DEVELOPMENT OF ROTARY DEHUMIDIFIER WITH SILICA-GEL-BASED COMPOSITE DESICCANT

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The desiccant dehumidification system's key component, the desiccant wheel, can perform effectively using composite desiccant materials. Evaluation of the desiccant wheel's performance using composite desiccant material is the primary goal of this study. Authors have compared the performance of two desiccant wheels; one is packed with traditional Silica-gel, and the other is a composite of Silica-gel and calcium chloride in a ratio of 3:2 by weight. A rotary wheel is developed with rectangular channels parallel to the wheel's axis. The novelty of this research lies in the improved design of the desiccant wheel. Unlike other techniques involving pressure losses and ineffective space utilization, this design offers better space utilization and fewer pressure losses. In addition, wheel fabrication is less costly and easily reusable with other desiccants. Three performance indicators were evaluated through experimentation: dehumidification capability, moisture removal capacity, and dehumidification coefficient of performance. Results show that the Parallel channel desiccant wheel achieves 25% higher dehumidification capability and 55% greater moisture removal capacity. The specific humidity of the air is reduced by 35% using the composite desiccant wheel. Comparing the composite desiccant to traditional Silica-gel, its dehumidification coefficient of performance is 40% higher.

Key words: *Desiccant wheel, composite desiccant, Dehumidification, Adsorption*

1. Introduction

Generally, commercial HVAC systems are based on Vapor Compression Refrigeration System (VCRS), designed to simultaneously handle both the sensible and latent load. During sensible load handling in VCRS, the space temperature is reduced below the Dry Bulb Temperature (DBT). During latent load handling, the system needs to minimize temperature well below its dew point temperature, and in addition, reheating is necessary to supply air at the required comfort temperature. Here, a latent load is more significant than a sensible load, and the electrical potential needed for an air conditioner is high, increasing the overall system's operating cost. Implementing solid desiccant systems that use the desiccant wheel is one of the most appropriate solutions to these concerns. HVAC systems powered by desiccant wheels are gaining popularity among researchers due to the following proven benefits [1]:

- A desiccant-wheel-based dehumidification system allows an HVAC system to handle Sensible and Latent loads separately.
- Because desiccant wheel-based systems can be powered by low-grade energy sources such as solar energy and industrial waste heat, they have significant energy-saving potential and reduces the system's reliance on fossil fuel sources.
- It has a low environmental impact because it has a negligible Global Warming Potential (GWP) and zero Ozone Depletion Potential (ODP).
- Because there are fewer moving parts, the system is less sensitive to shocks at its installation location.
- A wide range of input sources, ranging from 50 °C to 500 °C, can be used directly in the system.

Desiccant wheel-based systems are not widely accepted due to their few drawbacks, which are as follows [2]:

- The system's adsorption and regeneration times are incredibly long.
- When a honeycomb structure matrix is used, the system has significant pressure drops.
- Lower DCOP and lower Specific cooling power lead to an increase in specific energy consumption and system size.

To overcome these problems, many researchers [1–10] have adopted a variety of composite desiccant-adsorbate pairs, which may increase adsorption and regeneration time. High adsorption rates and low regeneration temperatures are characteristics of composite desiccant pairs. Many researchers [11–13] have demonstrated that composite desiccant-adsorbate pairs can improve system performance. Composite desiccant materials will have more adsorption capacity and moisture removal rate than conventional desiccant materials [11, 14]. Ponomorenco et al. [8] use a composite desiccant material made of dry Silica-gel and Calcium chloride to overcome the problems associated with traditional desiccant materials. As the most crucial component of the system, the wheel's performance must be prioritized. Improvements in the design and operation of the wheel will propel this technology into the mainstream as a viable alternative to traditional VCRS. To achieve this goal, the current study's authors conducted an experimental analysis of a desiccant wheel filled with composite desiccant material. A composite was developed using Silica-gel, and calcium chloride was used as a desiccant material in the wheel. Experiments on the test set-up were conducted to determine the effect of air's physical properties on the system's performance. The experimentation yielded the following performance parameters –

- Dehumidification Capability (DC)
- Moisture Removal Capacity (MRC)
- Dehumidification Coefficient of Performance (DCOP)

2. Methodology

The project's methodology involved comparing the performance of two desiccant wheels: conventional Silica-gel and composite desiccant made of calcium chloride and Silica-gel. The goal was to evaluate the desiccant wheel's performance using the composite desiccant material. First, a new rotary wheel design was developed, including rectangular channels parallel to the wheel's axis. This design attempted to increase space utilization and decrease pressure losses compared to conventional methods. The wheel's construction was created to be inexpensive and easily adaptable to various desiccants. The performance of the two desiccants in the experimental setting was evaluated based on two critical variables: DBT of the process air and regenerative air. It is important to note that the size and overall cost of the system depend on the performance parameters. Three performance parameters, along with their significance, are as follows:

- Dehumidification Capability of Desiccant material (DC) – This is the amount of moisture removed from the air by the desiccant material. Higher DC values are always preferred.
- Moisture Removal Capacity (MRC) - The mass flow rate of water vapor removed by the desiccant wheel is defined as MRC. Higher MRC values indicate that the desiccant material can remove moisture from the air in a shorter amount of time.
- The Dehumidification Coefficient of Performance (DCOP) – represents the amount of power consumed by the wheel for dehumidifying air over the energy required to regenerate the wheel. Higher values of DCOP are always preferred.

The equations adopted in this study to calculate the performance parameters were taken from Ge et al. [15] and Angrisani et al. [16]. They’re as follows:

$$DC = \omega_2 - \omega_3 \tag{1}$$

$$\mathrm{MRC} = \rho_1 \times \dot{V}_P \times (\omega_2 - \omega_3) \tag{2}$$

where, $\rho_1 = 1.225\,;kg/m^3$

$$DCOP = \frac{\rho_1 \times \dot{V}_P \times \Delta h_s \times (\omega_2 - \omega_3)}{\dot{V}_R \times C_P \times (t_5 - t_6)} \tag{3}$$

where, $\Delta h_s = 2500 - \left[(t - 273.15) \times 2.422449\right]$

Δh_S- is the latent heat of the vaporization of water, and it is calculated using White's [17] function. Subscripts 1, 2, 3, 4, 5, and 6 represent the measurment locations shown in Fig. 2.

3. Preparation of Silica-gel-based composite desiccant material

Desiccant material is prepared in the laboratory in a controlled environment. A novel approach is adopted to prepare the composite desiccant material which has more heat and mass transfer than the conventional Silica-gel. The ratio of Silica-gel and calcium chloride is selected in the proportion of 3:2 by weight. First, Silica-gel granules were utterly dehydrated by keeping them in the oven at 100 °C. Material is weighed every 15 minutes and removed from the furnace once the measurement difference is less than 1 gram.

Silica gel granules

Calcium chloride powder

Composite of Silica gel and calcium chloride (2:3)

Fig.1. Preparation of desiccant material

Meanwhile, solid calcium chloride is dissolved in the distilled water. Dried Silica-gel granules were soaked into the prepared solution for 15 hours to ensure that the solution penetrated the Silica-gel pores to fill the entire volume. Once all poor concentrated calcium chloride solution penetrates the Silica-gel granules, obtained material is sieved. The desiccant material was again dehydrated in the oven at 100 °C until the difference between the measurements was less than 1 gram. Prepared material is shown in Fig. 1.

4. Experimental facility

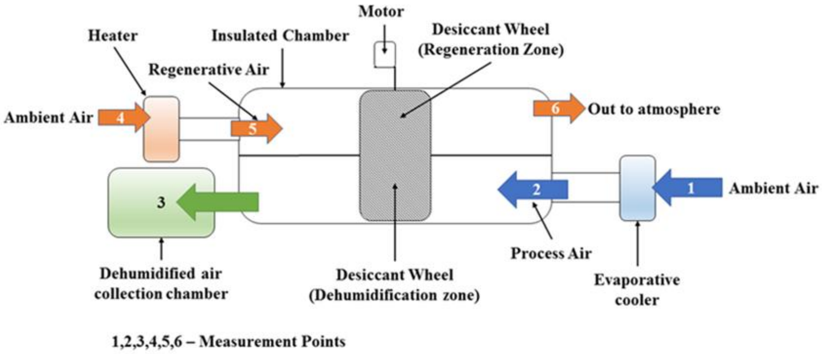


Fig.2. Layout of test set-up with measurement locations

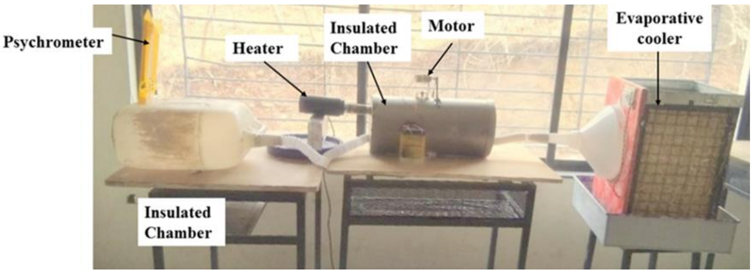


Fig.3. Photograph of actual Experimental set-up

As shown in Fig. 2 and Fig. 3, a state-of-the-art test facility is developed to perform the experiments on the desiccant wheel. The 3D models of the desiccant wheel and assembly of the test chamber are shown in Fig. 4 and Fig. 5. A circular wheel is fabricated using a 6 mm thick GI sheet. The desiccant wheel is divided into two distinct regions with a 1:1 ratio, which ensures that total adsorption and regenerative surface areas are equal. A horizontal tray-like structure is constructed to avoid pressure drop issues in other matrix shapes. A composite of Silica-gel and Calcium chloride is prepared in the laboratory by the earlier process. 2 kg of desiccant material is kept in the trays, and the whole wheel is wrapped with a thin metal net. The shaft is fixed precisely at the center and mounted on the ball bearings for smooth rotation. A gap between the partition wall and the wheel is essential for ensuring the wheel's smooth rotation. In the proposed design, this gap measures just 2 mm, an extremely small distance. Moreover, all the welds are meticulously sealed, ensuring their leak-proof nature. Consequently, the mixing between the process and regenerative air remains minimal. The wheel chamber has a closing lid to close the section. Necessary openings are provided to the lid to connect the humid and regenerative air supply pipe. The wheel is rotated with the help of a DC high torque motor situated well above the wheel. A V-Belt is used to connect the wheel to the motor. The battery supply is used to run the motor. Here, the industrial dryer is used to supply hot regenerative air. An evaporative cooler increases the humidity of process air as the average humidity in the region is low in the summer. Air at the exit of the evaporative cooler is called process air. All components and their specifications are mentioned in Table 1. The measurement instruments used in the system, along with their range and accuracy, are mentioned in Table 2.

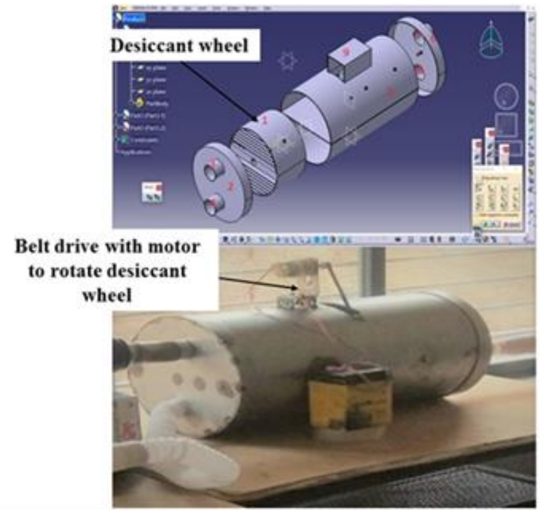


Fig.4. CAD model and photograph of assembly of desiccant wheel chamber

Fig.5. CAD model and photograph of the desiccant wheel with rectangular channels

Table 1- Specifications of the test set-up.

Component	Parameter	Value
Desiccant wheel	Diameter of the wheel	350 mm
	Width of the wheel	170 mm
	Thickness of one rectangular channel	2 mm
	Thickness of outer shell	5 mm
	Distance between two rectangular channel	15 mm
	Weight of desiccant material	2 kg
	No. of channels	16
Desiccant wheel chamber	Diameter of the outer casing	355 mm
	Length of the outer casing	700 mm
	Gap between the wheel and casing	5 mm
	Thickness of the partition at center	50 mm
Air flowing conduits	Inner diameter	25.4 mm
	Outer diameter	25.7 mm
Closing lids	Diameter of Circular holes	3 mm
Shaft (to rotate desiccant wheel)	Diameter	30 mm
	Length	175 mm
Evaporative Cooler	Height	3 ft
Belt drive	Material	Rubber

Table 2 - Details of the measuring instruments

Property	Name of instrument	Accuracy and Range
DBT – regenerative side	Industrial glass thermometer	± 0.1 °C (Range: -10°C TO 250°C)
Velocity	Digital hot wire Anemometer	±0.2 m/s
DBT and WBT– process air side	Sling Psychrometer	±2% (Range: -10°C TO 50°C)
Atmospheric temperature	Digital Thermometer	± 0.1 °C
All Psychrometric properties	Open-source Psychrometric plug-in for Microsoft Excel	Psych uses only equations from the ASHRAE 2005 Fundamentals Handbook, chapter 6

Table 3 - Thermodynamic properties of desiccant and air

Component	Property	Value	Unit
Desiccant material	Specific heat	921	$J/kg.K^{-1}$
	Thermal Conductivity	0.29	$W.m^{-1}.K^{-1}$
	Density	1200	kg/m^3
Air	Specific heat	1000	$J/kg.K^{-1}$
	Thermal Conductivity	0.027	$W.m^{-1}.K^{-1}$
	Density	1.225	kg/m^3

Table 4 - Baseline and Parametric variation of operating conditions

Parameter	Baseline value	Variation
The rotational speed of the desiccant wheel	18 RPH	-
Dry bulb temperature of process air	35 °C	-
Dry bulb temperature of process air	30 °C	27 °C to 35 °C
Dry bulb temperature of regenerative air	85 °C	70 °C to 90 °C
Specific humidity of process air	0.016 kg of moisture/kg of dry air	-
Specific humidity of process air	0.020 kg of moisture/kg of dry air	-
Specific humidity of regenerative air	0.012 kg of moisture/kg of dry air	-
The velocity of process air	2.2 m/s	-
The velocity of regenerative air	2.2 m/s	-

5. Experimentation

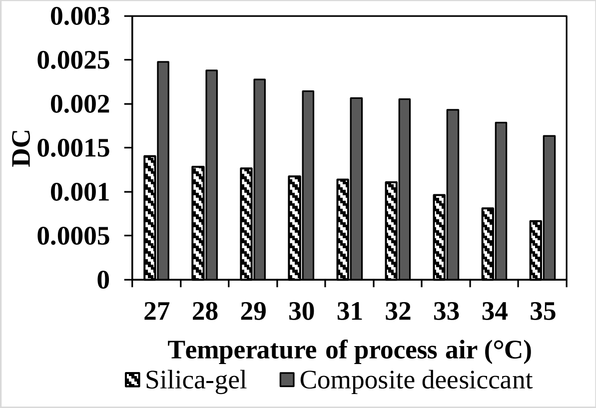
Experiments were performed on the test set-up using process and regenerative air operating conditions. Table 3 indicates the properties of desiccant material and air. Two experimental cases were adopted for the experimentation. One is changing the DBT of process air but keeping the DBT of regenerative air constant; the other is the opposite of the first case. In both cases, performance parameters were determined. Baseline and parametric variations of the operating conditions are mentioned in Table 4. The desiccant wheel has an equal ratio of dehumidification and regeneration. The wheel is rotated 180° for dehumidification and the same for regeneration. Due to the test set-up's limitations, the authors could not change the flow rates of the process and regenerative air.

6. Result and Discussion

The authors have followed a simple and less costly measurement method to determine the performance parameters mentioned earlier. DBT and WBT values of the process and dehumidified air were continuously measured at the different locations using a sling psychrometer. With the help of these readings, various properties of air, such as specific humidity, relative humidity, etc., are calculated using an Open-source psychrometric plug-in for Microsoft Excel Developed by the Western Cooling Efficiency Center. All parameters obtained are essential to estimate the performance indicators. In this section, the authors discuss the effect of DBT of process air and regenerative air on the performance indicators.

6.1. Dehumidification capability (DC)

Fig. 6 indicates the effect of the process and regenerative air on the dehumidification capability. DC decreases against the rise in DBT of process air. The reason behind this is the exothermic heat of the reaction. The adsorption process is exothermic and is always favored by low temperatures. This excess heat accumulates in the system, which slows down the moisture removal process. Across the temperature range, DC is more for the composite desiccant. Around 25% less DC is reported when Silica-gel alone is used as a desiccant in the system.



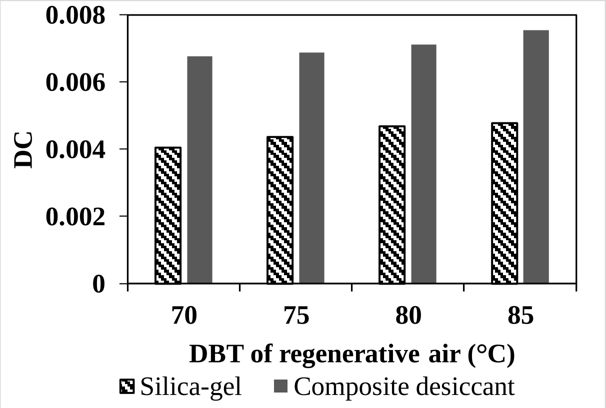


Fig.6. Effect of DBT of process air on DC of desiccant material

Fig.7. Effect of DBT of regenerative air on DC of desiccant material

On the other hand, as shown in Fig. 7, DC increases when the DBT of regenerative air rises from 70 °C to 85 °C. At high regeneration temperatures, the water vapor confined inside the pores of the desiccant material undergoes accelerated evaporation. As a result, the desiccant material gains the ability to absorb a greater amount of water vapor throughout the adsorption cycle. Consequently, the DC increases. The DC of composite desiccant material is increased by approximately 10%. The authors suggest operating the system at lower process air temperatures to improve the performance of desiccant wheel. Still, regeneration of the desiccant material should be done at higher temperatures.

6.2. Moisture Removal Capacity (MRC)

As shown in Fig. 8, MRC decreases against the rise in DBT of process air. As we have already seen, increasing the system's exothermic heat reduces the desiccant material's DC and hence the MRC. We can see around 38% and 60% reduction in MRC for composite and conventional Silica-gel, respectively. MRC is consistent across the whole temperature range under consideration and is around 25% higher for composite desiccant than for traditional Silica gel. It is essential to observe that composite desiccant performs better than the conventional Silica-gel alone. DBT of regenerative air plays a significant role in increasing the MRC of the systems.

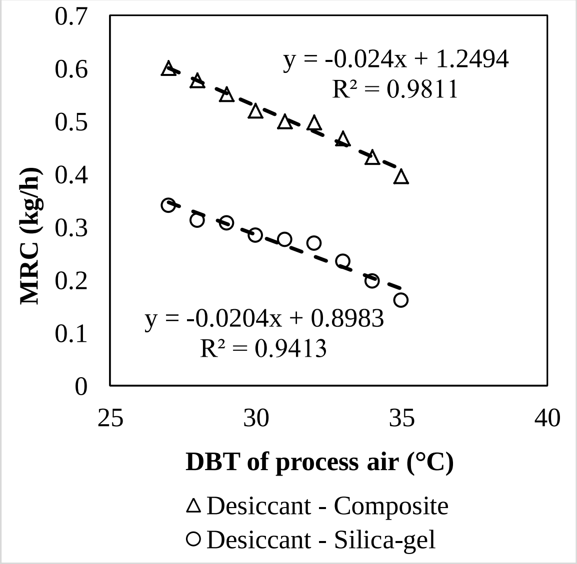


Fig.8. Effect of DBT of process air on MRC of desiccant material

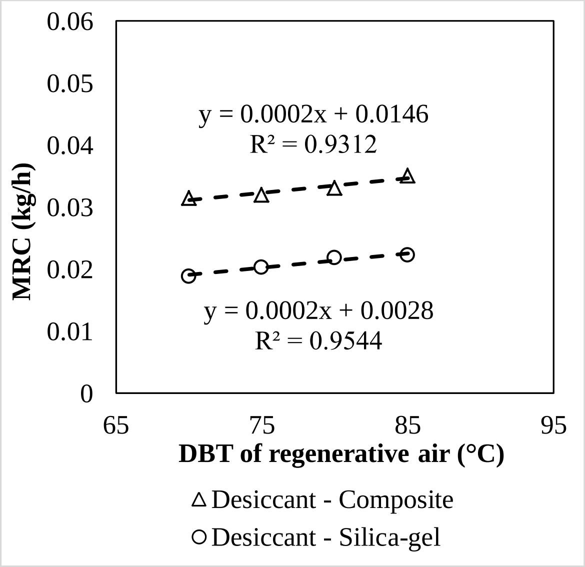


Fig.9. Effect of DBT of regenerative air on MRC

As shown in Fig. 9, the MRC of the system is growing as the DBT of regenerative air rises. With the increase in DBT of regenerative air, desiccant material regenerates faster; hence MRC of the system increases. Authors have observed around 13% and 18% increase in the MRC when composite and conventional Silica-gel is used in the wheel, respectively. The MRC of composite desiccant is almost 50% more than the MRC obtained by traditional Silica-gel. The authors suggest operating the system at higher regenerative temperatures so that the MRC of the system can be increased.

6.3. Increase (%) in MRC for composite desiccant

For composite desiccant, authors have observed a maximum 150% increase in the MRC across the range of DBT of process air. Fig. 10 indicates that MRC increases sharply when the desiccant composite is used instead of conventional Silica-gel alone.

Fig. 11 shows the variation in MRC against the DBT of regenerative air. A maximum 65 % increase in the MRC is obtained when the system is operated at 70 °C.

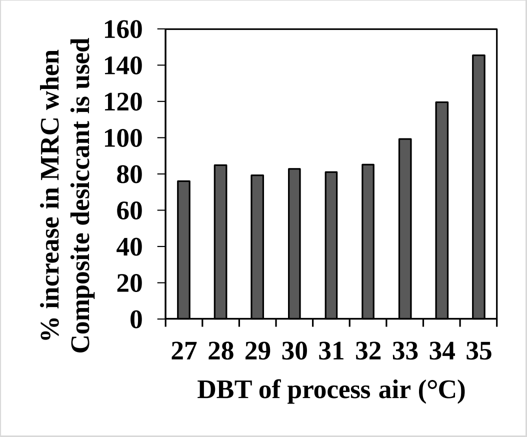


Fig.10. Variation in MRC (%) against the DBT of process air

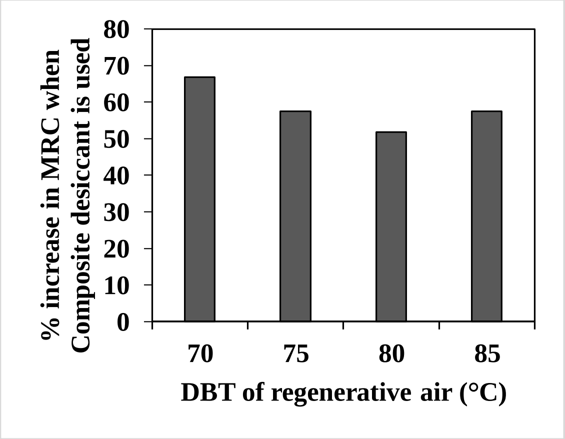


Fig.11. Variation in MRC (%) against the DBT of regenerative air

6.4. Reduction in specific humidity of process air

Magnitude of specific humidity reduction investigated when the system is powered by varying DBT of process air. Fig. 12 depicts the percentage reduction in specific humidity of process air caused by the composite desiccant compared to conventional Silica-gel for the specified temperature range. The authors reported a 25% decrease in the specific humidity when the DBT of process air varied, which is more than 5% lower than traditional Silica-gel.

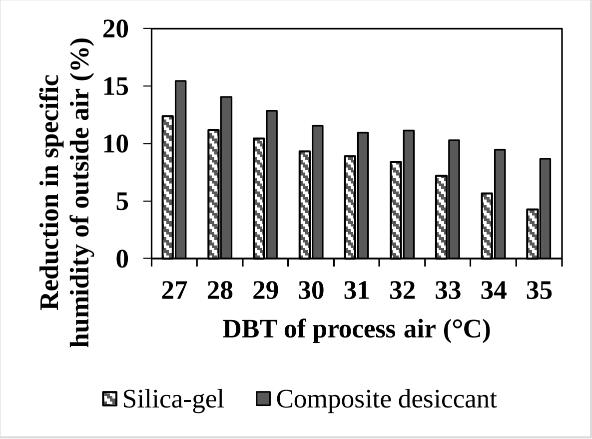


Fig.12. Reduction in specific humidity of process air against DBT of process air

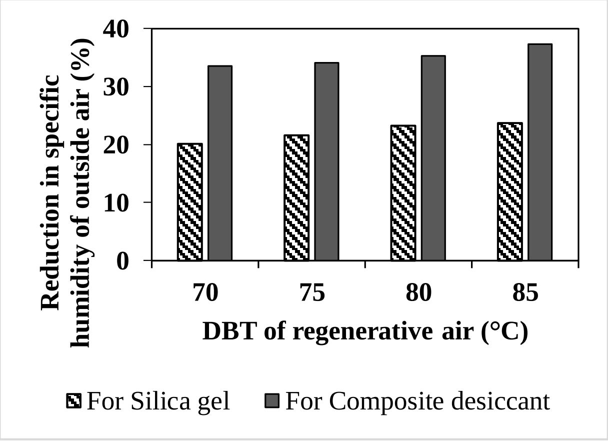
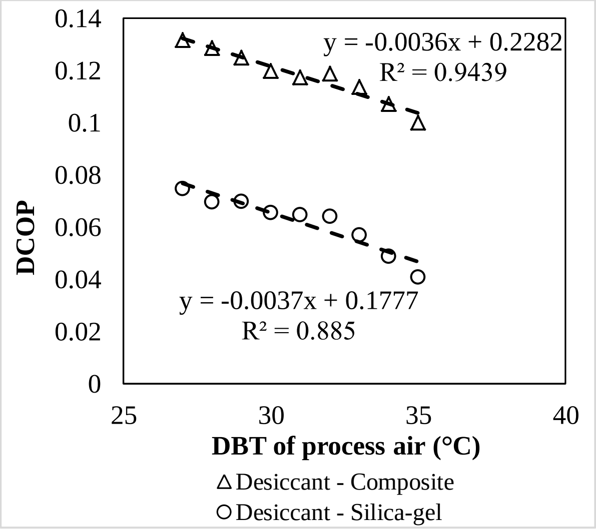


Fig.13. Reduction in specific humidity of process air against DBT of regenerative air

On the other hand, the same system contributes to a 35% reduction in the specific humidity of process air in the range of varying DBT of regenerative air. As shown in Fig. 13, composite desiccant works better than traditional Silica-gel throughout the whole DBT range of process and regeneration air.

6.5. Dehumidification Coefficient of Performance (DCOP)

When the system is powered by varying DBT of process air, DCOP decreases slightly. As shown in Fig. 14, DCOP values almost remain constant for composite desiccant and fall very slightly for conventional Silica-gel, which is negligible. Equation (3) indicates that DCOP is inversely proportional to air temperature difference before and after dehumidification. The main reason for the drop in the DC of the desiccant material is an increase in the outlet temperature of process air. Along with the increased outlet temperature of the air, the enthalpy of the air also increases. Here, authors have observed stable values of DCOP across the temperature range for both the desiccants; hence, both are excellent desiccant materials for dehumidification.



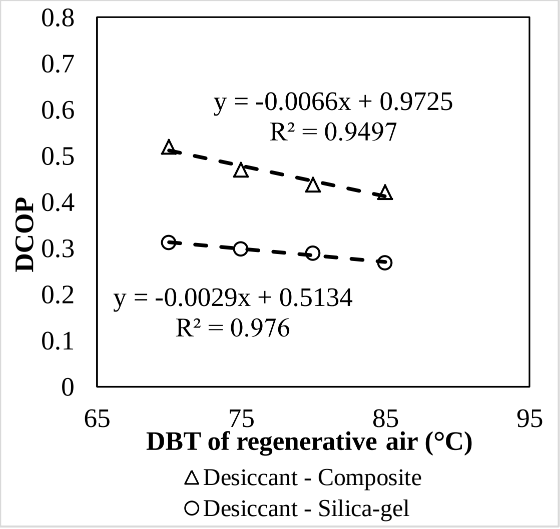


Fig.14. Effect of DBT of process air on DCOP of desiccant material

Fig.15. Effect of DBT of regenerative air on DCOP of desiccant material

When the system is powered by varying DBT of regenerative air, a 40% increase in the DCOP is observed for composite desiccant. As depicted in Fig. 15, a maximum decrease of 19% in the DCOP across the temperature range is observed for composite desiccant, whereas it is only 12% for conventional Silica-gel. From this analysis, it is clear that DCOP decreases rapidly for composite desiccant than for traditional Silica-gel.

7. Conclusions

A series of experiments were carried out on the desiccant wheel test facility. A desiccant wheel is packed with a Silica-gel and Calcium chloride composite. The weight ratio of Silica-gel to calcium chloride was 3:2. The following are the work's significant findings:

- It is found that the DC of the composite desiccant is more than traditional Silica-gel by 25 %. For both the desiccants, DC increases when the DBT of regenerative air rises. But, DC decreases if the DBT of process air increases.
- MRC of the composite desiccant is around 55% more than traditional Silica-gel. As the process air's DBT rises, MRC values decline, while they rise with an increase in the regenerative air's DBT. From the experimental findings, the authors suggest operating the system at higher regenerative temperatures but note that regenerative temperature should not be greater than the melting point of desiccant material.
- A minimum 25% and maximum 35% decrease in the specific humidity of process air is recorded when the composite desiccant is used instead of traditional Silica-gel. Maximum reduction in specific humidity is recorded when the highest DBT of regenerative air (85 °C) powers the system. Overall, the performance of composite desiccant is better than that of conventional Silica-gel when dehumidification is concerned.
- DCOP is more than 40% when the composite desiccant is used instead of traditional Silica-gel. Of course, the composite desiccant should always be preferred over conventional Silica-gel. Still, fluctuation in the values of DCOP is significantly less for both the composite and conventional

Silica-gel desiccant. So, both the desiccant materials are good at handling dehumidification across the range.

- A rise in process air DBT causes the system's surplus heat of adsorption to increase, which lowers the wheel's DC and MRC. The authors suggest a remedy for this as one should use an additional cooling device next to the desiccant wheel, which will help to reduce the temperature of dehumidified air. Removing the adsorption heat from the wheel is a must for comfort applications.
- DC and MRC are directly proportional to the hot regenerative air's DBT. A system should be operated at higher regenerative temperatures to obtain better performance. But note that regenerative temperature should not be greater than the point of deterioration of desiccant material.

In summary, regenerative air has a bigger impact on performance parameters than process air's DBT. In the future, more work is expected to happen in this field to determine the effect of different properties on the performance of desiccant wheels, such as the rotational speed of the wheel, the ratio of the air volume flow rates, different shapes of channels of the wheel matrix, etc.

Nomenclature

DC : Dehumidification Capability (kg of water vapor/kg of dry air)
MRC : Moisture removal capacity (kg / h)
$DCOP$: Dehumidification Coefficient of Performance
RH : Relative Humidity (%)
$\dot{V}$: Volumetric flow rate (m^3 / h)
P : Pressure (Pa)
t : Temperature ($^\circ C$)
h : Specific Enthalpy (kJ / kg)
C_p : Specific heat at constant pressure ($kJ / kg \cdot {}^\circ C$)
RPH : Revolutions per hour
DBT : Dry Bulb Temperature
WBT : Wet Bulb Temperature

Greek letters

ρ : Density (kg / m^3)
ω : Specific humidity/humidity ratio (kg / kg)
Δh_s : Latent heat of vaporization (kJ / kg)
ϕ : Relative humidity (%)

Subscripts

P : process air
R : regenerative air

References

[1] Tso, C.Y., Chao, C.Y.H., Activated Carbon, Silica-Gel And Calcium Chloride Composite Adsorbents For Energy Efficient Solar Adsorption Cooling And Dehumidification Systems, Int. J. Refrig., 35 (2012), 6, pp. 1626-1638

[2] Karmakar, A., et al., A Review Of Metal-Organic Frameworks (MOFs) As Energy-Efficient Desiccants For Adsorption Driven Heat-Transformation Applications, Appl. Energy, 269 (2020), April, pp. 115070

[3] Solovyeva, M. V., et al., MOF-801 As A Promising Material For Adsorption Cooling: Equilibrium And Dynamics Of Water Adsorption, Energy Convers. Manag., 174 (2018), August, pp. 356-363

[4] Fu, H.X., et al., A Dual-Scale Analysis Of A Desiccant Wheel With A Novel Organic-Inorganic Hybrid Adsorbent For Energy Recovery, Appl. Energy, 163 (2016), pp. 167-179

[5] Chiang, Y.C., et al., Circulating Inclined Fluidized Beds With Application For Desiccant Dehumidification Systems, Appl. Energy, 175 (2016), pp. 199-211

[6] Yu, N., et al., Development And Characterization Of Silica Gel–LiCl Composite Sorbents For Thermal Energy Storage, Chem. Eng. Sci., 111 (2014), pp. 73-84

[7] Glaznev, I., et al., Composites CaCl2/SBA-15 For Adsorptive Transformation Of Low Temperature Heat: Pore Size Effect, Int. J. Refrig., 34 (2011), 5, pp. 1244-1250

[8] Ponomarenko, I. V., et al., Synthesis And Water Sorption Properties Of A New Composite “CaCl2 Confined Into SBA-15 Pores,” Microporous Mesoporous Mater., 129 (2010), 1-2, pp. 243-250

[9] Cui, Q., et al., Performance Study Of New Adsorbent For Solid Desiccant Cooling, Energy, 30 (2005), 2-4 SPEC. ISS., pp. 273-279

[10] Jia, C.X., et al., Use Of Compound Desiccant To Develop High Performance Desiccant Cooling System, Int. J. Refrig., 30 (2007), 2, pp. 345-353

[11] Gordeeva, L., et al., Adsorption Cooling Utilizing The “LiBr/Silica – Ethanol” Working Pair: Dynamic Optimization Of The Adsorber/Heat Exchanger Unit, Energy, 75 (2014), pp. 390-399

[12] Saha, B.B., et al., A New Generation Cooling Device Employing CaCl2-In-Silica Gel–Water System, Int. J. Heat Mass Transf., 52 (2009), 1-2, pp. 516-524

[13] Pan, Q.W., et al., Experimental Investigation Of An Adsorption Refrigeration Prototype With The Working Pair Of Composite Adsorbent-Ammonia, Appl. Therm. Eng., 72 (2014), 2, pp. 275-282

[14] Aristov, Y.I., New Family Of Solid Sorbents For Adsorptive Cooling: Material Scientist Approach, J. Eng. Thermophys., 16 (2007), 2, pp. 63-72

[15] Ge, T.S., et al., A Mathematical Model For Predicting The Performance Of A Compound Desiccant Wheel (A Model Of Compound Desiccant Wheel), Appl. Therm. Eng., 30 (2010), 8-9, pp. 1005-1015

[16] Angrisani, G., et al., Experimental Analysis On The Dehumidification And Thermal Performance Of A Desiccant Wheel, Appl. Energy, 92 (2012), pp. 563-572

[17] White, J., Computational Fluid Dynamics Modelling And Experimental Study On A Single Silica Gel Type B, Model. Simul. Eng., 2012 (2012)

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