Performance Evaluation of Solid Desiccant Wheel Dehumidifier for Agricultural Crop Drying

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Abstract

The performance of the rotary bed desiccant dehumidifier was evaluated for different air mass flow rates of 0.32, 0.63, 0.95 and 1.30 kg s⁻¹ and different reactivation temperatures of 60, 70, 80, 90, 100, 110 and 120 °C, respectively. Obtained experimental data including temperature and absolute humidity at both process and reactivation side via random factorial scheme are analyzed. Comparison of data average is carried out with the help of the multi amplitude test of Tukey. Statistical analysis of experimental data shows that reactivation temperature (RT) and air mass flow rate (AMFR) have a reasonable impact on the process and reactivation out temperature and absolute humidity. However, a combined effect of reactivation temperature (RT) and air mass flow rate (AMFR) on process and reactivation out temperature and absolute humidity is not meaningful (p>0.05). Process air inlet moisture content affects outlet moisture, if air is more humid entering the dehumidifier, it will be more humid leaving the unit. More moisture is removed from the process air as inlet humidity ratio increases. Process air mass flow rate through the desiccant bed strongly affects leaving moisture. Outlet humidity ratio is less if process air flow rate is less. Thus, more moisture is removed when the air mass flow rate is less. Results shows that by controlling air mass flow rate and reactivation temperature, a good range of temperature can be attained which is suitable for drying of agricultural crops at low humidity. Low temperature food drying enhances the product quality, drying rate and retention of nutrients.

1. Introduction

Drying is one of the most common used method which improves the shelf-life of the food products. However, drying is not only the efficient and economic method but also yield high quality products based on flavor, nutrients, color, rehydration, uniformity, appearance and texture (Zhang et al., 2015). Food loss and waste are heavily dependent on the specific conditions and local situation in a given country or culture. It is estimated yearly global food loss and waste by quantity at roughly 30% of cereals, 40–50% of root crops, fruits and vegetables, 20% of oilseeds, meat and dairy products, and 35% of fish after harvest because of inefficient handling and poor implementation of post-harvest technology (FAO, 2015). Most of the agricultural food products are normally harvested at a moisture content of 18% to 40% depending on the nature of the crop needs to be dried to a level of 7% to 12% depending on storage and market requirement. Research work in industrial drying has intensified in recent years to reduce energy use and operating costs. The approach has changed from modifications of existing dryer systems to development of new designs and concepts (Mujumdar, 2007). Some significant developments in food product drying are dry-aeration, multistage drying (Cernisev, 2010), a combination of low humidity and low temperature drying (Nagaya et al., 2006), layer drying, drying with intermittent rest periods, recirculating the exhaust air, stir drying and use of food preservatives.

Desiccant dehumidification was initially investigated for use in air-conditioning in order to reduce energy consumption
and improve efficiency of vapor-compression systems. Now a day, solid desiccant cooling technology has become a research focus for its features of energy-saving and eco-friendly (Ge et al., 2013). The advancements made in desiccant technology led to its expansion into other fields such as crop protection (Clements and Jackson, 1989), aeration and cooling of stored grain (Thoruwta et al., 1998), food production (Davies, 2005) and grain drying (Hodali and Bougard, 2001). Desiccant wheel is the main part of desiccant dehumidifier which is filled with desiccant material. Solid desiccant using silica gel has been investigated for use in air-conditioning applications and air dehumidification systems especially in food processing and beverages (Krishna and Murthy, 1989; Ahmed et al., 2005). Among commercially available desiccants, silica gel, activated alumina, and activated charcoal have high adsorption capacities. Conventionally, the dry air is produced by cooling the air below the dew point temperature (Mitchell and Braun, 1997) but this system is costlier and consumes more electricity. Now a day’s desiccant dehumidifier is used for food drying purpose which is a best alternative method. The dehumidified air is also used in food processing industries for drying of food product. Desiccant dehumidifier enhances the drying rate and reduces drying time because the low humidity air has better moisture adsorption capacity. Low temperature and low humidity can be acquired for drying of agricultural produce by controlling reactivation temperature and air mass flow rate. Low temperature drying of agricultural produce leads to high retention of nutrients and better quality. Hence, desiccant dehumidifier is the best alternative method for food drying. This paper presents the performance of a compact bed rotary desiccant dehumidifier, effect of reactivation temperature and air mass flow rate on adsorption and desorption side.

2. Materials and Methods

Performance studies of desiccant dehumidifier were carried out in two phases; adsorption at process side and desorption at reactivation side. The experiment was conducted in the month of February, 2013 and the process inlet temperature and relative humidity maintained constant throughout the experiment. The temperature and relative humidity was maintained at 26.8 °C and 42.3%.

Experimental tests were carried out in the Renewable Energy Laboratory of Department of Processing and Food Engineering, College of Agricultural Engineering and Technology, CCS HAU, Hisar which is located at 29°10'/N latitude and 75°46'/E longitudes with an altitude of 215 meters above mean sea level in semi-arid region of North Western India.

2.1. Description of desiccant dehumidifier

A rotary bed desiccant dehumidifier is a device that removes moisture from air but do so without cooling the air below its dew point. Desiccant dehumidifier comprises of a desiccant wheel filled with silica gel, reactivation heater and blower. The desiccant wheel is further divided into 2 portions called adsorption (process side) and desorption (reactivation side). About 75% of the wheel area is used for adsorption and the remaining is used for desorption. In a desiccant dehumidifier, water vapor from a process stream of moist air adsorbs onto the surface of a desiccant material. Eventually, the desiccant material becomes saturated with water and must be regenerated through a drying process. The process and reactivation air streams operate at the same time and a wheel of desiccant material rotates between the streams. At any given time, a portion of the desiccant is being regenerated while the remainder is adsorbing water from the process stream.

The working of the rotary bed desiccant dehumidifier has been explained in Figure 1. The desiccant begins the cycle at point one. Its surface vapor pressure is low because it is dry and cool. As the desiccant picks up moisture from the surrounding air, the desiccant surface changes to the condition described by point two. Its vapor pressure is now equal to that of the surrounding air because the desiccant is moist and warm. At point two, the desiccant cannot collect more moisture because there is no pressure difference between the surface and the vapor in the air. The desiccant surface vapor pressure is now very high, higher than the surrounding air, so moisture moves off the surface to the air to equalize the pressure differential. At point three, the desiccant is dry, but since it is hot, its vapor pressure is still too high to collect moisture from the air.

2.2. Performance evaluation of rotary bed desiccant dehumidifier

The moisture removal capacity (MRC) is used as performance indicator for rotary bed desiccant dehumidifier. The MRC is defined as the mass of water vapor removed from the process air unit⁻¹ of time.
MRC = \frac{m_{PA} \times (W_{PA, in} - W_{PA, out})}{\Delta T_{PA}}

Where,
MRC = Moisture removal capacity, g s\(^{-1}\)
m\(_{PA}\) = Process air mass flow rate, kg s\(^{-1}\)
\(W_{PA, in}\) = Mass of water vapor present in the process air at inlet
\(W_{PA, out}\) = Mass of water vapor present in the process air at outlet

The experiments performed at 4 air mass flow rates of 0.32, 0.63, 0.95 and 1.30 kg s\(^{-1}\) and 7 reactivation temperatures viz., 60, 70, 80, 90, 100, 110 and 120 °C, respectively. The experiments were repeated 3 times at each reactivation temperature and air mass flow rate, and experimental results were recorded. The ambient temperature and relative humidity were maintained at 26.8 °C and 42.3% throughout the experiment. Obtained experimental data including temperature and absolute humidity at both process and reactivation side were analyzed via random factorial scheme. Comparison of data average is carried out with the help of the multi amplitude test of Tukey. The Statistical Analysis Software (SAS) system was used for this purpose.

2.3. Observations recorded
2.3.1. Temperature
The temperature was recorded using digital thermo hygrometer located at the ambient, process inlet, process outlet, reactivation inlet, reactivation outlet. Operating range of the device was from -20 °C to 200 °C with an accuracy of ±2%.

2.3.2. Relative humidity (RH)
The RH of air was measured again with digital thermo hygrometer located at the ambient, process inlet, process outlet, reactivation inlet, reactivation outlet. Operating range was from 0 to 100% with resolution 0.1% RH and accuracy ±3.5% RH.

2.3.3. Air flow rate
The velocity of air was measured with digital anemometer located at the process inlet, process outlet, reactivation inlet, reactivation outlet. The air mass flow rate of air was calculated by multiplying air velocity with duct area and density of air.

3. Results and Discussion
3.1. Effect of change in reactivation temperature at process side
The maximum and minimum temperature at process out was 57 °C and 40 °C at the reactivation temperature of 120 °C and 60 °C at air mass flow rate of 0.32 kg s\(^{-1}\) likewise at the reactivation temperature of 60 °C and air mass flow rate 1.3 kg s\(^{-1}\), the process out temperature decreased to 37 °C. Figure 2 also shows that process out temperature decreases with increase in process inlet air mass flow rate and the process out temperature increases with increase in reactivation temperature. It was found that at higher reactivation temperature and low process

TPO- Process out temperature, AMFR-Air mass flow rate, RT- Reactivation temperature

Figure 2: Influence of reactivation temperature on process out temperature at different air mass flow rates

The results of variance analysis of process out temperature are listed in Table 1. In this table, degree of freedom and sum of squares for each factor are estimated according to the no. of considered levels and the obtained experimental data. In the

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob.</th>
</tr>
</thead>
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<tr>
<td>RT</td>
<td>6</td>
<td>2616.65</td>
<td>436.11</td>
<td>436.11</td>
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<tr>
<td>AMFR</td>
<td>3</td>
<td>178.61</td>
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<tr>
<td>RT×AMFR</td>
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<td>9.64</td>
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<td>0.54</td>
<td>0.93</td>
</tr>
<tr>
<td>Error</td>
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<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Corrected</td>
<td>83</td>
<td>2860.89</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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</table>
was 17.7% and 12.8% at air mass flow rate of 1.3 kg s⁻¹ and 0.32 kg s⁻¹ at reactivation temperature of 60 °C. The difference between the relative humidity at higher and lower air mass flow rate was 4.9%. It was also observed that at reactivation temperature of 120 °C, the maximum and minimum relative humidity at process out was 10.7% and 7.6% at air mass flow rate of 1.3 kg s⁻¹ and 0.32 kg s⁻¹. The results showed that the average value of relative humidity at process out was 11.5% when the ambient relative humidity throughout the experiment was maintained at 42.3% (Figure 3). With respect to variance analysis of process out relative humidity which is listed in Table 2 shows that reactivation temperature and air mass flow rate, individually have a reasonable impact on process out relative humidity but their combined effect is not meaningful (p>0.05).

Adsorption capacity is the capacity of the desiccant wheel to absorb moisture on the surface and it is the difference between process inlet and process out absolute humidity as shown in Figure 4. It was observed from the results that the adsorption capacity decreases with increase in reactivation temperatures. It was observed that the maximum adsorption capacity in process side is 3.5 g kg⁻¹ dry air at 60 °C reactivation temperature and at air mass flow rate of 0.32 kg s⁻¹.

The adsorption capacity decreased to 2.4 g kg⁻¹ dry air at an air mass flow rate of 1.30 kg s⁻¹ and reactivation temperature of 60 °C. The minimum adsorption capacity at process side is 1.1 g kg⁻¹ dry air at 120 °C reactivation temperature and process air mass flow rate of 0.32 kg s⁻¹ likewise, at the reactivation temperature of 120 °C and air mass flow rate 1.30 kg s⁻¹, the adsorption capacity decreases to 0.2 g kg⁻¹ dry air. It is also observed that the adsorption capacity at process side decreases with increase in air mass flow rates. With respect to variance analysis of adsorption capacity at process side which is listed in (Table 3) shows that reactivation temperature and air mass flow rate have a reasonable impact on process out adsorption capacity, but their combined effect is not meaningful (p>0.05).

3.2 Effect of change in reactivation temperature at reactivation side

The maximum temperature at reactivation side was 68 °C when reactivation temperature and air mass flow rate of was

![Interaction plot for RHPO](image)

Interaction plot for RHPO

**AMFR** 0.32 + 0.62 × 0.95 + 1.3

![Interaction plot for WPO](image)

Interaction plot for WPO

**AMFR** 0.32 + 0.62 × 0.95 + 1.3

Figure 4: Effect of reactivation temperature on adsorption capacity at process side at different air mass flow rates

**WPO-** Process out adsorption capacity, **AMFR-Air mass flow rate, RT- Reactivation temperature**

Table 2: Effect of different parameters on process out relative humidity with respect to variance analysis

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
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<th>Mean square</th>
<th>F value</th>
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<tbody>
<tr>
<td>RT</td>
<td>6</td>
<td>397.09</td>
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<tr>
<td>AMFR</td>
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</tr>
<tr>
<td>RT×AMFR</td>
<td>18</td>
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<td>0.29</td>
<td>0.30</td>
<td>0.9</td>
</tr>
<tr>
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<td>56</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Corrected</td>
<td>83</td>
<td>619.34</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>total</td>
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</table>

Table 3: Effect of different parameters on adsorption capacity at process side with respect to variance analysis

<table>
<thead>
<tr>
<th>Source</th>
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<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob.</th>
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<tr>
<td>RT</td>
<td>6</td>
<td>397.09</td>
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<td>66.18</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>AMFR</td>
<td>3</td>
<td>160.90</td>
<td>53.63</td>
<td>53.64</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>RT×AMFR</td>
<td>18</td>
<td>5.34</td>
<td>0.29</td>
<td>0.30</td>
<td>0.99</td>
</tr>
<tr>
<td>Error</td>
<td>56</td>
<td>56</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Corrected</td>
<td>83</td>
<td>619.34</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td></td>
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<td></td>
</tr>
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</table>
120 °C and 0.32 kg s⁻¹ likewise at reactivation temperature of 120 °C and air mass flow rate 1.3 kg s⁻¹, the reactivation side temperature decreases to 62 °C. The minimum temperature at reactivation side was 46 °C at 60 °C reactivation temperature and air mass flow rate of 0.32 kg s⁻¹ likewise, at the reactivation temperature of 60 °C and air mass flow rate 1.3 kg s⁻¹, the reactivation temperature decreases to 41 °C. The results shows that the temperature at reactivation out increases with increase in reactivation temperature and decreases with increase in air mass flow rates (Figure 5). With respect to variance analysis of reactivation out temperature at reactivation side which is

Figure 5: Effect of reactivation temperature on reactivation out temperature at different air mass flow rates

It was observed from the Figure 6 that when air mass flow rate was 0.32 kg s⁻¹, the reactivation out relative humidity decreased from 15.9% at 60 °C to 7.1% at 120 °C similarly 23.3% at 60 °C to 10.2% at 120 °C, respectively at air mass flow rate of 1.3 kg s⁻¹. Results show that the relative humidity at reactivation out decreases with increase in reactivation temperature for all air mass flow rates. The reactivation out relative humidity at reactivation temperature of 60 °C was 15.9, 18.2, 20.0 and 23.3% respectively and at reactivation temperature of 120 °C, humidity’s were 7.1, 8.3, 9.0 and 10.2% respectively, at process side air mass flow rates of 0.32, 0.63, 0.95 and 1.3 kg s⁻¹ respectively. The observation shows that relative humidity increases with increase in air mass flow rate at reactivation out. With respect to variance analysis of reactivation out relative humidity at reactivation side which is listed in (Table 5) shows that reactivation temperature and air mass flow rate have a reasonable impact on process out relative humidity, but their combined effect is not meaningful (p>0.05).

Table 5: Effect of different parameters on relative humidity at reactivation side with respect to variance analysis

<table>
<thead>
<tr>
<th>Source</th>
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<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob.</th>
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<td>6</td>
<td>1119.16</td>
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<td>186.53</td>
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<tr>
<td>AMFR</td>
<td>3</td>
<td>233.70</td>
<td>77.90</td>
<td>77.90</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>RT×AMFR</td>
<td>18</td>
<td>28.96</td>
<td>1.60</td>
<td>1.61</td>
<td>0.08</td>
</tr>
<tr>
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<td>56</td>
<td>56</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Corrected</td>
<td>83</td>
<td>1437.83</td>
<td>-</td>
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<td>-</td>
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</table>

Figure 7 shows that the maximum absolute humidity at reactivation out was 14 g kg⁻¹ dry air at reactivation temperature of 120 °C and process air mass flow rate of 1.3 kg s⁻¹ and the minimum reactivation out absolute humidity was 12.8 g kg⁻¹ dry air at the reactivation temperature of 120 °C and process air mass flow rate of 0.32 kg s⁻¹. The absolute humidity in reactivation out increases with increase in reactivation temperatures for all air mass flow rates.
air flow rate and reactivation temperature thereby it is used for
drying of agricultural products in controlled conditions. Low
temperature and low humidity air can enhance the drying rate
and quality characteristics of the food materials.

5. References

and optimization of solar desiccant wheel performance.

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drying of vegetables, fruits and aquatic products.
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10.1080/10408398.2014.979280.

Table 6: Effect of different parameters on absolute humidity
at reactivation side with respect to variance analysis

<table>
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<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Prob.</th>
<th>&lt;.0001</th>
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<tr>
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<td>70.56</td>
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<td>AMFR</td>
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<td>Error</td>
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<td>2.24</td>
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<td>Corrected total</td>
<td>83</td>
<td>89.81</td>
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</table>

temperature and air mass flow rate have a reasonable impact
on reactivation out relative humidity, but their combined effect
is not meaningful ($p>0.05$).

4. Conclusion

The effect of reactivation temperature on outlet humidity ratio
was studied and it was seen that as reactivation temperature
increased, more moisture got removed from process air. Results
indicated that desiccant dehumidifier coupled with drying
chamber can create efficacious drying conditions by controlling

WRO-Reactivation out absolute humidity, AMFR-Air mass
flow rate, RT-Reactivation temperature

Figure 7: Effect of reactivation temperature on reactivation out
absolute humidity at different air mass flow rates

Absolute humidity at reactivation out increases with increase
in air mass flow rates for all the reactivation temperatures. At
reactivation temperature of 60 °C the reactivation out absolute
humidity were 10.0, 10.4, 10.8 and 11.3 g kg$^{-1}$ dry air similarly
for reactivation temperature of 120 °C, the reactivation out
absolute humidity were 12.8, 13.1, 13.5 and 14.0 g kg$^{-1}$ dry
air for process air mass flow rate of 0.32, 0.63, 0.95 and 1.30
kg s$^{-1}$. The results indicate that increase in air mass flow rate
will leads to increase in reactivation absolute humidity. With
respect to variance analysis of absolute humidity at reactivation
side which is listed in (Table 6) shows that reactivation

Interaction plot for RHRO

AMFR = 0.32 + 0.62 × 0.95 + 1.3