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Optimization of Process Parameters of Adsorption Process in Solid Desiccant Dehumidification System Using Genetic Algorithm

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Keywords：air dehumidification, molecular sieve 13X, optimization, genetic algorithm

ABSTRACT

Air dehumidification using desiccants is an important unit operation in drying heat sensitive products like herbs to enhance the preservation properties close to fresh condition after drying. In this present study, an attempt is made to optimize the process parameters on the adsorption rate in the packed bed solid desiccant dehumidifier using molecular sieve 13X desiccant by using Taguchi method. An experimental setup is developed with a filter, flow regulator, on line and off line towers for adsorption and desorption and flow control valve. The effect of process air entry pressure at adsorption tower, desiccant mass and purge air flow rate for desorption tower are studied to evaluate the adsorption performance. A special design of orthogonal arrays obtained in Taguchi's method is used for the experimentation to study all the parameters with minimum number of experiments. MATLAB genetic algorithm is employed to enhance the parametric optimisation. Statistical results show that the process air entry pressure at adsorber entry is the most influencing parameter compared to desiccant mass, and purge air flow rate for desorption tower for the dehumidification system. The predicted value of response by both the tools is very close to each other, and the fitness function can be taken as the basis for the design of dehumidification system.

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INTRODUCTION

Hot and humid climatic conditions are present in many parts of India. In such an environment, dehumidification of atmospheric air is essential for many important applications in the domestic and industrial sector like herbs drying, medicinal plants drying and etc. Drying at low temperature has low energy efficiency and is considered as the main drawback. Raising the temperature of process air to improve efficiency is not a good idea due to heat sensitivity of many products. In such a situation, removing the water content from the process air is the best option.

Chou *et al.* (1987) improved the driving force for drying by removing water vapour. The water vapour in the air can be reduced by cooling it to condense the water vapour or by compressing it to evaporate water vapour or by passing air through the desiccant materials, which adsorbs moisture from the process air through vapour pressure difference. Among these, the desiccant dehumidification of air could represent an interesting alternative to traditional dehumidification processes.

Desiccants are hygroscopic substances that exhibit such a strong affinity for moisture that they can draw water vapour directly from the surrounding air. The low vapour pressure is the essential characteristic of desiccants. The desiccant can attract moisture from air, when it is cool and dry (Ruthven et al.,1984).The solid desiccant materials are having certain advantages over liquid desiccant materials in dehumidification applications (Collier et al.,1997;Sur et al.,2017;Alami et al.,2016). They are very low dew point temperature and easy humidity control at process air outlet, low energy consumption, and CFC's reduction.

Many researchers reviewed the different methods for adsorption and regeneration of many desiccants. The test results depicted that solid desiccant have been more environment friendly and claims less operating cost (Rambhad et al., 2016, Amorium et al., 2013). Some investigators proposed a simulation model describing the heat and mass transfer in a porous adsorbent operating in an isothermal and adiabatic or cooled-bed mode (Majumdar et al., 1989). The result reported that isothermal adsorption process is more effective than adiabatic one. Solid desiccants find application in air conditioning purposes (El-Samadony et al., 2013). The no-staged regeneration and staged regeneration with regeneration temperature ranging from 65ºC to 160ºC are employed in the study. The result depicted that no-staged regeneration is suitable for low temperature application.

The effect of process air flow rate and a cooling coil in silica gel packed bed is studied (Ramzy et al.,2015) to control heat of adsorption produced during adsorption which is not desirable for air conditioning applications. The result showed that adsorption mass by the desiccant is increased by 22% due to intercooling of the desiccant bed. The air with humidity content of 5.067 to 10.04 gm/kg could be dried to 0.7754 gm/kg humidity ratio at outlet in a vertical bed silica gel desiccant dehumidification system for air conditioning applications. The desorption rate is mainly influenced by regeneration air inlet temperature in a packed bed with eight layers of silica gel desiccant (Kabeel et al., 2009).

Many researchers studied silica gel desiccant packed bed system to identify the most influencing parameter in regeneration (Chang et al., 2004) and the result shows that adsorbent regeneration temperature affects the degree of adsorption rate more. Some researchers investigated the use of silica gel desiccant in removing moisture from the process air and increase its adsorption capacity (Attkan et al., 2014). Regeneration temperature and air flow rate is controlled to ensure minimal damage while drying the Fenugreek green leaves. The result shows that the maximum adsorption capacity in process side achieved is 3.5 gm/kg dry air at 60ºC regeneration temperature and process air flow rate of 0.32 kg/sec.The average regeneration capacity is 2.5 gm/kg of dry air.

The parabolic collector and evacuated solar air collector can also be used in the regeneration of different solid desiccants (Kumar et al., 2014; Yadav et al., 2013).The test result shows that silica gel performs better adsorption than the other selected desiccants and can be well regenerated by using parabolic dish collector and evacuated solar air collector for Indian climatic conditions.

The solid desiccant is successfully investigated in agricultural products drying applications (Amorium et al., 2017, Foued et al., 2014). The parameters namely temperature, mass flow rate of air, and humidity effect on drying time for seaweed drying (Djaeni et al., 2015). During drying of air using Zeolite desiccant, the water vapour in process air is removed by 80 to 90% and 5 to 10ºC increase in temperature is achieved due to exothermic reaction. The result shows that higher temperature with low humidity content gives the shorter drying time. Higher temperature increased moisture diffusivity while low relative humidity enhances the driving force for drying. Zeolite 4A can also be used in the adsorption of water vapour (Gorbach et al., 2004). The developed kinetic model forms a basis for optimization of drying processes of zeolite 4A desiccant system. Some studies are carried out to investigate the use of Zeolite 5A in mushroom drying at low temperature to avoid the heat damage to the product while drying (Gurtas Seyhan et al., 2000). The result shows that 50 to 75% of the moisture is removed from the mushroom within 6 hours. Dehumidified air with low humidity content and low temperature from Zeolite 5A desiccant dehumidifier is effective in reducing the browning reactions of the dried product.

In these studies, the process parameters of the system using different desiccants are determined based on engineering judgment alone. The possibility of improving system performance by optimal choice of operating conditions is not explored. The information required for design of desiccant dehumidification system and for determining the suitable desiccant adsorption mechanism in respect of selected product to be dried is the adsorption rate as a function of the cumulative significant parameters.

Many researchers proposed several techniques like Taguchi method, genetic algorithm, and etc., for parameter optimization and design a new system (Zhang et al., 2018, Arulraj et al., 2018; Sowrirajan et al., 2018).

Taguchi method is an efficient statistical tool that provides a regression model that analyses the objective function with respect to the decision variables while respecting defined constraints (Taguchi et al., 1986). The main objective of this study is to obtain this information experimentally which can be used to design the dehumidification system using molecular sieve 13X desiccant and enhance the parametric optimization for better adsorption performance of the system by using MATLAB genetic algorithm. Finally, confirmation test is carried out at an optimum level of parameters to confirm the predicted values in both the methods and closeness to the experimental values are checked.

TAGUCHI’S DESIGN OF EXPERIMENTS

Taguchi’s design of experiments (DOE) approach based on L_{16} orthogonal arrays and analysis of variance (ANOVA) are used for this study (Taguchi et al., 1987). The specific steps involved in the Taguchi’s method are described as follows.

Process Parameters Identification

This study investigates the potential of applying solid desiccant dehumidification system using molecular sieve 13X to produce dry air suitable for drying of medicinal plants at low temperature. The target process air concentration at the outlet of dehumidification system directly determines the process air inlet temperature and humidity. A well designed system should be able to process the air to meet the target outlet condition. This study targets the produce of dry air at a dry bulb temperature of 40ºC maximum and absolute humidity of 0 kg_{wv} per kg_{da}. Therefore, process air inlet parameters and target process air outlet parameters are fixed and constant.

The performance of desiccant dehumidification system is largely dependent on the desiccant which is capable of achieving lowest dew point temperature of air at the outlet of the system. Molecular sieve 13x is the most suitable desiccant for achieving lowest possible dew point temperature

Therefore the primary importance is given for the operational parameters namely, (i) process air pressure at entry to the adsorber, (ii) desiccant mass, (iii) purge air flow rate to the desorber.

Process Air Pressure at Entry to the Adsorber

The humidity of process air entering the dehumidifier can be varied by changing the pressure of compressed air. Based on literature survey, the moisture content is varied from 0.5 g/min to 0.8 g/min which are much suitable for drying applications (Ramzy et al., 2014).This can be set by varying the pressure of process air from 3 bar to 9 bar.

Desiccant Mass

Water vapour adsorption by desiccant from the process air depends on the mass of desiccant placed in the online tower. More quantity of desiccant will results in pressure drop and creates more air friction. So, the amount of desiccant need to optimized. Based on the literature survey, the amount of desiccant taken for study is ranging from 1000 gram to 2500 gram (Hamed et al., 2002; McCabe et al., 1993; Yadav et al., 2012).

Purge Air Flow Rate to Regenerator

This system uses two towers namely online tower and off line tower to dehumidify the air. While online is engaging in the adsorption of air, the offline tower is being desorbed to make saturated desiccant in previous cycle into unsaturated one for the next cycle. Desorption is achieved by purging in which a portion of the adsorbed air from the online tower is directed back to the desorption tower. The dry air used to desorb the saturated desiccant is considered wasted air since it is not recoverable for application use and is for that reason optimized to minimum. Based on this, purge air flow rate is tested for 5% to 25% of dehumidified air from online tower.

ORTHOGONAL ARRAY SELECTION

Based on the assumptions and references made, three parameters with four levels each are taken to conduct experiment based on L_{16} orthogonal array. The process parameters and their levels are given in Table 1.

Table 1. Process control parameters and their levels

Process parameter	Notation	Level 1	Level 2	Level 3	Level 4
Process air pressure at entry to adsorber (bar)	A	3	5	7	9
Desiccant mass (gram)	B	1000	1500	2000	2500
Purge air flow rate (%)	C	5	10	15	20

EXPERIMENTATION

The experimental order with the combination of different levels of parameters is arrived by Taguchi method.

Experimental Setup and Procedure

A desiccant dehumidification system using molecular sieve 13X desiccant (Figure 1 & Figure 2) employs a pressure swing adsorption cycle. Any water contents and particulates are prevented from entering the dryer by filter arrangement. As the air contacts the desiccant material while entering the dehumidifier, humidity content from the wet process air is adsorbed by the dry desiccant, however, desiccants have a fixed adsorption capacity and once this capacity is reached, they must be desorbed. Therefore, to ensure a continuous supply of dehumidified air, two towers are used in the system.

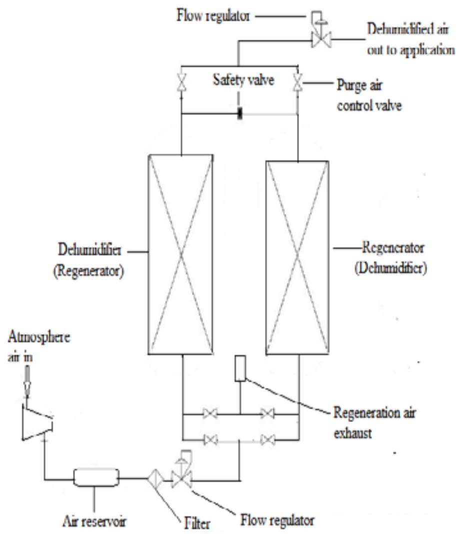

Fig.1. Schematic diagram of experimental setup

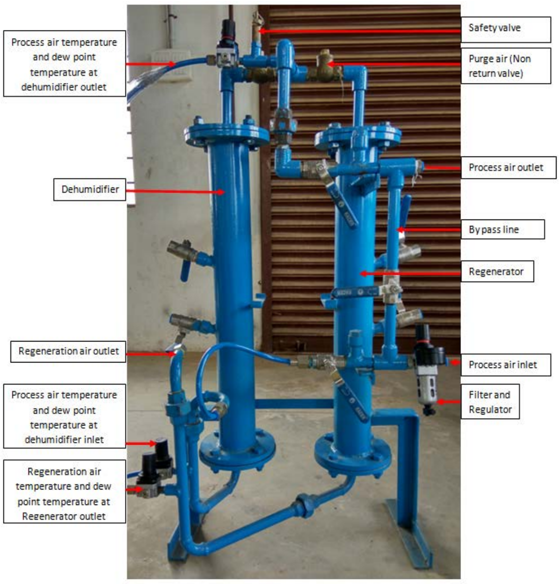

Fig.2. Photographic view of experimental setup

The dehumidification system uses two towers; one is adsorption tower and the second one is desorption tower. Adsorption tower receives humid process air through filter. The variation of humidity content in process air is achieved by adjusting its pressure. The dehumidified air at the top of the adsorption tower is sent for selected applications. At the same time, the second tower is in regeneration mode. During this stage, the regeneration tower pressure is expanded to ambient pressure. A portion of the dehumidified air from the online tower in the adsorption phase is bled to the top of the regenerating tower now at ambient pressure. The humidity stored in the desiccant pores is gained by this dry air and removed out the purge muffler. After the tower is purged, the orifice continues to bleed dry air into the regeneration tower, building it up to system pressure. When the system is switched into the online drying mode, the tower is fully pressurized.

The towers are used alternately as adsorber or desorber by simultaneous manual switching. Water vapour content in the inlet and outlet of the adsorption tower and desorption tower are determined by dew point measurements. The pressure gauge in on-line tower will read line set pressure and in regenerating tower will read 0 psig.

The dew point temperature, dry bulb temperature, humidity ratio at the entry and exit of the adsorption tower and regeneration tower are recorded at regular intervals.

Then the procedure is repeated for other runs.

ANALYSIS OF RESULTS

Signal-to-Nosie (S/N) Ratio Response

Adsorption rate by the desiccants is selected as response with the category of "larger the better" characteristics. The estimated S/N ratio for all the parametric setting is given in Table 2.

Table 2. Estimated S/N ratio

Exp. No	Parameter level			Adsorption rate	S/N ratio
	A	B	C	gram/hour	
1	1	3	3	99.00	39.9127
2	2	1	2	78.97	37.9492
3	1	4	4	77.80	37.8196
4	2	2	1	75.34	37.5405
5	1	2	2	68.75	36.7455
6	2	4	3	112.00	40.9844
7	2	3	4	90.24	39.1080
8	3	2	4	96.28	39.6707
9	3	1	3	127.00	42.0761
10	3	3	1	112.00	40.9844
11	1	1	1	54.55	34.7359
12	4	2	3	74.25	37.4139
13	3	4	2	105.00	40.4238
14	4	3	2	98.00	39.8245
15	4	1	4	66.25	36.4237
16	4	4	1	78.90	37.9415
Mean, $\bar{Y}$					38.7221

The significant levels of the process parameters influencing overall performance of the system is shown in Table 3 and the optimal value found is $A_3B_3C_3$ (Process air pressure: 7 bar, Desiccant mass: 2000 grams, Purge air flow rate: 15%).

Table 3. Response table for S/N ratio

	A	B	C
Level 1	37.30	37.80	37.80
Level 2	38.90	37.84	38.74
Level 3	**40.79**	**39.96**	**40.10**
Level 4	37.90	39.29	38.26
Delta	3.49	2.16	2.30
Rank	1	3	2
Optimum level	A_3	B_3	C_3

ANALYSIS OF VARIANCE (ANOVA)

The influence of the significant parameter is determined by analysis of variance from the experimental results. F test is used to know the significant parameter on the response. The values for sum of squares, mean of squared deviation, degree of freedom, mean sum of squares ratio, pure sum of squares, and percentage of contribution for all parameters is shown in Table 4.

Table 4. ANOVA results

Source	DOF	Adj SS	Seq SS	Adj MS	F-ratio	PC (%)
A	2	2923.70	2923.70	974.57	12.57	50.11
B	2	1181.58	1181.58	393.86	5.08	20.25
C	2	1263.75	1263.75	421.25	5.43	21.66
Pooled error	6	465.30	465.30	77.55		7.98
SS_{Total}	15		5834.33			

From Table 4, it is evident that parameters namely, process air pressure at entry, Desiccant mass, Purge air flow rate contributes the better adsorption rate by 50.11%,20.25% and 21.66% respectively.

Using non-linear regression analysis and MINITAB 16 software, the relationship between the significant process parameters and their effects on adsorption rate is modeled as follows.

Adsorption rate= $-83.2032+77.3450\ A+22.3728\ B+56.1407\ C-11.2081\ A^2\ -0.8369\ B^2\ -6.9756\ C^2\ -3.2842\ A*B\ -5.1776\ A*C\ -3.6010\ B*C$ (1)

$R^2= 92.02\ \%$

Since R^2 value is close to unity, this model can be taken as an objective function for analyzing the same using genetic algorithm to find out the optimum parametric condition. Using equation (1), the theoretical adsorption rate of the dehumidification system for optimal parametric condition is calculated and the value is 112.63 gram/hour.

OPTIMAL PARAMETRIC CONDITIONS VIA GENETIC ALGORITHM

Genetic and Evolutionary Algorithm Toolbox with Matlab tool is used to find the optimum condition for the maximization of adsorption rate in this study. The mathematical model given in eqn. (1) is suitably modified and used as fitness function. The constraint for significant process parameters is fixed as follows.

Process air pressure at entry to adsorber (bar)	$3\leq\ A\leq 9$
Desiccant mass (gram)	$1000\leq B\leq 2500$
Purge air flow rate (%)	$5\leq C\leq 20$

Genetic algorithm is run with several trials with various evolutionary parametric settings. It is noted that the trial with the evolutionary parametric setting [Number of variables (3),Lower bounds (1 1 1),Upper bounds (3 3 3),Population type (Double vector),Population size (20),Creation function (Constraint dependent),Fitness scaling selection function (Rank),Selection (Stochastic uniform),Reproduction cross over fraction (0.8),Mutation (Constraint dependent),Gross over function (Scattered),Migration (Forward),Migration fraction (0.2),Distance measure function (Default),Stopping criteria generation (100),Stall generation limit (50),Plot functions (Best fitness, Best individual)] exhibited better result among the other trials. It is observed in the said trail that the fitness value increased through generations as shown in Figure 3.The optimal parametric condition is achieved in the final (51st) generation and the fitness function to maximize the response is as follows.

Adsorption rate=$83.2032-77.3450\ A-22.3728\ B-56.1407\ C+11.2081\ A^2+0.8369\ B^2+6.9756\ C^2+3.2842\ AB+5.1776\ AC\ +3.6010\ BC$ (2)

Using equation (2), the theoretical adsorption rate for optimal parametric condition is found to be 112.68 gram/hour.

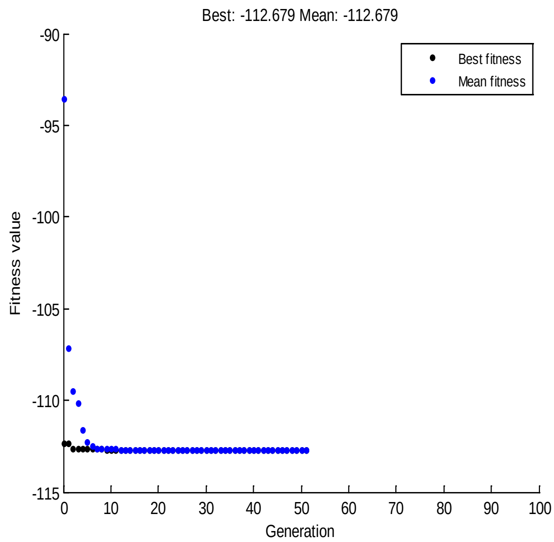

Fig.3. Fitness function values via generations

Confirmation Experiments

The optimal levels of significant parameters arrived from both the methods are noted to be close to each other and verified by conducting confirmation experiment. From the results given in Table 5, it is concluded that the optimal parametric conditions are refined by genetic algorithm for the same output as in Taguchi method.

Table 5. Results comparison

<table>
<tr><th rowspan="2">S. No</th><th rowspan="2">Optimization tool</th><th rowspan="2" colspan="2">Optimal parameters</th><th colspan="2">Adsorption rate (gram/hr)</th><th rowspan="2">Percentage of error</th></tr>
<tr><th>The</th><th>Exp</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Taguchi method</td><td>A</td><td>7 bar</td><td rowspan="3">112.63</td><td rowspan="3">108.37</td><td rowspan="3">3.78 %</td></tr>
<tr><td>B</td><td>2000 gram</td></tr>
<tr><td>C</td><td>15 %</td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">Genetic algorithm</td><td>A</td><td>5.944 bar</td><td rowspan="3">112.68</td><td rowspan="3">109.50</td><td rowspan="3">2.82 %</td></tr>
<tr><td>B</td><td>2000 gram</td></tr>
<tr><td>C</td><td>11.66 %</td></tr>
</table>

Comparison of results with existing methods

The mathematical correlation (Eqn. 1) is developed using the experimental results for derived combination of process parameters. The error between the calculated values with the actual one to the present correlation is deviating within 2.82%. Table 6 shows the results of similar work carried out by Samadony et al. using other desiccant material to lower the humidity content of process air.The approach and result validation of our work agrees well with the similar work with other desiccant material. Therefore to lower the humidity content of process air to lowest value, molecular sieve 13X desiccant material can be recommended.

Table 6. Results validation

<table>
<tr><th colspan="2">Description</th><th>Work by Samadony et al.</th><th>Our work</th></tr>
<tr><td rowspan="2">Process parameters</td><td>Desiccant</td><td>Silica gel</td><td>Molecular sieve 13X</td></tr>
<tr><td>Inlet humidity</td><td>5.067 to 10.04 g_{wv}/kg_{da}</td><td>7.6 to 8.1 g_{wv}/kg_{da}</td></tr>
<tr><td>Response</td><td>Outlet humidity</td><td>0.7754 g_{wv}/kg_{da}</td><td>0.13 g_{wv}/kg_{da}</td></tr>
<tr><td>Mathematical correlation validation</td><td>Error percentage</td><td>0.09</td><td>2.82</td></tr>
</table>

CONCLUSIONS

A solid desiccant dehumidification system has been developed and investigated to study the effect of process parameters on the adsorption rate using molecular sieve 13X desiccant. It is concluded that:

- The optimal dehumidification parameters are found using Taguchi method and Genetic algorithm, confirmed with the experimental value. The predicted value of response by both the tools is very close to each other, fitness function can be taken as the basis for the design of dehumidification system for large scale.
- The humidity content of process air at inlet to the dehumidification system influences more on the adsorption rate of water vapour by the desiccant.
- Molecular sieve desiccant can be used to lower the humidity content of process air the level of 0.13 $g_{water\ vapour}/kg_{dry\ air}$.

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