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Performance evaluation of a rotary dehumidifier with molecular sieve desiccant using coupled regeneration mode: Experimental investigation

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A R T I C L E I N F O

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A B S T R A C T

The increasing demand for energy-efficient and environmentally friendly air conditioning systems has led to the development of innovative technologies such as desiccant cooling systems. This study presents a comprehensive experimental analysis of the dehumidification and thermal performance of a rotary dehumidifier with molecular sieve desiccant designed to effectively remove moisture from the air by utilizing coupled regeneration mode (complete waste heat liberated out of condenser and electric rod heat). Various experiments were conducted to investigate different performance parameters including moisture removed from air by adsorption, moisture added to air by regeneration, dehumidification effectiveness, regeneration effectiveness, moisture removal capacity (MRC), regeneration rate (RR) at different process air inlet temperatures ranging (28–34 °C) and at different regeneration air inlet temperatures ranging (55–62 °C). These experiments were conducted at same air velocity for both adsorption and regeneration segments of rotary solid desiccant wheel using molecular sieve. The results showed that the performance of the desiccant wheel was affected by inlet temperature and humidity ratio for adsorption and regeneration segments. The findings emphasize the system's ability to provide efficient dehumidification and cooling while simultaneously promoting sustainable energy practices. Moreover, the waste heat recovery system significantly contributes to the overall efficiency improvement of the rotary dehumidifier with molecular sieve desiccant, making it an environmentally friendly alternative to conventional air conditioning technologies.

1. Introduction

The growing global concern over energy consumption and environmental impact has spurred the search for advanced air conditioning technologies that can alleviate the burden on traditional cooling systems. Conventional vapor-compression air conditioning systems, while widely employed, are notorious for their significant energy consumption and reliance on harmful refrigerants, contributing to greenhouse gas emissions and exacerbating climate change. In response, researchers have shifted their focus towards novel, energy-efficient alternatives that can mitigate these adverse effects [1,2]. Desiccant-based cooling systems have emerged as a promising alternative to traditional cooling methods. These systems operate on the principle of moisture removal from the air, offering effective humidity control while requiring lower energy input compared to vapor-compression systems. By integrating desiccant technology with conventional cooling components, the Hybrid Desiccant Air Conditioning System (HDACS) aims to harness the advantages of both systems and overcome their individual limitations. The HDACS presents a unique opportunity to enhance the efficiency and sustainability of air conditioning, making it a focal point of investigation in this study [3–5]. In parallel with the quest for energy-efficient cooling, waste heat recovery has gained prominence as a vital component of sustainable engineering. Waste heat, a by-product of various industrial processes and power generation, is often released into the atmosphere, resulting in energy wastage and environmental harm. Incorporating full waste heat recovery into the HDACS seeks to capture and utilize this otherwise lost energy to optimize the system's overall efficiency. By recycling waste heat, the HDACS not only enhances its cooling performance but also reduces the strain on primary energy sources, thereby contributing to a more sustainable and eco-friendly cooling solution [6,7]. As the world grapples with the challenges posed by climate change and depleting energy resources, the HDACS, with its innovative combination of desiccant cooling and waste heat recovery, has the potential to transform the cooling industry. The study's results will provide valuable insights into the feasibility and effectiveness of the HDACS, paving the way for its implementation in diverse applications, from residential and commercial buildings to industrial facilities [8]. D'souza and Brahmbhatt [9] conducted an experimental study on solid desiccants, activated alumina, and molecular sieve 13x in a heatless air dryer with a 10 CFM capacity. They compared the dew point temperatures achieved by each

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Nomenclature

ω_{pgi}	Adsorption inlet humidity ratio (kg/kg)
ω_{pgo}	Adsorption outlet humidity ratio (kg/kg)
ω_{rgo}	Restoration outlet humidity ratio (kg/kg)
ω_{rgi}	Restoration inlet humidity ratio (kg/kg)
V	Velocity (m/s)
ε_{deh}	Dehumidification effectiveness
ε_R	Regeneration effectiveness
MRC	Moisture removal capacity
RR	Regeneration Rate
VCRS	Vapour compression refrigeration system
HDACS	Hybrid desiccant air conditioning system
$\dot{m}$	Mass flow rate (kg/s)

Greek symbols

ρ	density of air (kg/m^3)
ω	humidity ratio (kg/kg)
ε	effectiveness
φ	relative humidity

Subscripts

d	desiccant
h	enthalphy
i	inlet
m	moisture
o	outlet
r	regeneration
p	process side

desiccant and also tested a mixture of both. The results aided in selecting the appropriate desiccant for the desired dew point. This research provided insights into the performance of solid desiccants, helping in applications where specific dew point requirements are crucial. The study's findings contribute to the understanding of desiccant selection for effective moisture removal in various industries and applications. Nie et al. [1] investigated the air dehumidification performance of two solid desiccants, MIL-101(Cr) and MIL-101(Cr)-SO3H, used in a solid desiccant air conditioning (SDAC) system and compared with conventional desiccant materials including silica gel, molecular sieve and activated carbon. The researchers focused on assessing the moisture saturated adsorption capacity of MIL-101(Cr) under varying conditions. The results revealed that MIL-101(Cr) exhibited an impressive moisture saturated adsorption capacity ranging from 1206 to 1392 mg/g at temperatures of 25.0 to 33.5 °C and relative humidity of 95 %. Notably, this capacity was found to be 4 to 6 times higher than that of conventional adsorbents. The findings highlight the potential of MIL-101(Cr) as an efficient solid desiccant for air dehumidification applications, offering significantly improved adsorption performance. Behede et al. [10] researched on aluminosilicate zeolites, aluminophosphate-based molecular sieves, and aerogels as Nanoporous inorganic desiccant. They found out that aluminosilicate zeolites, aluminophosphate-based molecular sieves and aerogels possess high adsorption capacity and low regeneration temperatures that conventional desiccant materials such as silica-gel, activated carbon, zeolites, etc. One more important conclusion was that aluminophosphate-based molecular sieves possess low regeneration temperature compared to aluminosilicate zeolites and aerogels. Tao et al. [11] conducted a primary investigation on the water absorbing and releasing performance of molecular sieve desiccant. The researchers explored the capabilities of molecular sieve desiccants to absorb and release water under varying conditions. Through experimental analysis, they examined the desiccant's water adsorption capacity, equilibrium moisture content, and the effects of temperature and relative humidity on its performance. The study provided valuable insights into the water absorption and release characteristics of molecular sieve desiccants, which are essential for applications requiring precise moisture control. These findings contribute to the understanding and optimization of desiccant-based systems for efficient humidity regulation. Obaidi et al. [12] examined the adsorption capabilities of silica gel, zeolite, and molecular sieve as solid desiccants. The researchers found that silica gel exhibited a remarkable water absorption capacity, absorbing 48 % of water during the experiment. They also conducted numerical simulations to determine the appropriate regeneration temperature for reactivating silica gel, revealing that 35 °C was the suitable temperature. Additionally, the study evaluated the thermal effectiveness of the regeneration process, which was found to be 0.375. These findings provide valuable insights into the adsorption properties of solid desiccants, specifically silica gel, and offer guidance for their practical application in humidity control and moisture removal. Li and Tao [13] introduced a novel concept of adsorption/desorption in stages using type-S isotherm desiccants to enhance the performance of a counter flow type desiccant wheel. The researchers aimed to increase the moisture transfer driving force during both the dehumidification and regeneration processes. By adopting this approach, they sought to optimize the efficiency and effectiveness of the desiccant wheel system. The concept of adsorption/desorption in stages with type-S isotherm desiccants offers potential improvements in moisture removal and regeneration, which can contribute to enhanced overall performance and energy efficiency. Their research provides a valuable contribution to the advancement of desiccant wheel technology. Lee et al. [14] studied the water adsorption capacity of desiccant materials which get affected significantly if particulates are present in the air that is to be processed. Desiccants used in the present work included silica gel and molecular sieve 13X. Experiments were carried out under dynamic conditions using a packed bed adsorber at 298 K and at a relative humidity of ≈50 %. The adsorption and regeneration cycles were repeated 15 times using the same adsorbent. Significant amounts of hydrocarbons and particulates were removed by both silica gel and the molecular sieve during the initial period of a run. The equilibrium water uptake capacity of silica gel at higher relative humidities decreased significantly after 15 cycles but that of the molecular sieve remained almost the same as that of a fresh sample. Also, a molecular sieve that was exposed to tobacco smoke could be regenerated at a lower temperature than the exposed silica gel. Muthu et al. [15] used an novelty designed desiccant wheel. The innovative design of rotary desiccant wheel presented in this paper enhances the moisture removal capacity by using multiple desiccant materials over the width of the wheel and increases the moisture removal capacity and efficiency of the wheel without increasing the overall dimensions of rotary desiccant wheel. The numerical results of this multiple desiccant wheels (Hybrid) are compared with conventional wheel made up of either molecular sieves or Silica gel. The results show that the performance of the wheel can be enhanced by 10–25 % by using this innovative design. Malan et al. [16] studied the regeneration of various saturated desiccant (wet basis) such as silica gel, activated alumina, molecular sieve, and novel composite desiccant using Scheffler Solar Concentrator (SSC). The maximum regeneration rate of 0.07440 kg/hr is achieved in novel composite and maximum weight loss percentage of 22.74 % is achieved in silica gel. Regeneration time taken by silica gel, activated alumina, molecular sieve, and novel composite desiccant are 160, 90, 140, and 110 min, respectively. Paulus et al. [17] compared the desiccants used for monitoring atmospheric tritium concentrations in a semi-arid climate. Data collected during air sampling periods were compared with meteorological data collected, and atmospheric moisture collection efficiencies were determined. Breakthrough of atmospheric moisture past the desiccant material was suspected with both media at elevated temperatures indicating that smaller sample volumes, lower volumetric flow rates, or longer adsorbent columns should be used during summer when ambient temperatures are elevated.

The primary objective of this research paper is to conduct a comprehensive experimental analysis of the rotary dehumidifier with molecu-

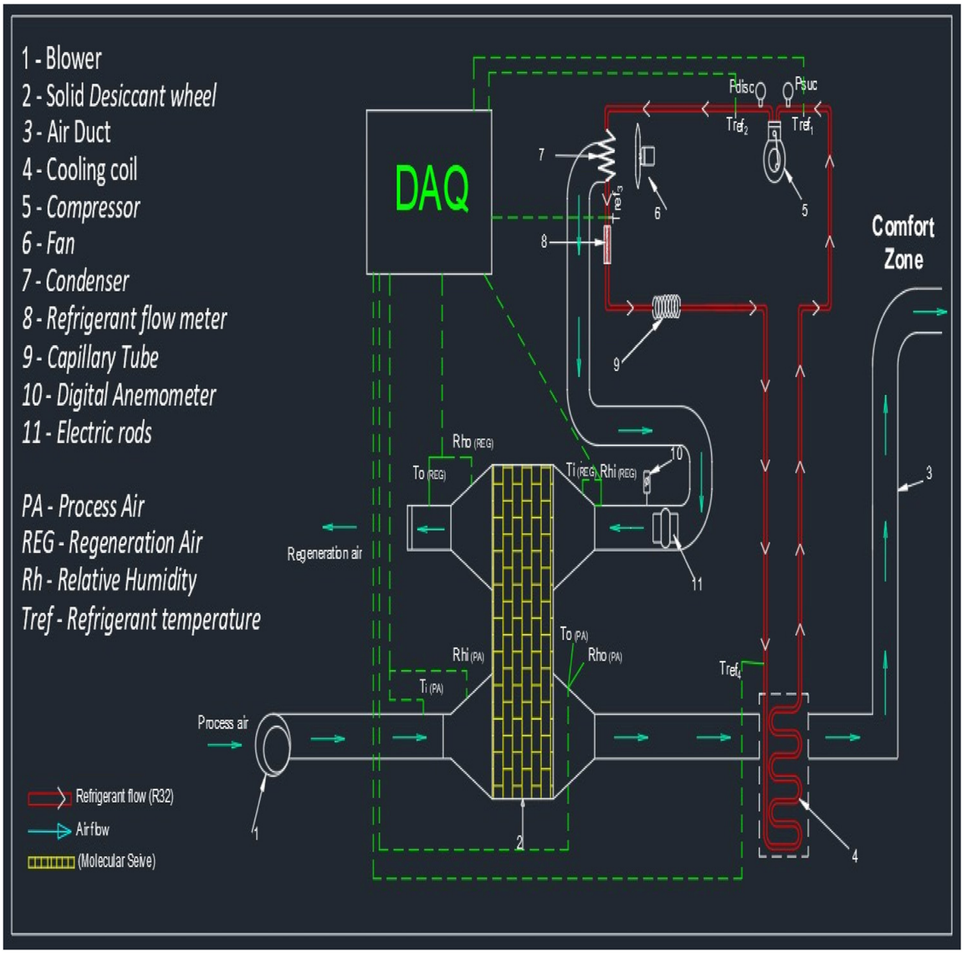

Fig. 1. Line diagram of an experimental setup.

lar sieve desiccant. Also to evaluate the dehumidification capabilities of the solid desiccant wheel using molecular sieve under various operating conditions to understand its moisture removal efficiency and assessment of the thermal performance of rotary dehumidifier. The originality of this work is the utilization of coupled regeneration mode (complete waste heat liberated by the condenser and electric rod heat) for regenerating the desiccant material using molecular sieve.

2. Methodology

2.1. Experimental setup and working principle

The Fig. 1 shows line diagram of an rotary dehumidifier with molecular sieve desiccant using coupled regeneration mode (complete waste heat liberated by the condenser and electric rod heat) for the regeneration of desiccant material present at the Refrigeration and Air Conditioning Laboratory in Aligarh Muslim University, India. At the adsorption inlet, air is introduced into the system through a blower. In our experimental analysis we have used the air pretreatment section which consists of a humidifier and an electrical heater. As the air comes out of air pretreatment section, at the inlet of adsorption sector humidity ratios of process air inlet is obtained within the range (0.0170–0.0194 kg/kg) and temperatures of process air inlet is obtained within the range (28-34 °C). This incoming air carries a certain level of relative humidity (RH) and temperature. As the air passes through the desiccant wheel, it undergoes a dehumidification process. The desiccant material within the wheel has a high affinity for moisture, leading to the adsorption of water vapor from the air. As a result, the relative humidity of the air decreases. The adsorption process occurs due to the difference in vapor pressure between the desiccant material and the moisture in the air. The desiccant material attracts and traps the moisture molecules, effectively removing them from the air stream. However, it is important to note that while moisture is being removed, the temperature of the air increases simultaneously. The temperature rise is a result of the heat released during the adsorption process. As the desiccant material adsorbs moisture, it releases heat energy. This increase in temperature is a consequence of the thermodynamics involved in the adsorption phenomenon. Therefore, as the air flows through the desiccant wheel, it undergoes a reduction in relative humidity as moisture is removed via adsorption, but it experiences a temperature increase due to the heat released during the process. These combined effects contribute to the dehumidification and conditioning of the air, creating a more comfortable indoor environment. To maintain the increased temperature resulting from the adsorption process, a cooling coil is employed. The cooling coil is responsible for reducing the temperature of the air before it is delivered through the ducts into the comfort zone. By cooling the air, the system ensures that the conditioned air is at an appropriate temperature for comfort. In the overall air conditioning process, the solid desiccant wheel primarily handles the removal of moisture or the latent heat part. As air passes through the desiccant wheel, moisture is adsorbed, reducing the humidity of the air. This process addresses the latent heat component, which refers to the heat associated with the moisture content in the air. The speed of the desiccant wheel is 20 rph. On the other hand, the cooling coil handles the sensible heat part of the air conditioning process. Sensible heat refers to the heat associated with the temperature of the air. The cooling coil extracts heat from the air, thereby reducing its temperature and ensuring that the air delivered into the comfort zone is at a desirable temperature. In the vapour compression refrigeration system (VCRS), there are four main components: the compressor, condenser, capillary tube and cooling coil. These com-

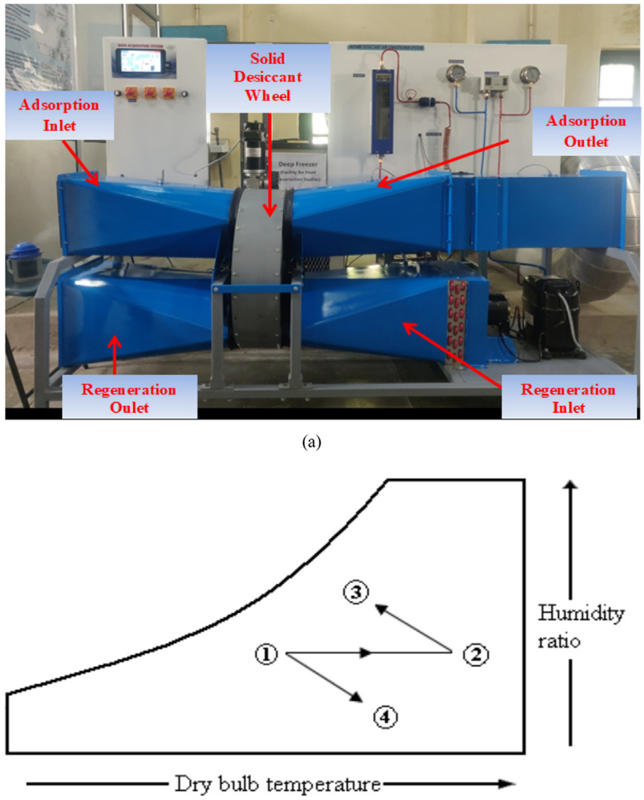

Fig. 2. (a). Image shows a setup for an rotary dehumidifier with molecular sieve desiccant using coupled regeneration mode (complete waste heat liberated by the condenser and electric rod heat), Fig. 2 (b). Psychrometric processes during adsorption, regeneration and sensible heating.

ponents work together to facilitate the refrigeration cycle and provide cooling. The compressor compresses the refrigerant, the condenser releases heat from the refrigerant, the capillary tube regulates the flow of refrigerant, and the cooling coil facilitates the heat exchange process. The refrigerant used in this VCRS system is R-22. R-22 is a commonly used refrigerant known for its favorable properties in terms of efficiency and environmental impact. Overall, the combination of the solid desiccant wheel and the vapour compression refrigeration system allows for effective dehumidification, moisture removal, and temperature control, resulting in comfortable and conditioned air in the desired environment. The heat produced by the condenser and the electric rods serves a crucial role in the regeneration of the desiccant wheel material (molecular sieve). As the wheel rotates, the second half of the cycle initiates the desorption process. During this phase, moisture is extracted from the desiccant material, enabling it to be reused for subsequent dehumidification cycles. Additionally, as the moisture is removed, the temperature of the air discharged from the system increases. This temperature rise is a result of the heat released during the desorption process. By utilizing the available heat sources effectively, the desiccant-based air conditioning system achieves efficient regeneration and ensures the proper functioning of the overall air conditioning process. Fig. 2 (a) shows the experimental facility for rotary dehumidifier with molecular sieve desiccant using coupled regeneration mode (complete waste heat liberated by the condenser and electric rod heat).

Fig. 2(b) shows psychrometric processes during adsorption, regeneration and sensible heating. Process (1-4) shows the adsorption process which occur at adsorption segment of desiccant wheel where the moisture from incoming processed air is adsorbed on the surface of desiccant. Process (2-3) shows the regeneration process which occur at regeneration segment of desiccant wheel where the surface of desiccant releases the moisture to incoming regenerated air. Process (1-2) shows the sensible heating of air using coupled regeneration mode (complete waste heat liberated by the condenser and electric rod heat).

2.2. Measuring instruments

This research work measured multiple physical parameters using an data acquisition system (DAQ). The data acquisition system (DAQ) was used to measure the relative humidity and temperature, while an anemometer measured the air velocity. The humidity ratio of air has been calculated from dry bulb temperature and relative humidity using a Psychrometric calculator. Table 1 shows measuring instruments used. The results are obtained when steady state is reached.

2.3. Details of a rotary solid desiccant wheel

A rotary solid desiccant wheel using molecular sieve has been used in the experimental set-up. It is divided into two sectors. The first sector is the adsorption sector which equals 50 % of the total surface area of the wheel. The second sector is the regeneration sector that equals the remaining 50 % of the total surface area. Table 2 shows the physical specifications of the desiccant wheel using molecular sieve.

2.4. Uncertainty analysis

In this research, the root sum square method proposed by Kline and McClintock [20] is used to conduct uncertainty analysis. Performance parameters including moisture removed from air by adsorption, moisture added to air by regeneration, dehumidification effectiveness, regeneration effectiveness, MRC and RR are computed based on the observed values of factors such as relative air humidity, temperature, and velocity. These performance parameters are accompanied by a corresponding level of uncertainty, which is determined through the root sum square method.

The relationship for uncertainty analysis is as follows:

$$\frac{\Delta z}{z} = \left[\left(\frac{\partial f}{\partial y_1}\right)^2\left(\frac{\Delta y_1}{z}\right)^2 + \left(\frac{\partial f}{\partial y_2}\right)^2\left(\frac{\Delta y_1}{z}\right)^2 + \ldots + \left(\frac{\partial f}{\partial y_n}\right)^2\left(\frac{\Delta y_1}{z}\right)^2\right]^{1/2}$$

Where Δy_1 represents absolute uncertainty and f is a function of the independent variable y_1, Δz represents absolute uncertainty and z is a dependent variable, and Table 3 shows the uncertainty in the results.

2.5. Performance parameters

Numerous factors influence the operation of the rotary dehumidifier with molecular sieve desiccant using coupled regeneration mode (complete waste heat liberated by the condenser and electric rod heat). To achieve consistent performance, the manufacturer typically adjusts most of these variables. The key parameters that effect the performance of the desiccant wheel include the specific humidity, the regeneration air flow rate, the structural design of the wheel, ambient temperature and the moisture-absorbing characteristics of the material used are shown in Eqs. (1–6) [18,19,21,22]:

(1) Moisture removed from air by adsorption: It is defined as amount of water vapour removed from the incoming air at process segment by the adsorption.

$$\text{Moisture removed from air by adsorption} = \omega_{pgi} - \omega_{pgo} \tag{1}$$

(2) Moisture added to air by regeneration: It is defined as amount of water vapour added to the regeneration air at regeneration segment

Table 1
Measuring instruments used.

Equipments	Measuring Property	Voltage	Range	Accuracy
Data acquisition system	Temperature	Single phase 220V Standard supply	-10 to+85 °C	± 0.5 °C
	Humidity	Single phase 220V Standard supply	0 to 100 %	±2.5 %
Digital Anemometer	Air Velocity	3.0 V DC	0 to 30m/s	±5 %

Table 2
Physical specifications of the desiccant wheel using Molecular Sieve.

Factor	Measurement
Chemical Formula	CH_2F_2 (50 %) & CHF_2CF_3 (50 %)
Vapour Pressure at 21 °C	1.383 MPa
Critical Temperature (°C)	72.8
Critical Pressure	4.90 MPa
Wheel diameter, D (m)	0.37
Length of a wheel, L_w (m)	0.1
Material of Desiccant Wheel	Molecular Sieve

Table 3
Uncertainty in results.

S.No	Results	Nomenclature	Uncertainty %
1	Moisture removed from air by adsorption	-	± 7.56
2	Moisture added to air by regeneration	-	± 7.10
3	Dehumidification effectiveness	ε_{deh}	± 7.39
4	Regeneration effectiveness	ε_R	± 8.28
5	Moisture Removal Capacity	MRC	± 7.79
6	Regeneration Rate	RR	± 7.21

by the regeneration.

$$\text{Moisture added to air by regeneration} = \left(\omega_{\text{rgo}} - \omega_{\text{r}gi}\right) \tag{2}$$

(3) Dehumidification effectiveness (ε_{deh}): The dehumidification effectiveness, as represented by Eq. (1), is defined as the ratio between the change in specific humidity at the inlet and outlet to the specific humidity at the inlet and the specific humidity at the equilibrium state.

$$\varepsilon_{deh} = \frac{\omega_{pgi} - \omega_{pgo}}{\omega_{pgi}} \tag{3}$$

(4) Regeneration effectiveness (ε_R): It is defined as the ratio of the differences in water vapour in the regeneration zone to the initial water vapour content.

$$\varepsilon_R = \frac{\left(\omega_{\text{rgo}} - \omega_{\text{r}gi}\right)}{\omega_{\text{r}gi}} \tag{4}$$

(5) Moisture Removal Capacity (MRC): The mass flow rate of water vapour extracted by the wheel is represented by the MRC.

$$\text{MRC} = \dot{m}_{\text{pg}} \times \left(w_{pgi} - w_{pgo}\right) \tag{5}$$

(6) Regeneration Rate (RR) [1]: The ability of the desiccant wheel to remove water vapour from its surface through the desiccan depends on the effectiveness of the restoration process that removes water vapour from the desiccant.

$$\text{RR} = \dot{m}_{\text{Rg}} \times \left(w_{rgo} - w_{rgi}\right) \tag{6}$$

3. Results and discussions

3.1. Variation of moisture removed from air by adsorption with process air inlet temperature

The process of adsorption involves the attachment of water molecules to the surface of an adsorbent material (molecular sieve). The adsorption capacity of molecular sieve is affected by temperature. Fig. 3 shows that moisture removed from air by adsorption increases with decreasing temperature. This means that lower process air inlet temperatures typically result in higher moisture removal rates. The reason for this is that at lower temperatures, the adsorbent material's surface becomes more attractive to water molecules, leading to a higher rate of moisture uptake. Conversely, as the process air inlet temperature increases, the adsorption capacity decreases, and the moisture removal rate declines. At higher temperatures, the water molecules have higher kinetic energy, reducing their ability to adhere to the adsorbent's surface.

3.2. Variation of dehumidification effectiveness with process air inlet temperature

Fig. 4

3.3. Variation of moisture removal capacity (MRC) with process air inlet temperature

Fig. 4 shows that when the process air inlet temperature is lower, the dehumidification effectiveness generally increases. This is because colder air has a lower moisture-holding capacity, and as it passes through the dehumidification system, more moisture is removed to achieve a lower dew point. Lower process air temperatures also improve the moisture adsorption capacity of adsorbent material (molecular sieve) or the water condensation rate in refrigeration-based dehumidifiers, enhancing the overall dehumidification process. On the other hand, higher process air inlet temperatures lead to reduced dehumidification effectiveness. Warm air has a higher moisture-holding capacity, so less moisture is removed during the dehumidification process. Higher temperatures can also lead to reduced condensation rates in refrigeration-based dehumidifiers, as the air may not cool sufficiently to reach its dew point.

Fig. 5 illustrates the relationship between the process air inlet temperature and moisture removal capacity (MRC). The findings from the experiment reveal a clear negative correlation between these two factors. In other words, as the process inlet temperature increases, the MRC decreases. This observed relationship can be explained by understanding the influence of temperature on the adsorption potential of the desiccant material (molecular sieve). When the process inlet temperature rises, the air vapor pressure decreases. This decrease in air vapor pressure directly impacts the adsorption potential of the desiccant material (molecular sieve). In simpler terms, the desiccant's ability to remove moisture from the air is closely linked to the pressure difference between the desiccant's surface and the air vapor pressure. As the inlet air temperature increases, this pressure difference diminishes, resulting in a reduced MRC. To elaborate further, at higher temperatures, the water

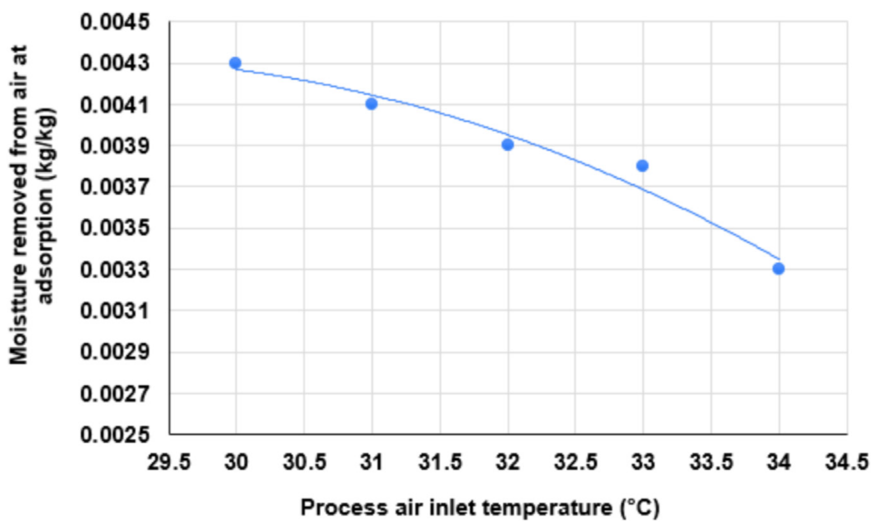

Fig. 3. Variation of moisture removed from air by adsorption with process air inlet temperature.

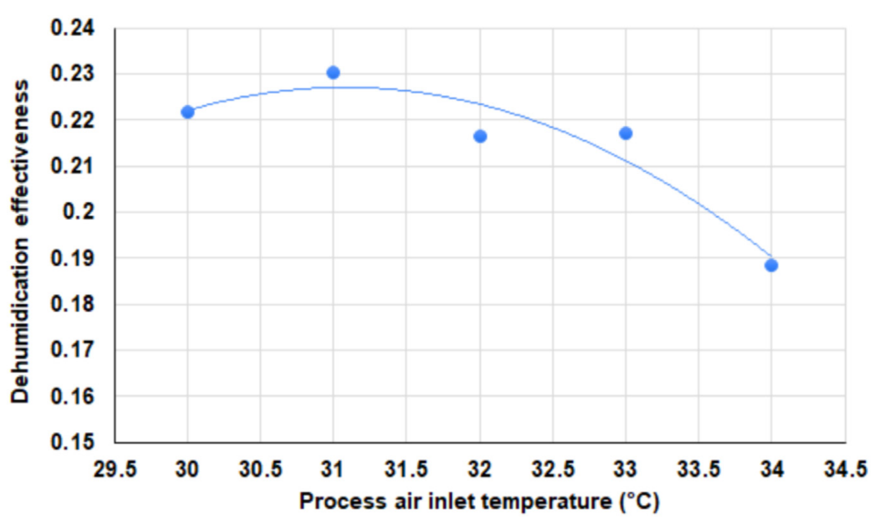

Fig. 4. Variation of dehumidification effectiveness with process air inlet temperature.

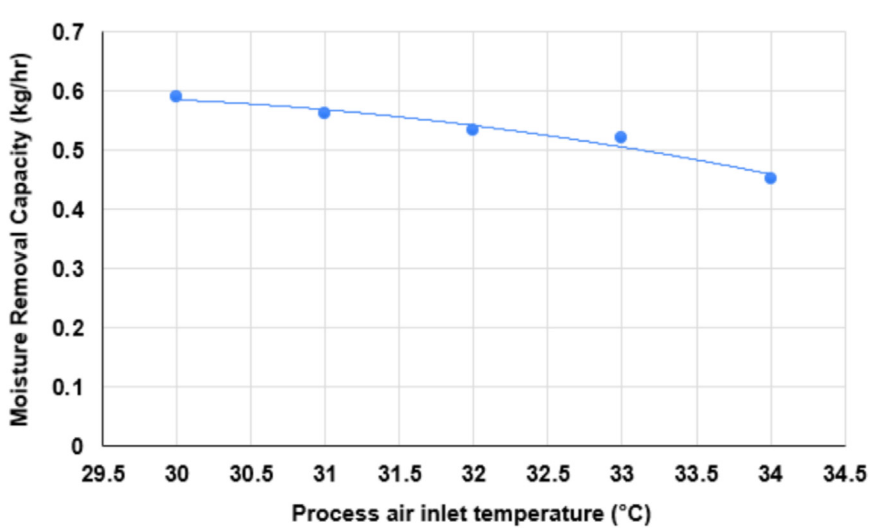

Fig. 5. Variation of moisture removal capacity (MRC) with process air inlet temperature.

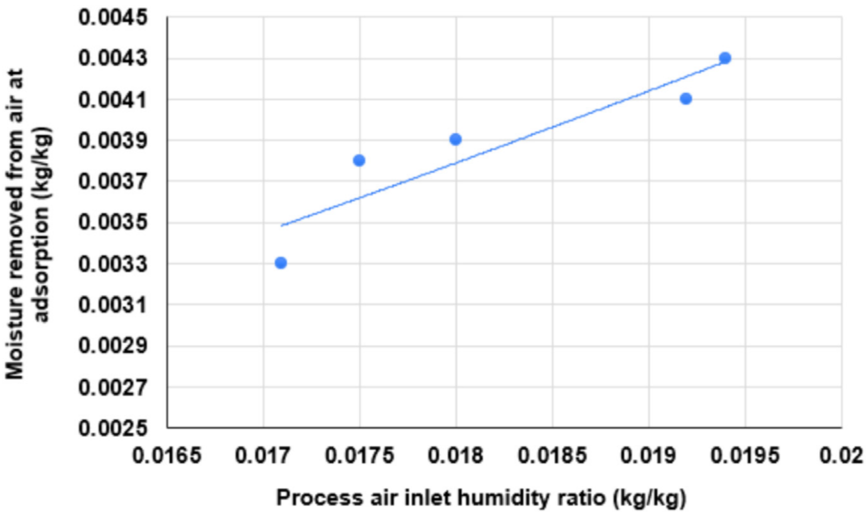

Fig. 6. Variation of moisture removed from air by adsorption with process air inlet humidity ratio.

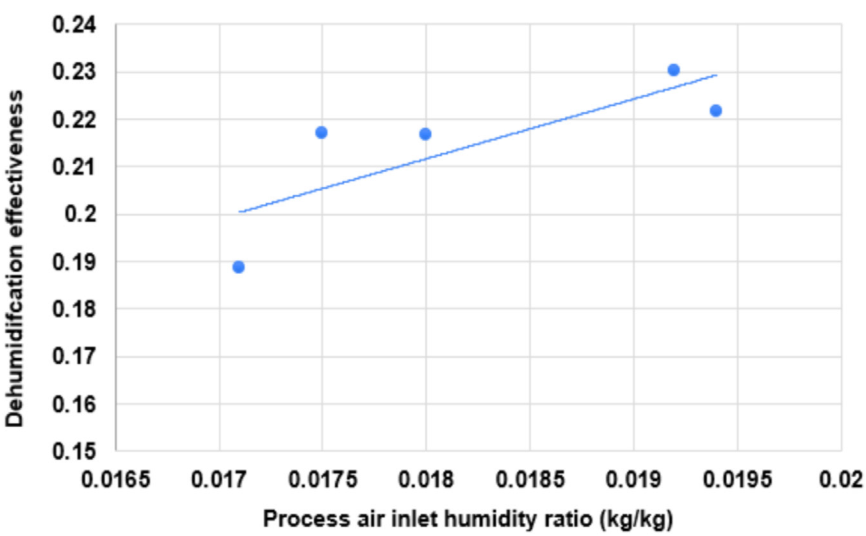

Fig. 7. Variation of dehumidification effectiveness with process air inlet humidity ratio.

vapor present in the air has lower pressure. As a consequence, the desiccant's ability to interact with and remove this water vapor decreases, making it less effective in the moisture removal process. This reduced efficiency in moisture removal can lead to suboptimal performance of the air conditioning system. It elucidates how increasing the temperature of the incoming air leads to reduced moisture removal efficacy of the desiccant due to the corresponding decrease in air vapor pressure.

3.4. *Variation of moisture removed from air by adsorption with process air inlet humidity ratio*

Fig. 6

3.5. *Variation of dehumidification effectiveness with process air inlet humidity ratio*

Fig. 7

3.6. *Variation of moisture removal capacity (MRC) with process air inlet humidity ratio*

(Figs. 6–8) investigated the relationship between relative humidity and humidity ratio at lower temperatures, with a specific focus on the role of desiccant material, particularly molecular sieve. The experiments revealed that as the relative humidity increases at lower temperatures, the corresponding values of the humidity ratio also rise. This finding highlights the importance of considering humidity ratio in environments with varying temperatures and humidity levels. In the context of using desiccant material like molecular sieve, the observed relationship between relative humidity and humidity ratio is of particular significance. When a molecular sieve is initially cold and dry, it creates a higher vapor pressure difference at low temperatures. This phenomenon arises due to the molecular sieve's capacity to adsorb moisture from the surrounding air. As the temperature decreases, the moisture in the air tends to condense, and the molecular sieve's adsorption capability becomes more pronounced. The higher vapor pressure difference between the surrounding air and the desiccant material at lower temperatures results in a greater disparity between their moisture contents. This leads to a more efficient removal of moisture from the air. In other words, the molecular sieve can effectively extract moisture from the surrounding air, making it an excellent choice for dehumidification applications in colder conditions. At lower temperatures, the exothermic nature of the adsorption process provides an additional benefit to the moisture removal process. The released heat aids in maintaining a conducive environment within the desiccant material, ensuring its effectiveness and efficiency in absorbing moisture from the surrounding air. Consequently, the desiccant material can perform optimally even in colder conditions, efficiently removing moisture and maintaining a dry atmosphere.

However, as the temperature increases, the impact of this exothermic heat of adsorption becomes less pronounced. At higher temperatures,

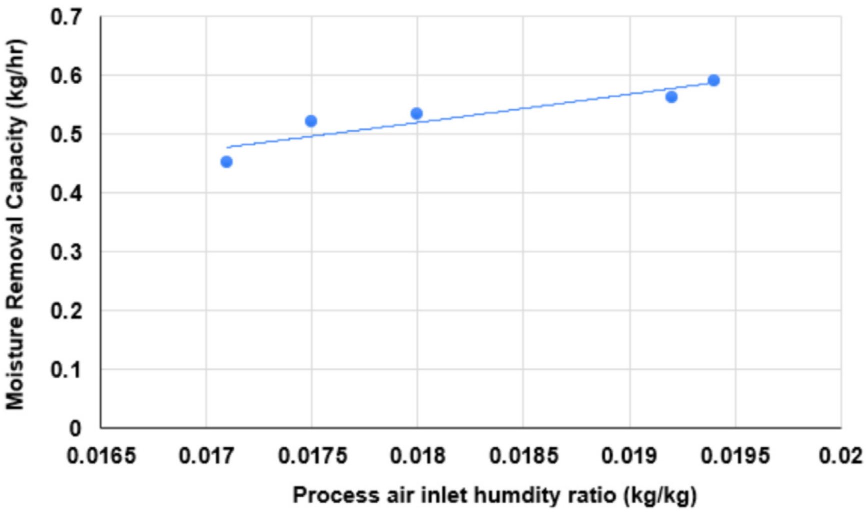

Fig. 8. Variation of moisture removal capacity (MRC) with process air inlet humidity ratio.

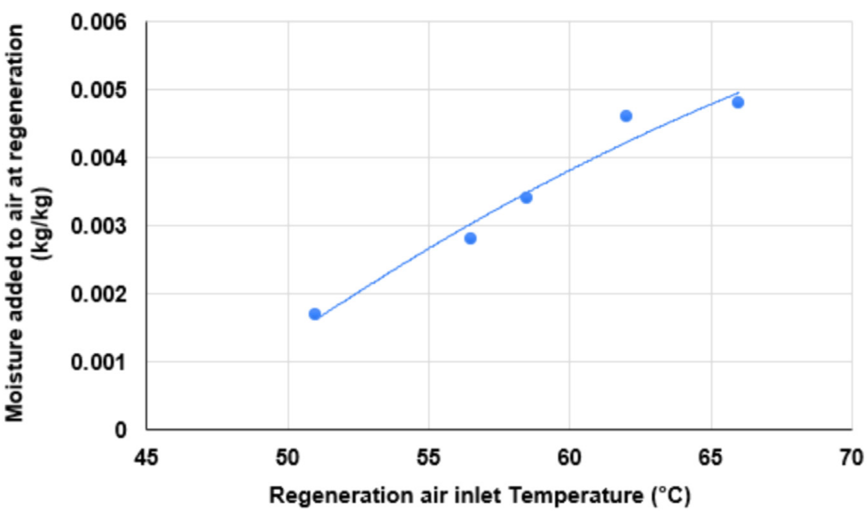

Fig. 9. Variation of moisture added to the air by regeneration and regeneration air inlet temperature.

the vapor pressure difference between the desiccant material and the surrounding air decreases. As a result, the efficiency of moisture removal by the desiccant material diminishes. This reduction in efficiency is due to the decreased driving force for adsorption at higher temperatures, which leads to a decreased rate of moisture uptake by the desiccant material.

3.7. *Variation of moisture added to the air by regeneration and regeneration air inlet temperature*

Fig. 9

3.8. *Variation of regeneration effectiveness with regeneration air inlet temperature*

Fig. 10

3.9. *Variation of regeneration rate with regeneration air inlet temperature*

(Figs. 9–11) show that the regeneration process was investigated to understand its effect on moisture removal from the surface of the molecular sieve. A key parameter that was varied during the experiments was the regeneration air inlet temperature ranging (55–62 °C). It was observed that when a higher regeneration air inlet temperature was employed, it played a crucial role in efficiently removing moisture from the molecular sieve and restoring its adsorption capacity. The higher regeneration air inlet temperature created a significant vapor pressure difference between the dry air at the inlet of the regeneration process and the moisture that had accumulated on the surface of the molecular sieve. This vapor pressure difference acted as the driving force for the transfer of moisture from the molecular sieve to the air during the regeneration process. As a result, the accumulated moisture was effectively removed from the desiccant material (molecular sieve). During the regeneration process, the higher temperature of the regeneration air served as a carrier for the moisture. It facilitated the removal of moisture from the molecular sieve, allowing the desiccant material to be effectively regenerated and prepared for subsequent cycles. This moisture removal process was crucial, as it ensured that the molecular sieve could regain its maximum adsorption capabilities. As the molecular sieve became dry once again due to the efficient moisture removal during regeneration, it was able to efficiently attract and retain moisture from the surrounding air during the subsequent adsorption phase. This maximized its moisture adsorption capacity, enabling it to effectively perform its intended function of reducing the moisture content in the system. The experimental results highlight the significant role played by the higher temperature of the regenerate air in the regeneration process. This higher temperature created a favorable vapor pressure difference, which facilitated the transfer of moisture from the molecular sieve to the air, resulting in effective moisture removal. By efficiently regenerating the molecular sieve, it was prepared to adsorb more moisture in the subsequent

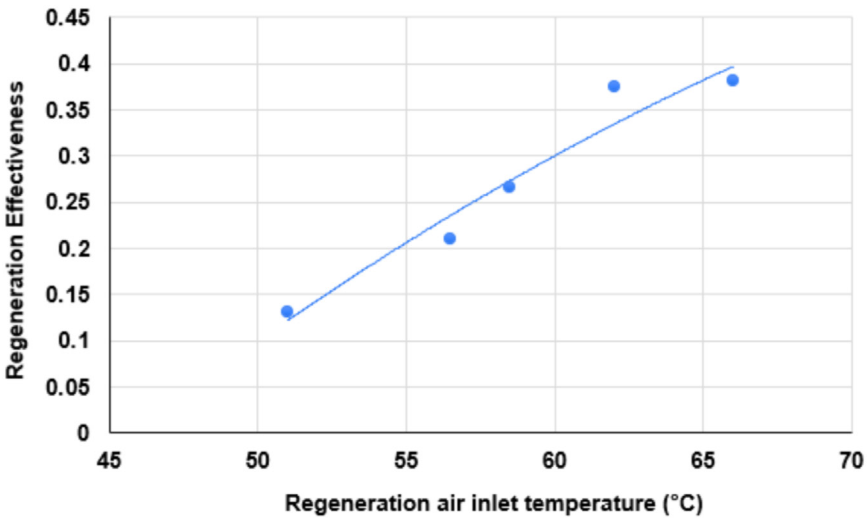

Fig. 10. Variation of regeneration effectiveness with regeneration air inlet temperature.

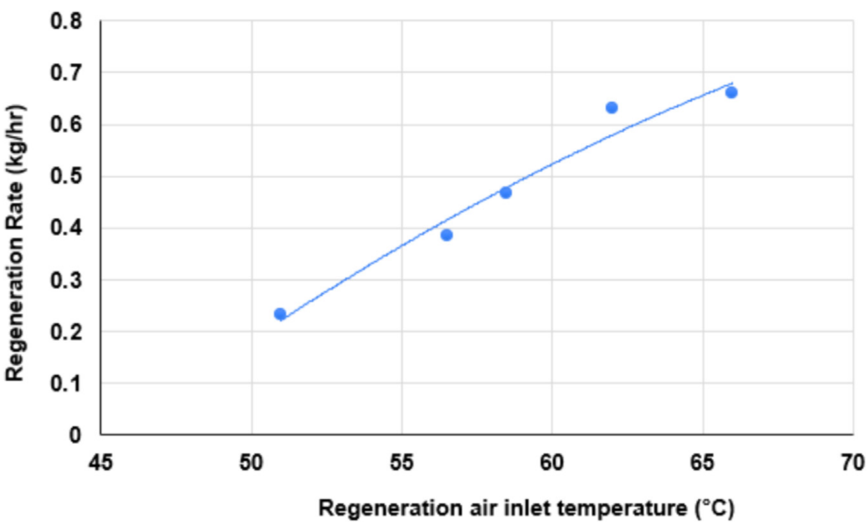

Fig. 11. Influence of regeneration rate with regeneration air inlet temperature.

absorption phase, making it a critical component for maintaining the overall efficiency of the system.

3.10. Variation of moisture added to air by regeneration with regeneration air inlet humidity ratio

Fig. 12

3.11. Variation of regeneration effectiveness with regeneration air inlet humidity ratio

Fig. 13

3.12. Variation of regeneration Rate with regeneration air inlet humidity ratio

(Figs. 12–14) show that the when the relative humidity at the inlet of the regeneration site is low, it results in a lower value of the humidity ratio. The humidity ratio represents the amount of moisture present in the air relative to the dry air component. In this scenario, the low humidity ratio indicates a relatively smaller concentration of moisture in the air. The low relative humidity and humidity ratio at the regeneration site's inlet play a significant role in the regeneration process of the desiccant material, specifically the molecular sieve. The lower humidity ratio creates a higher vapor pressure difference between the dry air at the inlet and the moisture accumulated on the surface of the desiccant material. This significant vapor pressure difference drives the release of moisture from the surface of the molecular sieve. The higher vapor pressure of the moisture trapped within the desiccant material allows it to be released into the dry air stream flowing through the regeneration site. As a result, the desiccant material is effectively regenerated, as the moisture is removed from its surface. By capitalizing on the higher vapor pressure difference created by the low humidity ratio, the regeneration process successfully eliminates the accumulated moisture from the molecular sieve. This enables the desiccant material to regain its adsorption capacity for subsequent cycles. To summarize, when the relative humidity and humidity ratio at the regeneration site's inlet are low, a higher vapor pressure difference is established. This facilitates the release of moisture from the surface of the desiccant material, such as the molecular sieve, leading to its regeneration and preparing it for further moisture adsorption in subsequent cycles.

4. Conclusions

Based on the objectives of this study, which aimed to investigate the performance parameters of rotary dehumidifier with molecular sieve desiccant using coupled regeneration mode (complete waste heat lib-

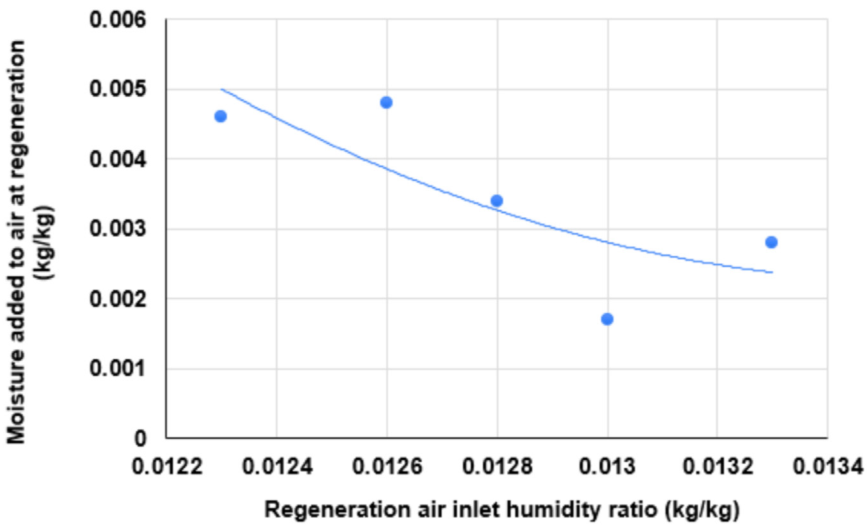

Fig. 12. Variation of moisture added to air by regeneration with regeneration air inlet humidity ratio.

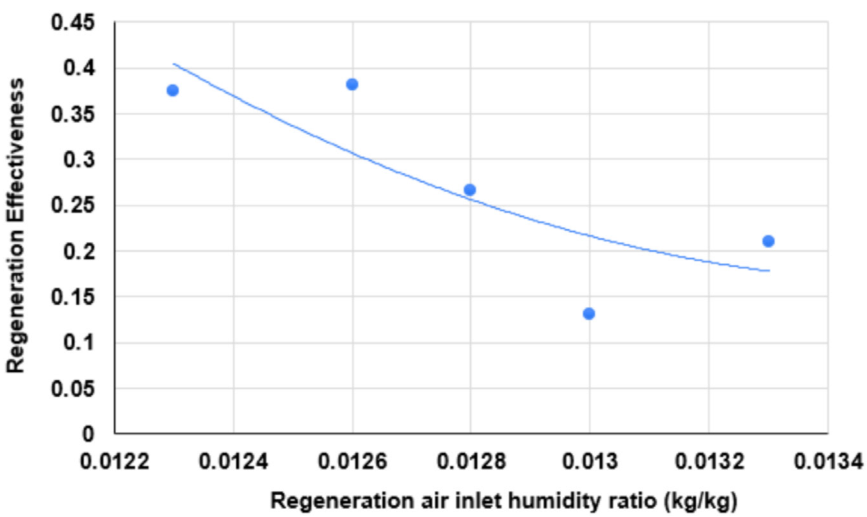

Fig. 13. Variation of moisture added to air by regeneration with regeneration air inlet humidity ratio.

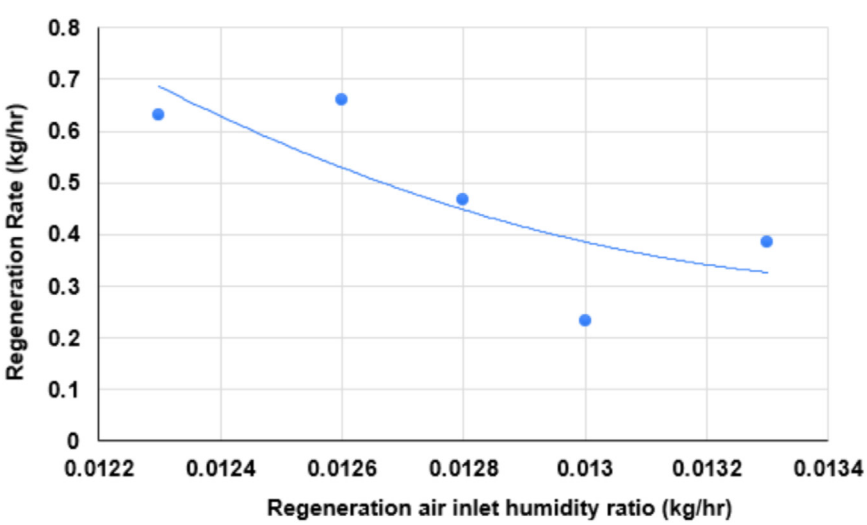

Fig. 14. Variation of regeneration rate with regeneration air inlet humidity ratio.

erated by the condenser and electric rod heat) for the regeneration of molecular sieve, several key findings were identified:

- When process air inlet temperature increases the moisture removed from air at the adsorption, dehumidification effectiveness and moisture removal capacity will decrease at the adsorption segment.
- When process air inlet humidity ratio increases the moisture removed from air at adsorption, dehumidification effectiveness and moisture removal capacity will increase at the adsorption segment.
- The restoration air inlet temperature had a direct impact on the regeneration rate and regeneration effectiveness.
- When temperature of regeneration air at inlet increases, the moisture added to the air, regeneration effectivenss and regeneration rate will increase at the regeneration segment.
- When the inlet humidity ratio of air at regeneration increases then the moisture added to air, regeneration effectiveness and regeneration rate will decrease at the regeneration segment.

It is important to note that the proper use of desiccant wheels in air conditioning and ventilation systems can have significant benefits in terms of energy efficiency and indoor air quality. In conclusion, the study provides valuable insights into the performance parameters of a solid desiccant wheel using molecular sieve and highlights the impact of various factors on its efficiency. These findings can be useful in optimizing the design and operation of solid desiccant wheels for effective air conditioning and dehumidification.

Future research activities could be useful with reference to this topic

- It can be studied which affecting factor has more influence on desiccant wheel performance.
- The benefits of the proposed molecular sieve desiccants in comparison to the conventional desiccants (silica gel) can also be compared.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Hussam Bin Mehare: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation. **Taliv Hussain:** Writing – review & editing, Conceptualization. **Mohd Aqib Zia:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation. **Saif Saleem:** Writing – original draft, Visualization, Resources, Methodology, Investigation.

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