An experimental assisted mathematical modeling to study the desorption capacity of the clay based solid desiccant

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Abstract
Since the moisture present in the vegetables and fruits are initially more, they are endangered to spoil quickly. The ability of the desiccant materials to absorb moisture can be used for drying. By incorporating desiccants in the drying process, drying can also be carried out during no sunshine periods. The absorbed moisture can be desorbed by passing hot air stream through the desiccants. A cylindrical desiccant mould with varying diameters of concentric holes, comprising of vermiculite (20%), bentonite (60%), cement (10%) and calcium chloride (10%) has been prepared. The sizes of the concentric holes were made in three different diameters as 6, 12 and 18 mm. Different mass flow rates and temperatures were followed to conduct the experiment as per Box- Benhen design. The ANOVA analysis was performed to arrive the percentage of contribution of influence over the desorption. Various indicators including the percentage of error between measured and predicted responses were employed to uphold the accuracy of the proposed mathematical model. The extensive statistical study reveals that the 6 mm of hole diameter, 0.003 Kg m\(^{-2}\)s of mass flow rate and 60 °C temperature are the optimal parameters for the solid desiccant to regenerate effectively.

1. Introduction
The quality of vegetables and fruits are easily imperiled, because of the presence of more moisture content. Hence, the drying is not properly done, it will lead to a considerable amount of spoilage [1]. Drying is a heat transfer process to any product and dissipation of moisture to the environment (mass transfer) until equilibrium moisture level reaches. Different methods of drying can be adopted for various substances [2]. The traditional solar drying is very late and more loss will occur with product quality reduction [3]. For small farmers, one of the useful processes of food preservation is open sun drying. But, it is not useful during the no sunshine periods. During no sunshine period, the availability of solar energy has a problem with energy storage. The ability to absorb moisture by the desiccants is apt for drying processes [4].

Drying was carried out to test the absorption capability of magnesium perchlorate with exfoliated vermiculite. The prepared desiccant was having the physical contents of 9287 g/ Cu ft. bulk density. However, the carrier weight and anhydrous magnesium perchlorate were 23.75 and 76.25% respectively. The desiccant absorbed 34.5% of its weight [5]. For dehumidification of air in the dryer chemical desiccants were also used. Among desorption ability of various desiccants, the regeneration of silica gel using direct solar energy was technically viable and found that the higher airflow rate enhances the desorption ability due to increased mass transfer co-efficient and the difference in humidity ratio [6]. With the same glaze surface, two types of the solar system were developed to test the regeneration of silica gel with particle sizes range between 2–4 and 6–8 mesh. Both systems found to be more efficient and energy saving than the conventional electric dehumidifiers [7]. A SDERC (Solar Desiccant Enhanced Radiative Cooling) system which comprises three alternate systems was built on the two sides of the house and on the rooftop. Silica gel with 6–8 mesh particle size was used as a solid
humidity were the in absorption unit enhanced the drying and minimize the drying time to 44 h from 52 h. The desiccant absorbed 33% more moisture fabricated and tested experimentally. The results revealed that the desiccant moulds with 5 mm particle size cement and calcium chloride, the vermiculite particles size can be checked. Four kinds of desiccants have been mirror improved the drying potential by 20% and reduced the drying time sunshine periods for drying 20 kg of sliced pineapple and green peas. The inclusion of desiccants and re-chamber, reversible type fan and a centrifugal blower was fabricated to function during sunshine and no phase change materials has practical difficulties. The vital problems in salt hydrates were low thermal conductivity, regeneration of salt during repeated charging and discharging cycles and recrystallization. Agricultural products were dried using a rock bed slat plate drier coupled with a thermal storage system. A solar desiccant wheel was fabricated and compared the enthalpy of air at the inlet and outlet. The set up consisted of a heater by which the desiccant wheel is regenerated and the air conditioning process was kept in control. The efficiencies of the desiccant wheel improved when the speed of the desiccant wheel increased to 24 revolution/hour from 4 revolution/hour. A study on regeneration and dehumidification of a cross-flow air-liquid desiccant contacting surfaces was carried out using calcium chloride solution as a liquid desiccant. The results revealed that the system’s payback period is 11 months and the cost/year is reduced by 31.24% in comparison with the vapour compression system (VCS). In the aspect of energy efficiency, regenerating the desiccants at low temperature has more benefits. To reduce the operation cost electric heater, unused heat and solar energy can be used for regeneration in general.

A conventional desiccant consisted of silica gel was fabricated and compared with a novel Composite Desiccant material (CDM). The new CDM fabricated with silica gel and LiCl in an optimized method had a lower regeneration temperature for the same moisture removal. The study also revealed that the higher regeneration temperature is influencing more on moisture removal but beyond a certain temperature, moisture removal ability is not obvious.
From the review of literature, knowledge of regeneration ability of the composite solid desiccant, within the suitable range of the air temperature and flow rate of drying air is necessary for the betterment of farmers. Therefore in this work, the optimum mass flow rate and temperature of drying air for the faster regeneration of composite solid desiccant is chosen.

2. Experimental design, materials, and methods

2.1. Materials

Low-cost solid desiccant consists of bentonite, vermiculite, calcium chloride and cement. Three various types of moulds were prepared with the composition of vermiculite (20%), bentonite (60%), cement (10%) and calcium chloride (10%) as shown in table 1. Figures 1 (a) and (b) shows the pictorial view of mould components while, figure 2 represents the pictorial view of sample moulds.

| S.No. | Type | Composition |
|-------|------|-------------|
| 1     | Type 1 | Bentonite (60%), Vermiculite (20%) Calcium chloride (10%), and Cement (10%) with 6 mm multiple holes (8 nos.) |
| 2     | Type 2 | Bentonite (60%), Vermiculite (20%) Calcium chloride (10%), and Cement (10%) with 12 mm multiple holes (5 nos.) |
| 3     | Type 3 | Bentonite (60%), Vermiculite (20%) Calcium chloride (10%), and Cement (10%) with 18 mm multiple holes (3 nos.) |
3. Methods

A desiccant bed of $0.5 \times 0.3 \times 0.3 \text{ m}^3$ was prepared to examine the regeneration ability of the solid desiccant. Insulation was done at inside of the desiccant chamber and the desiccants were placed at the bottom of the chamber which was prepared by steel wire mesh, acts as a tray. Figure 3 depicts the photographic view of the desiccant chamber as per the details given in the table 2.

With proper composition of desiccant components [15], moulds were prepared in three different configurations. The moulding mixture was prepared and filled inside the split patterns, which has the height and diameter of 115 and 75 mm, respectively with multiple holes. Moulds were removed from the pattern after it became solid. After fabricating the moulds, they were placed within the oven for 24 h at $50^\circ \text{C}$ for processing and another 24 h for expelling the water and moisture. Now completely dried solids moulds were prepared. The dry moulds were weighed by an electronic weighing apparatus of 0.1 g accuracy and kept on the desiccant chamber tray. A pictorial view of the fabrication of mould is shown in figure 4.

An electrical heater was employed to heat the air during the regeneration process and the required temperature of the air was maintained between 55 to 65 $^\circ \text{C}$ by using a temperature controller. An electric blower was used to pass the air through the desiccants which were placed inside the chamber. The mass flow rate was manipulated between 0.001 and 0.003 kgm$^{-2}$s$^{-1}$ using control valves. To monitor the temperature, three thermocouples were placed at the entry and exit of the desiccant chamber and at the heater space, respectively. All three thermocouples were connected with the digital temperature indicators. Hot air with various temperature and mass flow rate is allowed to pass through the desiccants. Moulds were weighed at every hour interval and noted. Measurement was done three times under the same conditions thrice and the average value was considered to obtain the proper result.

Percentage of moisture desorbed is determined by using the equation (1).

\[
\text{Moisture percentage} = \frac{W_w - W_d}{W_d} \times 100
\]  \hspace{1cm} (1)

where,

$W_w$, $W_d$ -weight of the dry and wet mould, respectively.

### Table 2. Details of desiccant chamber.

| Type of desiccant chamber | Direct type with forced-circulation |
|---------------------------|-----------------------------------|
| Dimensions of chamber | $0.5 \times 0.3 \times 0.3 \text{ m}^3$ |
| Number of desiccant trays | Single |
| Insulation | Thermocol of 10 mm thickness |
| Blower | 650 W |
| Heater | 850 W |
| Air flow rate | Up to 200 m$^3$h$^{-1}$ |
| Air duct specification | 50 mm diameter, insulated pipe |

Figure 4. Pictorial view of moulds inside the oven.
4. Mathematical model

The nonlinearity behaviour of absorption and desorption weighed after the experiments need an investigation of the nonlinear model to arrive the optimum correlation between predicted and experimental results. RSM is a key statistical tool, which is used to execute and model the relationship between independent and dependent variables as follows

\[
\text{Response(Desorption)} = f(h, m, t) + \text{errors}
\]

Usually residual errors are used to quantify the experimental errors in this study. The response Y is written in quadratic polynomial regression as follows
\[ Y = a_0 + \sum_{i=1}^{3} a_i x_i + \sum_{i=1}^{3} a_{ii} x_i^2 + \sum_{i<j}^{3} a_{ij} x_i x_j \]  

Where, \( a_0 \) is a constant, \( a_i, a_{ii} \) and \( a_{ij} \) are the coefficient of linear, quadratic and interaction terms respectively.

The inclusion of holes in the desiccants, mass flow rate and temperature to influence the absorption and desorption, draws the expression of individual response \( Y \) as follows.
As per RSM design layout 15 experiments were carried out. The analysis of response data were executed on Central Composite Design (CCD) basis with face centred cubic point [21–28]. A full factorial design was framed by including all factors at two levels. The mid-point of the face centred cubic was considered as star point which locates at the mid of the value of \( \alpha \) as 0. The higher and lower values of \( \alpha \) are +1 and −1 respectively. The mid-point value of the factors considered were 12 mm of hole diameter, 0.002 Kg m\(^{-2}\)s of mass flow rate, and 60\(^\circ\)C of temperature. The table 3 shows the experimental parameter and their levels. Table 4 shows the values of recorded responses for each experimental trial as per the design sequence and order of levels.

5. Results and discussions

The Box Benhen design was employed to model and analyze the influence the effects of experimental parameter on desorption. The ANOVA analysis was executed to uphold the efficiency of the proposed mathematical model. Few indicators like significance of the model, significance of coefficient of the model, test for lack of fit and an adequacy precision were utilized to show case the accuracy of the model [29, 30]. In the extension of ANOVA analysis, ranking of influence and percentage of contribution of influence over the response were also executed. Table 5 shows the ANOVA analysis for absorption, from the table, it is quite obvious that the hole diameter influences the desorption capacity of the desiccant in most significant way, because the p-value is very much less than 0.05. Similarly another parameter mass flow rate also impacts the desorption in considerable way, as its score second rank. The third parameter is considered to be least significant parameter, which does not impact much. The figure 5 shows the main effect plot which also confirms the ranking influence level of each parameter. A\(_1\)B\(_3\)C\(_2\) are considered to be the optimum level of parameter for the efficient desorption. More number of holes with lesser diameter implies the distributed surface area promotes desorption ability in an efficient way. However, the more volume of air obviously absorbs more moisture from the desiccant. But the effect of temperature seems to be moderate due to the combined effect of distributed surface area of the desiccant and more volume of air during the experiment.

Figure 6 shows the surface graphs have been plotted to analyze the effect of various parameters over desorption. Figure 6(a) explores the trend of increasing the capacity of desorption with the increment of mass flow rate and also with more number of holes with lesser diameter. This phenomenon attributes to the larger the mass the higher desorption and more holes with lesser diameter, higher the distributed surface area. Figure 6(b) acknowledges the same fact that, more holes with lesser diameter aids the desorption capacity, due to the penetration of hot air through the moisture filled desiccant in an uniformly distributed way additionally moderate increment in temperature also ensures the desorption capacity. Figure 6(c) highlights the fact of increasing desorption with increase in both mass flow rate and temperature.

\[
Y = \alpha_0 + \alpha_1 h + \alpha_2 m + \alpha_3 t + \alpha_{11} h^2 + \alpha_{22} m^2 + \alpha_{33} t^2 + \alpha_{12} hm + \alpha_{23} mt + \alpha_{31} th
\]

Desorption = 0.8953 − 0.0306A + 0.025B + 0.0181C − 0.0042AB− 0.0055AC + 0.0053BC + 0.0928A\(^2\) − 0.0039B\(^2\) − 0.0127C\(^2\)
The predicted uncoded value of desorption was calculated using the regression equation. The plotted graph between the measured value and predicted one is shown in figure 7. The percentage error was calculated between measured and predicted one for each experimental reading, and is shown in table 6. The maximum error recorded between measured and predicted response is 1.11%. The value of $R^2$ and Adj $R^2$ from the ANOVA analysis is very closer to the value of unity. This phenomenon emphasizes that the proposed model is accurate and valid.

Figure 8 confirms the optimized parameters for the highest desorption are 6 mm hole diameter, 0.003 Kg m$^{-2}$s of mass flow rate and 60 °C of temperature. The lesser diameter hole reflects the reduced area of contact. Whenever the effective mass transfer area becomes reduced this promotes the mass transfer coefficient as acknowledged by the following equation

$$k_e = \frac{\dot{n}_A}{A \Delta C_A}$$  

| Experiment no | Measured (desorption) | Predicted (desorption) | Percentage of error |
|---------------|-----------------------|------------------------|---------------------|
| 1             | 0.937                 | 0.9328                 | 0.45                |
| 2             | 0.922                 | 0.9322                 | 1.11                |
| 3             | 0.884                 | 0.8803                 | 0.42                |
| 4             | 0.863                 | 0.8666                 | 0.42                |
| 5             | 0.921                 | 0.9271                 | 0.66                |
| 6             | 0.894                 | 0.8953                 | 0.15                |
| 7             | 0.847                 | 0.8408                 | 0.73                |
| 8             | 0.983                 | 0.9825                 | 0.05                |
| 9             | 0.979                 | 0.9856                 | 0.67                |
| 10            | 0.899                 | 0.8953                 | 0.41                |
| 11            | 1.04                  | 1.0441                 | 0.39                |
| 12            | 0.957                 | 0.9575                 | 0.05                |
| 13            | 1.04                  | 1.0297                 | 0.99                |
| 14            | 0.893                 | 0.8953                 | 0.26                |
| 15            | 0.981                 | 0.9743                 | 0.68                |
Where, \( k \) is mass transfer coefficient, \( \dot{n}_A \) is mass transfer rate, \( A \) is the effective mass transfer area and \( \Delta_{CA} \) driving force concentration difference. It is obvious that the increased mass transfer coefficient with lesser diameter hole enhances the dissipation capacity of the solid desiccant.

6. Conclusions

The mathematical model of desorption capacity of solid desiccant, earned through Response Surface Methodology has been elaborated in this article. The influence of hole diameter, mass flow rate and temperature over the desorption capacity has been analyzed through RSM platform. The following conclusions were arrived:

1. The multiple hole with 6 mm hole diameter is the key parameter to influence the desorption capacity, followed by the mass flow rate.
2. Very meager error of 1.11% has been recorded between the predicted and observed responses
3. The results of ANOVA confirms the ranking sequence of influences as hole diameter, mass flow rate and temperature.
4. The surface graphs acknowledge that the increased mass flow rate improves the desorption capacity of the solid desiccant.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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