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Parametric Study of Pressure-Swing Adsorption Process using Molecular Sieve 4a for Air Dehumidification

SURESH KANNAN V [1*], LENIN V R[2*], L PERIYANNAN[3], P SARAVANAN[4], R RAMKUMAR[3]

[1] *Department of Mechanical Engineering, Madanapalle Institute of Technology and Science, Madanapalle, Andhra Pradesh, India – 517325.*

[2]*Department of Mechanical Engineering, Anil Neerukonda Institute of Technology & Sciences, Sangivalasa, Visakhapatnam, Andhra Pradesh, India – 531162.*

[3] *Department of Mechanical Engineering, Mahendra Engineering College, Namakkal, Tamilnadu, India – 637503.*

[4] *School of Aeronautical Sciences, Hindustan Institute of Technology & Science, Chennai, Tamilnadu, India – 603103.*

*Corresponding author: SURESH KANNAN V, LENIN V R

Abstract

Drying of heat sensitivity products assisted with dehumidified air plays a vital role in agriculture. Solid desiccant system is mostly used to produce continues dehumidified air. An experimental setup is developed with on line and off line towers for adsorption and desorption. The effect of humidity content in feed air at entry to adsorption tower, desiccant mass and purge air flow rate for desorption tower is studied to evaluate the adsorption performance. A Taguchi's method based experimental design is used for the experimentation. Statistical results show that the process air humidity content at dehumidifier 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 is very close to each other with confirmation experiment.

Keywords*: Air dehumidification; Molecular sieve 4A; ANOVA*

Introduction

Drying leafy vegetables is a major unit operation done at low temperature (less than 50ºC) for green leafy vegetables at atmospheric pressure to conserve the quality attributes. 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, lessening the moisture from the feed air is the best option.

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 adsorption process in desiccant medium operating at 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 (below 80ºC).

The effect of feed 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

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desorption rate is mainly influenced by regeneration air inlet temperature with eight layers of silica desiccant (Kabeel et al., 2009).

Many researchers studied silica gel adsorption system to identify the most influencing parameter in regeneration (Chang et al., 2004) and the result shows that adsorbent desorption temperature affects the degree of dehumidification rate more. Some researchers investigated the use of silica gel desiccant in removing water vapour 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 process air moisture adsorption achieved is 3.2 gm/kg at 60ºC desorption temperature and 0.35 kg/sec flow rate. The average regeneration capacity is 2.7 gm/kg.

The solid desiccant is successfully investigated in agricultural products drying applications (Amorium et al., 2017, Foued et al., 2014). 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. 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 product heat stress while drying (Gurtas Seyhan et al., 2000). The result shows that 50 to 75% of the water is adsorbed from the mushroom within 6.1 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 are determined based on engineering judgment alone. There is good scope for using optimal conditions to be used to maximize the outcome. Therefore, 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 moisture adsorption rate as a function of the cumulative significant process 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).

Taguchi method is an efficient statistical tool that provides a regression model that analyses the objective function while respecting defined constraints. The aim of this work is to get regression equation experimentally which can be used to design the dehumidification system using molecular sieve 4A. 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.

Design of experiments

Taguchi's method based on L_{16} orthogonal arrays and analysis of variance are used for this study (Vadugapalayam et al.,2017,2020; Venkatesha et al.,2018; Lenin et al.,2018,2019).

Process parameters identification

This study investigates the potential of applying solid desiccant dehumidification system to produce dry air 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 of 40ºC maximum and absolute humidity of 0 kg_{wv} per kg_{da} using molecular sieve 4A desiccant (Kannan et al.,2017,2020,2021).

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

2.1.1 Process air pressure at entry

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 0.6 to 1 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.

2.1.2 Desiccant mass

Removal of feed air moisture using desiccant particles mostly depends on mass of desiccant placed in the online tower. More quantity of desiccant will result in pressure drop and creates more air friction. So, the amount of desiccant need to optimized. From literature survey, mass of adsorbent taken for study is ranging from 1000 gram to 2500 gram (McCabe et al., 1993; Yadav et al., 2012, Sureshkannan et al.,2021).

Purge air flow rate to the regenerator

This system uses two towers namely online tower and off line tower to dehumidify the air. While online is engaging in the dehumidification of air, the offline tower is being regenerated to make saturated desiccant in previous cycle into unsaturated one for the next cycle. Regeneration is achieved by purging 5% to 25% in which a portion of the dry air from the online tower is directed back to the regeneration tower (Venkatachalam et al.,2019,2020).

Orthogonal array selection

Based on the assumptions, the experiments are conducted based on L_{16} orthogonal array and parametric conditions are given in Table 1.

Experimentation

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

Experimental setup and procedure

An adsorption system using molecular sieve 4A desiccant (Fig.1 & Fig.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 adsorbent material while entering the dehumidifier, process air moisture is adsorbed by the dry adsorbent, however, desiccants have a fixed moisture adsorption capacity and once this capacity is reached, they must be regenerated. Therefore, to ensure a continuous supply of dehumidified air, two towers are used in the system.

Table 1 Parameters and levels

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

The dehumidification system uses two towers; one is adsorption tower and the second one is regeneration tower. Adsorption tower receives humid process air through filter. The dehumidified air at the top of the adsorption tower is sent for selected applications. At the same

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time, the second tower is in regeneration mode. During this stage, the regeneration tower pressure is expanded to ambient pressure. A portion of the dry air from the online tower in the dehumidification 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 allows portion of dry air into regeneration column, and rise in column pressure. When the system is switched into the online drying mode, the tower is fully pressurized. The temperature and moisture content at the entry and the exit of the adsorption tower and regeneration tower are recorded at regular intervals.

Then the procedure is repeated for other runs.

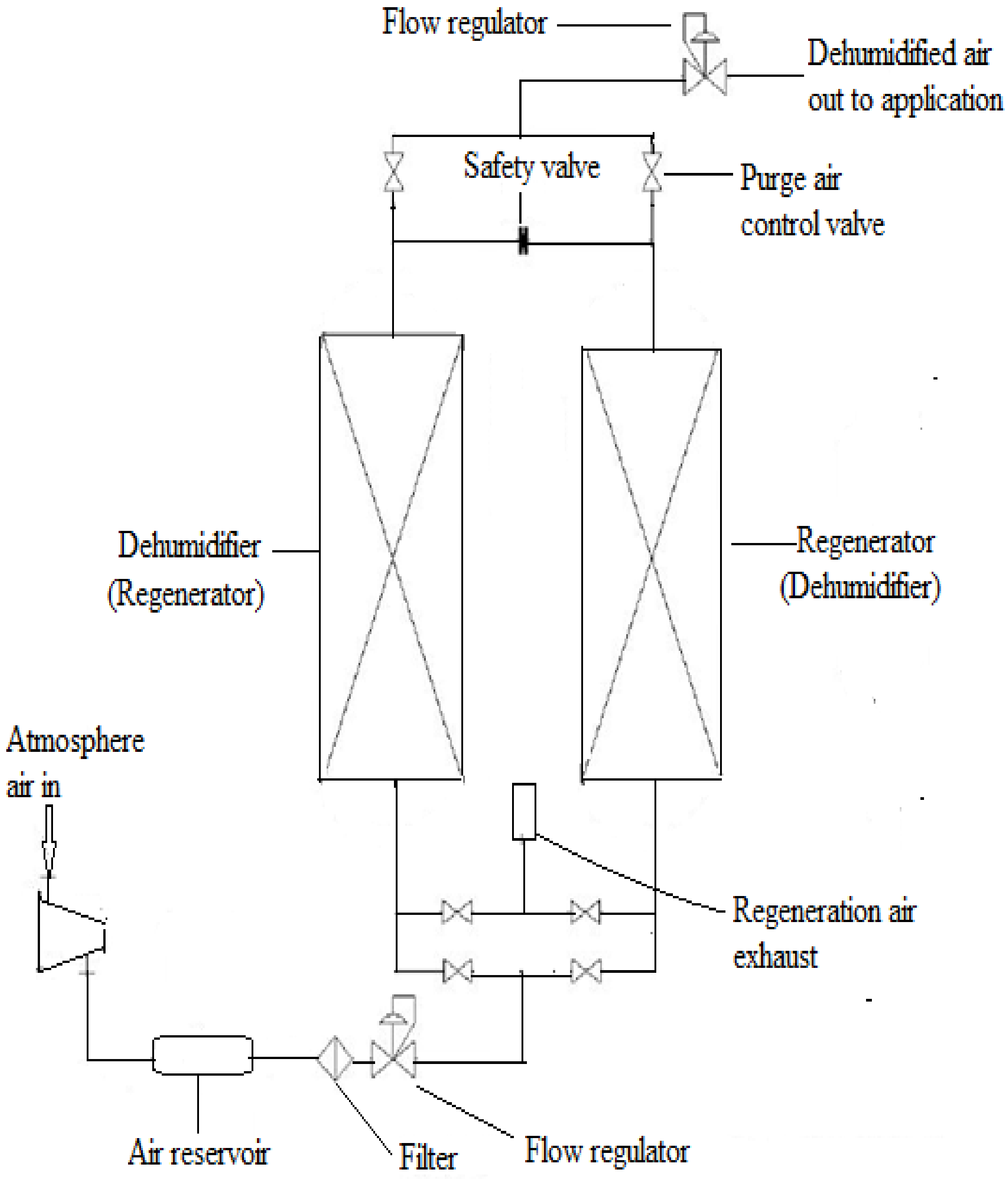

Fig.1 Diagram of developed setup

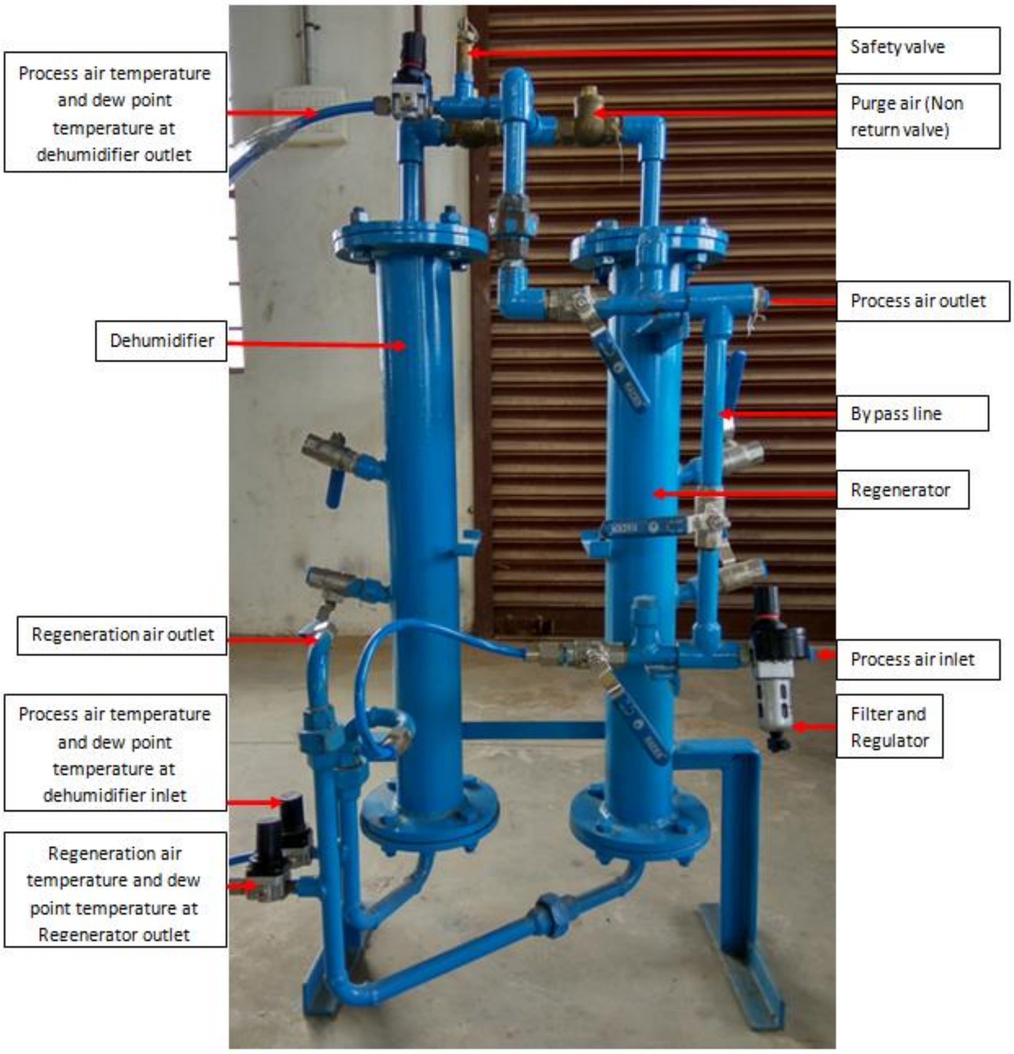

Fig.2 Photographic view of developed setup

Results analysis

S/N (Signal to Noise) ratio

In this experiment, higher the adsorption rate is preferred as a response among the runs. The estimated S/N ratio for all the parametric setting is given in Table 2.

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

Table 2 Estimated S/N ratio

Exp. No	Parameter level			Moisture adsorption	S/N ratio
	A	B	C	g/hr	
1	1	3	3	98.00	39.9127
2	2	1	2	77.97	37.9492
3	1	4	4	76.80	37.8196
4	2	2	1	74.34	37.5405
5	1	2	2	67.75	36.7455
6	2	4	3	111.00	40.9844
7	2	3	4	89.24	39.1080
8	3	2	4	95.28	39.6707

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9	3	1	3	126.00	42.0761
10	3	3	1	111.00	40.9844
11	1	1	1	53.55	34.7359
12	4	2	3	73.25	37.4139
13	3	4	2	104.00	40.4238
14	4	3	2	97.00	39.8245
15	4	1	4	65.25	36.4237
16	4	4	1	77.90	37.9415
				Mean, $\bar{Y}$	38.7221

Table 3 Table for Signal to Noise ratio

	A	B	C
Level 1	37.30	37.80	37.80
Level 2	38.90	37.84	38.74
Level 3	**39.79**	**39.68**	**39.10**
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

ANOVA

The influence of significant parameter is determined by ANOVA. From Table 4, it is concluded that parameters namely, process air pressure at entry, Desiccant mass, Purge air flow rate contributes the better moisture adsorption rate by 51.11%,19.25% and 21.66% respectively.

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

$$\text{Adsorption rate} = -82.2032+76.3450\,A+21.3728\,B+55.1407\,C-10.2081\,A^2-0.7369\,B^2-6.8756\,C^2-3.1842\,A*B-5.0776\,A*C-3.5010\,B*C \quad (1)$$

$$R^2 = 92.02\ \%$$

Since R^2 value is close to unity, this developed model can be used as an objective function for analyzing the same using confirming experiment to find out the optimal value of parametric condition. Using equation 1, the theoretical output of the dehumidification system for optimal parametric condition is calculated and the value is 111.63 gram/hour.

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	51.11
B	2	1181.58	1181.58	393.86	5.08	19.25
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			

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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 (Table 5). From the results, it is concluded that the optimal parametric conditions are refined by confirmation experiments for the same output as in Taguchi method.

Table 5 Comparison of results

S.No	Optimization tool	Optimal parameters		Adsorption rate (gm/hr)		Percentage of error
				Theoretical value	Experimental value	
1	Taguchi method	A	7 bar	111.63	107.37	3.78 %
		B	2000 gram			
		C	15 %			
2	Confirmation experiment	A	5.844 bar	111.68	108.50	2.82 %
		B	2000 gram			
		C	12%			

Conclusions

A developed pressure-swing dehumidification system is investigated to get the significant parameters influence on adsorption rate using molecular sieve 4A desiccant. It is concluded that:

- The optimal dehumidification parameters are found using Taguchi method and confirmation experiment, 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 adsorption system design.
- From the analysis, it is concluded that feed air moisture in the developed system influences more on the adsorption rate of water vapour.

Nomenclature

°C	degree Celsius
DPT	Dew point temperature
m	Metre
NRV	Nonreturn valve
%	Percent
R^2	Regression coefficient

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