

실리카 젤의 再生에 關한 實驗的 및 理論的 研究

Experimental and Theoretical Study on Silica Gel Regeneration

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要 約

現在 先進國에서 널리 利用되고 있는 穀物의 火力乾燥는 穀物의 品質을 損傷시킬뿐만 아니라 損失을 增加시키고 있다. 火力에 依한 乾燥는 또한 燃料의 節約面에서 볼 때 역시 問題點들을 內包하고 있다. 이러한 問題點들을 解決하기 爲하여 近來에는 실리카 젤과 같은 吸濕性의 乾燥劑를 사용한 穀物의 乾燥 實驗이 進行中에 있으며 좋은 結果를 보여 주고 있다. 실리카 젤은 그 自體 무게의 40%까지 動的 및 靜의 下에서 水分을 吸收하는 性質을 가지고 있으며 일단 包和狀態가 되면 수천번 再生이 可能하다. 본 研究에서는 이와 같은 실리카젤의 再生實驗을 一次的으로 室內에서 空氣의 溫度를 一定하게 한 狀態에서 實施하였으며 一般的으로 실리카 젤은 300°F에서 完全 再生이 可能하나 本實驗에서 사용된 再生溫度는 平面式 太陽熱 集熱機로 부터 얻을 수 있는 150°F 內外에서 試圖하였다. 本實驗과 併行하여 乾燥中 空氣와 실리카 젤의 에너지 및 質量變化에 따른 理論式을 만들어 주어진 여러가지 條件에 대하여 4개의 微分方程式을 컴퓨터에 의하여 解決하였으며 乾燥(再生) 時間에 따른 空氣의 溫度와 濕度 및 실리카 젤의 含水量을 求하였다. 위의 理論的인 分析結果는 後에 太陽熱集熱機를 利用한 再生實驗을 分析하는데 適用될 것이다. 本 研究結果를 要

約하면 다음과 같다.

1. 本 研究에서 유도한 理論式은 실리카 젤의 再生過程을 만족스럽게 表示하였으며 再生 時間에 따른 空氣의 溫度와 濕度 및 실리카 젤의 含水量變化의 理論値는 實驗値와 近似하였다.

2. 理論値와 實驗値를 一致시키기 위하여 吸着過程에서 算出된 熱 및 質量 傳達係數를 1/5로 調整 使用하였다.

3. 실리카 젤은 120°F에서 9%, 180°F에서 1% 內外로 再生이 可能하였다.

4. 本 研究에서 유도된 理論的인 分析方法은 다른 여러가지 형태의 物質의 乾燥 또는 冷却過程을 分析하는데 사용될 수 있다.

Introduction

Silica gel was discovered by W.A. Patrick for the Chemical Warfare Service for use in gas masks during World War II. Further developments of the material made by the Davison Chemical Corp. after the war have resulted in a product which has been used in the drying of liquids, as a catalyst carrier, in cosmetic and toilet preparations, and in the refining of oils (Dehler, 1940). However, its

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principal use is in the drying of gases and air.

Recently, several experiments have been conducted (Chung and Fleske, 1973; Danziger et al., 1972; Hsiao, 1974; Rodda, 1975) to solve grain quality problems by using silica gel as the agent for grain drying and maintaining dry grain in storage. Danziger et al. (1972) investigated the utilization of silica gel as an agent for drying wet corn at ambient temperature. Two drying systems were investigated in their study; one involved an intimate mixture of corn and silica gel sealed in a container and the other employed air circulation through separate beds of silica gel and corn in which a pressure difference between the drying air and the corn to be dried was created by simply removing moisture from the air. The results showed that the corn dried to a safe moisture content for storage with a definite quality advantage. Chung and Fleske (1973) tested the effectiveness of five solid adsorbents (lime, CaCl_2 , NaCl , CaSO_4 , and silica gel) in grain drying. They found that silica gel was the most effective for removing water from corn. Hsiao (1974) verified the tests of Chung and Fleske (1973) and tested corn drying with and without airflow in the corn bed. The results showed that to dry the 24% initial moisture content of the corn to the average safe moisture content of 13%, it took 12 days without corn deterioration. Rodda (1975) developed a humidity controlled drying process in which a pressure difference between the air and the material to be dried was created by simply removing moisture from the air.

Once silica gel reaches the maximum absorbing capacity it needs regeneration for further use. Silica gel is ideally suited for air drying; it remains dry and free flowing even when saturated, it is resistant to attri-

tion and fouling and is easily regenerated by heating at an elevated temperature.

The main problem of the silica gel utilization is its regeneration. It is estimated that the annual production of silica gel in the USA is 20×10^6 to 40×10^6 tons. Once this amount of silica gel has reached a saturated state, it has to be regenerated. Thus, the energy required to regenerate this amount of silica gel annually would be around 9.3×10^{13} to $18.6 \times 10^{13} \text{ kJ}$ (8×10^{13} to $16 \times 10^{13} \text{ Btu}$) based on an average 4652 kJ per kg (2000 Btu/lb) of water removed. Furthermore, if the silica gel is again regenerated for further use, the energy requirement for the regeneration will increase in proportion to the number of times of regeneration.

Usually, silica gel is regenerated at 149—177°C (300—350°F). However, from exploratory laboratory tests it was found that silica gel can be regenerated successfully at a temperature in the range of 48.9—82.2°C (120—180°F) which can be easily achieved by a simple flat-plate solar collector. The increased emphasis placed on solar energy utilization in many areas is in response to the diminishing expendable amount of fuels available in the U.S.

There are a number of experiments on silica gel adsorption (wetting). Static adsorption measurements on silica gel have been reported by a number of investigators (Ewing and Bauer, 1937; Hubard, 1954; Patrick and Cohan, 1973; Taylor, 1945). Dynamic adsorption on silica gel has also been measured and reported in the published literature (Ahlberg, 1939; Bullock and Threlkeld, 1966; Ross and McLaughlin, 1956). Theories have been advanced to explain the observed adsorption phenomena by silica gel, and a number of mathematical models have been proposed (Bullock and Threlkeld, 1966; Hougen and

Marshall, 1947; Simpson and Cummings, 1964).

However, an extensive literature review disclosed that neither data nor adequate models have been presented for the adiabatic desorption of water vapor from silica gel (regeneration).

The main objectives of this study are two fold: to develop a fundamental analysis describing the regeneration process of silica gel at temperatures obtainable from flat-plate solar collectors and to verify the proposed models by direct comparisons with the results of experiments.

Nomenclature

English Letters

Symbol	Definition		
A	Cross sectional area of silica gel bin, m^2	H_s	kJ/kg dry air Enthalpy of moist silica gel, kJ/kg dry silica gel; H_{s0} is an initial enthalpy of moist silica gel
A, B, \dots, M	Constants defined in Eqn. (24)	h_c	Convection heat transfer coefficient, $kJ/hr\ m^2\ ^\circ C$
A_v	Silica gel external surface area per unit volume, m^2/m^3	h_D	Mass transfer coefficient, $(kg\ water/hr\ m^2)/(kg\ water/kg\ dry\ air)$
C_{pa}	Specific heat of dry air at constant pressure, $kJ/kg\ ^\circ C$	h_w	Heat of vaporization of water in silica gel, $kJ/kg\ water$
\bar{C}_{pma}	Specific heat of moist air, $kJ/kg\ ^\circ C$	ΔH_w	Integral heat of wetting, $kJ/kg\ dry\ silica\ gel$
\bar{C}_{pms}	Specific heat of moist air at the temperature of silica gel, $kJ/kg\ ^\circ C$	L	Enthalpy of water vapor in the moist air, kJ/kg
C_{ps}	Specific heat of dry silica gel, $kJ/kg\ ^\circ C$	L_e	Lewis number defined in Eqn. (27), dimensionless
C_{pw}	Specific heat of water vapor in the air, $kJ/kg\ water\ ^\circ C$	m	Constant defined in Eqn. (24)
D_p	Average particle diameter of silica gel, m	n	Constant defined in Eqn. (24)
F	Porosity, dimensionless	P	Moist air pressure, in. Hg
G_a	Face air mass velocity, $kg/hr\ m^2$	P_{ve}	Vapor pressure of water in equilibrium with silica gel, in. Hg
H_a	Enthalpy of moist air, $kJ/kg\ dry\ air$; H_{a0} is enthalpy of inlet air	R_1, R_2	Functions defined by Eqns. (17) and (19), respectively
H_e	Equilibrium enthalpy of moist air at the temperature of silica gel,	t	Moist air temperature, $^\circ C$
		t_s	Silica gel temperature, $^\circ C$
		V_a	Air face velocity, m/hr
		W	Humidity ratio of moist air, $kg\ water/kg\ dry\ air$; W_0 is a humidity ratio of inlet air
		W_e	Humidity ratio of moist air in equilibrium with silica gel, $kg\ water/kg\ dry\ air$
		X	Moisture content of silica gel, $kg\ water/kg\ dry\ silica\ gel$; X_0 is an initial moisture content of silica gel
		y	Distance along the bed, m ; Δy is an arbitrary increment in y
		dy	Total depth of silica gel in the bin, m
		Z	Dimensionless bed depth defined

in Eqn. (15); ΔZ is an arbitrary increment in Z

Greek Letters

θ	Time, hr; $\Delta\theta$ is an arbitrary increment in θ , hr
μ	Dynamic viscosity of air, kg/m hr
ρ_a	Density of dry air, kg dry air/m ³
ρ_s	Bulk density of silica gel based on dry matter, kg dry silica gel /m ³
τ	Modified time defined in Eqn. (16), dimensionless; $\Delta\tau$ is an arbitrary increment in τ

Fundamental Analysis

Consider a cylindrical bin containing silica gel of depth y , a cross sectional area A and an initial moisture content x_0 over which warm air of known inlet properties is blown at a constant rate. Consider also an elemental control volume within the bin at a distance y from the entrance, and of depth dy as shown in Fig. 1. In developing the following governing equations of heat and mass transfer

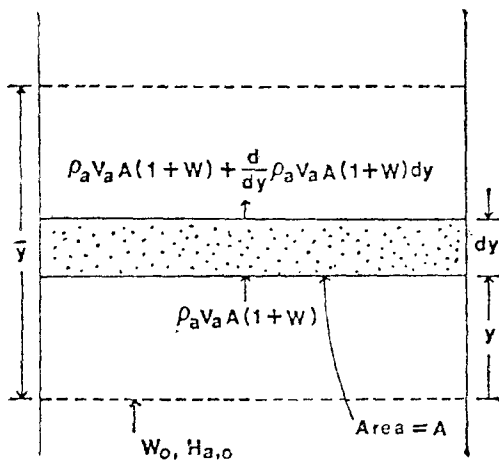


Fig. 1. Schematic diagram of control volume.

for the regeneration process, the following

assumptions are made.

1. The sides of the bed are well-insulated, and there are no transverse gradients in temperature or moisture content across the bed.
2. The air mass velocity is unidirectional and constant with time.
3. The heat and mass transfer coefficients are independent of temperature, moisture content, position and time. The coefficients are overall quantities, and include the effects of the air-side boundary layer and mass diffusion and heat conduction within the solid particles.
4. The physical properties of silica gel are considered constant.
5. Temperature and moisture gradients within the silica gel granules are negligible.

Mass Balance on the Moist Air

The rate of water vapor carried by the air out of the control volume minus its rate carried in, plus the rate of change in the humidity of the air in the void spaces, is equal to the rate of moisture loss by the silica gel within the control volume.

$$\rho_a V_a \frac{\partial W}{\partial y} + \rho_a F \frac{\partial W}{\partial \theta} = -\rho_s \frac{\partial X}{\partial \theta} \quad (1)$$

Energy Balance on the Moist Air

Similarly, the energy balance on the moist air is given by Eqn. (2).

$$\rho_a V_a \frac{\partial H_a}{\partial y} + \rho_a F \frac{\partial H_a}{\partial \theta} = -\rho_s \frac{\partial H_s}{\partial \theta} \quad (2)$$

Mass Balance on the Silica Gel

The rate of change of mass of the silica gel within the control volume is equal to the rate of moisture transfer from the silica gel granules to the air which can be written as:

$$-\rho_s \left(\frac{\partial X}{\partial \theta} \right) = h_D A_v (W_e - W) \quad (3)$$

Energy Balance on the Silica Gel

The rate of energy transfer by convection

from the air to the silica gel has two components: (a) the energy transferred by convection

$$Q_s = h_c A_v (t - t_s) A \quad dy \quad (4)$$

and (b) The energy rate required for the evaporation of moisture from the granules, given by

$$Q_e = h_D A_v (W_e - W) A \quad dy \quad h_w \quad (5)$$

Thus, the equation for the energy balance of silica gel is:

$$\rho_s \frac{\partial H_s}{\partial \theta} = h_c A_v (t - t_s) + h_D A_v (W - W_e) h_w \quad (6)$$

The moist air enthalpy of dry air is

$$H_a = C_{pa} t + W L \quad (7)$$

where

$$L = 1075 + 1.86 t \quad (8)$$

Therefore, we have

$$\begin{aligned} H_a &= (1.005 + 1.86 W) t + 1075 W \\ &= \bar{C}_{pma} t + 1075 W \end{aligned} \quad (9)$$

and similarly

$$H_e = \bar{C}_{pma} t_s + 1075 W_e \quad (10)$$

From Eqns. (9) and (10) and assuming

$$\bar{C}_{pma} = \bar{C}_{pms} = C_{pms} = 1.005 + 1.86 W \quad (11)$$

We have

$$t - t_s = \frac{1}{C_{pms}} [(H_a - H_e) - 1075(W - W_e)] \quad (12)$$

Using the above relations, and the Lewis number, defined by the following equation:

$$L_e = \frac{h_c}{h_D C_{pms}} \quad (13)$$

we obtain the energy balance on the silica gel as

$$\begin{aligned} \frac{\partial H_s}{\partial \theta} &= \frac{h_D A_v}{\rho_s} [L_e (H_a - H_e) \\ &\quad + (W - W_e) (h_w - 1075 L_e)] \end{aligned} \quad (14)$$

In order to non-dimensionalize the space and time coordinates in Eqns.(1)-(3), and (14), modified space and time coordinates were defined as:

$$Z = \left(\frac{h_D A_v}{G_a} \right) y \quad (15)$$

$$\tau = \frac{h_D A_v}{\rho_s} \left[\theta - \left(\frac{\rho_a F}{G_a} \right) \right] \quad (16)$$

With the new coordinates, the mass and energy balance equations [Eqns. (1), (2), (3), and (14)] are reduced to

$$\frac{\partial W}{\partial Z} = -(W - W_e) = -R_1(W, X, H_s) \quad (17)$$

$$\frac{\partial X}{\partial \tau} = (W - W_e) = R_1(W, X, H_s) \quad (18)$$

$$\begin{aligned} \frac{\partial H_s}{\partial Z} &= -[Le(H_a - H_e) + (W - W_e)(h_w \\ &\quad - 1075 Le)] = -R_2(W, H_e, X, H_s) \end{aligned} \quad (19)$$

$$\begin{aligned} \frac{\partial H_s}{\partial \tau} &= [Le(H_a - H_e) + (W - W_e)(h_w \\ &\quad - 1075 Le)] = R_2(W, H_e, X, H_s) \end{aligned} \quad (20)$$

The initial and boundary conditions are

$$\begin{aligned} X(Z, 0) &= X_0 \\ H_s(Z, 0) &= H_{s,0} \\ W(0, \tau) &= W_0 \\ H_a(0, \tau) &= H_{a,0} \end{aligned}$$

In general, the set of four partial differential equations (Eqns. (17)-(20)) has no analytical solution, due to the nonlinear relations among the four unknowns W , H_a , X , and H_s . However, these equations with known initial and boundary conditions can be solved numerically on a digital computer employing a combined modified Euler and predictor-corrector method (Milne, 1953; Hamming, 1962).

In Eqn. (16), the second term accounts for the effect of air-filled voids between silica gel particles. The effect, however, can safely be neglected for the bed depth of 30.48cm (1ft) or less.

Evaluation of Parameters

Certain parameters are needed for solving the governing equations. These parameters are certain physical and thermal properties of silica gel and the heat and mass transfer

coefficients.

Hougen and Marshall (1947) have given dimensional properties of silica gel particles including the equivalent particle diameter D_p and the particle external surface area A_v . The bulk density may be found to be 736.85 kg/m³ (46.0 lbm/ft³) for particle size passing through a 6 to 16 mesh screen (Grace, 1967).

The enthalpy of moist silica gel may be expressed in terms of the enthalpies of the pure components and the heat of wetting. Thus

$$H_s = (C_{ps} + C_{pw}X)t_s + \Delta H_w \quad (21)$$

The integral heat of wetting ΔH_w represents the enthalpy change of the system, expressed per unit mass of dry solid, resulting from the addition of a given quantity of liquid to an initially dry solid. Ewing and Bauer (1937) have presented data for ΔH_w for silica gel and Bullock (1966) expressed their data in the following polynomials:

For $X < 0.05$ kg water/kg dry gel

$$\Delta H_w = 2.326(-237,500X^3 + 23,000X^2 - 916.25X)$$

For $X \geq 0.05$ kg water/kg dry gel

$$\Delta H_w = 2.236(-459.43X^3 + 598.65X^2 - 283.01X - 5.28)$$

By substituting the values of $C_{ps} (= 0.921$ kJ/kg^oC = 0.22Btu/lb_m^oF) and $C_{pw} (= 4.187$ kJ/kg^oC = 1.0Btu/lb_m^oF) in Eqn. (21), the enthalpy H_s is given by

$$H_s = (0.921 + 4.187X)t_s + \Delta H_w \quad (22)$$

where the enthalpies of the dry silica gel and water are taken as zero at 0°C (32°F).

The equilibrium humidity ratio W_e can be expressed by

$$W_e = 0.622 \frac{P_{ve}}{P - P_{ve}} \quad (23)$$

The equilibrium vapor pressure data for silica gel were presented by Hubard (1954) and it was represented as polynomials by Bullock and Threlkeld (1966) in the following

equation in which P and P_{ve} were given in inch Hg and t_s in °F.

$$P_{ve} = (At_s^3 + Bt_s^2 + Ct_s + D)X^m + (Et_s^3 + Ft_s^2 + Gt_s + M)X^n \quad (24)$$

where A through G and M are constants which apply to a specific interval over X and are given in the paper of Bullock and Threlkeld (1966).

The heat of vaporization of water in silica gel, h_w , is defined as the energy required to vaporize moisture from the silica gel and is a function of moisture content and temperature of silica gel. Unfortunately, no information could be found on the change in h_w with moisture content and temperature. However, its value was found to be 4652 kJ/kg (2000 Btu/lb_m) of water removed from the reference (Williams-Gardner, 1971).

Hougen and Marshall (1947) have given the following semiempirical relations for heat and mass transfer coefficients and Lewis number for the adiabatic adsorption of water vapor from moist air by silica gel based on the experimental data of Ahlberg (1939):

$$h_c = 0.671 G_a C_{pm} \left(\frac{D_p G_a}{\mu} \right)^{-0.51} \quad (25)$$

$$h_D = 0.704 G_a \left(\frac{D_p G_a}{\mu} \right)^{-0.51} \quad (26)$$

$$Le = \frac{h_c}{h_D C_{pm}} = 0.953 \quad (27)$$

Since the regeneration process is precisely the reverse of adsorption, it appears reasonable to use the above equations for the present study.

Experimental Investigation

Laboratory tests were performed to check the accuracy of the fundamental analysis for the regeneration process. The tests consisted of forcing warm air heated to temperatures in the range of 48.9–82.2°C (120–180°F) through the silica gel bed and measuring the

moisture content at the top layer of the silica gel bed and outlet air temperature and humidity ratio from the bed.

A schematic view of the experimental apparatus is shown in Fig.2. It included a cylindrical steel bin 76.2 cm(30 in) in dia-

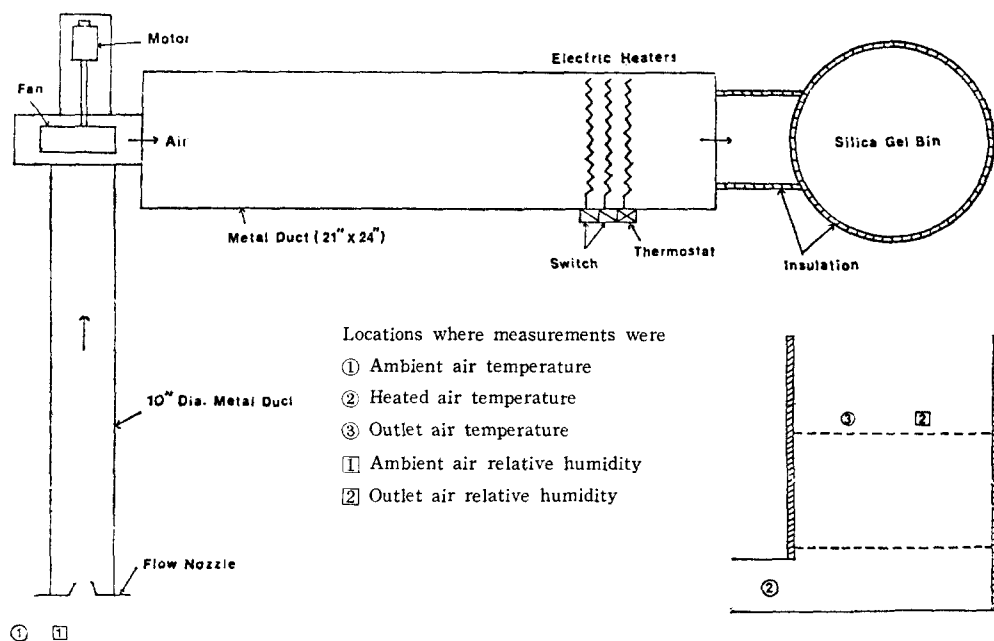


Fig. 2. Plan view of silica gel regeneration system

meter and 122 cm(48 in) high. The bin was attached from the bottom to a duct system which supplied the air at the desired temperature and flow rate. The desired temperature was obtained by a 9 kW electric heater and controlled by a thermostat. The fan with variable-speed drive arrangement was a backward curved centrifugal blower with a 30.48 cm(12 in) diameter wheel and was powered by a 0.375kW (1/2 hp) motor.

Three copper-constantan thermocouples were used to measure air temperatures at locations shown in Fig. 2 and the temperatures were recorded continuously. To measure the airflow rate, a nozzle was attached to the entrance of the air duct and the pressure drop across

the nozzle was measured by an inclined micromanometer. Airflow rate was estimated based on the pressure drop. The relative humidity was measured by using a hygrothermograph and a hygrometer.

Before each test, the bed was wetted with atmospheric air until the desired moisture content was obtained. As soon as the silica gel bed reached a desired moisture content, heated air was forced through the bed. The regeneration was continued until no change in the moisture content of the bed was noticed. In measuring the moisture content of silica gel during regeneration, samples at different locations on the top layer were collected for every one to four hours. The reason for

sampling the top layer only was to avoid disturbing the rest of the silica gel bed during regeneration.

It is known that commercial silica gel adsorbs water equivalent to about 40% of its weight. Properly activated silica gel contains 5 to 6% residual water. This residual water can be removed by heating at 816°C (1500°F),

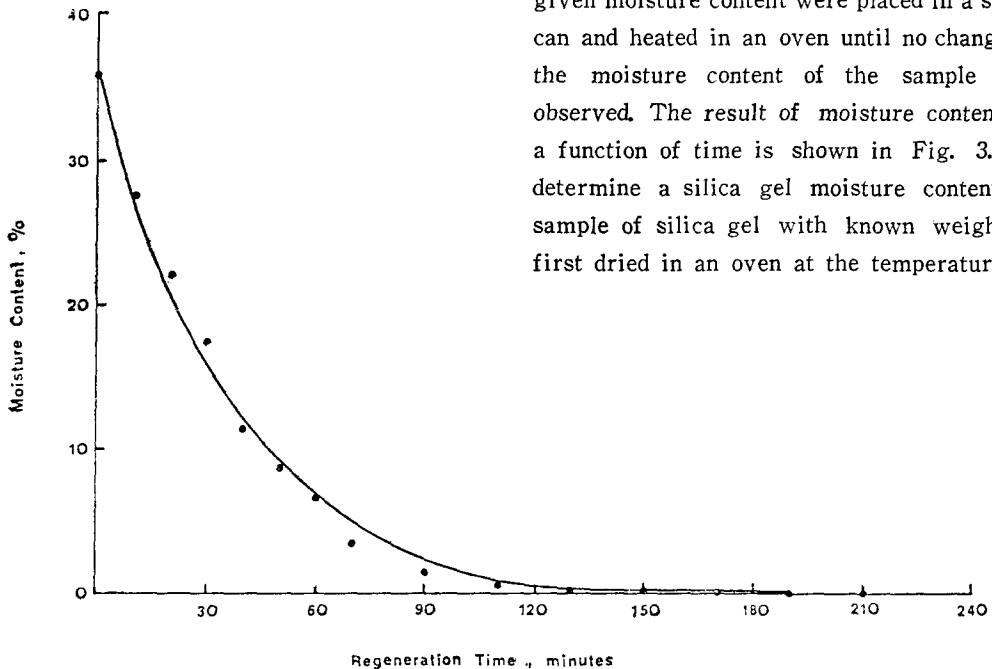


Fig. 3. Moisture content of silica gel versus regeneration time.

148.9°C (300°F) for 3 hours, the time for silica gel to reach the moisture content which contains residual water. The moisture content of silica gel is obtained by dividing the difference of the weight before and after 3 hours of drying by the weight of dried matter. The moisture content used in this study represents the moisture content based on the residual moisture.

A total of nineteen runs were performed using various bed depths and initial moisture contents of silica gel, various inlet air temperatures, and various air velocities. The silica gel used in this study was grade 05

but this treatment reduces its adsorptive capacity. Since no standard way is available for the determination of silica gel moisture content, it is necessary to determine the time required to reach the residual moisture content of silica gel by heating it at a temperature of 148.9°C (300°F).

Approximately 50 gm of silica gel with a given moisture content were placed in a small can and heated in an oven until no change in the moisture content of the sample was observed. The result of moisture content as a function of time is shown in Fig. 3. To determine a silica gel moisture content, a sample of silica gel with known weight is first dried in an oven at the temperature of

(6–16) mesh and had an average particle diameter of about 0.00176m (0.00577ft).

Results and Discussion

Before a complete numerical solution, it was attempted to compare a preliminary numerical solution with the experimental measurements, and to make the necessary adjustments in the heat and mass transfer coefficients to bring about the closest agreement between the numerical solution and experiments. Equations (25) and (26) for h_C and h_D were used for the analysis.

One of the experiments was used to test the accuracy of the predictions. Figure 4 shows the comparison of the predicted and measured

outlet air temperature and humidity ratio and moisture content of silica gel at the top layer of the bed. The agreement between

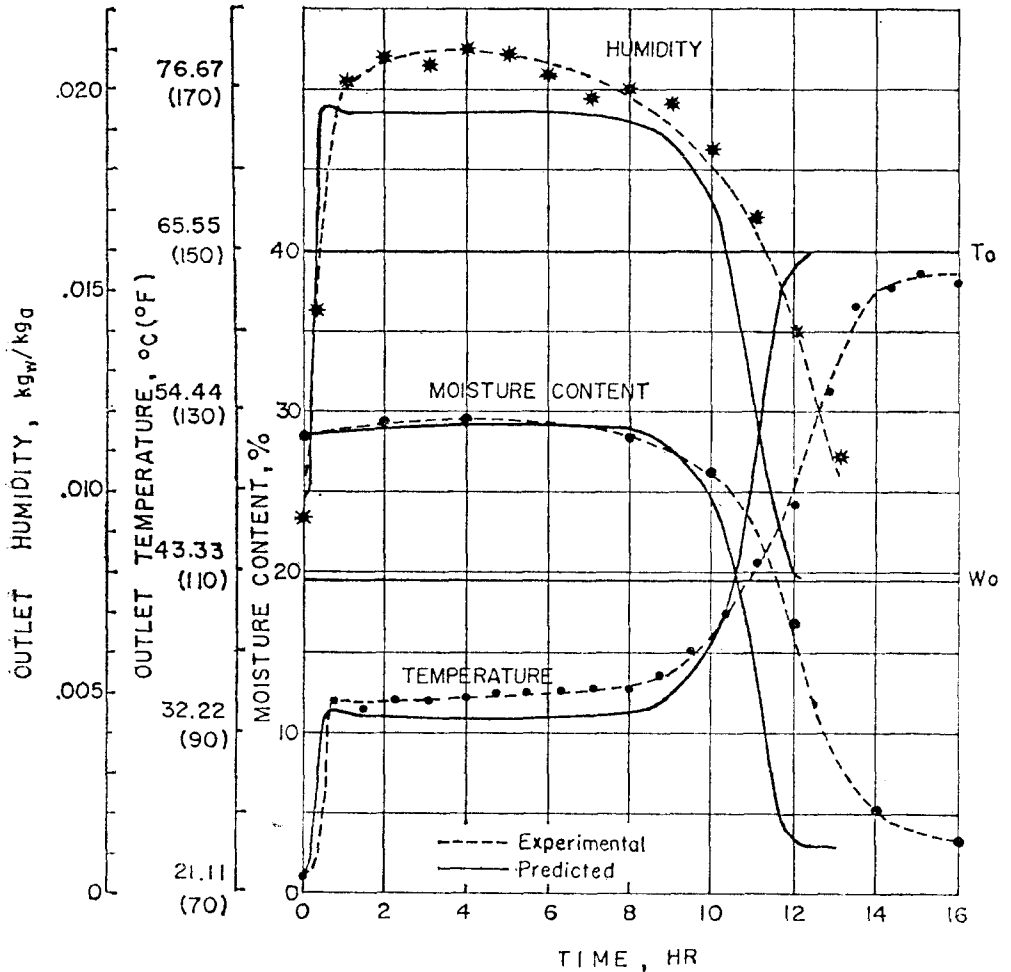


Fig. 4. Comparison between experimental and predicted outlet air temperature and humidity ratio and silica gel moisture content before the adjustment of parameters.

experimental measurements and the predicted values is quite good during the early period of regeneration but the deviation increased as regeneration continued. The results indicate that the predicted time required to reach equilibrium is faster than experimental time. This could be due to the high mass transfer coefficient h_D , used in the analysis.

Brunauer (1943) pointed out that the rate

of adsorption of water on silica gel at constant pressure decreased with increasing temperature, and the regeneration(desorption) and adsorption processes are reversible. The heat and mass transfer coefficients used in this study were developed based on the experimental data of Ahlberg(1939) of the adsorption of water vapor from air by silica gel at lower temperatures. Since the regeneration process

was performed at higher temperatures in this study than Ahlberg's, the mass transfer coefficient in the regeneration process should be smaller than that obtained in the adsorption process.

Therefore, an attempt was made to reduce h_c and h_D to obtain closer agreement between the analytical predictions and experimental

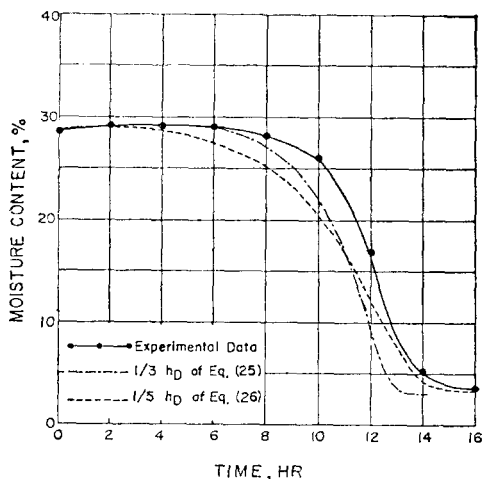


Fig. 5. Effect of mass transfer coefficient on the regeneration rate of silica gel.

measurements. Figure 5 shows the effect of such changes on the rate of silica gel regeneration. Finally, the modified heat and mass transfer coefficients reduced by 1/5 of the original values expressed by Eqns. (25) and (26), were used in this study.

Out of nineteen experimental runs, 14 were selected for comparison between experimental and predicted results. Computer solutions were made for these 14 runs using the same initial and boundary conditions as those of the experiments.

One of the experimental results, shown in Fig. 6, demonstrates the changes in outlet air temperature and humidity ratio, and moisture content at the top layer of the bed with respect to regeneration time. In general, the outlet air temperature rises very rapidly

to a certain temperature after which the rate of temperature rise decreases as the major portion of the heat input is utilized in removing the adsorbed water. The slow rate of temperature rise continues until the major portion of the water contained in the silica gel is released. At this point the latent heat requirements begin to diminish and the sensible heat of the air is not utilized and again results in an increase of the outlet air temperature. Towards the completion of the regeneration process the temperature of the outlet air rises rapidly to approach the inlet air temperature.

The curves of the silica gel moisture content as a function of the regeneration time indicate that no appreciable changes occur in moisture content before the outlet air temperatures begin to rise. Once the outlet temperatures of drying air begin to rise, the moisture contents of silica gel decrease continuously to an equilibrium state with the drying air.

The outlet air humidity ratio of air from the bed also rises very rapidly at the start. When water is practically released from the silica gel, it begins to drop, thus approaching the inlet air humidity ratio.

To conserve space, comparisons for only two typical runs are shown in Figs. 7(a), (b), (c) and 8 (a), (b), (c), respectively, for both outlet air temperature and humidity ratio, and silica gel moisture content at the top layer of the bed. Initial and boundary conditions of the tests are summarized in Table 1.

In general, the agreement between the experimental data and the predicted values is satisfactory. However, the predicted outlet air temperatures and humidity ratios are slightly higher than their corresponding experimental values during the initial period

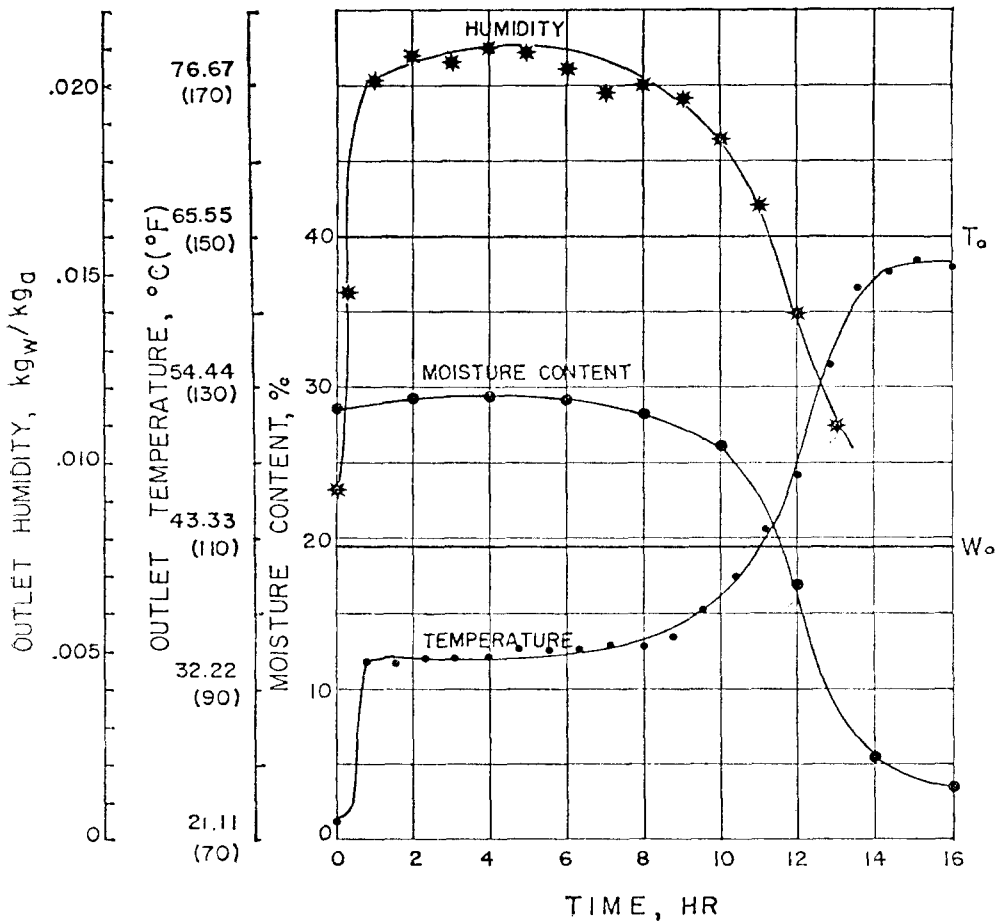


Fig. 6. Experimental outlet air temperature and humidity ratio and moisture content of the top layer of silica gel bed. T_0 and W_0 are the average inlet air temperature and humidity ratio, respectively.

of regeneration. Following the initial period the experimental outlet air humidity ratio remained relatively higher than the predicted value and the experimental outlet air temperature remained lower than the predicted value for the remainder of the regeneration in almost all comparisons.

The slight discrepancy may be attributed to the following uncertainties: (a) the vapor pressure data used in obtaining numerical solutions, (b) in neglecting the variability of h_w with moisture content and temperature

of silica gel, (c) in measuring the moisture content of silica gel, (d) the simplified assumptions (for example, air mass flow rate remained constant). Also, in the analysis it was assumed that there was no radial temperature gradient in the silica gel bed, but in the actual experiment heat loss to the surrounding air was inevitable. The assumed operating conditions may have also resulted in the discrepancies.

Finally, statistical tests of the comparison of two groups by predicted and experimental

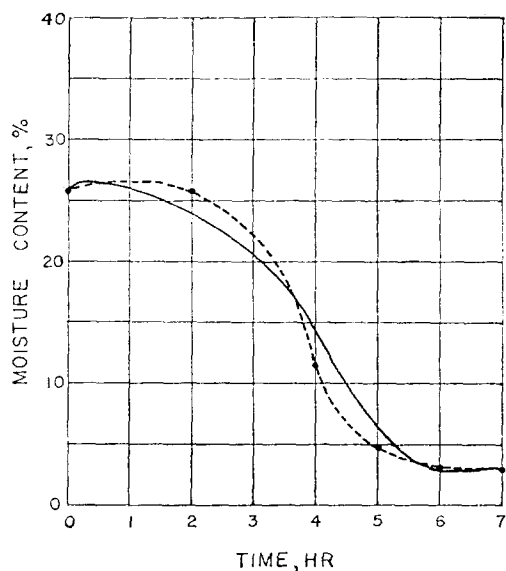


Fig. 7(a). Comparison between experimental and predicted moisture content of silica gel. Bed depth: 8.89cm, air velocity: 4.41 m/min.

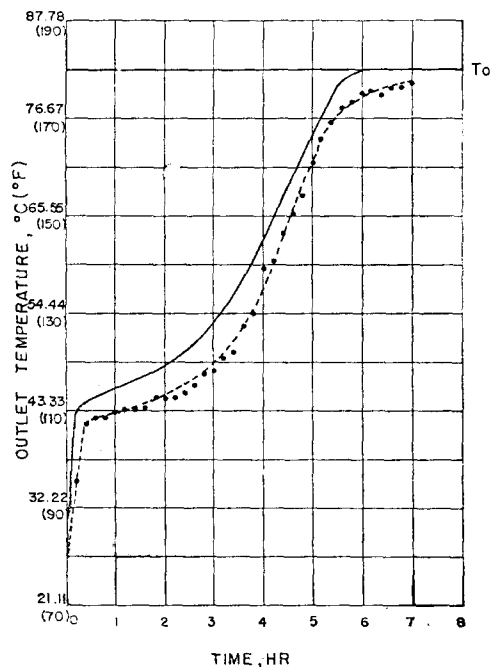


Fig. 7(b). Comparison between experimental and predicted outlet air temperature. T_o is average inlet air temperature. Bed depth: 8.89 cm, air velocity: 4.41 m/min.

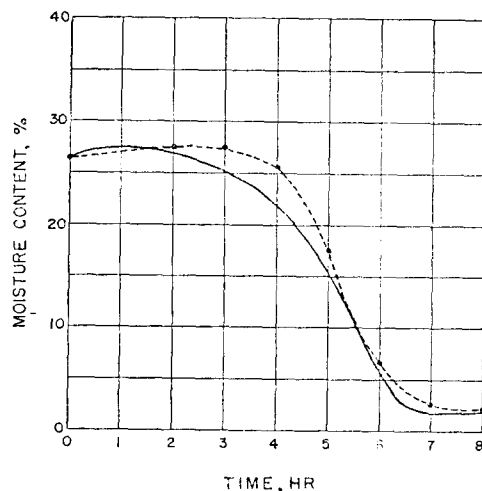


Fig. 8(a). Comparison between experimental and predicted moisture content of silica gel. Bed depth: 26.67cm, air velocity: 11.86 m/min.

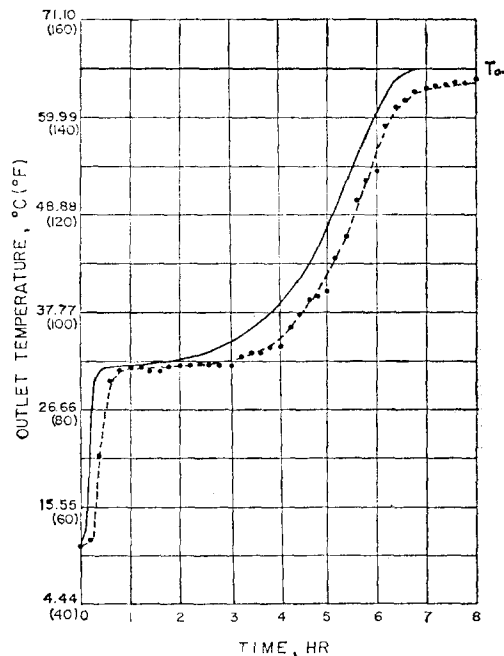


Fig. 8(b). Comparison between experimental and predicted outlet air temperature. T_o is average inlet air temperature. Bed depth: 26.67cm, air velocity: 11.86 m/min.

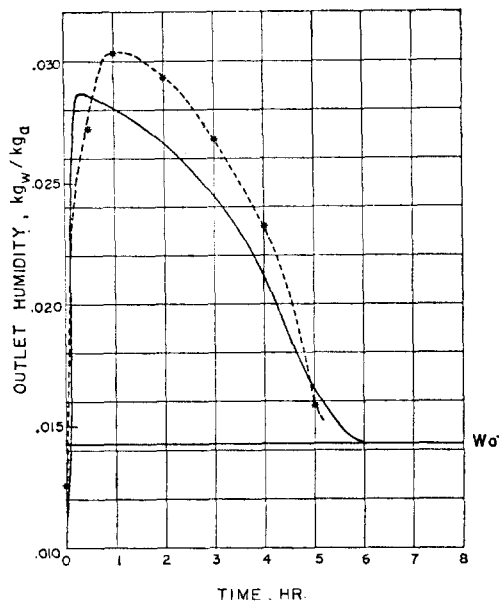


Fig. 7(c). Comparison between experimental and predicted outlet air humidity ratio. W_o is average inlet air humidity ratio. Bed depth: 8.89 cm, air velocity 4.41 m/min.

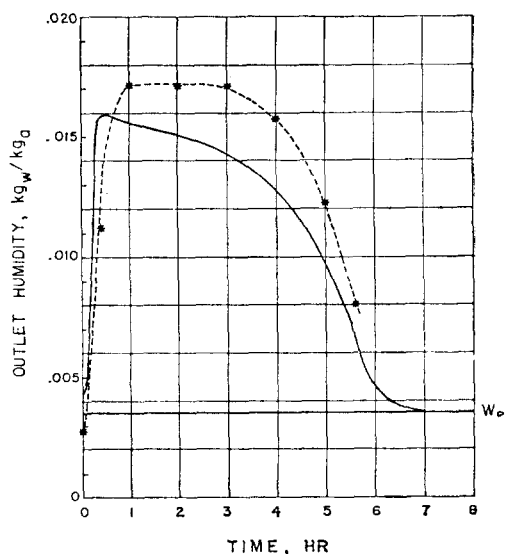


Fig. 8(c). Comparison between experimental and predicted outlet air humidity ratio. W_o is average inlet air humidity ratio. Bed depth: 26.67 cm, air velocity: 11.86 m/min

TABLE 1

	Fig. 7	Fig. 8	Units
Bed depth	8.89(3.5)	26.67(10.5)	cm(inch)
Inlet air temperature	82.2(180)	15.55(150)	°C(°F)
Inlet air humidity ratio	0.01421	0.00352	kg water/kg dry air
Initial silica gel temperature	26.67(80.0)	11.67(53.0)	°C (°F)
Initial silica gel moisture content	0.2575	0.2654	kg water/kg dry gel
Air face velocity	4.41(14.47)	11.86(38.92)	m/min(ft/min)

moisture content data were performed. The null hypothesis of no difference between the group of experimental data and the group of predicted data was accepted at α (the probability of a type I error) equal to 0.01 for

some selected experimental runs. Therefore the mathematical model developed in this study will be very useful in predicting, with minimum effort, the regeneration process of silica gel.

Conclusion

1. The mathematical model developed in this study satisfactorily represents the regeneration process of silica gel.
2. Heat and mass transfer coefficients were adjusted to achieve closer agreement between experimental and predicted results. The improvement was obtained by reducing the coefficients to one-fifth of those reported in the original adsorption studies.
3. The silica gel can be regenerated to about 9.0% moisture level with tempe-

perature of 48.9°C (120°F) and 1.0% with 8.22°C(180°F), depending on the inlet air humidity.

4. The analysis presented can be extended to other types of engineering problems, such as drying or cooling of an irregular shape of material, if the appropriate parameters can be identified.

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