Steady-State Analysis on Thermally Driven Adsorption Air-Conditioning System for Agricultural Greenhouses

Muhammad Sultan\textsuperscript{a,*}, Takahiko Miyazaki\textsuperscript{a}, Bidyut B. Saha\textsuperscript{a}, Shigeru Koyama\textsuperscript{a}, Valeriy S. Maisotsenko\textsuperscript{b}

\textsuperscript{a}Kyushu University, Kasuga-koen 6-1, Kasuga-shi, Fukuoka 816-8580, Japan
\textsuperscript{b}Idalex Inc. and Coolerado Inc., 5628 South Idalia Street, Centennial, CO 80015, USA

Abstract

In the present study, water vapor adsorption onto silica-gel, activated carbon powder (ACP) and activated carbon fiber (ACF) has been experimentally measured at 20°C, 30°C and 50°C. The adsorption data is fitted with Guggenheim–Anderson–De Boer and Dubinin–Astakhov adsorption models for silica-gel and ACP/ACF, respectively. Steady-state moisture cycled (MC\textsubscript{SS}) is determined for greenhouse demand category-I, II and III which are based on 60%, 40% and 20% relative humidity of dehumidified air, respectively. The ACP and ACF enable maximum MC\textsubscript{SS} for demand category-I and II, respectively. However, the silica-gel is found the only applicable adsorbent for demand category-III.

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1. Introduction

Photosynthesis and evapo-transpiration are the fundamental processes in agricultural greenhouses by which the absolute humidity increases continuously. The humidity variation in greenhouse causes the pests and fungus attack onto the plant, and condensation/dripping of water vapors through the greenhouse walls. The optimization of CO\textsubscript{2}...
The present study experimentally investigates the water vapor adsorption uptake by three kinds of adsorbents for greenhouse AC. The steady-state desiccant AC is analyzed on the psychometric chart and adsorption isobar of each adsorbent. The effect of regeneration temperature on steady-state moisture cycled and adsorbent to air mass fraction is determined for three demand categories.

2. Adsorption equilibrium

2.1. Materials

The adsorbents used in the present study are: (i) RD type silica-gel [2] which is a famous hydrophilic adsorbent provided by Fuji Silysia Chemical Ltd., Japan (ii) activated carbon powder (ACP) of type Maxsorb III [3] which is a highly porous adsorbent provided by Kansai Coke & Chemicals Co. Ltd., Japan, and (iii) activated carbon fiber (ACF) of type A-20 [4] which is also a highly porous adsorbent. The detail information about the materials can be found from the cited literatures.

2.2. Experiment

A volumetric method based experimental setup [5–7] had been employed to measure the water vapor adsorption onto the adsorbents. The schematic diagram of the experimental apparatus is shown in Fig. 1(a). The evaporator was consisting of two interconnected reservoirs which were designed in a way to facilitate small and bulk amount of adsorption measurement. The diameters of small and big evaporator reservoirs were 4.8 and 20 mm with manufacturing error of ±0.5 and ±0.7 mm, respectively.
Fig. 1. (a) Schematic diagram of the experimental apparatus; (b) Plot of adsorption uptake versus adsorption potential.

Fig. 2. (a) Normal and ideal greenhouse growth zones of agricultural products; (b) Water vapor adsorption isotherms at 30 °C (percentage adsorption uptake is ratio of equilibrium adsorption uptake to the saturation adsorption uptake).

Table 1. Adsorption model parameters for silica-gel, ACP and ACF.

<table>
<thead>
<tr>
<th>Adsorbents/ parameters</th>
<th>Silica-gel</th>
<th>ACP</th>
<th>ACF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_o$ [kg/kg]</td>
<td>-</td>
<td>2.463</td>
<td>0.618</td>
</tr>
<tr>
<td>$E$ [kJ/kg]</td>
<td>-</td>
<td>24.524</td>
<td>66.657</td>
</tr>
<tr>
<td>$n$ [-]</td>
<td>-</td>
<td>1.108</td>
<td>2.014</td>
</tr>
<tr>
<td>$M_{mo}$ [kg/kg]</td>
<td>0.121</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$q_m$ [kJ/kg]</td>
<td>190.458</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$C_o$ [-]</td>
<td>0.164</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$K_o$ [-]</td>
<td>1.966</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta H_o$ [kJ/kg]</td>
<td>464.225</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta H_k$ [kJ/kg]</td>
<td>-250.363</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$R^2$ [-]</td>
<td>0.992</td>
<td>0.993</td>
<td>0.973</td>
</tr>
</tbody>
</table>
The KL79 type pressure gauges were used which were ranging from zero to 20 kPa with an accuracy of ±0.30%F.S. The accuracies of K-type thermocouples and temperature control units were ±0.05 and ±0.10 °C, respectively. The adsorption amount was determined by recording the water level in the evaporator with the help of high resolution digital camera with an accuracy of ±0.25 mm. The maximum error was ranging from 6-8% of the total adsorption amount.

2.3. Adsorption isotherms

Water vapor adsorption onto silica-gel and two carbon based adsorbents (CBAs) had been experimentally determined at 20, 30 and 50 °C using the experimental apparatus shown in Fig. 1(a). The experimental data is fitted with Guggenheim [8], Anderson [9], De-Boer [10] (GAB), and Dubinin–Astakhov (D–A) [11, 12] adsorption models for silica-gel and CBAs, respectively.

The GAB model can be represented by Eqs. (1)-(4) in which the parameters $M_m$, $q_m$, $C_o$ and $K_o$ are the adjustable constant for the temperature effect, whilst $\Delta H_c$ and $\Delta H_k$ are the functions of sorption heat.

$$M = \frac{M_mCK(P/P_o)}{(1-K(P/P_o))(1-K(P/P_o)+CK(P/P_o))}$$  \hspace{1cm} (1)

$$M_m = M_{mo} \exp\left(\frac{q_m}{RT_{ads}}\right)$$  \hspace{1cm} (2)

$$C = C_o \exp\left(\frac{\Delta H_c}{RT_{ads}}\right)$$  \hspace{1cm} (3)

$$K = K_o \exp\left(\frac{\Delta H_k}{RT_{ads}}\right)$$  \hspace{1cm} (4)

The D–A equation for equilibrium adsorption uptake can be written by Eqs. (5)-(6) as below:

$$M = M_o \exp\left[-\left(\frac{A}{T}\right)^n\right]$$  \hspace{1cm} (5)

$$A = RT_{ads} \ln\left(\frac{P_o}{P}\right)$$  \hspace{1cm} (6)

The fitting constants of GAB and D–A equation are determined by the recommended direct technique [13] and linearization technique [14], respectively. The GAB and D–A equations successfully represent the adsorption data by possessing mean relative percentage deviation modulus [7] of 4-6%. The optimized numerical values of adsorption model parameters are furnished in Table 1.

To distinguish the adsorption behavior of CBAs from conventional silica-gel; Polanyi’s adsorption potential ($A$) is plotted against the equilibrium adsorption uptake using the experimental data as shown in Fig. 1(b). It can be noticed that the CBAs enabled very less adsorption amount as compared to silica-gel at adsorption potential $\geq$100 kJ/kg whereas identical adsorption uptakes are obtained by each adsorbent at adsorption potential $\approx$ 50 kJ/kg. It means that the CBAs could be more effective in greenhouse AC for adsorption potential <50 kJ/kg.

3. Greenhouse air-conditioning

3.1. Demand categorization

Most of the greenhouse plants grow well at VPD ranging from 0.45 to 1.25 kPa, ideally sitting at nearly 0.8 to 0.9 kPa [15, 16]. The greenhouse growth zones for agricultural products are determined as shown in Fig. 2(a) by
considering ideal growth temperature ranging 15-30 °C [17]. Fig. 2(a) shows the canopy air temperature increases with the increase in relative humidity (RH), and meanwhile the adsorption potential decreases (see Fig. 1(b)). The dehumidification performance by an adsorbent depends on the threshold adsorption potential as explained in section 2.3. To streamline the effect of adsorption potential on adsorption uptake, the adsorption amount is plotted against relative humidity at 30 °C as shown in Fig. 2(b). Each adsorbent enables a specific trend of adsorption isotherm which helps to categorize them on the basis of RH. For example as a nearest approximation, the ACP and ACF can dehumidify the greenhouse air reasonably when the process air relative humidity is more than 60% and 40%, respectively. However, silica-gel can dehumidify the greenhouse air at all the relative humidity range of process air. The demand categories used to investigate the steady-state potential of desiccant AC are listed in Table 2.

3.2. Theory and assumptions

Figs. 3(a) and (b) illustrate the block diagram of desiccant AC system and its psychometric representation. Numeric values of growth temperatures are taken for tomatoes and bitter gourd [17]. Simplified recirculation mode of AC is assumed in which the process/regeneration air flow rates are adjusted in a way that the resulted return air condition (point GA on Fig. 3) yields the extreme boundary conditions of the greenhouse growth zone (i.e. T=30 °C, RH = 90%). Typical summer outdoor air with T_{db}= 35 °C and RH = 70 % is used for desiccant regeneration. The dehumidification process is assumed isenthalpic in order to simplify the calculation. The inlet/outlet conditions of sensible heat exchanger (HX) and direct evaporative cooling (DEC) are determined by Eqs. (7)-(8) and (9)-(10), respectively, while the device effectiveness (C) equals 0.90. The air from the HX (point B/E/H) is further cooled to the greenhouse growth zone (point C/F/I) by the Maisotsenko cycle (M-Cycle) cooling—an indirect evaporative cooling (IEC) technique by which the air can be cooled to the dew point theoretically [18].

\[
T_{(B/E/H),db} = T_{(A/D/G),db} - \varepsilon_{HX} (T_{(A/D/G),db} - T_{L, db}) \quad (7)
\]
\[
T_{(B/E/H),dew} = T_{(A/D/G),dew} \quad (8)
\]
\[
T_{L, db} = T_{OA, db} - \varepsilon_{DEC} (T_{OA, db} - T_{OA,wb}) \quad (9)
\]
\[
T_{L, wb} = T_{OA, wb} \quad (10)
\]

The desiccant AC cycle on Figs. 3 and 4 for the demand category-I can be explained as: The greenhouse return air and the desiccant are in equilibrium at point GA. For the desiccant exit RH= 60%, the exit air and the desiccant will be equilibrium at point A. The minimum regeneration temperature (T_{reg}) to maintain this cycle is about 39 °C which is point 2. This point can be found either by taking the same bed loading as at point A or by utilizing the dew point of regeneration air for RH= 60%. The air drying cycle will process 2.26 g/H_2O/kg_DA by changing conditions from GA→A. The outlet regeneration condition which corresponds to cycling of 2.26 g/H_2O/kg_DA is point 3. The average steady-state moisture cycled (MC_{SS}), assuming a linear distribution within the adsorbent bed, is estimated by Eq. (11). The MC_{SS} indicates the steady-state ability of an adsorbent to dehumidify the specific air on a particular regeneration temperature [19]. The higher MC_{SS} can be obtained by increasing the regeneration temperature; however, it does not guarantee the improvement in coefficient of performance and/or final cooling effect of a desiccant AC system.

\[
\text{Avg. MC}_{SS} = \frac{(MC_{SS})_{bed\ entrance} + (MC_{SS})_{bed\ exit}}{2} \quad (11)
\]

Packed beds of thickness ≈10 mm are being used for solar drying applications [20] in which the length of theoretical mass transfer zone will be several times of bed thickness that means the linear distribution profile is a decent assumption.
Fig. 3. (a) Block diagram of desiccant AC system while operating on simplified recirculation mode; (b) Psychometric representation of desiccant AC cycle. Blue, red and black lines represent the demand category-I, II and III, respectively, as explained in Table 2.

Fig. 4. Pictorial view of desiccant AC cycle on water vapor adsorption isobars for: (a) silica-gel; (b) ACP; and (c) ACF. Lines are drawn by adsorption models for the water vapor pressure corresponding to the dew point temperature. Points represent the AC cycle explained in Fig. 3.

Table 2. Categorization of the demand conditions according to outlet relative humidity.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Tin</th>
<th>RHin</th>
<th>RHout</th>
<th>Desiccant cycle</th>
<th>Applicable adsorbent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand category-I</td>
<td></td>
<td></td>
<td>60 %</td>
<td>GA → A</td>
<td>All</td>
</tr>
<tr>
<td>Demand category-II</td>
<td>30 °C</td>
<td>90 %</td>
<td>40 %</td>
<td>GA → D</td>
<td>Silica-gel/ ACF</td>
</tr>
<tr>
<td>Demand category-III</td>
<td></td>
<td></td>
<td>20 %</td>
<td>GA → G</td>
<td>Silica-gel</td>
</tr>
</tbody>
</table>

1 The symbols are presented in Fig. 3.
3.3. Steady-state analysis

The water vapor adsorption isobars are developed in order to express the points of desiccant AC cycle for steady-state adsorption measurement as shown in Figs. 4(a)-(c). Fig. 5(a) shows the effect of $T_{reg}$ on $MC_{SS}$ which is determined by increasing the temperature sensibly from 39 °C (point 2) to 45, 50, 60 and 70 °C (point 2a, 2b, 2c, and 2d) that exits at point 3a, 3b, 3c and 3d, respectively (see Fig. 4(b)). The ACP enables maximum $MC_{SS}$ at all regeneration temperatures, ideally sitting at 47 °C which is nearly 6.5 and 2.5 times of the silica-gel and ACF, respectively. Similar kind of trend is observed for ACF that enables nearly 2.5 times of $MC_{SS}$ as compared to silica-gel. However, there is no significant change in $MC_{SS}$ by the ACP and ACF at $T_{reg}$ more than 47 °C and 52 °C, respectively. Similarly, the average $MC_{SS}$ is calculated for the demand category-II and III, though the ACP and ACF are not applicable in category-II, III and category-III, respectively, as explained in Table 2. It can be noticed from Figs. 5(b) and (c) that the ACF enables nearly double $MC_{SS}$ as compared to silica-gel for the demand category-II at $T_{reg} \geq 59$ °C whereas the conventional silica-gel is the only applicable adsorbent in case of the demand category-III.

For the minimum regeneration temperature, adsorbent to air mass fraction (MF$_{A-A}$) [$g_{ads}/kg_{DA}$] for each demand category is estimated by the following relationship [21].

$$MF_{A-A} = \left( \frac{\Delta X}{\Delta W} \right)_{T_{reg}} = \left( \frac{x_1-x_2}{W_2-W_1} \right)_{T_{reg}}$$

The terms X and W represent the humidity ratio [$g_{H_2O}/kg_{DA}$] and steady-state adsorption uptake [$kg_{H_2O}/kg_{ads}$], respectively. The ACP and ACF require 9.5 and 2.5 times less adsorbent mass as compared to silica-gel to run the desiccant AC cycle for demand category-I and II, respectively. However, the CBAs are unable to run the desiccant AC cycle in case for demand category-III and consequently, silica-gel is the only choice for this category.

In order to optimize the honeycomb/bed-type desiccant rotor/block size, the volumetric MF$_{A-A}$ [$cm^3_{ads}/kg_{DA}$] is estimated at minimum regeneration temperature. The bulk densities were measured with the help of Micromeritics GeoPyc 1360 Pycnometer provided by Micromeritics Instrument Corporation for applied pressure ranging from 140-560 kPa. The average bulk densities for silica-gel, ACP, and ACF were found 0.73, 0.29 and 0.19 g/cm$^3$, respectively. In case of demand category-I, the ACP allows minimum system size by enabling minimum volumetric MF$_{A-A}$ i.e. 6 cm$^3_{ads}/kg_{DA}$ followed by the silica-gel and ACF which possess nearly 30 and 23 cm$^3_{ads}/kg_{DA}$, respectively. However, in case of demand category-II the ACF is found unable to reduce the system size by possessing volumetric MF$_{A-A} \leq 41$ cm$^3_{ads}/kg_{DA}$ as compared to silica-gel which carries 27 cm$^3_{ads}/kg_{DA}$. As the CBAs are unable to run desiccant AC cycle for demand category-III (see Table 2), so the silica-gel is only the applicable adsorbent with volumetric MF$_{A-A}$ $\geq 34$ cm$^3_{ads}/kg_{DA}$. 

![Fig. 5. Effect of regeneration temperature on $MC_{SS}$ for: (a) demand category-I; (b) demand category-II; and (c) demand category-III.](image-url)
4. Conclusions

Water vapor adsorption uptake by silica-gel, activated carbon powder (ACP), and activated carbon fiber (ACF) has been experimentally measured at 20, 30 and 50 °C. The experimental data is successfully fitted with GAB and D–A equations for silica-gel and ACP/ACF, respectively. Steady-state moisture cycled (MCSS) is determined for demand category-I, II and III which are based on 60, 40 and 20% RH at the desiccant bed exit for air drying, respectively. In case of demand category-I, the ACP enables maximum MCSS at all regeneration temperatures (Treg), ideally sitting at 47 °C which is nearly 6.5 and 2.5 times of the silica-gel and ACF, respectively. The ACF enables nearly double MCSS as compared to silica-gel during the demand category-II at Treg ≥ 59°C. The ACP and ACF require 9.5 and 2.5 times less adsorbent mass as compared to silica-gel to run the desiccant AC cycle on minimum Treg for the demand category-I and II, respectively. Furthermore, the ACP allows minimum system size in case of demand category-I whereas, the ACP and ACF are unable to reduce the system size in case of demand category-II. However, the silica-gel is found the only applicable adsorbent in case of demand category-III. As all of the demand categories can access the greenhouse growth zone by manipulating the air mass flow rate so the ACP and ACF will be more effective by employing minimum regeneration temperature and for the maximum MCSS.

References