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EXPERIMENTAL STUDY OF A DESICCANT DEHUMIDIFIER USING SILICA GEL

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Abstract*- Desiccant dehumidification techniques are cost-effective and environmentally more sustainable compared to other traditional refrigerant dehumidifiers. Among all types of desiccant based dehumidification systems, the rotary desiccant dehumidifier is the most convenient because of its easy-to-manufacture and handling process. It is a wheel of air channels containing solid desiccants. The wheel face area consists of two parts- processing area and regeneration area. The dehumidification of humid air is done by rotating the wheel periodically between the adsorption and desorption zone. The factors affecting the process are generally as follows- The adsorbent materials, Regeneration and Process area percentage, Channel size and shape, turning speed of the wheel and Condition of the air streams. In this study, an experimental analysis of silica gel rotor has been carried out for different working conditions to find out how the performance of the system changes due to the variation in air mass flow rates, regeneration air temperatures and wheel revolution on the fabricated system. The performance of the system is measured by moisture removal capacity and dehumidification efficiency. Consequently, the study can conclude on an optimized system of dehumidification.*

Keywords: Solid desiccant dehumidifier, Silica gel, Wheel rotational speed, Humidity ratio and Reactivation temperature

1. INTRODUCTION

Excessive humidity is harmful to men, machine and material. The human body regulates body temperature by sweating. Normally, sweat evaporating from the skin cools the body. But when the air is already saturated with water, sweat remains in the skin and gives an uncomfortable feeling. High level of humidity results in the increased activity of micro-organisms. Wood, building materials and other hygroscopic materials soak up moisture and gives rise to mold, mildew, and rot — powders and granulate clump together - affecting the property and causing blockages in processing equipment. It is also a major cause of corrosion and rust which results in short-circuit and flashovers in the electric device causing permanent damage. Humidity also increases the conductivity of electric wires. The three primary terms used to represent the quantity of water vapor in the atmosphere are specific humidity, absolute humidity, and relative humidity. The higher the value of these terms, the more significant water contents are in the air.

The dehumidifier is a solution to this excessive humidity problem. A desiccant dehumidifier has a different working principle compared to traditional refrigerated dehumidifiers. Desiccants are the hygroscopic materials with a high absorptivity for water vapor at moderate temperatures. At cold temperature and dry state, a desiccant absorbs moisture from the air; but if heated to regeneration temperature, it desorbs water. As larger surface area maximizes the interaction between the desiccant and surrounded air, a high surface area-volume ratio is a desirable characteristic of desiccant. Other desirable characteristics include – high sorption capacity, low regeneration temperature, low-pressure drop, inexpensive, less deterioration and maintenance [1].

A study on desiccant dehumidifiers is becoming a popular field of interest with the development of various bio-desiccants and composite desiccants [2]. Silica materials, activated carbons, zeolites, molecular sieves, activated alumina, quicklime, gypsum are some of the commonly used solid desiccants. By surveying some previous studies and by considering adsorption capacity, performance, cost, and availability, it is found that silica gel is the most suitable desiccant for this rotary desiccant dehumidifier. Microscopic interconnected pores of silica gel provide a vast surface area of 700-800 m2/gram with an intake capacity for water up to 40% of its dry mass [3]. It attracts and holds water content by adsorption and capillary condensation.

There is a bunch of experimental and simulation analysis on desiccant dehumidification system. To evaluate performance test, Ursula Eicker [4] investigated several rotors to analyze experimental uncertainties and the parameters; that control the performance of the rotors. He found that, higher the regeneration air temperatures higher the dehumidification where dehumidification efficiency remains the same. Regeneration air humidity did affect the system performance. With rising water content, the dehumidification capacity increased, while the dehumidification efficiency was not that much affected. Avadhesh Yadav and V.K. Bajpai [5] proposed a mathematical model to evaluate the performance of the desiccant rotor. The model presents the heat and mass transfer mechanism of both air and desiccant material. Kamsah, Mohamed Kamar, Zawawi [6] carried out an experimental investigation considering the influence of operating variables on the system performance under the steady-state condition. The analysis shows that both thermal effectiveness and dehumidification efficiency decrease with increasing reactivation temperature and process air velocity. The moisture removal rate improves with increasing reactivation temperature, but process air outlet velocity does not affect it. Hamamoto, Mori, and Mastuoka [3] evaluated the dehumidification performance of the rotor by choosing a suitable regeneration temperature. For different desiccant rotor, optimum regeneration temperature was found by numerical simulation to obtain dry air in a short length rotor. Antonellis, Joppolo, and Molinaroli [7] investigated desiccant wheel performance to optimize the result for better efficiency. Several performance criteria were introduced to obtain the optimal wheel criteria, and the best sectors were identified. Stevan Weintraub [8] experimented the performance based on different types of silica gels to select the most efficient cost-effective silica for a particular application. T.S. Ge and Y.Z.Dai [9] investigated one rotor two-stage rotary desiccant for air cooling. They tried to reduce the total volume of the traditional cooling system under various operating conditions with two desiccant wheels without any reduction in system performance. D.B. Jani, Manish Mishra, P.K. Sahoo [10] experimentally evaluated the operation of a desiccant and vapor-compression air conditioning system in tropical hot and humid weather. The change of performance with the change of outdoor temperature was focused.

Desiccant wheel performance with the variation of operating parameters has been analyzed by many researchers with the help of experimental investigations and mathematical simulations These inspired in doing a practical investigation of desiccant dehumidifier which will cover the impact of operating variables such as flow rate of air, wheel speed, regeneration temperature, on the overall performance of the system.

2. EXPERIMENTAL SETUP

A dehumidification wheel is a complex network of small airways with thin layers of solid desiccants applied to them. The wheel is connected with two fans on both sides to ensure that the mutually opposite flow of supply and regenerate air are passing through the wheel simultaneously. This system also has a motor by belt mechanism to rotate the wheel and a heater to heat the reactivation airstream. An electrical control panel controls the overall process. When humid air passes through the airways, desiccants remove the moisture from the air and the process releases heat of adsorption. As a result, dehumidified air becomes hotter than the inlet humid air. Hot air streaming through the reactivation zone desorbs the desiccants. Periodical rotation of the wheel through two opposite air streams ensures the continuity of adsorption and desorption spontaneously. The mixing of the humid and the regeneration is prevented by completely separating the adsorption and desorption zone of the wheel.

For this study, a cylindrical wheel with a 28 cm diameter and 10.5 cm length has been built using an aluminum sheet. A great number of parallel airways has been achieved by attaching metal roof sheets of corrugated galvanized steel on the wheel. The wheel is divided into two separate zones of processing and regenerating in such a way that both zones obtain the same amount of surface area. Silica gel is glued to the areas between airways to work as a desiccant. A-frame has been constructed using the acrylic sheet and steel bar to accommodate the wheel and other components of the system. Polystyrene foam has been used to create a barrier inside the frame to prevent the mixing of process and reactivation airstream. The wheel is placed inside the frame with the help of a fixed shaft. The shaft also allows the wheel to rotate about a drive shaft of a motor through a belt drive mechanism. A dc motor of 12V and 35 rpm drives the wheel. The r.p.h. of the wheel is varied using a buck converter in series. Two axial fans of 12v and 3A have been bolted to the opposite sides of the frame. The buck convertor also controls the airflow rates. The regeneration fan directed the flow of air towards the heater; as a result, heated air passed through the regeneration unit and reactivated the silica. An electrical tubular heater of 200W twisted with nichrome wire works as the heat source. Figure:1 represents the photograph of the fabricated system

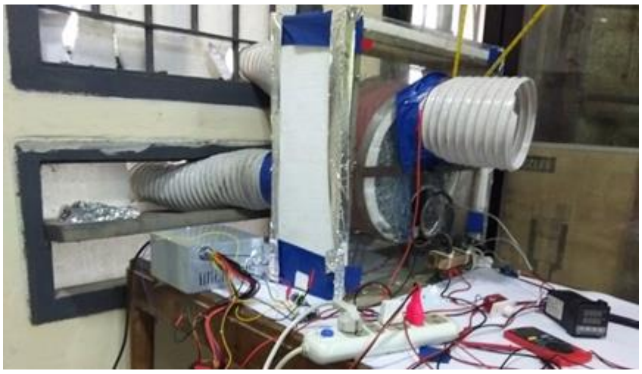

Fig..1: Photograph of experimental setup

3. EXPERIMENTAL DATA

The experiment has been carried out in an airtight room. The humidity ratio of the processed air has been measured from the psychometric chart using dry bulb and wet bulb temperature of the air. The inlet and outlet condition of air is the primary concern of this experimental analysis. For each specific analysis, inlet air condition is considered to be constant.

Moisture Removal Capacity (MRC): It represents the amount of moisture removed from moist air by using desiccant dehumidifier [11].

Dehumidification efficiency (ϵ): it indicates the performance of the dehumidification system [12].

$$MRC = \dot{m}_{da} \left(Y_{g,in} - Y_{g,out}\right) \times 1000 \tag{1}$$

$$\epsilon = \frac{Yg,in - Yg,out}{Yg,in} \times 100 \quad (2)$$

3.1 Data to Evaluate the Influence of Air Mass Flow Rate on Wheel Performance

Rotational speed and regeneration temperature was kept constant at 29 rph and 50°C while taking these data.

Table 1: Inlet data

T_{DB} (°C)	T_{WB} (°C)	RH (%)	$Y_{g,in}$ (kg/kg dry air)	ρ (kg/m^3)
25	23.7	92	0.018	1.17

Table 2: Different dry air mass flow rates

V (m/s)	A (m^2)	$m_a = \rho AV$ (kg air/min)	$\dot{m}_{da} = \frac{\dot{m}_a}{1 + Yg,in}$ (kg dry air/min)
1.5	0.0154	1.6216	1.5929
2.0	0.0154	2.1622	2.1340
2.5	0.0154	2.7027	2.6549
3.0	0.0154	3.2433	3.1860
3.5	0.0154	3.7838	3.7169
4.0	0.0154	4.3243	4.2479

Table 3: Outlet data for different air mass flow rate

$\dot{m}_{da}$ (kg dry air/min)	T_{DB} (°C)	T_{WB} (°C)	RH (%)	$Y_{g,out}$ (kg/kg dry air)	ϵ (%)	MRC (gm moisture/min)
1.59	29.7	23.7	61	0.016	11.11	3.19
2.13	30.0	23.7	59	0.0159	11.67	4.48
2.65	30.0	23.6	59	0.0157	12.78	6.12
3.19	29.7	23.8	61	0.0161	10.56	6.05
3.72	29.2	23.8	64	0.0164	08.87	5.95
4.25	29.0	24.0	66	0.0168	06.67	5.10

Table 1 represents the condition of air at inlet. Table 2 is the table of different mass flow rates of air & dry air as air is the mixture of both dry air and water vapor. Table 3 represents the MRC and efficiency of the dehumidifier for different air mass flow rates.

3.2 Data to Evaluate the Influence of Wheel Rotational Speed on Wheel Performance

The air mass flow rate for maximum dehumidification efficiency has been chosen for this analysis and regeneration temperature was kept constant at 50°C.

Table 4: Inlet data

m_{da} (kg dry air/min)	T_{DB} (°C)	T_{WB} (°C)	RH (%)	$Y_{g,in}$ (kg/kg dry air)	ρ (kg/m^3)
2.65	26	24.5	89	0.0188	1.17

Table 5: Outlet data for different wheel rotational speed

N (rph)	T_{DB} (°C)	T_{WB} (°C)	RH (%)	$Y_{g,out}$ (kg/kg dry air)	ϵ (%)	MRC (gm moisture/min)
25	28.3	24	70	0.0171	9.04	4.51
27	28.5	24	70	0.0170	9.57	4.78
29	29.2	24	65	0.0167	11.17	5.58
31	29.6	24	63	0.0165	12.23	6.12
33	29.7	24	63	0.0165	12.23	6.11
35	29.6	24.2	64	0.0168	10.63	5.31
37	29.6	24.2	64	0.0168	10.63	5.31
40	29.5	24.2	66	0.0172	8.52	4.25

Table 4 represents the inlet condition which is assumed to be constant for the performance evaluation based on different wheel speeds. Table 5 represents different RH, humidity ratio, MRC and dehumidification efficiency at outlet for different rotational speed of wheel.

3.3 Data to Evaluate the Influence of Regeneration Temperature on Wheel Performance:

Generally, the regeneration temperature of silica lies between 40°C-170°C. As here, the reactivation temperature of silica is unknown and maximum effectiveness is only 12.23 % at 50°C, regeneration temperature has been increased further to analyze the performance of the wheel.

Table 6: Inlet data

m_{da} (kg dry air/min)	T_{DB} (°C)	T_{WB} (°C)	RH (%)	$Y_{g,in}$ (kg/kg dry air)	ρ (kg/m^3)	N (rph)
2.65	24.9	23.5	87	0.0178	1.17	31

Table 7: Outlet data of different regeneration temperature

T_R (°C)	T_{DB} (°C)	T_{WB} (°C)	RH (%)	$Y_{g,out}$ (kg/kg dry air)	ϵ (%)	MRC (gm moisture/min)
50	29.4	23.4	62	0.0158	11.24	5.31
60	30	23.5	58	0.0156	12.36	5.84
70	31.4	23.7	53	0.0153	14.04	6.64
80	32.5	24	50	0.0153	14.04	6.64

90	33.6	24.2	46	0.0151	15.37	7.19
100	35	24.3	42	0.0147	17.42	8.23
110	35.8	24.3	39	0.0144	19.10	9.03
120	36.2	24.3	38	0.0142	20.22	9.56

Table 6 represents the inlet condition of air and Table 7 represents different RH, humidity ratio, MRC and dehumidification efficiency at outlet for increasing regeneration temperature.

4. RESULTS AND DISCUSSION

Dehumidifier performance for various operating conditions has been discussed below:

4.1 Influence of Air Mass Flow Rates on Wheel Performance

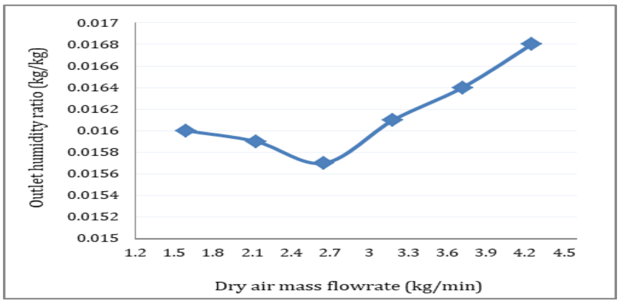

Fig. 1: Variation of outlet humidity ratio

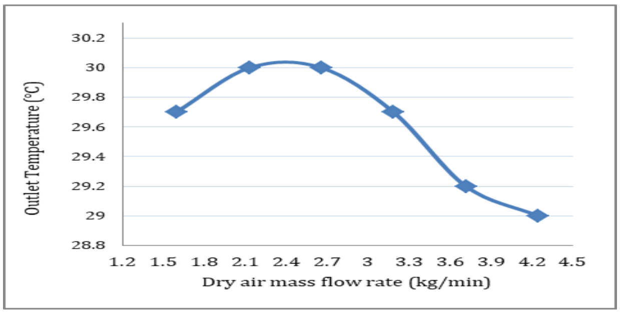

Fig. 2: Variation of outlet temperature

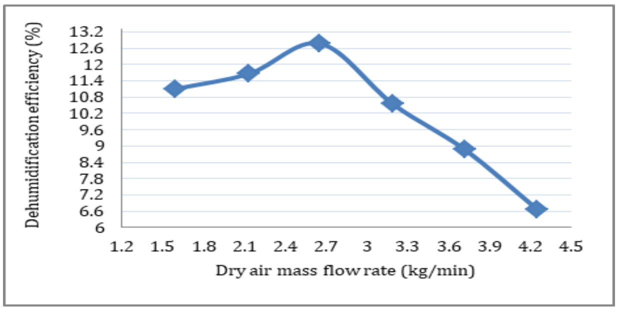

Fig. 3: Variation of dehumidification efficiency

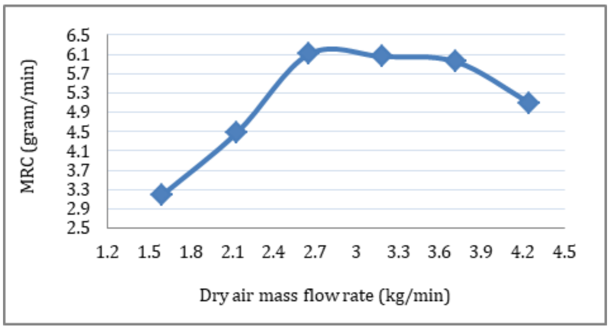

Fig. 4: Variation of MRC

Figure 1 shows that the outlet humidity ratio decreases with the increasing air mass flow rate up to a point then it starts to rise. Figure 2, Figure 3 and Figure 4 respectively represent that the outlet air temperature, dehumidification efficiency and moisture removal capacity of the wheel increase up to the minimum outlet humidity ratio point and then decrease with increasing air mass flow rate.

Initially, humidity ratio drops and dehumidification efficiency and MRC rise as silica gel absorb water vapor from the air flowing over the surface. However, the residence time of air reduces with increasing air velocity. Molecules of moisture escape the desiccant wheel without getting adsorbed. Consequently, MRC and effectiveness of the wheel gradually fall. Outlet processed air is hotter than the inlet air because of the heat of adsorption and carryover of regeneration heat by the matrix material. At the point of minimum outlet humidity, outlet temperature is maximal due to the maximum possible adsorption of moisture from the air.

4.2 Influence of Wheel Rotational Speed on Wheel Performance

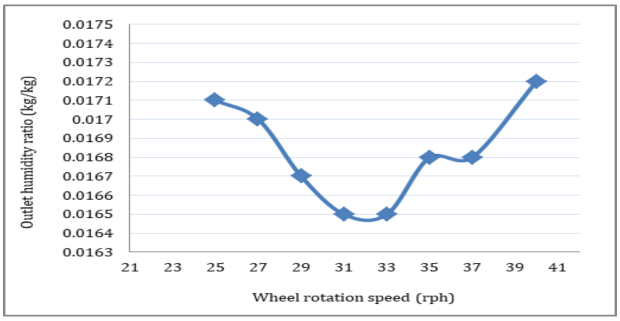

Fig. 5: Variation of outlet humidity ratio

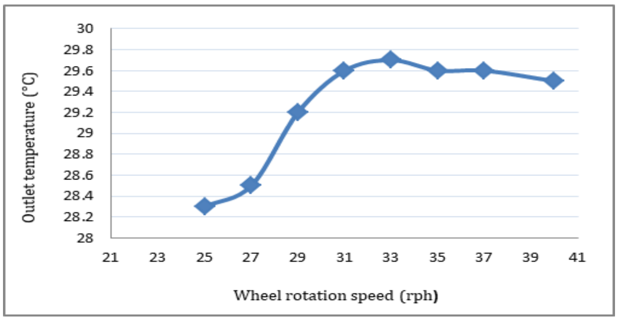

Fig. 6: Variation of outlet temperature

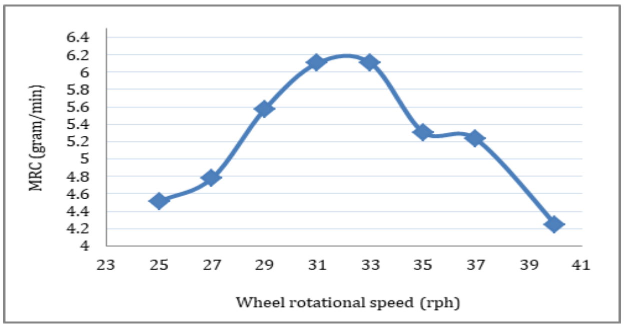

Fig. 7: Variation of moisture removal

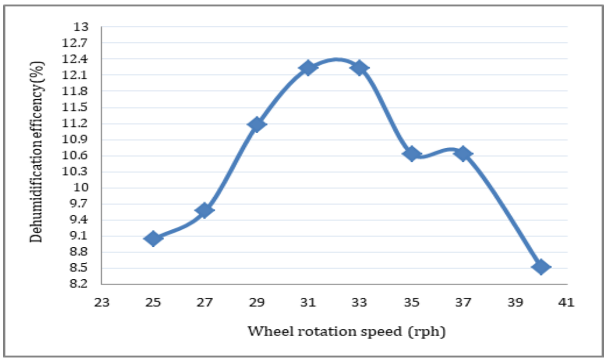

Fig. 8: Variation of dehumidification efficiency

Figure 5 represents the variation of outlet humidity ratio for the different rotational speeds of the wheel. It shows that humidity ratio is reducing with the increase of wheel rotation but after a certain point, it increases gradually with increased rotation. Figure 6, Figure 7 and Figure 8 respectively present the variation of outlet temperature, mass removal capacity and dehumidification efficiency with increasing rotational speed of the wheel.

When the wheel rotates slowly, the silica remains in its equilibrium condition for too long and cannot dry the supply air anymore. Thus, the humidity ratio at outlet decreases with the increased rotational speed of the wheel and reaches the maximum value. But beyond this value humidity ratio again starts to drop at the outlet. This is because when the wheel rotates with further increasing speed, the processing period becomes too short that the silica is still able to adsorb water content from the air. Thus the adsorption capacity has not been fully utilized. The outlet temperature of processed air does not vary that much with the revolution speed. There are two optimum speeds at which outlet humidity ratio is minimal and adsorption capacity and efficiency of the wheel are maximal.

4.3 Influence of Regeneration Temperature on Wheel Performance

Figure 9 shows that with increasing regeneration temperature outlet humidity ratio decreases. Figure 10, Figure 11, Figure 12 respective show that increasing regeneration temperature increases the outlet temperature, dehumidification efficiency and the moisture removal capacity of the wheel.

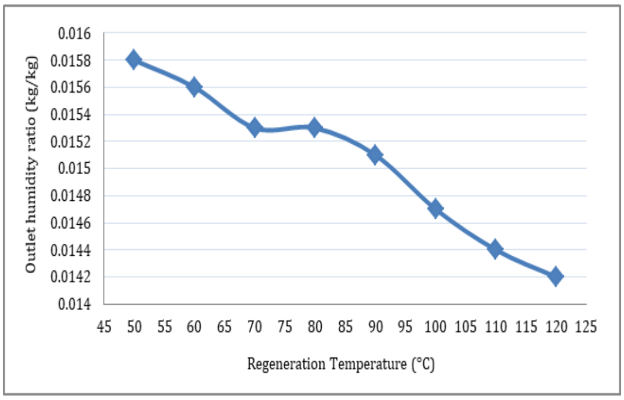

Fig. 9: Variation of outlet humidity ratio

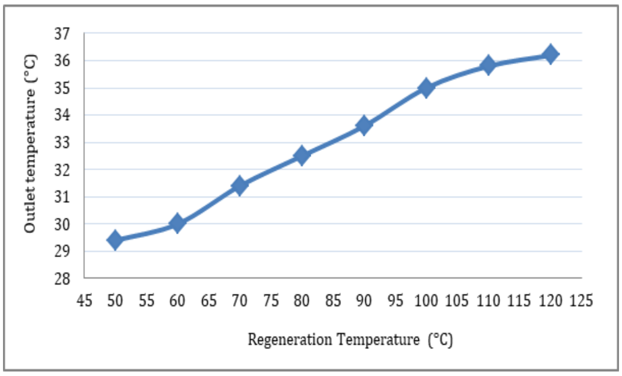

Fig. 10: Variation of outlet temperature

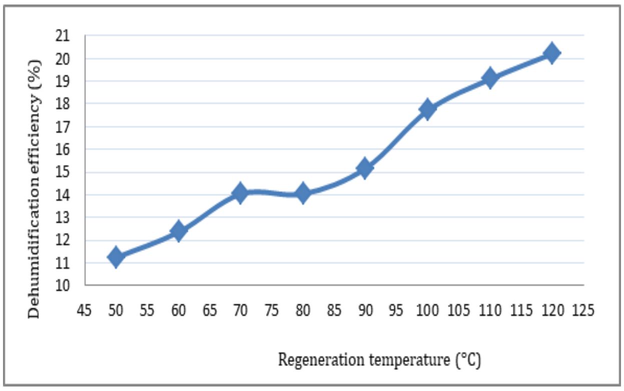

Fig. 11: Variation of dehumidification efficiency

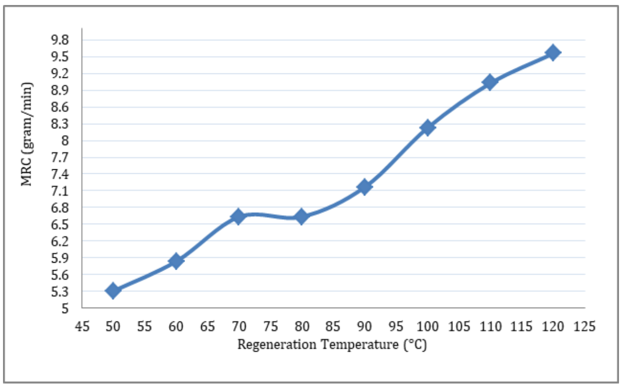

Fig. 12: Variation of moisture removal capacity

Lower the regeneration temperature, lower the outlet temperature, and higher the outlet humidity ratio. Thus, dehumidification efficiency and moisture removal capacity is less. With increased regeneration temperature, more heat is added to the reactivation air that dries the desiccants more completely. Thus, the desiccant can absorb more moisture, which increases dehumidification efficiency and moisture removal capacity. However, with reactivation temperature, outlet temperature increases proportionally.

5. CONCLUSION

The objective of this study was to analyze the impact of different operating parameters on the silica-based rotary dehumidifier system. During this analysis, some limitations were experienced. An assumption of inlet air condition remaining constant has been undertaken. Practically, inlet air condition changes over time. Conglutination of silica gel instead of coating led to a lesser surface area and adsorption rate. The outlet air temperature was influenced by the carryover heat of the matrix material. There was a possible mixing of process air and regeneration air inside the insulated box.

It has been found that higher fluid motion led to a higher mass transfer rate but if the velocity of the air stream is too high, molecules of moisture leave the wheel without getting absorbed. In this particular system, the optimum mass flow rate of air is, $\dot{m}a$ = 2.7027 kg/min and the mass flow rate of dry air is, $\dot{m}da$ = 2.6549 kg/min. This particular system yields the best outcome when the rotational speed of N= 31 rph and 33 rph occurs. It has been observed that low regeneration temperature results in poor performance due to less mass removal. The processed air temperature is always greater than inlet air due to the heat of absorption and carryover of regeneration heat. When the reactivation temperature increases, the outlet humidity ratio decreases and reaches a minimum value when the reactivation temperature is highest (120°C in this system). It should be noted that when reactivation temperature increases, outlet temperature also increases due to heat transfer from the regeneration unit as desiccant remains hot when it enters the processing unit. The performance of this system is barely affected by the inlet humidity ratio, although outlet humidity ratio increases with an increased inlet humidity ratio.

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8. NOMENCLATURE

Symbol	Meaning	Unit
$\dot{m}_{da}$	Mass flow rate of dry air	kg dry air/min
m_a	Mass flow rate of air	kg air/min
$Y_{g,in}$	Humidity ratio of inlet air	kg/kg dry air
$Y_{g,out}$	Humidity ratio of outlet air	kg/kg dry air
MRC	Moisture removal capacity	gm moisture/min
ϵ	Dehumidification efficiency	Dimensionless
T_{DB}	Dry bulb temperature	°C
T_{WB}	Wet bulb temperature	°C
RH	Relative Humidity	Dimensionless
ρ	Density of air	kg/m^3
V	Velocity of air	m/s
A	Cross-sectional area of fan	m^2
N	Wheel rotational speed	rph
T_R	Regeneration Temperature	°C