

Experimental Procedure to Develop the Isotherm Equation for Moisture Adsorption on Silica Gel Particles

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Abstract— In this work, a simple procedure for developing the isotherm equation of moisture adsorption on silica gel is presented. The proposed procedure does need only a hygrometer, sensitive balance along with source of air and no more devices are needed. The isotherm curve obtained from the present experimental approach has been found to lie in between the isotherm curves collected from the literature. In addition, the isotherm equation and various isotherms from literature have been used to study the adsorption and desorption process in packed bed for step input of inlet air using semi analytical method to solve the PGC model. It has been found that by using the isotherm relevant to the silica gel used in the present work, the numerical results of exit air humidity ratio and temperature are in good agreement with the experimental results.

Keywords— adsorption; desorption; silica gel; dehumidification; desiccants; drying

I. INTRODUCTION

The desiccant cooling and dehumidification systems have attracted the interest of the researchers due to its low regeneration temperature. The ability to use the waste heat or solar energy and being more safe for the environment are the main advantages of these systems over the conventional vapor compression systems. The desiccant bed with different configurations like vertical packed bed [1], radial packed bed [2], desiccant wheel [3] and fluidized bed [4] is the key component of the desiccant systems. The optimization of the desiccant bed design requires the mathematical simulation of the heat and mass transfer interactions in the desiccant bed. Considering the desiccant air dehumidification systems, an isotherm is defined as the relation between relative humidity of the air in equilibrium with the desiccant particle and the water content of the particle at a specified temperature. It is considered as one of the important physical properties of the desiccant material which is a must for theoretical modeling of the heat and moisture transfer interactions during adsorption and desorption processes in various kinds of desiccant dehumidification systems. Many investigators have presented different procedures to identify the isotherm equations required for their theoretical simulations. Nutter and Burnet [5] used a linear equilibrium approximation for the molecular sieve-water vapor provided by the manufacturer. Carter [6] used a linear relation with an equilibrium coefficient for water vapor-activated alumina

isotherm. The equilibrium coefficient has been identified by measuring the water content of desiccant samples which have been directed to humid air flow until equilibrium. The samples were kept in vessels and immersed in a constant temperature water bath. Tamon et al. [7] calculated the adsorption isotherm by calculating the sum of capillary condensed and surface adsorbed SiO₂ and CF₂Cl₂ in the pores of Linde silica gel and compared with experimental data. Pesaran and Mills [8,9] have used the equilibrium isotherm of water vapor provided by the manufacturer for regular and intermediate silica gels which are independent of temperature. Okazaki et al. [10] measured the adsorption isotherms of C₂H₄, C₃H₆, iC₄H₁₀ and SO₂ on porous Vycor glass using standard volumetric apparatus. Chihara and Suzuki [11] used linear relation for water vapor-activated alumina isotherms in which the adsorption coefficient was extracted from literature. Chihara and Suzuki [12] identified the adsorption isotherm of water vapor on silica gel by fitting the final uptake conditions of each experimental runs in Freundlich equation form. Schork and Fair [13] developed the equilibrium isotherm of propane carried by nitrogen stream with activated carbon experimentally. A Micromeritics Accusorb 2100E was used to develop the isotherms. Kim et al. [14] developed the isotherms of water vapor and alumina, zeolite 13X and zeolite X/activated carbon composite using static volume apparatus. The total mass of gas admitted into the system and the amount of gas in the vapor phase remaining after adsorption equilibrium were determined by appropriate measurements. Reviewing the previous work in which the desiccant isotherm equations were used; it has been observed that a group of researchers have used the equilibrium data provided by the manufacturers which is not always available. The other group of researchers have put a significant effort to obtain the necessary isotherm which requires time, effort and relatively expensive devices. During this study, a simple procedure has been proposed to identify the water vapor- silica gel isotherm which requires less time, effort and cost. A review for various isotherm equations for water vapor and silica gel has been presented. The semi-analytical solution to the PGC model of heat and mass transfer in silica gel packed beds has been used for testing the isotherm equation found in the present work when applied for adsorption and desorption processes.

II. REVIEW FOR WATER VAPOR-SILICA GEL ISOTHERMS

As one of the most common desiccant for air drying purpose, the isotherm of water vapor –silica gel is considered a much needed equation for the design of air dehumidifiers. In this work a summary for different isotherm equations which have been used in the literature are presented. Ahleberg [15] presented the silica gel –water vapor isotherm as a linear relation for the full range of silica gel water content (0.0-0.42) and air relative humidity (0.0-100.0%). Anderson et al. [16] have determined the equilibrium water-uptake properties of silica gel in an atmosphere of pure water vapor. Pesaran and Mills [8-9], Dai et al. [17] and Zhang et al. [18] fitted the data provided by the manufacturer for regular density (RD) silica gel as follows,

$$RH^* = s_1 + s_2W + s_3W^2 + s_4W^3 + s_5W^4 \quad (1)$$

where s_1 to s_5 are 0.0078, - 0.05759, - 24.1655, - 124.16554, and 204.226, respectively.

Pesaran and Mills [8-9] have obtained the following polynomial to the manufacturer data for intermediate density (ID) silica gel as,

$$RH^* = \sum_{i=1}^4 s_i W^i \quad \text{when } W \leq 0.07 \quad (2)$$

$$RH^* = s_5 + s_6W \quad \text{when } W > 0.07 \quad (3)$$

where s_1 to s_6 are 1.235, 267.99, - 3170.7, 10087.16, 0.3316, and 3.18, respectively.

Majumdar and Worek [19] obtained equilibrium sorption isotherms for silica gel felt by fitting a curve to the experimental data that resulted in,

$$W = s_1 + s_2T_s^2 + s_3RH^{*2} + s_4RH^{*3} + s_5T_s^3RH^{*2} + s_6T_s^3RH^{*3} \quad (4)$$

where s_1 to s_6 are 0.0329 , $- 0.4113 \times 10^{-5}$, 0.0105×10^{-3} , 0.6286×10^{-6} , 0.7894×10^{-10} , and 0.6747×10^{-12} , respectively. Dupont et al. [20] used the manufacturer data for the isotherms which has the following form:

$$RH^* = s_1T_sW^2 + s_2T_sW + s_3W^4 + s_4W^3 + s_5W^2 + s_6W \quad (5)$$

Where T_s is the temperature in °C, and the coefficients s_1 to s_6 are - 0.04031298, 0.02170245, 125.470047, - 72.651229, 15.5223665, and 0.00842660, respectively. An experimental investigation of silica gel water adsorption isotherm characteristics was carried out by Ng et al. [21] and Chua et al. [22]. An experimental setup (control volume-variable pressure apparatus) has been fabricated for this purpose. Experimental tests have been carried out for three types of silica gel. It has been found that Henry's law can characterize the silica gel-water vapor isotherms. The detailed Henry's law's correlation for silica gel has been presented by Ng et al. [21] as follows,

$$W = K_0^1 \exp\left(\frac{Q_{st}}{R(T_s + 273.15)}\right) P_v \quad (6)$$

where, P_v is the partial pressure of vapor in the air in Pa, R is the gas constant of air in $J \text{ kg}^{-1} \text{ K}^{-1}$, and the constants, K_0^1 , and Q_{st} depend on the type of silica gel as shown in Table 1. San et al. [23] presented the isotherms for water vapor-silica gel in terms of absolute humidity and particle temperature as follows,

$$W(C, T_s) = s_1 + s_2T_s + s_3T_s^2 + s_4C + s_5C^2 + s_6T_sC + s_7T_s^2C + s_8T_sC^2 + s_9T_s^2C^2 \quad (7)$$

Table 1. Regression coefficients of water vapor- silica gel isotherm Eq.(6), [21].

Silica gel type	K_0^1 [Pa ⁻¹]	Q_{st} [kJ/kg]
Type 3 A	5.2×10^{-12}	2.38×10^3
Type RD (1992 batch)	2.0×10^{-12}	2.51×10^3
Type RD (Current batch)	5.5×10^{-12}	2.37×10^3

The coefficients S_1 to S_6 are presented in Table 2 for three ranges of silica gel water content. Ni and San [24] obtained the isotherms of water vapor –silica gel by summarizing the final equilibrium data from each dynamic uptake rate measurement. Totally six adsorption isotherms have been measured to cover the range of 0 - 0.4 for silica gel water content and and temperature range of 5 - 80 °C. The experimentally obtained data have been curve fitted as a function of the air absolute humidity and silica gel temperature as follows,

Table 2. Regression constants of water vapor- silica gel isotherm Eq. (7), [23].

Constant	$W < 0.05$	$0.05 < W < 0.3$	$W > 0.3$
s_1	8.98e-3	0.22807	0.40416
s_2	-5.15e-4	-6.02e-3	-0.77e-2
s_3	6.04e-6	4.5e-5	4.16e-5
s_4	4.39e+2	5.32	2.28
s_5	-1.07e+5	-9.84e+2	-3.27e+2
s_6	-1.13	-1.1084	-0.39024
s_7	7.45e-2	5.81e-3	0.15e-2
s_8	2.97e+3	2.58	8.1546
s_9	-2.05	-0.16933	-5.11e-2

$$W(T_s, C) = (C \exp(-S_2))^{S_1} \quad (8)$$

$$S_1 = -1.526 \times 10^{-6} T_s^3 + 5.075 \times 10^{-4} T_s^2 - 4.168 \times 10^{-2} T_s + 3.223 \quad (9)$$

$$S_2 = 2.455 \times 10^{-4} T_s^2 + 3.721 \times 10^{-2} T_s + 3.793 \quad (10)$$

where, C is the air absolute humidity in g/m^3 . Sun and Besant [25] fitted a polynomial for different experimental points on the silica gel-water vapor isotherm curve. Each point required air with a controlled temperature and humidity ratio to pass over silica gel bed for 48.0 hours to achieve equilibrium bed water content. The same procedure is repeated to collect other points for different air conditions. The fitted curve for the isotherm is as follows,

$$RH^* = 100 \times (-0.02833 + 8.18612W - 41.7964W^2 + 82.9974W^3) \quad (11)$$

III. HEAT AND MASS TRANSFER MODEL

The physical model for the silica gel vertical packed bed is illustrated in Fig. 1. In packed beds of adsorbing material, air loses part of its moisture content to the particles in a transient heat and moisture transfer process. Adsorption/desorption processes are accompanied by the significant heat source/sink and they leads to the strong coupling between heat and mass transfer. The derivation of the equations of heat and mass transfer in desiccant packed bed of desiccant material has been presented by many investigators [8, 25-26]. In the current work the relations of the semi-analytical solution proposed by Ramzy et al. [26] for the PGC model proposed by Barlow [29] are used.

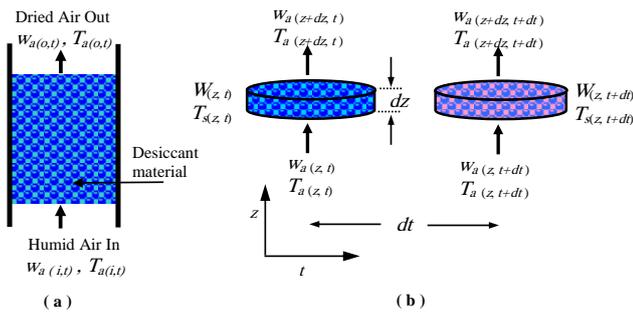


Fig. 1. Schematic of the adsorptive packed bed (a), and Physical model of the bed for semi-analytical solution (b), [26].

The heat of adsorption of water vapor on the surface of silica gel is calculated from the relations presented as follows [8],

$$H_A = \begin{cases} 3500.0 - 13400.0 \times W & W \leq 0.05 \\ 2950.0 - 1400.0 \times W & W > 0.05 \end{cases} \quad (12)$$

The density of silica gel particle is 1200.0 kg/m^3 . The specific heats of silica gel and humid air are calculated as follows [8],

$$c_s = 4186.0 \times W + 921.0, \quad (13)$$

$$c_a = 1884.0 \times w_a + 1004.0(1 - w_a) \quad (14)$$

Once relative humidity (RH^*) and the bed temperature (T_s) have been calculated, the equilibrium moisture content of the air adjacent to the particle surface (w_s) is calculated as follows [8],

$$w_s = \frac{0.622RH^* \times P_{sat}(T_s)}{P_{tot} - 0.378RH^* \times P_{sat}(T_s)} \quad (15)$$

The bed porosity has been taken as 0.35. The convective heat and mass transfer coefficients in cylindrical packed bed of spherical particles are calculated using the following relations [8],

$$h = 0.683 \rho_a \nu c_a \text{Re}^{-0.51} \quad (16)$$

$$h_m = 0.704 \rho_a \nu \text{Re}^{-0.51} \quad (17)$$

IV. EXPERIMENTAL PROCEDURE FOR EVOLVING ISOTHERM

It is believed that the water vapor –silica gel isotherm is an important relation which is mandatory for any researchers who are investigating the heat and moisture transfer in desiccant silica gel beds. Moreover, it is well known that silica gel properties are not similar for different batches which are normally manufactured under different manufacturing conditions. Many factors affect the silica gel properties like pH values, gelling and dehydration temperatures [27]. All these conditions and others affect the silica gel properties like average diameter, surface area and volume of pores which in turn affect the dynamic adsorption properties of the silica gel [27]. Therefore, it is recommended that the isotherm equation should be identified for the desiccant material before progressing to various research activities.

During this study, a simple procedure has been proposed to identify the water vapor- silica gel isotherm which requires less time effort and cost. Moreover, it provides an acceptable prediction for the isotherm equation.

IV-1 INITIAL WATER CONTENT OF SILICA GEL

The water content of silica gel can be identified using a device called moisture analyzer in which the silica gel sample is dried using infrared rays. The mass of the silica gel sample is recorded using built in sensitive balance before and after drying the silica gel sample. During this study, similar technique is used but without using the moisture analyzer as follows; Although silica gel has a very high melting temperature ($1600 \text{ }^\circ\text{C}$), it will lose its chemically bound water and hygroscopic properties if heated above $300 \text{ }^\circ\text{C}$ [28]. Based on this fact, a sample of 55.3 g of the silica gel has been heated in a high temperature furnace at $800 \text{ }^\circ\text{C}$ for 1.0 hr . After the heating process the silica gel sample is totally dried and the sample loses its ability to adsorb water vapor from air again. The new weight of the sample is measured after the heating process and found to be 50.3 g . The heated sample is let to cool in the atmospheric air for more than 3.0 hrs . It was observed that there is no change in the silica gel color and weight which indicates that the sample has lost its ability to adsorb the water from the ambient air. In addition, it is ensured that the sample is totally dry. Using the initial weight (before heating process) and the dry weight (after heating process) the initial water content of the silica gel has been calculated and found to be $0.0995 \text{ kg}_w/\text{kg}_{\text{dry silica gel}}$.

IV-2 LOCATING DIFFERENT POINTS ON THE ISOTHERM CURVE

The isotherm for the silica gel which was used during the present experiments has been identified using the following procedure. Twenty (20) samples of silica gel particles with 10.0% initial water content have been separated and sealed in plastic bags. The weight of each sample ranges from 60.0 to 110.0 g of silica gel.

To change the water content of each sample, separate adsorption and desorption processes in fluidized bed have been conducted. Each sample of silica gel is subjected to different: (i) conditions of inlet air, (ii) air flow rates and (iii) duration of exposure to air flow.

These different conditions of air temperature, relative humidity of air, and air flow rates have been achieved using the air processing unit as shown in Fig. 2. In this air processing unit air heater and cooler are fixed in parallel along with a bypass to control the fluidization air temperature. The air heater is a copper tube fixed above a LPG burner and the air cooler is a vortex tube. To increase the range applicability of the isotherm being worked out, the water content in the silica gel must be increased; hence an air humidifier with bypass arrangement has been fixed after the air heater and cooler section as shown in Fig.2. Using the humidifier in the experiment, it was possible to achieve a maximum water content in the silica gel close to 0.386 kg_w/kg_{dry silica gel}.

After the fluidization processes, the samples have been sealed separately in plastic bags. The duration of air stream through each sample is varied so that at the end of fluidization process each sample will contain different amount of water. The initial weight (before fluidization process) and the new weight (after fluidization process) of the samples are furnished in Table 3.

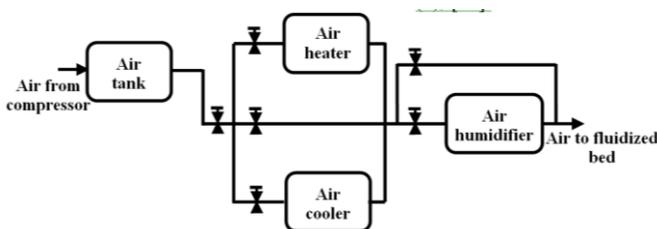


Fig. 2. Block diagram of the air processing unit used in the fluidization, adsorption and desorption processes.

All samples have been kept in closed chamber for 48 hours which provides the chance for the particles to attain equilibrium conditions with the air occupying the inter particles gap. A humidity transmitter is kept in each sample for 10.0 minutes to ensure the equilibrium condition. The reading of the humidity transmitter is recorded for 30.0 seconds. The variation of the relative humidity of the inter particle air with the silica gel water content is shown in Fig. 3. The conditions of the inter particle air (relative humidity and temperature) of each sample are recorded and listed in Table 3.

After locating the first group of the isotherm points the samples have been let in the atmospheric air for 5.0 minutes to change the silica gel water content of each sample. Again the new weight of each sample has been measured and the new water content has been calculated. The samples have been sealed again and kept in a closed chamber for another 48.0 hrs. The relative humidity of the inter particle air with the silica gel water content is measured again for each sample. The second group of the data has been plotted as filled triangles in Fig. 3. In addition, three samples of large mass (506.5 g, 613.2 g and 803.7 g) have been tested separately and are added as squares in Fig. 3.

The experimental data of isotherm points which is shown in Fig. 3 is subjected to a curve fit to obtain a polynomial which will be implemented during the modeling of heat and mass transfer analysis as follows,

Table 3. Summary of initial samples weight and after fluidization weight along with the inter particle air condition at temperature of 30.0 °C.

No.	m_i [g]	W_i	m_f [g]	W_f	RH^* [%]
1	80.5	0.1	81.9	0.12	10.21
2	78.4	0.1	80.9	0.137	14.14
3	86	0.1	86.1	0.101	4.97
4	76.2	0.1	76	0.097	4.33
5	63.6	0.1	66.9	0.161	21.9
6	73.9	0.1	81.4	0.218	37.67
7	91.8	0.1	102.8	0.238	41.08
8	82	0.1	94.5	0.276	46.93
9	85.9	0.1	99.4	0.281	49.99
10	102.1	0.1	117.3	0.27	45.17
11	70.3	0.1	82.7	0.305	50.65
12	76.3	0.1	82.7	0.197	29.1
13	83	0.1	88.6	0.178	25.15
14	86.3	0.1	105.6	0.357	58.46
15	82.2	0.1	102.6	0.386	63.79
16	75.7	0.1	93.6	0.374	62.58
17	77.9	0.1	84.4	0.196	32.1
18	77.6	0.1	96.1	0.376	62
19	66.5	0.1	72.1	0.198	30.3
20	100.3	0.1	103.4	0.135	14.10

$$RH_s [\%] = -23.36 + 315.82W - 222.11W^2 \quad (18)$$

The sensitive weight balance used is electronic type balance with a resolution of 0.1 g. The relative humidity and temperature of the inter particle air have been measured using humidity transmitters Rotronic-Hygroflex 435 with a time constant less than 10 sec, accuracy of $\pm 1.0\%$ for relative humidity and accuracy of ± 0.1 K for air temperature of 23°C.

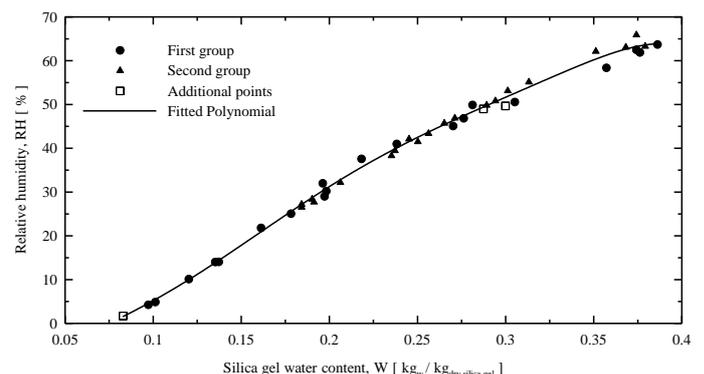


Fig. 3. Relative humidity of inter particle air at different silica gel water content.

The humidity transmitters are connected to a data acquisition voltage module NI-9221 which records the voltage output of the humidity transmitters with accuracy of $\pm 0.26\%$. The uncertainty analysis showed that the uncertainties in the measured values of air relative humidity and temperature are $\pm 2.77\%$ and $\pm 0.79\%$, respectively.

V. VALIDATION OF ISOTHERM CURVE

The adsorption isotherm curves for water vapor and silica gel introduced in different literatures have been plotted in Fig. 4. In addition, the isotherm polynomial obtained using the proposed methodology in the current study is plotted in Fig. 4. It can be seen that the minimum equilibrium relative humidity of 5.0 % is

obtained at silica gel loading of 0.1 and 0.15 in case of the isotherms of the present study and Ni and San [24], respectively. Moreover, the maximum equilibrium relative humidity of 95% is obtained at 0.37 in case of isotherms used by Pesaran and Mills [8] and Dupont et al. [20]. Also, it can be observed that the isotherm curve from the present work lies between isotherm curves of Ahleberg [15], Pesaran and Mills [8], Dupont et al. [20] and Ni and San [24] which indicates the acceptance of the data provided by the proposed methodology.

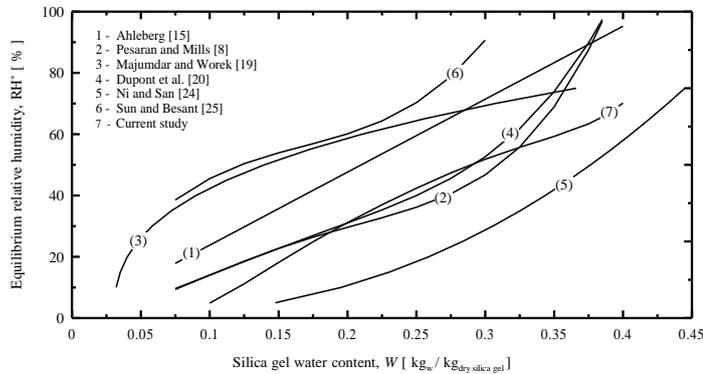


Fig. 4. Isotherms of water vapor- silica gel collected from literature along with the isotherm obtained from the present work.

To provide more strength to the validation of the proposed methodology in determining the water vapor – silica gel isotherm, the semi analytical solution [26] for the PGC model [29] is used to evaluate the bed performance during adsorption and desorption processes of water vapor from an air stream flowing through a silica gel packed bed. The PGC model has been already validated by Barlow [29] and Pesaran and Mills [8]. The isotherm equation obtained experimentally during the current study along with six curves from literature has been used in the PGC model to predict the exit air conditions during water vapor adsorption and desorption processes in a fixed packed bed of silica gel for step inlet conditions.

The specific experimental data of the adsorption and desorption has been extracted from authors experimental work are as follows [30]. The column wall of the packed bed is a glass cylinder with 0.16 m inner diameter and wall thickness of 12.0 mm. The silica gel bed height is 50.0 mm and the average particle diameter is 3.5 mm. The superficial velocity of the air flow through the packed bed during both adsorption and desorption processes is 0.75 m/sec. Temperature and relative humidity of the air at the inlet and exit sections of the silica gel bed have been recorded with a sampling rate of 2.0 sec⁻¹.

Theoretical results have been obtained for the conditions of the experimental tests using different isotherm equations 1 – 7 as illustrated in Fig. 5. The comparison of experimental data and theoretical results of exit air humidity ratio and temperature during adsorption process is shown in Fig. 5. It can be seen that the isotherm equation from the current study provides the better agreement with the experimental data compared to the other isotherm equations. The average error for the exit humidity ratio is found to be 3.89% and for exit air temperature it is 6.6%. The experimental and theoretical

results for desorption process are shown in Fig. 6. It can be observed that the exit humidity ratio predicted theoretically using the current isotherm equation is agreeing well with the experimental data with average errors of 3.77% and 11.4% for exit air humidity ratio and temperature, respectively. The high average error of the predicted temperature can be explained due to the increased heat losses to environment during thermal desorption process because of the elevated temperature of the bed. However, it can be seen that the theoretical prediction of the exit air temperature is taking a trend similar to the experimental data.

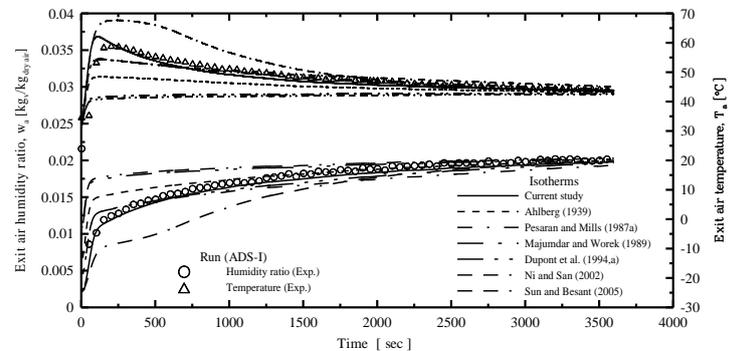


Fig. 5. Experimental and theoretical variations of exit air humidity ratio and temperature during adsorption process using different isotherm equations.

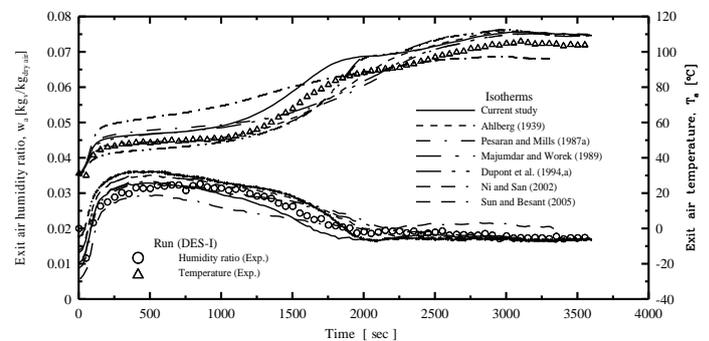


Fig. 6. Experimental and theoretical variations of exit air humidity ratio and temperature during desorption process using different isotherm equations.

VI. CONCLUSIONS

In this study, a simple procedure for developing the equilibrium isotherm equation of water vapor and silica gel is presented. A review for the water vapor silica gel isotherm equations from the literatures has been presented. The isotherm developed in the current study has been compared with isotherm equations collected from literature and it has been found that the developed isotherms developed from the present work lies in the same range of the isotherms obtained in literature. In addition, the semi analytical solution to the PGC model for heat and mass transfer in desiccant packed bed during adsorption and desorption processes has been used for testing the isotherm equation developed and the isotherms from literature. It has been found that implementing the isotherm equation of the current study provides the better agreement with the experimental data with an average error of 3.89% and 6.6% for exit air humidity ratio and temperature for adsorption process and 3.77% and 11.4% for exit air humidity ratio and temperature for desorption process, respectively.

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C	Air absolute humidity [g/m^3]
c	Specific heat [$\text{kJ}/\text{kg K}$]
d	Diameter [m]
h	Heat transfer coefficient [$\text{W}/\text{m}^2 \text{K}$]
H_A	Heat of adsorption [kJ/kg]
h_m	Mass transfer coefficient [$\text{kg}/\text{m}^2 \text{K}$]
L	Length of bed [m]
m_i	Initial mass [kg]
m_f	Final mass [kg]
\dot{m}	Mass flow rate [kg/sec]
P	Pressure [Pa]
RH^*	Equilibrium relative humidity [%]
T	Temperature [$^{\circ}\text{C}$]
t	Time [sec]
W	Gel water content [$\text{kg}_w/\text{kg}_{\text{dry silica gel}}$]
w	Humidity ratio [$\text{kg}_w/\text{kg}_{\text{dry air}}$]

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