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OPTIMIZATION OF PROCESS PARAMETERS OF PRESSURE-SWING ADSORPTION CYCLE IN A SILICA GEL DESICCANT DEHUMIDIFICATION SYSTEM

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ABSTRACT

Parametric study on pressure-swing adsorption cycle desiccant dehumidification system is a continuous engineering task with the aim of analyzing its effects and attains target quality of dry air for an industrial process. An experimental setup is developed with a dehumidification tower, regeneration tower,and flow control valve.The effect of process air inlet moisture content, cycle time ratio, and regeneration air flow rate on the adsorption performance is studied to evaluate the potential of the dehumidification system suitable for drying applications. The optimal dehumidification parameters are found, and a regression equation is also developed for the process. It is concluded that, process air inlet moisture is the most influencing parameter compared to regeneration air flow rate and cycle time ratio for the silica gel desiccant dehumidification system.

Keywords: Dehumidification of air; Silica gel; Surface chemistry; Adsorption rate; Taguchi method.

1.INTRODUCTION

Dehumidified air finds various applications like drying, air conditioning and etc. Air can be dehumidified by cooling it to a dew point temperature, or by raising the pressure, or by chemical dehumidification [1]. Drying at low temperatures also has low energy efficiency as main drawback. Because of the heat sensitivity of many food products, increasing the temperature is not a good solution to improve efficiency. Courtois et al. [2] pointed that removal of water vapor dehumidifies the air and thus improves the driving force for drying. An alternative to improve the drying capacity of air is by removing the water vapor in the air by using desiccants.

Determination of process parameters on adsorption rate is a continuous engineering task with the aim of reducing dehumidification time and attains desired quality dry air. There are many optimization techniques like Artificial Neural Network (ANN), Genetic Algorithm (GA), etc used by various researchers all over the world for finding the optimum condition of different parameters in desiccant dehumidification system. Cejudo et al. [3] developed an ANN model to calculate the outlet humidity ratio and temperature in the silica gel wheel. In their study, the experimental data are considered to validate the physical model. The results show that the values of humidity and temperature at the outlet for ANN model are in accordance with experimental data than the physical model. It is concluded that, a special attention must be required while calculating moisture content from experimental values of dry bulb temperature and relative humidity. Zeidan et al. [4] conducted an experimental study to analyze the performance of calcium chloride desiccant dehumidification system using ANN model. The experimental results show that the errors were below 1% for most of the variables. Their study found that the suggested model can be used as a tool for prediction to complement the experiments. Gandhidasan et al. [5] proposed a multilayer ANN model to simulate the relationship between entry and exit parameters of a randomly packed dehumidifier with lithium chloride as a liquid desiccant. The parameters considered in this study were air and desiccant temperature, desiccant and air flow rate, air and desiccant inlet temperature, humidity of air at the inlet, concentration of desiccant at inlet, temperature ratio, and cooling water inlet temperature and the ANN predictions for these parameters were reasonably matching the values obtained in the experimentation. Mohammad et al. [6] developed an ANN model to predict the performance of a triethylene glycol liquid desiccant dehumidifier. They used experimental data by 70% and 30% to train the model and to test the output respectively. They found that the maximum percentage differences between the ANN model and experimental value for dehumidifier effectiveness and water condensation rate were 9.0485% and 8.13% respectively. Seenivasan et al. [7] studied the effect of process parameters on water vapour removal rate in a liquid desiccant dehumidifier using Taguchi method. The length of the dehumidifier, specific humidity, air flow rate, desiccant concentration and mass flow rate of desiccant were selected as parameters. The results obtained by Taguchi method had a good agreement with experimental values.

It is found from the literature review that there are very few studies established on optimizing the liquid desiccant dehumidification system. Taguchi technique is an efficient statistical tool [8] which can be used to find the effect of process parameters on the adsorption capacity of the solid dehumidification system. There is no literature found to optimize the process parameters for pressure-swing adsorption process using silica gel desiccant material using Taguchi method. In this present study, an attempt is made in this direction to optimize the effects of process parameters on the adsorption rate of pressure-swing adsorption process in packed tower solid desiccant dehumidifier by using Taguchi method.

The main objectives of this study are (i) To optimize the various process parameters of solid desiccant dehumidification system,(ii) To develop a regression model to predict the performance of the pressure-swing adsorption process and (iii)To study the variation of outlet parameters of dehumidified air with respect to cycle time for optimal conditions.

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2.TAGUCHI'S DESIGN OF EXPERIMENT

Taguchi's design uses orthogonal arrays to define the experimental plans and the treatment of the experimental results based on the analysis of variance. The S/N ratio depends on the quality characteristics of the process to be optimized [9]. The specific steps involved in the Taguchi's method are described as follows:

- Identification of process parameters.
- Orthogonal array selection.
- Experimentation.
- Analysis of results.
- Confirmation test.

2.1. IDENTIFICATION OF PROCESS PARAMETERS

The performance of drying application will be better than average when the targeting air humidity of processing air after desiccant dehumidification is closer to 0 g_{wv}/ kg_{da}. The target air humidity achievability mainly depends on the desiccant characterisitcs, process air temperature and moisture content at inlet, cycle time ratio, and regeneration air flow rate [10]. The desiccant characterisitcs is manufacturing-dependent. Since the air used for processing is from compressor, there will not be any variation of temperature during the cycle. Therefore, desiccant characterisitcs, process air temperature at inlet and process air parameters at outlet of dehumidifier are fixed and assumed to be constant.

Based on the assumptions mentioned above, the primary emphasis is placed on operational parameters namely, (i) process air inlet moisture, (ii) cycle time ratio, and (iii) regeneration air flow rate.

2.1.1. Process air inlet moisture

Process air inlet moisture content is varied by changing the pressure of air leaving the compressor. The higher the outlet pressure, the lower the moisture content in the air. Based on literature survey, the moisture content is varied from 0.4 g/min to 0.8 g/min which are much suitable for drying applications [11].

2.1.2. Cycle time ratio

Cycle time ratio indicates the ratio between the time for dehumidification cycle and regeneration cycle. Based on literature survey, the cycle time used for study is ranging from 150 minutes to 350 minutes.

2.1.3. Regenration air flow rate

Many researchers [12-15] have tested various solid desiccants for drying application taking maximum mass flow rate level as 0.04 kg/sec for drying applications. Based on this, the regeneration air flow rate (purge air) is tested for 5% to 25% of outlet dehumidified air from dehumidification tower.

2.2. ORTHOGONAL ARRAY SELECTION

All parameters are set on three levels within the above boundary levels to conduct experiment based on L_{25} orthogonal array. The levels for the parameters are given in Table 1.

Table 1. Process control parameters and their levels

Process control parameter	Notation	Level 1	Level 2	Level 3	Level 4	Level 5
Process air inlet moisture (g/min)	A	0.4	0.5	0.6	0.7	0.8
Cycle time ratio	B	$\frac{150}{150}$	$\frac{200}{200}$	$\frac{250}{250}$	$\frac{300}{300}$	$\frac{350}{350}$
Regeneration air flow rate (%)	C	5	10	15	20	25

2.3. EXPERIMENTATION

The combination of various parameters is arrived by Taguchi method to conduct experiments.

2.3.1. Experimental set up

A solid desiccant dehumidification system is developed with a filter, pressure regulator, dehumidification tower, regeneration tower, and flow direction valve. The experimental system shown in Fig.1 is designed to pass process air at constant moisture content, temperature, and flow rate into a fixed tower (A & B) of adsorbent. The two towers are (A and B) filled with two kilogram silica gel desiccant each. The towers with 0.0762 m internal diameter and 0.60m height are used alternately as dehumidifier or regenerator by simultaneous manual switching. The flow direction valves are operated in such a way that after a selected cycle time period, the function of the tower is interchanged. All the connecting pipes in this system has 0.0127m internal diameter. In the experimental system the cycle time, moisture content of process air for dehumidifier and regeneration air flow rate are manually controlled. Water concentrations in the process air going into and coming out of the fixed tower are determined by dew point measurements. Air is supplied from a pressure line and passed through a standard air line filter and pressure regulator. The purpose of this filter was to trap all entrained particles and to adsorb small amounts of compressor oil in the air. The water content of the air stream entering the fixed bed adsorption column is controlled at a given temperature by the adsorption tower (A) pressure and is maintained by air line pressure regulator. All connecting piping is 0.0127m mild steel tubing. Inline switching valves are used to direct inlet air to dehumidification tower and purge air from regenerating tower to exhaust. Safety relief valve is provided at exit manifold to protect the tower from overpressure situation. Tower pressure gauges are furnished to read pressure in each tower. On-line tower will read line pressure; regenerating tower will read 0 psig.

The dry bulb temperature, dew point temperature, relative humidity and humidity ratio at the inlet and outlet of dehumidification chamber and drying chamber are recorded for every one hour. The detailed specification of instrument used for this experiment is given in Table 2.

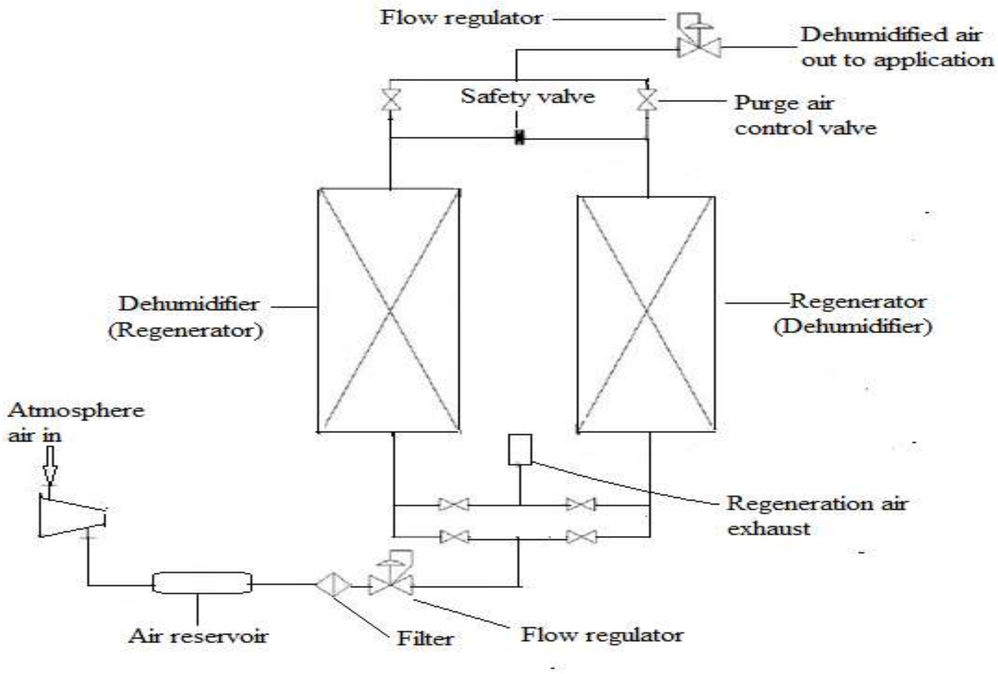

Fig.1 Schematic diagram of experimental setup

Table 2. Specification of instruments

Description	Make	Model	Range	Resolution	Accuracy
Digital Temperature & Humidity Meter	METRAVI	HT-3006	0 to 100% RH -30 to 100°C	0.01 % 0.01°C	± 2% RH ±0.5 °C
Anemometer	Kusam-meco	KM-909	0- 30 m/s	0.01 m/s	± 3%
Electronic balance	Accurate Electronics	ATC-10 W-Rear	0 to 10 kg	1 gm	±1gm
Pressure Gauge	Janatics	JE-901	0 to 10 bar	0.2 bar	± 2%

2.3.2. Uncertainity analysis

This study is conducted to find the air humidity ratio and adsorption rate. The air humidity ratio and adsorption rate is mainly influenced by two variables namely dry bulb temperature (T) and relative humidity (Ø). Let ω_R be the uncertainty in the result and ω_T, $\omega_Ø$ be the uncertainties in the variables. Then the uncertainty in the result is given as, [16]

$$w_w = \left[\left(\frac{\partial w}{\partial T} w_t\right)^2 \pm \left(\frac{\partial w}{\partial \varphi} w_\varphi\right)^2\right]^{\frac{1}{2}}$$

where

Uncertainty in temperature measurement, ω_T : ± 0.5ºC

Uncertainty in relative humidity measurement, $\omega_Ø$: ± 2 %

The uncertainties in the calculation of air humidity ratio and adsorption rate percentage are 0.28 % and 0.21 % respectively.

2.3.3. Experimental procedure

The basic principle used in this pressure swing adsorption (PSA) system is selective adsorption of water from a wet process air on a solid adsorbent in order to produce a dry process air. The process air enters the system through the inlet passage and is directed into the on-line drying tower via the inlet valves and lower manifold. The air is evenly distributed through the tower A and passes over the desiccant material, reducing the water vapour content. As the air contacts the adsorbent material, water vapour transfers from the wet process air to the dry desiccant. The dried process air then combines in the upper manifold and exits the adsorber via the outlet valves. However, adsorbent materials have a fixed adsorption capacity and once this capacity is reached, they must be regenerated.

At the start of the regeneration cycle, the exhaust valve of the dryer is closed and the off-line chamber is at full line pressure. The air in the off-line chamber has a dew point equal to the air leaving the dryer. The exhaust valve is then opened and the dry air within the chamber expands rapidly as it leaves the dryer via the exhaust silencer, forcing water to be removed from the desiccant material. Once the off-line chamber has de-pressurized, a continuous bleed of selected percentage of produced dry process air (purge air) from the on-line chamber as regeneration air is directed into the off-line upper manifold. With the exhaust valve open, the purge air expands from line pressure to atmospheric pressure and flows downwards through the columns, over the off-line desiccant material. As the purge air at line pressure contains a fixed amount of water vapour, allowing it to expand means the purge air becomes even drier, increasing its capacity to remove adsorbed water from the saturated desiccant bed. The outlet dew point is continuously monitored by using hand held hygrometer until the pre-set level has been achieved, at which point, changeover will occur. The dehumidifying and regenerating cycle will then continue normally until the end of the next tower changeover. Therefore, to provide a continuous supply of clean, dry air, adsorbent dryers utilize two towers (A & B) of desiccant material and at any one time, whilst one tower (A) is on-line, drying the incoming process air, the other (B) is either off-line, being regenerated or is re-pressurised, ready to come on-line.

In order to study the effect of regeneration air flow rate on adsorption rate, the readings are taken for the second cycle. After the run, the adsorbent is removed and weighed to ascertain the amount of water adsorbed. It is regenerated again, and the adsorbent weight after this regeneration also recorded. The run is started by passing the inlet air upward through the fixed bed. At frequent intervals the bed exit air dew point is measured.

Then the procedure is repeated parameters for the next experiment run order are set, and the experiment is conducted again and the adsorption rate is measured.

2.4. ANALYSIS OF RESULTS

Adsorption rate is selected as response with the category of “larger the better” quality characteristics. The estimated S/N ratio using for all parametric setting and the corresponding values obtained from Taguchi method are given in Table 3.

Table 3. Experimental observations and S/N ratio.

Experiment No	Dehumidification parameter level			Adsorption rate (gram/minute)	S/N ratio
	A	B	C		
1	1	1	1	0.542	-5.32001
2	1	2	2	0.561	-5.02074
3	1	3	3	0.571	-4.86728
4	1	4	4	0.520	-5.67993
5	1	5	5	0.520	-5.67993
6	2	1	2	0.541	-5.33605

7	2	2	3	0.595	-4.50966
8	2	3	4	0.589	-4.59769
9	2	4	5	0.416	-7.61813
10	2	5	1	0.445	-7.03280
11	3	1	3	0.596	-4.49507
12	3	2	4	0.585	-4.65688
13	3	3	5	0.546	-5.25615
14	3	4	1	0.546	-5.25615
15	3	5	2	0.496	-6.09037
16	4	1	4	0.461	-6.72598
17	4	2	5	0.461	-6.72598
18	4	3	1	0.420	-7.53501
19	4	4	2	0.440	-7.13095
20	4	5	3	0.461	-6.72598
21	5	1	5	0.522	-5.64659
22	5	2	1	0.494	-6.12546
23	5	3	2	0.519	-5.69665
24	5	4	3	0.544	-5.28802
25	5	5	4	0.544	-5.28802

Table 4 and Fig.2 depicts the process parameter variation on the overall performance of dehumidification system, and the optimal condition obtained is $A_3B_2C_3$ (Process air inlet moisture: 0.60 g/min, Cycle time ratio: $\frac{200}{200}$, Regeneration air flow rate: 15%).

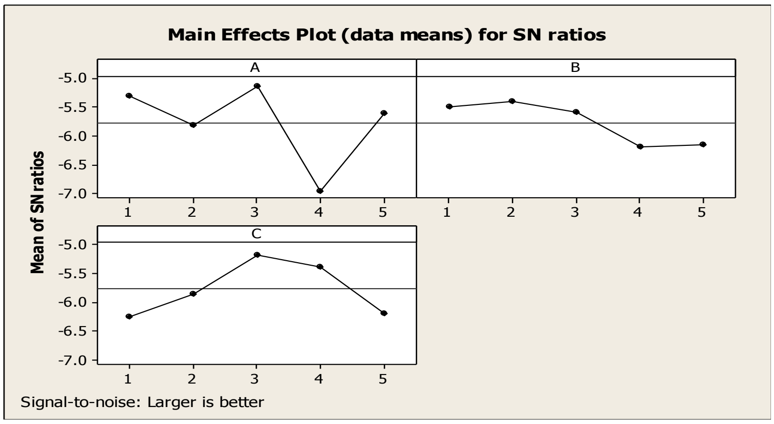

Fig.2 Main effects plot for signal to noise ratios

Table 4. S/N ratio response table for adsorption rate

	A (Process air inlet moisture)	B (Cycle time)	C (Regeneration air flow rate)
Level 1	-5.314	-5.505	-6.254
Level 2	-5.819	**-5.408**	-5.855
Level 3	**-5.151**	-5.591	**-5.177**
Level 4	-6.969	-6.195	-5.390
Level 5	-5.609	-6.163	-6.185

Delta	1.818	0.787	1.077
Rank	1	3	2
Optimum level	A_3	B_2	C_3

2.4.1 Development of regression model

The effect on average adsorption rate by the significant parameters is modeled using Taguchi method as follows.

Adsorption rate= 0.537240-0.052414 A-0.001954 B+0.072648 C+0.004386 A^2 -0.003514 B^2- 0.011914 C^2 +0.003771 A*B +0.001429 A*C

R^2=0.82

Using this equation, the predicted adsorption rate for optimal process parameters is found to be 0.547 g/min. Since R^2 is nearing unity, this model indicates the closeness of the model representing the response and can be taken as an objective function. This objective function forms the basis for the design of dehumidification system.

2.5 CONFIRMATION TEST

The variations of adsorption rate for the air dehumidification process for optimal process parameters (A_3 B_2 C_3) is studied for confirmation of derived value. From the confirmation test, it is concluded that the maximum adsorption rate of the silica gel desiccant is 0.530 g/min (Shown in Table 5).

Table 5. Comparison of predicted adsorption rate with the experimental value

Method	Process air inlet moisture (A)	Cycle time (B)	Regeneration air flow rate (C)	Adsorption rate
Taguchi method	0.60 g/min	$\frac{200}{200}$	15 %	0.547 g/min
Confirmation test	0.60 g/min	$\frac{200}{200}$	15 %	0.530 g/min
Percentage of error	-	-	-	3.10 %

For the optimal parameters,the variation of humidity ratio,vapour pressure,dry bulb temperature,dew point temperature and adsorption rate with respect to cycle time is plotted (Fig. 3 to 7).

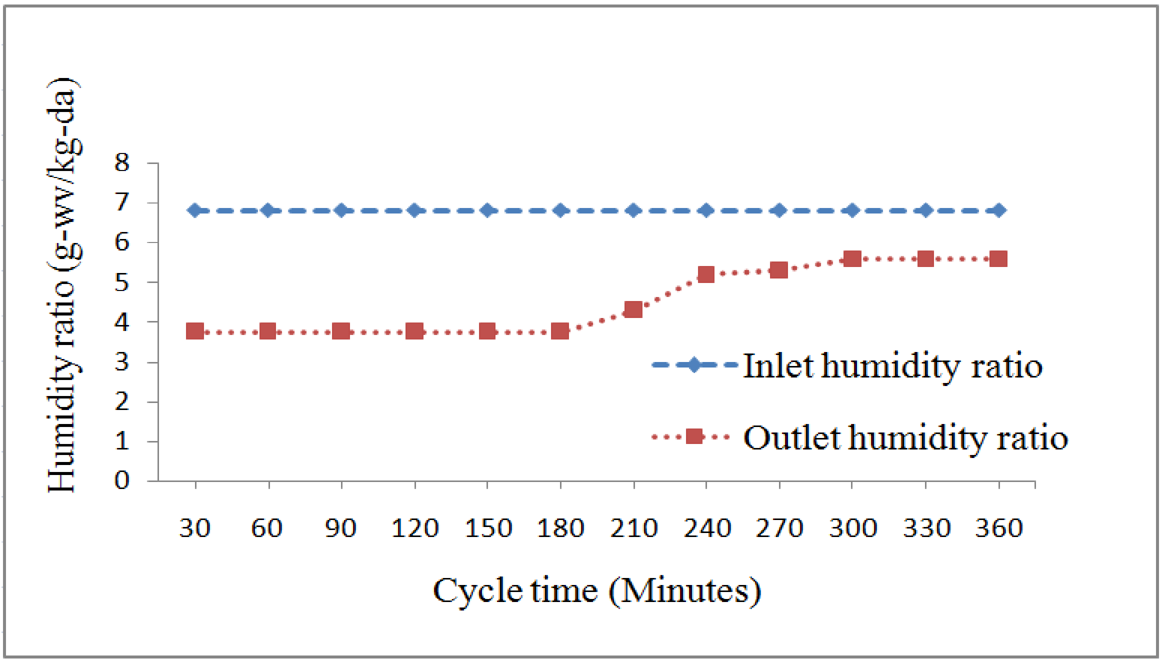

Fig.3 Variation of humidity ratioof process air with respect to cycle time

Fig.3 shows the variation of humidity ratio of process air with respect to time at the inlet and outlet of dehumidifier. Humidity ratio of process air at inlet is almost constant throughout the entire cycle of operation. Since the dehumidification of water vapour in process air is happening in the dehumidifier, the humidity ratio of process air at outlet of dehumidifier is less than as at inlet. Analysis of measured values of humidity ratio shows that the maximum rates of water vapour transfer from air stream to the bed occurs during the starting period of cycle.

Fig.4 shows the variation of vapour pressure of process air with respect to time at the inlet and outlet of dehumidification tower. The mass transfer potential can be expressed in terms of vapour pressure difference. Vapour pressure of process air at inlet is constant throughout the entire cycle of operation. As the water content in the bed increases with time the vapour pressure on the surface of silica gel particles also increases and the potential for mass transfer decreases. The dehumidification of air will take place until the vapour pressure of process air at inlet equals the value at outlet of the dehumidifier. At this condition, the desiccant becomes saturated. Then the desiccant should be regenerated to continue the adsorption process in the next cycle.

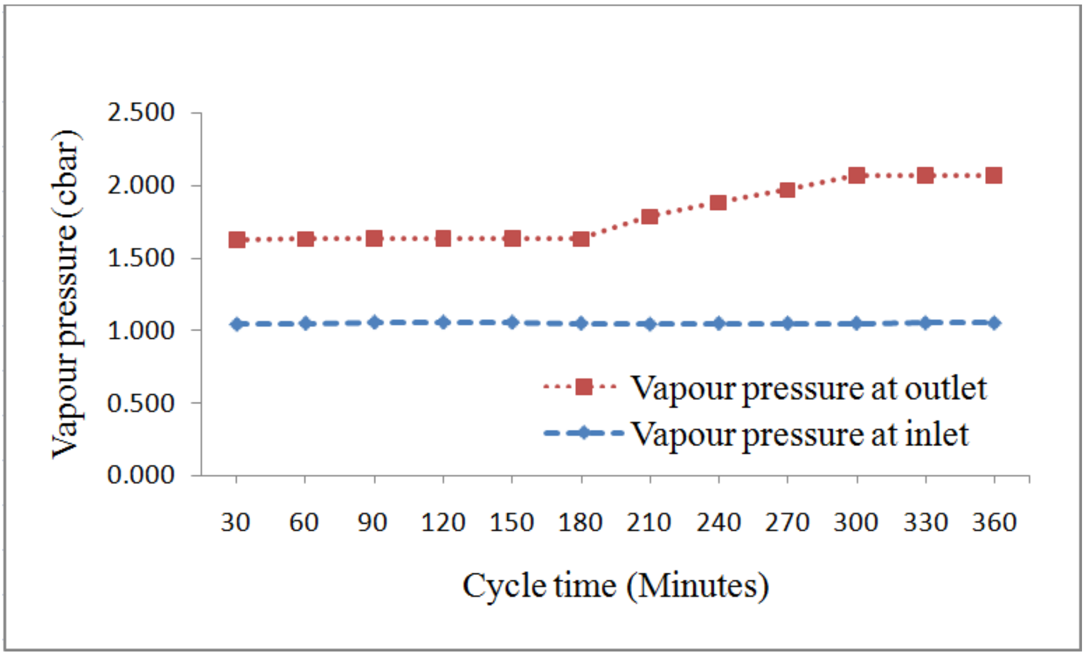

Fig.4 Variation of vapour pressure of process air with respect to cycle time

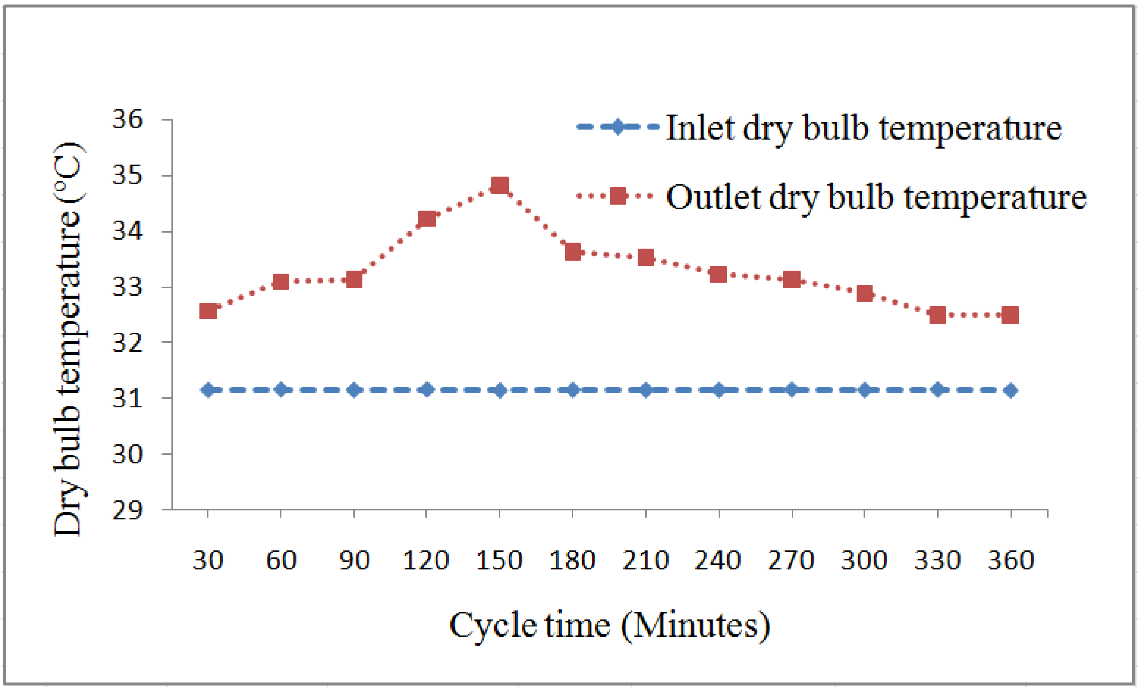

Fig.5 Variation of dry bulb temperature of process air with respect to cycle time

Fig. 5 shows the variation of temperature of inlet and outlet process air in the dehumidifier.The temperature of exit air stream also rises from a minimum value,which is nearly equal to the inlet temperature,to a nearly constant value.When adsorption starts,bed temperature has its lower value and consequently,the vapour pressure difference between air and bed surface is the maximum.The heat of adsorption rises the temperature of the bed at a rate equal to that of moisture transfer.Subsequent increase in bed temperature results in increase in vapour pressure on the bed surface and consequently a decrease in the mass transfer potential. As the vapor transfer from air decreases, the rate of generation of adsorption heat also decreases.

Fig.6 represents the variation of dew point temperature with respect to time in the dehumidifier.When process air at a specified rate flows through a bed of adsorbent it does not remain in contact long enough to establish a true equilibrium condition. Rather, a dynamic equilibrium condition develops. As the inlet process air with a dew point of 7.84ºC enters the bed, the first volume of it is quickly dried to a maximum dew point achievable by the desiccant in the lower part of the bed and passes up through the bed in equilibrium with it. The water vapour molecules condense and adhere to the surface of the pores. With more and more process air passing through the bed, the lower zone, which has adsorbed water until it is in equilibrium with the entering process air, becomes deeper and deeper until some water has been adsorbed by the upper layer of the bed and the exit process air has a dew point just greater than maximum achievable dew point by the desiccant.At this point, desiccants become saturated to the degree required in a particular process and adsorption ceases. The adsorption process is carried out until an increase in the exit air dew point is noticed. After saturation, the adsorbent is removed and weighed to ascertain the amount of water adsorbed.

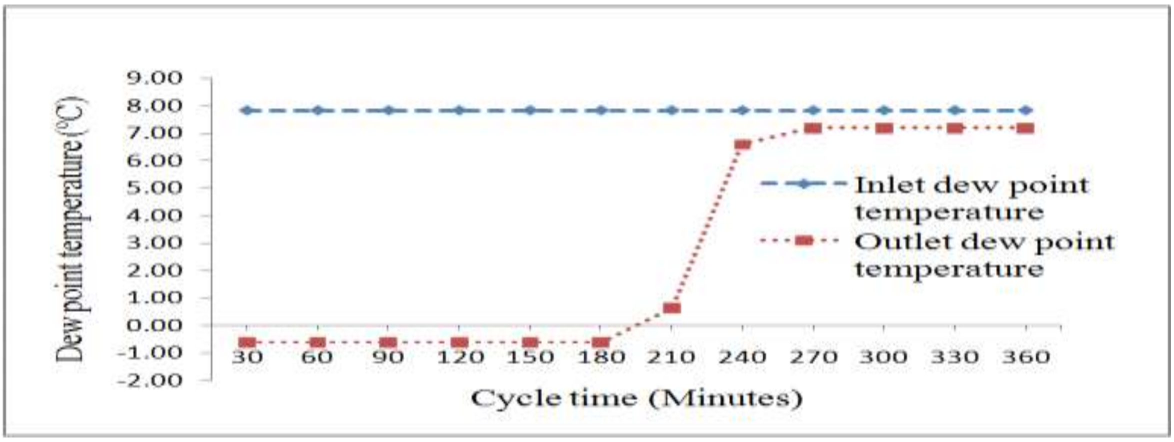

Fig.6 Variation of dew point temperature of process air with respect to cycle time

Fig.7 shows the variation of adsorption rate with respect to dehumidification time.As process air is passed through the fixed bed of solid adsorbents,the transfer of molecules from the process air to the adsorbent initially occurs at the bed entrance.The mass transfer zone then progressively move through the bed once the adsorbent in a region becomes saturated with the adsorbate molecules.Thus at any instant,the adsorbent particles upstream or downstream of the mass transfer zone do not participate in the mass transfer processes.Adsorbent particles have finite capacity for fluid phase molecules.An extended contact with the process air stream creates the thermodynamics equilibrium between the solid adsorbent and process air stream.At this equilibrium condition the rates of adsorption and desorption are equal and the net loading on the adsorbent cannot increase further,it is now becomes necessary either to regenerate the adsorbent or to dispose of it.

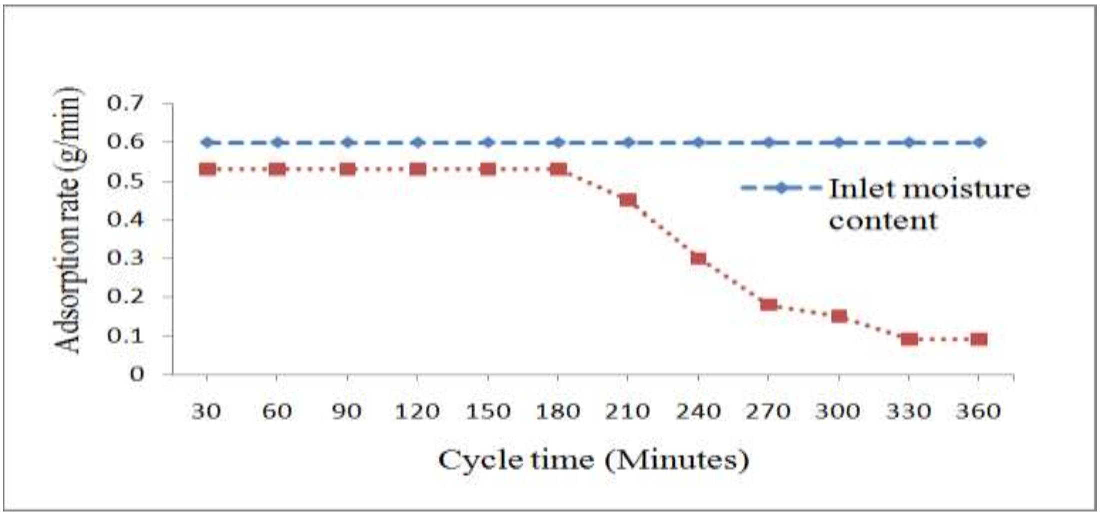

Fig.7 Variation of adsorption rate by the desiccant with respect to cycle time

3.CONCLUSION

A pressure-swing adsorption cycle silica gel desiccant dehumidifier is developed and investigated to study the potential of produce of dehumidified air suitable for drying applications.The following conclusions are drawn from the results.

- The process air inlet moisture is the most influencing parameter compared to regeneration air flow rate and cycle time ratio.
- The process air can be dehumidified to 3.76 g-wv/kg-da which favours the use for low temperature drying applications.
- The dehumidified air produced using silica gel favours low temperature drying applications.
- The optimal dehumidification parameters are found, and a regression equation is also developed for the process. It forms the basis for the design of dehumidification system.

REFERENCES

1. Ruthven, D. M.,1984,Principles of Adsorption and Adsorption Processes, John Wiley & Sons, New York, NY.
2. F.Courtois,2003, Drying of air-Encyclopedia of Agricultural, Food, and Biological Engineering,227-230.
3. J.M. Cejudo, R. Moreno, A. Carrill,2002, Physical and neural network models of a silica-gel desiccant wheel, Energy Buildings,837-844.
4. E.B. Zeidan, A.A. Ayman, A.M. Hamed,1010,Investigation on the effect of operating parameters on the performance of solar desiccant cooling system using artificial neural networks, Int. J. Therm. Environ. Eng.
5. P. Gandhidasan, M.A. Mohandes,2011,Artificial neural network analysis of liquid desiccant dehumidification system, Energy,36,1180–1186.
6. A.T. Mohammad, S.B. Mat, M.Y. Sulaiman, K. Sopian, A.A. Abduljalil,2013,Implementation and validation of an artificial neural network for predicting the performance of a liquid desiccant dehumidifier, Energy Conversion Management,67,240–250.
7. Seenivasan.D, Selladurai.V & Senthil.P,2014,Optimization of liquid Desiccant Dehumidifier performance using Taguchi Method, Advances in Mechanical Engineering,6,1-6.
8. Taguchi G,1990,Introduction to quality engineering, Asian Productivity Organization,Tokyo.
9. Taguchi G, Hocheng, Taguchi methods orthogonal arrays and linear graphs, tools for quality engineering, Dearborn, MI: American Supplier Institute, (1987) 35-38.
10. Lewis G.Harriman III, Editor,2002,The Dehumidification Handbook, Second edition, Munters Corporation Dehumidification Division.
11. Barry Crittenden,W John Thomas,1998,Adsorption Technology and Design,Butterworth-Heinemann.
12. K.A.Ramzy, Ravikiran Kadoli, T.P.Ashok Babu,2014,Significance of axial heat conduction in non isothermal adsorption process in a desiccant packed bed, International Journal of Thermal Sciences,76,68-81.
13. Ahmad M.Hamed,2002,Theoretical and experimental study on the transient adsorption characteristics of a vertical packed porous bed, Renewable Energy,27,525-541.
14. Avadesh Yadav, V.K.Bajpai,2013,The performance of solar powered desiccant dehumidifier in India: an experimental investigation, International Journal of Sustainable Engineering, Volume 6, No.3,239-257.
15. L.Warren,McCabe,C.Julian,Smith,Peter Harriott,1993,Unit operations of Chemical Engineering, Fifth edition, McGraw-Hill International Editions, Chemical and Petroleum Engineering Series.
16. J.P.Holman,2012,Experimental Method for Engineers, Eighth Edition, McGraw-Hill series in Mechanical Engineering.

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