
</tr>
<tr>
<td>Polyvinyl Alcohol Foam</td>
<td></td>
<td>100</td>
<td>1040</td>
<td>2.5 \times 10^{-9}</td>
<td>0.070</td>
</tr>
<tr>
<td>Polyvinyl Alcohol Composite</td>
<td></td>
<td>770</td>
<td>1025</td>
<td>7.0 \times 10^{-7}</td>
<td>0.150</td>
</tr>
<tr>
<td>Silica Gel</td>
<td></td>
<td>1131</td>
<td>921</td>
<td>2.4 \times 10^{-6}</td>
<td>0.29</td>
</tr>
<tr>
<td>Molecular Sieves</td>
<td></td>
<td>1121.8</td>
<td>963</td>
<td>2.9 \times 10^{-10}</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Test cases were run to demonstrate the wheel's performance with respect to the desiccant material. The working conditions are given in Table 2. The results of these runs are shown in Figs. 5-7.

**Table 2. The working conditions.**

<table>
<thead>
<tr>
<th>Thermodynamic properties at p = 1 atm</th>
<th></th>
<th>Wheel density, kg/m(^3), 2705</th>
<th></th>
<th>Outer diameter, m, 0.4</th>
<th></th>
<th>Inner diameter, m, 0.37</th>
<th></th>
<th>Support substrate density, kg/m(^3), 2705</th>
<th></th>
<th>Support substrate thickness, mm, 0.25</th>
<th></th>
<th>Specific heat of support substrate, J/kg.K, 900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temp. for exhaust side, °C</td>
<td>100</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
<td></td>
<td>Inner diameter, m, 0.37</td>
<td></td>
<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Air temp. for supply side, °C</td>
<td>33</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
<td></td>
<td>Inner diameter, m, 0.37</td>
<td></td>
<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Supply air velocity, m/s</td>
<td>2</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
<td></td>
<td>Inner diameter, m, 0.37</td>
<td></td>
<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
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<tr>
<td>Exhaust air velocity, m/s</td>
<td>2</td>
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<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
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<td>Support substrate density, kg/m(^3), 2705</td>
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<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Specific heat of dry air, J/kg.K</td>
<td>1009</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
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<td>Inner diameter, m, 0.37</td>
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<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
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<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Specific heat of water, J/kg.K</td>
<td>4170</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
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<td>Inner diameter, m, 0.37</td>
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<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Specific heat of water vapor, J/kg.K</td>
<td>2028</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
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<td>Inner diameter, m, 0.37</td>
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<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Air density, kg/m(^3)</td>
<td>1.016</td>
<td></td>
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<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Heat transfer coeff., W/m.K</td>
<td>0.0321</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
<td></td>
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<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Kinematic viscosity of air, m(^2)/s</td>
<td>16 \times 10^{-6}</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
<td></td>
<td>Inner diameter, m, 0.37</td>
<td></td>
<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Initial temp. of dehumidifier, °C</td>
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<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
<td></td>
<td>Inner diameter, m, 0.37</td>
<td></td>
<td>Support substrate density, kg/m(^3), 2705</td>
<td></td>
<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
</tr>
<tr>
<td>Air moisture content for supply side</td>
<td>0.017</td>
<td></td>
<td></td>
<td>Wheel density, kg/m(^3), 2705</td>
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<td>Inner diameter, m, 0.37</td>
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<td>Support substrate density, kg/m(^3), 2705</td>
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<td>Support substrate thickness, mm, 0.25</td>
<td></td>
<td>Specific heat of support substrate, J/kg.K, 900</td>
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</tbody>
</table>
Fig. 5. Modeling results of desiccant materials uptake curves.

Fig. 6. Modeling results of desiccant material desorption curves.
Fig. 7. Effect of air stream velocity on the efficiency of different types of PVA.

Note: the dashed lines represent the latent efficiency and the continuous represent the total efficiency.

According to Fig. 7, the more resident time the air is given, the more heat and mass transfer is allowed to take place. Therefore, it was observed that as the velocity of the air flows increases both the latent efficiency and total efficiency decrease.

CONCLUSION

In this paper, the performance of several polymeric desiccant materials for solid desiccant air conditioning systems has been studied. Under the same given conditions, experimental test results indicate that the polyvinyl alcohol can absorb moisture from the process air more than silica gel and activated alumina, and adsorb the moisture from the process air more rapidly. The simulation results using a validated model show that polyvinyl alcohol composite is greatly better than the other studied materials. The results obtained herein are useful for the design and development of desiccant cooling systems.

NOMENCLATURE

- $A_c$: cross-sectional area, m$^2$
- $D$: dehumidifier depth, m
- $f$: mass fraction of desiccant in dehumidifier
- $h$: convective heat transfer coefficient, W/Km$^2$
\(H\) enthalpy, J/kg
\(H_v\) heat of vaporization, J/kg
\(K_v\) convective mass transfer coefficient, kg/m²·s
\(M\) mass, kg
\(P\) perimeter, m
\(T\) temperature, K
\(V\) velocity, m/s
\(W\) desiccant's moisture-content, kg/kg_d
\(x\) axial position in the wheel, m
\(Y\) humidity ratio, kg/kg_d.a

**Greek symbols**
\(\eta\) efficiency
\(\rho\) density, kg/m³

**Subscripts**
\(a\) air
\(b\) boundary condition
\(d\) desiccant
\(e\) exhaust
\(ic\) initial condition
\(l\) latent
\(o\) initial
\(s\) supply
\(v\) vapor
\(w\) desiccant bed
\(1\) entering air
\(2\) exiting supply air
\(3\) entering exhaust air

**REFERENCES**


خصائص البديمات المجففة المستخدمة في أنظمة تكييف الهواء

ياسر ريحان و بدر بادي

1 مركز المعامل الحارة – هيئة الطاقة الذرية
2 كلية الهندسة – جامعة المنوفية

عملية التحكم في كل من درجات الحرارة والرطوبة داخل الأماكن المكيفة مهمة للغاية في كثير من التطبيقات المتعددة. تم في هذا البحث تطوير نموذج رياضي لدراسة خصائص تبادل الأنالاسي العجالة الدوارية بعد دراسة عملية ميدانية لعدة بديمات مجففة. وجد أن البولي فينيل الكحول هو الأفضل في خصائصه المطلوبة للعجالة الدوارية. تم نمذجة عدة أنواع مختلفة من البولي فينيل الكحول رياضيا كمادة مجففة للعجالة الدوارية لتبادل الأنالاسي الكلى. وضع المعادلات التفاعلية الحاكمة وكذلك معادلات الفرق المتناهي للعجالة الدوارية لتبادل الأنالاسي الكلي ومنتجها باستخدام طريقة الحجم الدقيق المعتمدة على معادلات بقاء الكتلة والطاقة.