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Full Research Article

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 food product driers operate by heating ambient air using solar energy and electric heaters. High temperature drying can cause breakdown of enzymes, which render the produce unsuitable for consumption. Solar drying has many advantages over the mechanical methods; but relies heavily on weather conditions. Hot air increases the temperature and reduces the relative humidity of the drying air thus allows the air to carry moisture from the product. Although this is adequate in relatively dry and less humid weather, it is not possible to reduce the actual moisture level from the air in humid climates. As a result, drying by heated air becomes costly, slow and less effective. 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 (Thoruwa 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

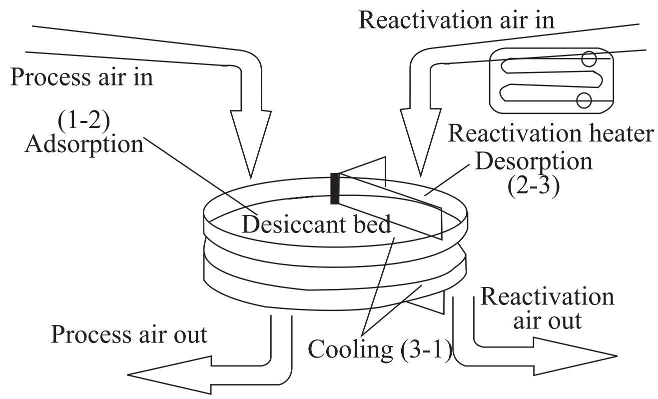


Figure 1: Operation of desiccant wheel

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.

$MRC=m_{PA}\times(W_{PA,in}-W_{PA,out})$

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.

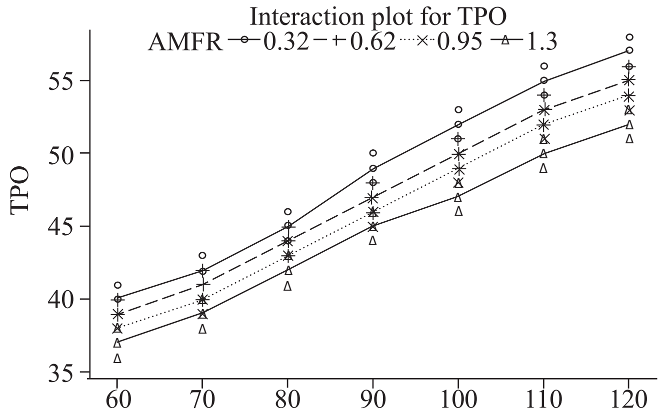
2.3.3. Air flow rate

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

inlet air mass flow rate, the process out temperatures were higher as compare to lower reactivation temperature and higher process inlet air mass flow rate.

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

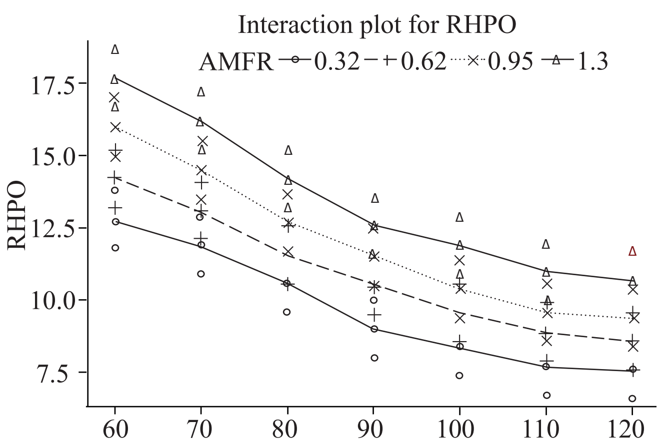
Table 1: Effect of different parameters on process out temperature with respect to variance analysis

Source	DF	Sum of squares	Mean square	F value	Prob.
RT	6	2616.65	436.11	436.11	<.0001
AMFR	3	178.61	59.53	59.54	<.0001
RT×AMFR	18	9.64	0.54	0.54	0.93
Error	56	56	1	-	-
Corrected total	83	2860.89	-	-	-

4th column, the ratio of sum of squares for each factor to its degree of freedom is given as mean square. F-value quantity is equivalent to the ratio of mean square of each factor to the error value shown in the fifth row and fourth column (mean square of error) of the table. It is a criterion for accepting the effectiveness assumption of each factor.

Probability values in the final column must be less than 5% for accepting the effectiveness assumption. So the results of this column in Table 1 show that Reactivation Temperature (RT) and air mass flow rate individually have their significant effect on process out temperature and their combined effect do not have significant impact.

The maximum and minimum relative humidity at process out 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).



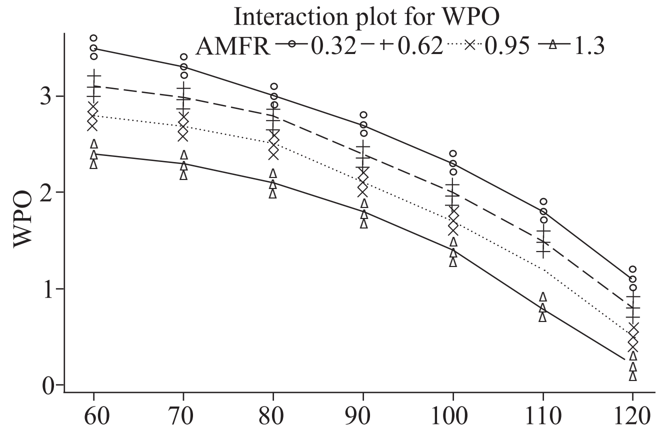
RHPO- Process out relative humidity, AMFR-Air mass flow rate, RT- Reactivation temperature

Figure 3: Effect of reactivation temperature on process out relative humidity at different air mass flow rates

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

Source	DF	Sum of squares	Mean square	F value	Prob.
RT	6	397.09	66.18	66.18	<.0001
AMFR	3	160.90	53.63	53.64	<.0001
RT×AMFR	18	5.34	0.29	0.30	0.9
Error	56	56	1	-	-
Corrected total	83	619.34	-	-	-

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}.



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

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

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).

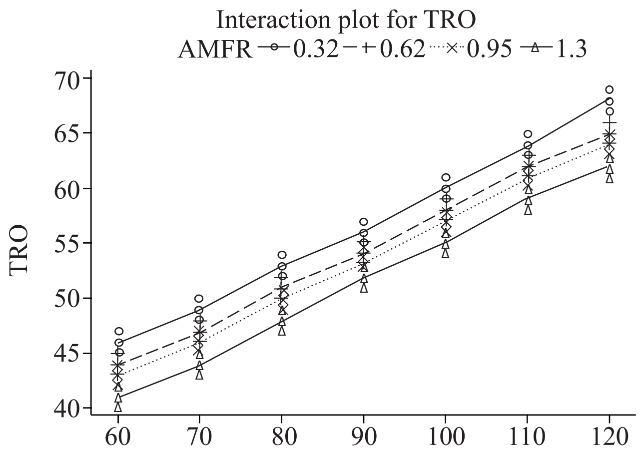
Table 3: Effect of different parameters on adsorption capacity at process side with respect to variance analysis

Source	DF	Sum of squares	Mean square	F value	Prob.
RT	6	397.09	66.18	66.18	<.0001
AMFR	3	160.90	53.63	53.64	<.0001
RT×AMFR	18	5.34	0.29	0.30	0.99
Error	56	56	1	-	-
Corrected total	83	619.34	-	-	-

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

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



TRO-Reactivation out temperature, AMFR-Air mass flow rate, RT-Reactivation temperature

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

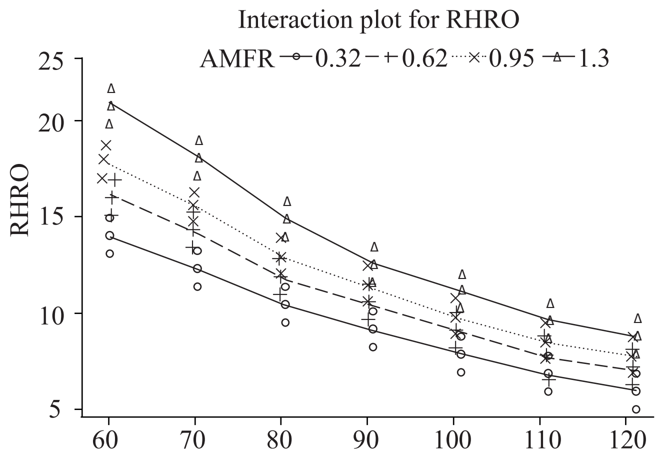
listed in (Table 4) shows that reactivation temperature and air mass flow rate have a reasonable impact on process out relative

Table 4: Effect of different parameters on temperature at reactivation side with respect to variance analysis

Source	DF	Sum of squares	Mean square	F value	Prob.
RT	6	4354.50	725.75	725.75	<.0001
AMFR	3	273.42	91.14	91.14	<.0001
RT×AMFR	18	4.07	0.22	0.23	0.99
Error	56	56	1	-	-
Corrected total	83	4688	-	-	-

humidity, but their combined effect is not meaningful (p>0.05).

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



RHRO-Reactivation out RH, AMFR-Air mass flow rate, RT-Reactivation temperature

Figure 6: Effect of reactivation temperature on reactivation out relative humidityat different air mass flow rates

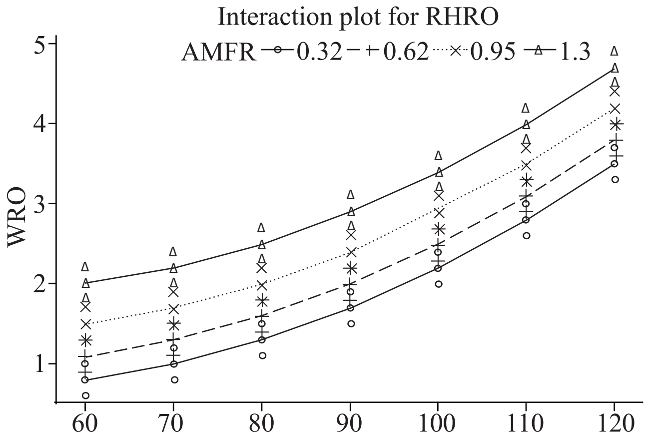
air mass flow rates. The reactivation out relative humidity at reactivation temperature of 60 °C was 15.9, 18.2, 20.0 and 23.3% respectively and at reactivation temperature of 120 °C, humidity's were 7.1, 8.3, 9.0 and 10.2% respectively, at process side air mass flow rates of 0.32, 0.63, 0.95 and 1.3 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

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

Source	DF	Sum of squares	Mean square	F value	Prob.
RT	6	1119.16	186.52	186.53	<.0001
AMFR	3	233.70	77.90	77.90	<.0001
RT×AMFR	18	28.96	1.60	1.61	0.08
Error	56	56	1	-	-
Corrected total	83	1437.83	-	-	-

reasonable impact on reactivation out relative humidity, but their combined effect is not meaningful (p>0.05).

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.



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 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).

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

Source	DF	Sum of squares	Mean square	F value	Prob.
RT	6	70.56	11.760	294.00	<.0001
AMFR	3	17.01	5.670	141.75	<.0001
RT×AMFR	18	0	0	0	1.0
Error	56	2.24	0.04	-	-
Corrected total	83	89.81	-	-	-

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 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.

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