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A comprehensive review on rotary desiccant wheel systems: the future of smart building climate control

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Abstract

This comprehensive review examines the development and potential of rotary desiccant wheel systems (RDWSs) for energy-efficient and sustainable climate control in smart buildings. Driven by the increasing demand for alternatives to conventional HVAC (heating, ventilating, and air-conditioning) systems, RDWSs advanced desiccant materials, such as silica gel composites, and innovative geometrical designs to achieve superior dehumidification and energy performance. The review explores the evolution of RDWS technology, including advancements in system configurations, hybrid integrations, and material innovations. Experimental and computational studies are analysed to assess key performance factors, encompassing energy consumption, moisture removal rates, and regeneration efficiency. The potential for integrating renewable energy sources, such as solar and waste heat, further enhances the sustainability of RDWSs. While significant benefits are evident, challenges remain in optimising operational parameters, scalability, and economic feasibility. Addressing these limitations through continued research and innovation will enable RDWSs to revolutionise indoor air management and contribute to global sustainability goals. This review provides valuable insights into the current state and future prospects of RDWSs for achieving energy-efficient and eco-friendly climate control in smart buildings. According to the recent literature, the dehumidification COP of RDWSs is in the range of 0.3–0.4 at a regeneration temperature of 50 °C and a fan speed of 2 m s^{-1}. In addition, at a regeneration temperature of 60 °C, the moisture removal/release rates are given to be 4.55/1.16 and 3.97/0.42 kg^{-1}(d.a.) for fan speeds of 2 and 4 m s^{-1}, respectively.

Keywords Smart buildings · Rotary desiccant wheel systems · Air-conditioning · Dehumidification

List of symbols

A	Cross section of channel (m^2)
D	Hydraulic diameter (m)
$\dot{E}$	Electricity power (kW)
M	Moisture flow rate (kg h^{-1})
P	Wet environment inside the channel (m)
$\dot{Q}_c$	Cooling effect of desiccant-assisted cooling device (kW)
T	Temperature (°C)
W	The amount of moisture removed (kg^{-1}(d.a.))
$\dot{W}$	Power (kW)
γ	Regeneration air flow rate
E_s	Sensible energy ratio
$\dot{m}$	Mass flow (kg h^{-1})
h	Enthalpy (kJ kg^{-1})

Greek letters

η	Thermal efficiency of solar air collector
ω	Specific humidity (kg^{-1}(d.a.))

Abbreviations

COP	Coefficient of performance
DCOP	Dehumidification coefficient of performance
DW	Desiccant wheel

Subscripts

a	Air
d	Desiccant

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th	Thermal
reg	Regeneration
abs	Absorption

Introduction

Global energy consumption and its associated greenhouse effect have become increasingly critical issues in recent years [1, 2]. Population growth, climate change, and technological advancements are primary drivers of this escalating energy demand [3]. Currently, two main energy sources exist: non-renewable energy and renewable energy [4]. Non-renewable energy sources, such as coal and fossil fuels, are detrimental to the environment, while renewable energy sources, including solar and hydroelectric power, are generally considered environmentally friendly, minimising harm to the ecosystem [5]. Despite their environmental impact, non-renewable energy sources are predominantly used today [6]. These sources have significant disadvantages, primarily their finite nature, being non-replenishable once consumed, and their contribution to global warming through CO_2 emissions [7]. For these reasons, the scientific community is actively seeking alternative energy solutions [8]. Renewable energy sources are identified as the most crucial and promising of these solutions, offering a sustainable and environmentally friendly approach to meeting energy needs [9, 10]. These resources can be considered virtually limitless and inherently eco-friendly [11]. These consumed energy resources have certain areas of use [12, 13]. A significant portion of global energy consumption is attributed to buildings, with approximately 40% of this building-related energy use consumed by heating, ventilation, and air-conditioning systems (ACs) [14, 15]. HVAC systems are units designed to enhance comfort in indoor spaces [16, 17], such as residential and commercial buildings, through various processes like dehumidification [18], heating [19], cooling [20], and ventilation [21], thereby achieving desired indoor comfort levels. The most common type of HVAC system is the traditional air-conditioning unit, which operates on a vapour compression cycle [22, 23]. In hot climates, ACs cool indoor air using refrigerants through evaporative cooling at 100% relative humidity [24]. The cooled air is then circulated back into the indoor environment, creating a cooler and more comfortable atmosphere [25]. Due to rising global temperatures, Acs have become increasingly popular in recent years, with sales tripling since 1990, averaging over 10,000 units sold every hour [26, 27]. ACs are predominantly used in urban areas, with limited adoption in rural settings due to various factors [28]. With half of the world's population residing in urban areas in 2020, and this figure is projected to exceed 70% by 2030 [29], AC usage is expected to rise in tandem with increasing urbanisation. For example, global AC penetration is predicted to increase from 35% in 2020 to 55% by 2050 [26, 30]. Despite their widespread use, ACs are not universally accessible due to the economic burden of purchase and electricity consumption. Households with ACs can experience up to a 42% increase in electricity costs, making them more prevalent in wealthier communities where comfort is prioritised [31]. Studies show that developed countries, being four times wealthier than developing countries, have three times higher per capita AC usage [32], consequently leading to higher CO_2 emissions in these developed nations [33].

A key metric in evaluating the performance of HVAC systems is the coefficient of performance, which compares the amount of heating or cooling produced to the amount of electrical energy consumed [34]. While air conditioners theoretically have the potential to achieve COP values of up to 30, in reality, achieved values do not exceed 3.5 [22]. This discrepancy highlights that while choosing an air conditioner may appear economically and performance-wise advantageous in theory, it is practically inefficient and requires improvement [35]. Beyond the economic considerations, the impact of air conditioners on climate change represents a significant drawback [36]. Refrigerants, which play a crucial role in the operation of air conditioners, contribute to the greenhouse effect and, consequently, to global warming [37]. The greenhouse effect increases the Earth's temperature by trapping a greater amount of incoming solar radiation in the atmosphere [38]. Therefore, the increasing use of air conditioners brings about global warming [39], creating a vicious cycle that further fuels the need for air-conditioning, ultimately harming our ecosystem. Furthermore, due to the operating principle of air conditioners, the cooled environment can reach 100% relative humidity, which can negatively impact human health. Studies indicate that the ideal relative humidity range for human comfort and health is between 40 and 60% [40]. Relative humidity levels below 40% can lead to discomfort, such as dry skin, while humidity levels above 60% increase the risk of spreading illnesses like the flu due to the rapid proliferation of microbes, as shown in Fig. 1 [41]. In addition, the human body naturally dissipates heat through perspiration; however, in high-humidity environments, this mechanism cannot function effectively, potentially leading to thermal discomfort (e.g. fever) [42, 43].

While numerous studies have made strides in minimising emissions from air conditioners, it has become evident that completely eliminating these emissions is not feasible [44–46]. As an alternative solution to address the negative impacts of the greenhouse effect, some scientists propose the use of dehumidifiers [47]. Dehumidifiers enhance human comfort in hot and humid environments by reducing the specific and relative humidity of indoor air. These devices are categorised into two main types: liquid desiccants and solid

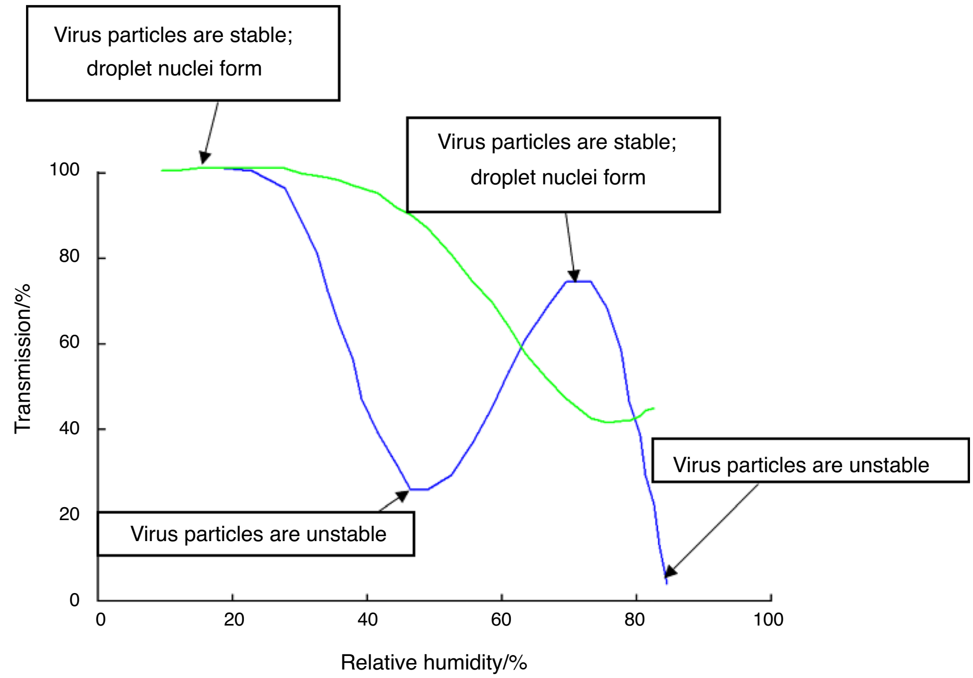

Fig. 1 Effect of relative humidity on the spread rate of viruses

desiccants. Liquid desiccants utilise hygroscopic liquids and halide salt solutions to absorb water vapour from the air stream. Since the vapour pressure of the dry solution is lower than that of the surrounding air at the surface, moisture is absorbed from the air [3, 17, 48–50]. Solid desiccants, on the other hand, offer higher water absorption capacity and a simpler structure compared to liquid desiccants [51]. These materials, such as silica gel and zeolite, are environmentally friendly [22]. A common implementation of solid desiccants is the rotary desiccant wheel, a key component of RDW systems, often featuring a honeycomb structure. RDWSs are HVAC systems designed to improve human comfort in hot and humid climates by reducing indoor humidity, as shown in Fig. 2.

A rotary desiccant wheel system operates in four stages: system intake, dehumidification, cooling, and regeneration [52]. In the intake stage, warm, humid air from the external environment enters the system and passes through the Rotary Desiccant Wheel [53]. The RDW, due to its moisture absorption capacity, removes water vapour from the

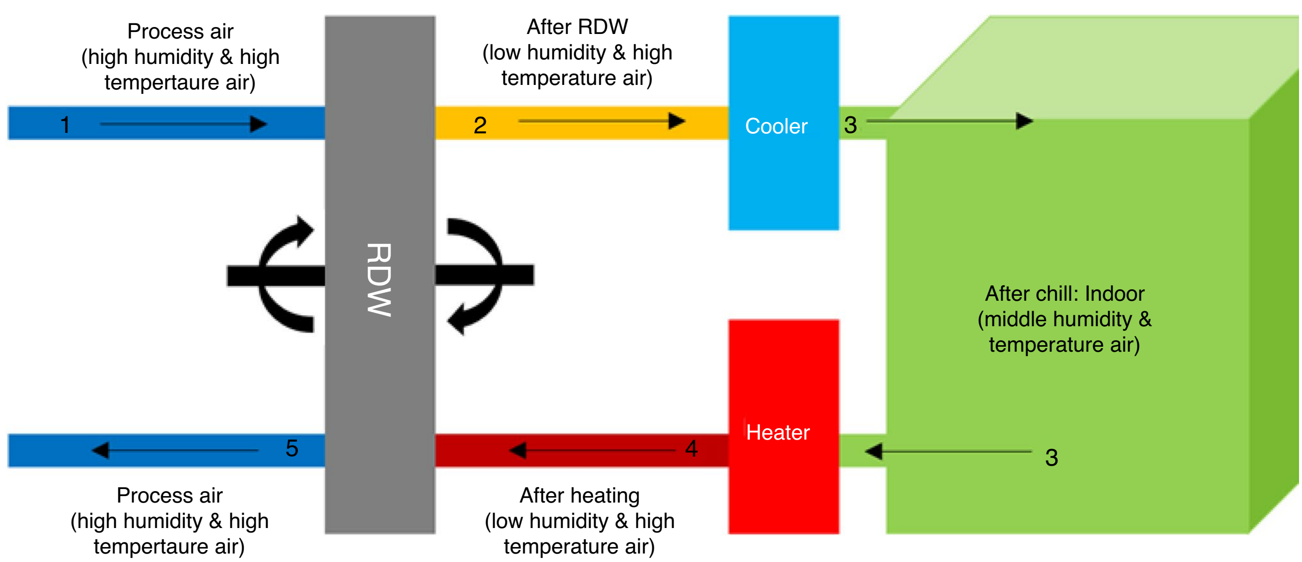

Fig. 2 RDWSs operating cycle

incoming air, thereby reducing its humidity [54, 55]. This dehumidified air is then cooled to the desired comfort conditions and supplied to the indoor environment. However, numerous studies indicate that desiccants have a finite moisture absorption limit, leading to a preference for desiccants with higher moisture uptake capacity [35]. Despite this, the continuous moisture extraction from the incoming air eventually saturates the RDW, rendering it unusable [56–58]. To restore the RDW's functionality, a regeneration process is employed [59]. Heated air is propelled through the RDW by a fan [57], physically removing the absorbed moisture from the desiccant material and making it readily available for reuse [60]. This cyclical operation of the RDWS is illustrated psychrometrically in Fig. 3.

The operational performance of HVAC systems can fluctuate based on ambient conditions [62]. Rotary desiccant wheel systems, depending on operating conditions, can significantly reduce electricity consumption, potentially by up to 50% [63]. RDWSs possess the capability of utilising low-grade energy sources such as waste heat and solar energy [64, 65]. A distinguishing feature of RDWSs compared to other air-conditioning systems is their capacity for continuous fresh air intake and supply due to constant draw from the external environment [66]. Because of their environmentally friendly operation and low energy consumption, RDWSs are currently emerging as a prominent alternative to conventional air-conditioning systems [67]. Key parameters influencing the cost, performance, and energy consumption of RDWSs include the material of the wheel [68], wheel geometry [15], inlet temperature [69], regeneration temperature [70], inlet and regeneration airflow rates [60], wheel thickness [71], hybrid system configurations [72], solar-powered regeneration [63], the number of segments within the wheel [73], and rotational speed [74]. It is anticipated that in the future, these systems will effectively address human comfort needs while mitigating environmental and health impacts. The primary advantages of rotary desiccant wheel systems are summarised in Fig. 4.

Extensive research, both numerical and experimental, has been conducted on rotary desiccant wheel systems since the 1930s. This body of work encompasses a wide range of investigations into the performance and optimisation of RDWSs. This current study undertakes a detailed comparison of historical and contemporary research on RDWSs, aiming to identify the most effective system parameter values for optimal performance. By analysing and synthesising the findings of previous studies, this research seeks to provide specific and actionable recommendations for the

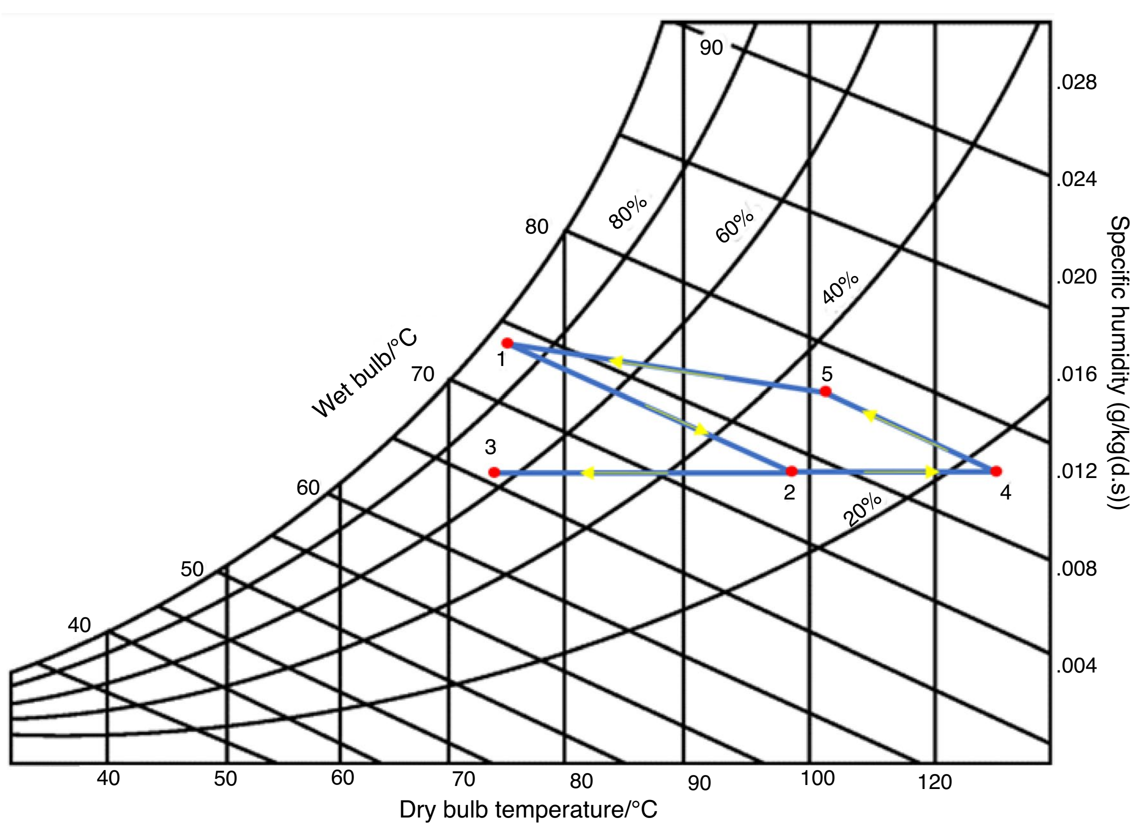

Fig. 3 Representation of the duty cycle on the RDWSs psychometric diagram [61]

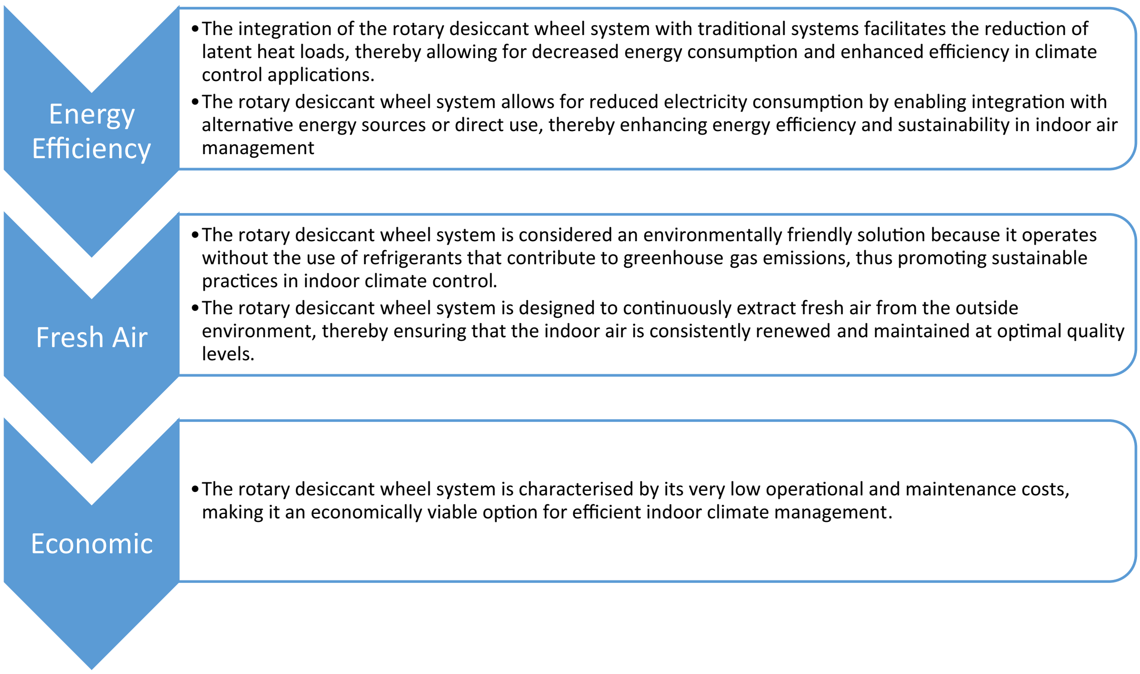

Fig. 4 Advantages of rotary desiccant wheel systems

continued development and refinement of RDWS technology. Furthermore, this study explores the potential future applications and advancements of RDWSs, considering their role in addressing evolving energy efficiency and sustainability needs within the broader context of heating, ventilation, and air-conditioning systems.

History of rotary desiccant wheel system technology

RDWSs are a relatively recent development in cooling-based HVAC systems, emerging within the last century [75]. Beginning in the early 1900s, factories producing or storing moisture-sensitive, high-value products like pharmaceuticals required low-humidity environments [76]. Until the 1990s, desiccant systems primarily served as dehumidification units in industrial settings, protecting these sensitive products from moisture damage and corrosion [77]. After the 1990s, research on desiccant cooling systems intensified due to their potential to address economic and environmental concerns [78]. While a similar air-conditioning unit was initially conceived by Pennington in 1955, as shown in Fig. 5 [79], wheels with laminar flow geometry, designed to minimise pressure drop in desiccant systems, weren't developed until the 1980s. In 1987, a silica gel parallel passage coated wheel was fabricated and experimentally tested [80]. That same year, this wheel was compared against a numerical and theoretical model, with the results proving insightful for contemporary systems [81]. Initially designed for dehumidification in industrial applications from the early to late twentieth century, RDWSs emerged as a potential alternative air-conditioning model in the late twentieth and early twenty-first centuries. Although RDWSs have yet to fully replace traditional air conditioners due to ongoing challenges such as size and regeneration requirements, they hold considerable promise as a future HVAC technology.

Rotary desiccant wheel dehumidification/cooling system

Rotary desiccant wheel geometry and desiccant material selection

Desiccant wheels are essential components within Rotary Desiccant Wheel Cooling Systems, responsible for dehumidifying the process air [82]. These wheels utilise desiccants, which are hygroscopic materials that absorb moisture from the air [83]. While various synthetic desiccants are available today, natural desiccants such as silicon dioxide also exist [84]. A classification of currently available desiccants is presented in Fig. 6 [85, 86].

While desiccant wheels are commonly employed in designs similar to the one illustrated in Fig. 7a, ongoing research and development efforts continue to explore and refine desiccant wheel designs [43]. For instance, O'Connor et al. developed a novel rotary desiccant wheel

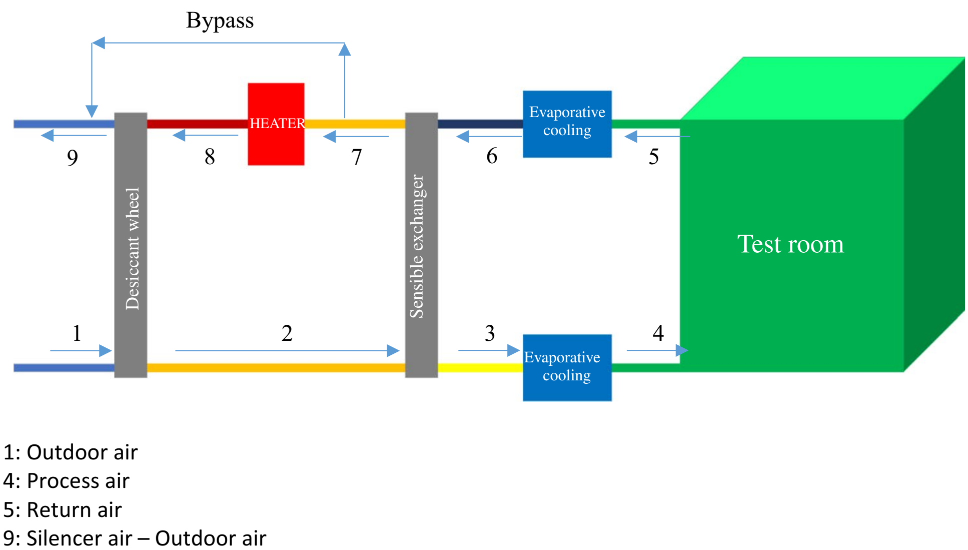

Fig. 5 Pennington cycle

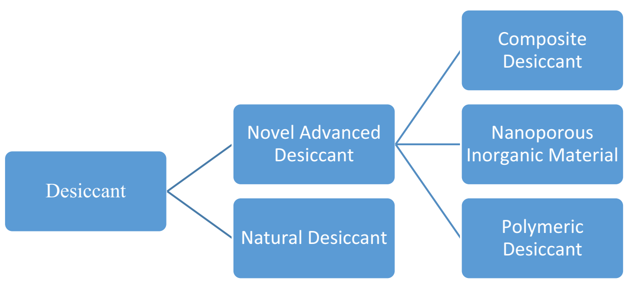

Fig. 6 Schematic representation of available dehumidifiers

based on silica gel, as depicted in Fig. 7b. This design demonstrated the ability to adsorb up to 65% of the moisture from the inlet air at a relatively low regeneration temperature of approximately 48 °C. Furthermore, the design achieved a minimal pressure drop of only 2 Pa, facilitating seamless integration into existing ventilation systems.

Traditional desiccant wheels are typically manufactured with a honeycomb structure, as illustrated in Fig. 7. As indicated by the literature review conducted in Sect. "Rotary desiccant wheel systems' dryer material selection and its effect on the system", the pores within these honeycomb structures can be enhanced with other moisture-absorbing materials. This characteristic has made the optimisation of these porous structures a focal point of ongoing research and development efforts [87, 88].

The effect of rotary desiccant wheel systems' honeycomb pore structure on the system

Figure 8 illustrates the pore structure within the honeycomb structure of a rotary desiccant wheel. Figure 9 provides a representative depiction of the pore geometry within this honeycomb structure. Modifications to this structure significantly influence the overall system performance. Within the dehumidifier, both dehumidification and a temperature increase

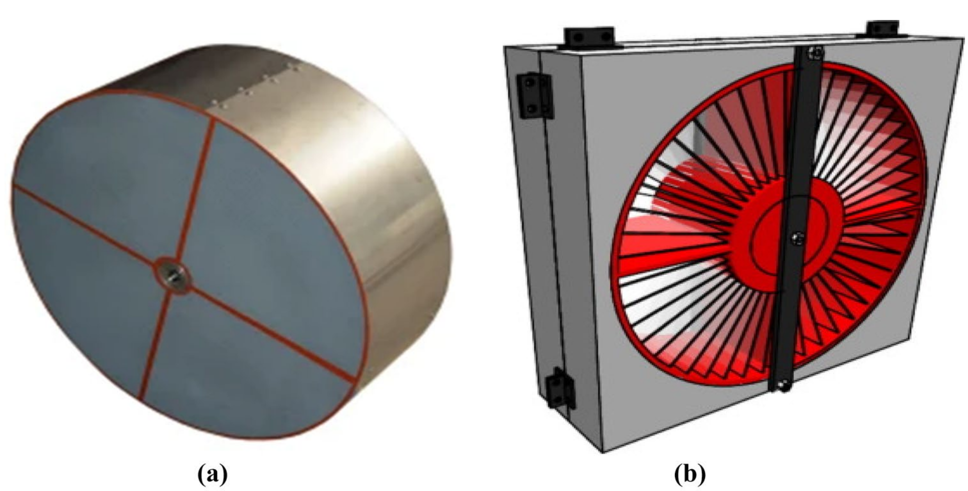

Fig. 7 **a** Traditional RDW, **b** Newly designed RDW [43]

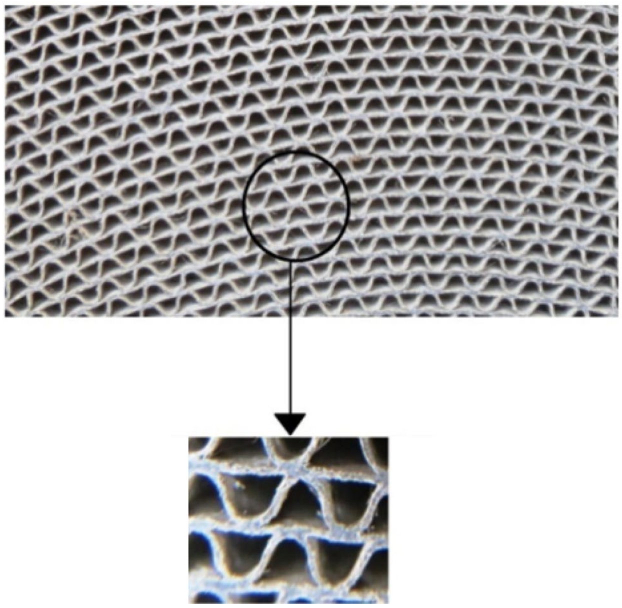

Fig. 8 Appearance of the honeycomb (porous) structure of RDWs [87]

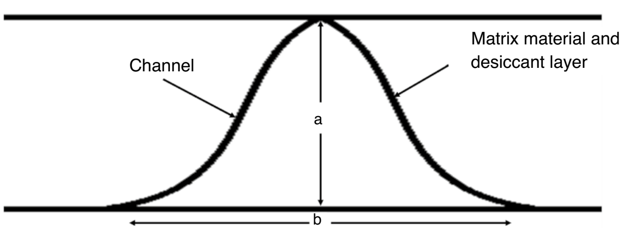

Fig. 9 Conventional RDW pore structure

occur simultaneously. This dual process necessitates the use of equations expressed in two distinct forms:

(1) Mass balance (expressed in terms of humidity)
(2) Energy balance (expressed in terms of temperature)

In computational fluid dynamics analysis (CFD), adherence to these principles of mass and energy balance is fundamental.

Energy balance equation:

$$\frac{\partial T_a}{\partial t} + u\frac{\partial T_a}{\partial x} = \frac{4h}{D_h C_{pa}}\left(T_a - T_d\right) \tag{1}$$

Mass balance equation:

$$\frac{\partial Y_a}{\partial t} + u\frac{\partial Y_a}{\partial x} = \frac{4h_m}{D_h}\left(\omega_a - \omega_d\right) \tag{2}$$

Side equations.

Wet environment inside the channel (m):

$$P = 2b + 2\sqrt{a^2\pi^2 + b^2}\frac{3 + \left(\frac{2a}{a\pi}\right)^2}{4 + \left(\frac{2b}{a\pi}\right)^2} \tag{3}$$

Cross section of channel (m^2):

$$A = 2ab = 8.1 \times 10^{-5} \tag{4}$$

Hydraulic diameter of the channel (m):

$$D_h = \frac{A}{P} \tag{5}$$

From these equations, it is evident that the channel cross section plays a crucial role in determining the performance of dryer cooling systems. For instance, Deep et al. [89] conducted a computational fluid dynamics (CFD) study in Mathematica, simulating the physical properties depicted below.

$$a = 4.5 \times 10^{-3}\text{m}, \text{a} = 9 \times 10^{-3}\text{m}$$

$$b = 9 \times 10^{-3}\text{m}, b = 9 \times 10^{-3}\ \text{m}$$

$$\rho_a = 1.207\,\text{kg m}^{-3}$$

$$\rho_d = 720\,\text{kg m}^{-3}$$

$$T_d = 30\ ^\circ\text{C}$$

$$Y_d = 0.0007\text{kg kg}^{-1}$$

$$u = 3\text{m s}^{-1}$$

$$C_{pg} = 30\text{J kg}^{-1}\ \text{K}^{-1}$$

$$h = 45.01\text{W m}^{-2}\ \text{K}^{-1}$$

$$h_m = 4.1 \times 10^{-10}\ \text{m}^2\ \text{s}^{-1}$$

Following the numerical study, the comparison between "Sinusoidal Geometry (a:b = 1:2) and (a:b = 1:1)" is conducted. At the results, threshold (1:2) and (1:1) temperature difference and specific humidity difference are 46.37%, 49.8% and 24.71%, 21.76%, respectively. Considering that low-temperature difference and high moisture removal rate are more effective in the dryer cooling system, it is seen that the wheel with 1:2 cross-sectional dimensions will be preferred. Deep et al. verify the accuracy of their numerical study by comparing it with the numerical analysis conducted by Narayanan et al. [90]. The comparison reveals that the two studies exhibit similarities, further affirming the validity of their findings.

Rotary desiccant wheel systems' dryer material selection and its effect on the system

According to Collier et al. [91], there remains considerable potential for enhancing the performance of readily available desiccants. In the twenty-first century, research focusing on novel wheel designs has intensified, encompassing both numerical and experimental approaches. Jia et al. [92] designed a wheel composed of a double layer of lithium chloride integrated into the structure of a silica gel-based honeycomb with a pore surface area of 194 m^2 and a honeycomb pore diameter of 3.98 m. This design aimed to improve the performance of RDWSs. In their experimental study, the newly designed wheel exhibited a 25% increase in moisture removal capacity and a 35% improvement in COP compared to silica gel wheels. Muthu et al. [93] numerically simulated a hybrid desiccant wheel using CFD code. This hybrid wheel combined silica gel with molecular sieves. The isotherm of the simulated homogenous mixture of SG and MS within the hybrid wheel is illustrated in Fig. 10.

At inlet and regeneration temperatures of 40 °C and 90 °C, respectively, the newly simulated hybrid wheel demonstrates a 27% higher COP compared to silica gel wheels. Zhang et al. [94] fabricated a composite SG-CaCl2 wheel composed of silica gel and calcium chloride. In a comparative experimental test, the composite desiccant reached equilibrium faster than the SG desiccant and exhibited sufficient water absorption properties for desiccant wheel applications. Zheng et al. [95] developed a novel alumina sheet coated with a composite of silica gel and lithium chloride. They

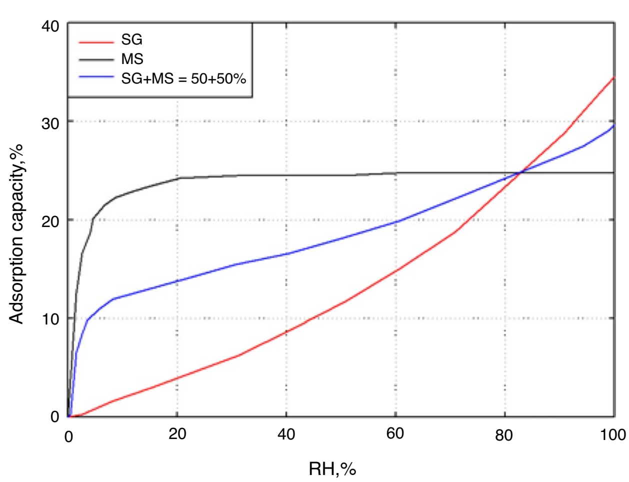

Fig. 10 Isotherm of homogeneous mixture of SG: MS [93]

experimentally compared the dehumidification performance of this composite-coated sheet with another alumina sheet coated only with silica gel, using a condensation-type dehumidification technology. The results indicated an approximately 30% increase in the dehumidification capacity of the composite-coated heat exchanger. Zhang et al. [96] developed a composite wheel containing silica gel and calcium chloride for use in an RDW within a dehumidification system. In their experimental study, varying amounts of calcium chloride salt were impregnated into a porous structure to demonstrate the influence of salt quantity on performance. Numerical simulations further confirmed the effectiveness of this composite rotary wheel within a dehumidification device, suggesting that performance enhancements can be achieved by adjusting various operating and system parameters. Xue et al. [97] conducted comparative tests between silica gel and a polymer material characterised by high water absorption and low regeneration temperature requirements. At regeneration temperatures between 40 and 70 °C, the polymer exhibited a 350% higher equilibrium adsorption capacity and a 45% higher desorption rate than silica gel under high-humidity and cool conditions. Kadu et al. [98] investigated the impact of varying silica gel and calcium chloride mixture ratios on wheel performance. Five samples with a total mass of 5 g were tested, with SG:CaCl2 ratios of (1) 4:1, (2)3.5:1.5, (3) 3:2, (4) 2:3, and (5) 1:4, respectively. Experimental results revealed that mixture yielded the highest dehumidification rate. The overall performance ranking was (2) > (3) > (4) > (5) > (1). Rambhad et al. [99] tested three composite wheels in an RDWS where solar energy powered the regeneration air. The wheels consisted of the following compounds: SG:MS (90% SG, 10% MS), SG:CaCl2 (90% SG, 10% CaCl2), and SG:MS:CaCl2 (80% SG, 10% MS, 10% CaCl2). While the regeneration rate of SG was 1.757 kg h^{-1}, the SG:MS:CaCl2 composite exhibited a regeneration rate of 1.979 kg h^{-1}. Experimental tests revealed that SG:MS, SG:CaCl2, and SG:MS:CaCl2 had approximately 5%, 10.4%, and 20.4% better regeneration rates than SG, respectively. Yadav et al. [100] conducted a comparative mathematical modelling study of silica gel, lithium chloride, and calcium chloride, including composite materials. The study focused on SG-LiCl and SG-CaCl2 composite wheels. Their numerical analysis suggested that using pure LiCl and CaCl2 wheels might be less desirable due to temperature differences. However, despite also exhibiting high-temperature differences, the SG-LiCl and SG-CaCl2 composite wheels could be preferable due to their higher dehumidification capacities. Yaming et al. [101] devised and patented a novel method for preparing a lithium chloride and silica gel composite rotary wheel. This method involves impregnating a silicate solution (10–30%), floating it in an acid solution (3–30%), calcining it at 400–500 °C, and finally impregnating lithium chloride (15–40%) into the wheel body, all between the rotary wheel rounding and moulding processes. Wheels produced using this method reportedly offer superior dehumidification performance, lower regeneration temperatures, easier manufacturing, and longer lifespans compared to conventional wheels. Chen et al. [102] experimentally tested a silica gel/polymer-based composite desiccant wheel in a building, utilising a 40–50 °C regeneration heat source from a heat pump. The composite desiccant wheel, composed of 80% silica gel, 10% polyacrylic acid, and 10% sodium polyacrylate, achieved a 130% performance improvement over silica gel-based systems with an energy factor of 2.3 and consumed less power than traditional wheel systems. You et al. [103] developed a novel silica gel production method for rotary desiccant wheels. Instead of corrosive acids, they used CO_2 to neutralise a 3.3 modulus water glass solution impregnated onto a glass fibre sheet, forming the honeycomb matrix. The resulting silica gel was characterised using conventional methods. Silica gel produced with 0.25 MPa CO2 achieved a water adsorption capacity of 287.4 mg/g at 50% relative humidity, surpassing previously reported results. A comparison between the developed wheels and conventional silica gel wheels is presented in Table 1.

Considering the studies on different wheel structures discussed in Sect. ”Rotary desiccant wheel geometry and desiccant material selection” and the analyses presented in Sect. ”Multi-stage rotary desiccant wheel systems”, the following conclusions can be drawn:

RDWs influence not only dehumidification but also the system's COP.

RDW selection should consider the holistic system performance, not just the wheel structure itself. Factors such as temperature, high regeneration inlet temperature differences, and low regeneration rates can lead to increased energy consumption, higher cooling load capacity requirements, and the need for elevated regeneration temperatures.

It is important to interpret these findings within the context of each study's specific operating conditions and environmental parameters. As mentioned in introduction, different studies yield unique values and results due to varying conditions. Section ”Multi-stage rotary desiccant wheel systems” elaborates on these differences and presents the optimal outcomes.

Applications of RDWs in conventional air-conditioning units

While RDWs are commonly used in RDWCSs, numerous studies demonstrate their potential for enhancing the performance of existing conventional air-conditioning systems. Shekoor [104] experimentally have investigated the performance and energy efficiency improvements achieved by integrating a silica gel/calcium chloride composite desiccant wheel with traditional air conditioners in Kosangrad and Korela. The air-conditioning unit's performance was tested both with and without the dehumidification wheel. When the wheel was connected, the system exhibited a 3.4% increase in cooling effect, a 4.2% reduction in compressor work input, and a 30% improvement in COP. Furthermore, a 15% reduction in energy consumption was observed. However, due to the environmentally friendly and cost-effective nature of RDWs, eco-friendly RDWCSs are preferred for reducing global emissions.

Multi-stage rotary desiccant wheel systems

Multi-stage rotary desiccant wheel systems are designed to enhance dehumidification performance. Traditional rotary desiccant wheels have a single stage where air is dehumidified as it passes through the desiccant material. A multi-stage system uses multiple wheels or multiple sections within a wheel to progressively dry the air. This can lead to more effective moisture removal and potentially improve energy efficiency.

RDWCSs typically consist of systems operating with a single rotary desiccant wheel [105–110]. However, in environments with extreme humidity and temperature conditions, two-stage systems utilising two desiccant wheels are

Table 1 Comparison of composite RDWs with each other [91–103]

Composite RDW	Better moisture removed/%	Regeneration rate/%
SG: MS (40:60%)	20 to SG	–
SG: CP: $CaCl_2$ (90:10%)	50 to SG	–
SG: LiCl (60:40%)	~34 to SG	–
SG: $CaCl_2$ (60:40%)	21 to SG: $CaCl_2$ (90:10)	–
SG: PA: PS (80:10:10%)	16 to SG	–
SG: MS (90:10%)	–	~5 to SG
SG: LiCl (90:10%)	–	~10 to SG
SG: MS: LiCl (80:10:10%)	–	~20 to SG
Composite polyacrylonitrile	~350 to SG	~45 to SG

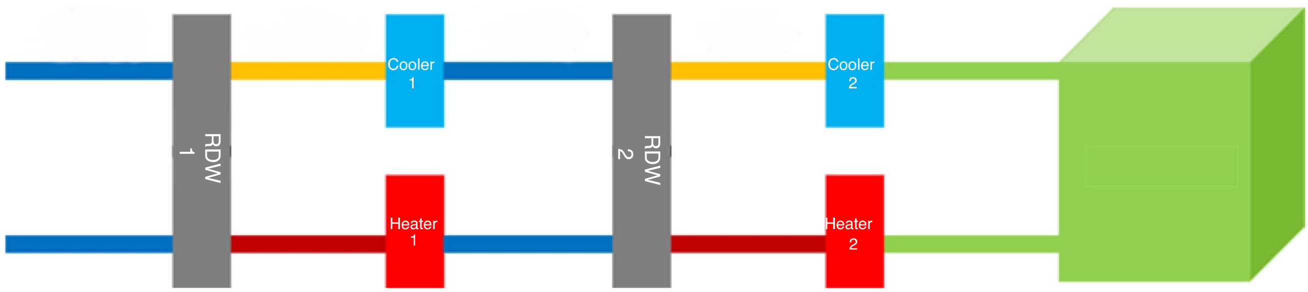

Fig. 11 Two-stage rotary dryer wheel cooling system

sometimes employed [111]. A two-stage RDWCS is illustrated in Fig. 11.

Two-stage systems offer certain advantages:

Enhanced dehumidification: They remove unwanted moisture from the outside air more effectively and rapidly. By progressively drying the air, multi-stage systems can achieve lower humidity levels than single-stage systems. In addition, optimising each stage of the process can potentially reduce the overall energy consumption of the system. Multi-stage desiccant wheel systems are suitable for applications requiring precise humidity control, such as hospitals, pharmaceutical production, food storage and supermarkets.

Faster air equilibration Compared to single-stage RDWCSs, they achieve indoor air balance more quickly.

Flexibility Multi-stage systems can be designed to handle a wider range of inlet air conditions. Desiccant wheels can be regenerated using waste heat or renewable energy sources, further enhancing their energy efficiency.

However, two-stage systems also have drawbacks:

Higher energy consumption They require more energy to operate.

Larger size They occupy more physical space.

RDWSs can be adapted for use in extreme climates, but specific modifications and considerations are necessary. In very cold climates, managing moisture becomes critical to prevent condensation and ice buildup, which can damage building materials and reduce insulation effectiveness. Hot and humid climates present a significant challenge for maintaining comfortable indoor conditions. High-humidity levels can lead to mould growth and discomfort. Arid climates often experience large temperature swings between day and night. RDWSs can help stabilise indoor temperatures and reduce the need for excessive heating or cooling. Airborne dust and sand can clog desiccant wheels and reduce their efficiency. Choosing the right desiccant material is crucial. In dusty environments, pre-filters are essential to remove particulate matter before it enters the desiccant wheel. Enhanced sealing can minimise air leakage and maintain optimal performance in extreme temperatures. Adjusting the regeneration temperature and airflow can optimise performance under different climatic conditions. In remote locations with limited access to electricity, RDWS can be powered by renewable energy sources such as solar thermal collectors.

Effect of working conditions on the performance of the system

In RDWCSs, each parameter is interconnected and directly influences system performance. For instance, the rotational speed of the desiccant wheel significantly affects both moisture adsorption and regeneration. If the wheel rotates too slowly, some of the adsorbed moisture can be re-released into the air. Conversely, if it rotates too quickly, the desiccant wheel cannot regenerate effectively, leading to premature saturation due to excessive moisture retention. Furthermore, the rotational speed is also linked to the regeneration temperature [112].

RDWs operate in two primary sections, as depicted in Fig. 12a: dehumidification (adsorption) and regeneration (desorption). While some studies have explored different section configurations, a common ratio between the regeneration and process air streams is 3:1. However, alternative configurations exist, such as a two-stage RDW with a 3(135°):1(45°):3(135°):1(45°) ratio. Ge et al. [73] propose

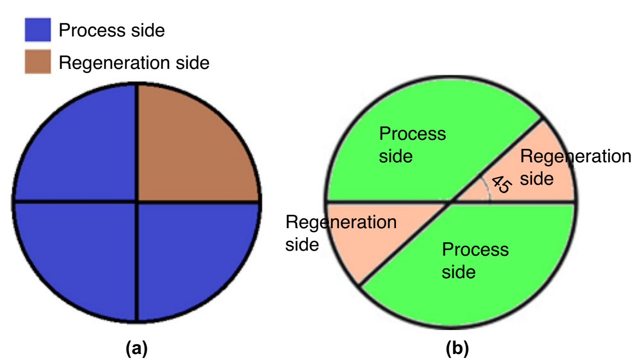

Fig. 12 **a** RDWs conventional process sections. **b** two-stage RDW with a single rotary impeller

that a single-stage RDW with two sections, as shown in Fig. 12b, can reduce system size without compromising performance, as opposed to using a two-stage RDWCS.

The optimal rotational speed of an RDW is determined by the amount of moisture removed [113]. The ideal wheel speed increases with higher regeneration temperatures. Additionally, RDWs should rotate faster in high humidity conditions and slower in low-humidity conditions [114]. For example, in a system where the regeneration air temperature is increased from 45 °C to 65 °C, raising the rotational speed from 6 to 10 rph yields optimal results. Similarly, if the outdoor air humidity increases from 8.62 to 11.1 g kg^{-1}, the rotational speed should be increased from 7 to 10 rph [112].

Beyond these examples, determining the optimal rotational speed also involves the following considerations [115]:

- To increase the amount of moisture removed, a slower rotational speed should be selected.
- To elevate vapour pressure, a faster rotational speed is preferable.
- For higher DCOP values, a slower rotational speed is recommended.
- As regeneration air intake velocity increases, the rotational speed should also increase.
- With a larger process air section area, a slower rotational speed is more suitable.

In addition to rotational speed, the thickness of the desiccant wheel also plays a crucial role in dehumidification performance. A detailed comparison is presented in Table 2.

Regeneration temperature directly impacts the COP of a desiccant cooling system [108], where COP represents the cooling capacity relative to energy input. There are two primary methods for heating in regeneration: electric heating and solar collectors [120]. While less common, utilising waste heat for regeneration is also possible [121]. A temperature range of 60–90 °C is generally sufficient for regeneration, although many studies focus on regeneration temperatures exceeding 90 °C [122]. Higher regeneration temperatures increase heating power demand and cooling load, negatively affecting the COP [123]. However, increased regeneration temperatures also enhance moisture removal from the process air [124]. Additionally, regeneration temperature influences the temperature of the process air entering the system [125]. Because the RDW acts as a heat exchanger due to the heat supplied during regeneration [126], pre-cooling is often employed to mitigate this effect [127].

Pre-cooling involves cooling the process air before it enters the RDW, reducing the temperature increase caused by the regeneration heat [128]. Pre-cooling systems offer higher enthalpy and dehumidification efficiency compared

Table 2 Change of dehumidification efficiency in the system according to rotation speed and impeller thickness [73, 92, 116–119]

Rotational speed	Different moisture removed /%	Wheel thickness	Different moisture removed/%
4–20rph	~36 Worse [73]	40–70 mm	~6 Better [73]
4–8rph	~7 Worse [73]	40–100 mm	~10 Better [73]
8–12rph	~5 Worse [73]	50–100 mm	~25 Better [92]
12–16rph	~15 Worse [73]	100–150 mm	~8 Worse [92]
16–20rph	~15 Worse [73]	150–200 mm	~12 Worse [92]
10–60rph	~32 Better [116]		
10–20rph	~16 Better [116]		
20–30rph	~2 Better [116]		
30–40rph	- [116]		
40–50rph	~4 Worse [116]		
50–60rph	~3 Worse [116]		
10–20rph	~17 Better [116]		
10–20rph	~21 Better [117]		
20–30rph	~7 Better [117]		
30–40rph	~3 Worse [117]		
40–50rph	~3 Worse [117]		
50–60rph	~3 Worse [117]		
10–30rph	~13 Worse [118]		
10–20rph	~5 Worse [118]		
20–30rph	~8 Worse [118]		
20–40rph	~1 Worse [119]		
40–60rph	~2 Worse [119]		

to systems without pre-cooling [69, 129]. Lower pre-cooling temperatures result in reduced dehumidification. Pre-cooling can be achieved using various methods, such as heat exchangers or exhaust air, targeting the area indicated by number one in the schematic diagram shown in Fig. 2 [69, 115]. Table 3 shows the relationship between regeneration temperature and moisture absorption, based on some experimental studies. Table 4 shows the effect of pre-cooling on dehumidification.

Table 3 Relationship between regeneration temperature and moisture absorption [71, 116, 119, 121, 130]

Regeneration temperature	Better moisture removed/%
50–80 °C	~20 [71]
50–70 °C	~18 [71]
50–90 °C	~30 [71]
50–70 °C	~19 [130]
60–70 °C	~15 [116]
70–80 °C	~26 [116]
50–60 °C	~4 [119]
60–70 °C	~2 [121]

Table 4 Effect of pre-cooling on dehumidification [131]

Pre-cooling temperature	Moisture removed/%
20 °C to 24 °C	16.7 to 18% [131]

Furthermore, the impact of composite wheels on system performance is examined in Sect. "Rotary desiccant wheel geometry and desiccant material selection". Additionally, Du and Lin's [132] study presents a performance comparison of various desiccant types and structures, considering their parameter influences and operating conditions, as illustrated in Table 5. This table highlights the significant impact of wheel structure variations on overall system performance.

Thermodynamic analysis of rotary desiccant wheel cooling systems

The thermodynamic analysis of rotary desiccant wheel cooling systems often considers two primary regeneration heat sources: electrical energy and solar energy [133].

The rotary dehumidification wheel cooling system operates through the following sequential stages: References by Fig. 2.

1. Air intake into the RDWCS

1-2. Moisture extraction from the air via the wheel

2. Dehumidified air emerges from the wheel

2-3. Adjustment of air to desired comfort levels through sensible cooling

3. Indoor air attains optimal temperature and humidity for comfort

3-3'. Discrepancy arising from potential leakage

3'-4. Indoor air heated for circulation within the system

4. Sensible heating raises temperature of hot, dry air

4-5. Warm, dry air absorbs moisture from the wheel

5. Disposal of waste air to the external environment

Analysis of rotary desiccant wheel cooling system [52, 63, 134–142]:

Losses will be neglected in this system analysis ($3' = 3$).

RDWCS' analysis, which feeds the regeneration part from electrical energy

$$W_{\text{abs}} = \omega_1 - \omega_2$$

$$\dot{m}_{\text{ven}} = \frac{HL}{\omega_3 - \omega_2}$$

$$\Delta h = h_1 - h_2$$

$$M_{\text{abs}} = \dot{m}_1 \left(\omega_1 - \omega_2\right)$$

$$M_{\text{reg}} = \dot{m}_1 \left(\omega_5 - \omega_4\right)$$

$$\dot{Q}_{\text{c}} = \dot{m}_3 \cdot \Delta H$$

Table 5 Effect of wheels consisting of different structures on the parameters on the system [132]

Dehumidifier	Adsorption bed type	Inlet temperature/°C	Inlet relative humidity/%	Regeneration temperature/°C	DCOP	Dehumidification/g kg^{-1}
Silica gel	Honeycomb wheel	28	40	100	1.8	4.0
Silica gel + lithium chloride	Honeycomb wheel	28	40	100	3.3	6.1
Silica gel + lithium chloride	Honeycomb wheel	28	42	100	1.7	3.2
Silica gel + polyvinyl alcohol	Honeycomb wheel	28	72	100	2.1	1.9
Activated aluminium	Filling form	30	70	25 40	1.1 0.9	1.7 2.1
Polyacrylic acid + activated aluminium	Filling form	16–33	65–78	25–40	3.21	-
Polyacrylic acid sodium salt	Filling form	30	70	50	–	1.31
	Smear form	25–30	75	60	0.45–0.5	1.2
Silica gel + sodium polyacrylate	Filling form	16	45	40–50	–	7.0
Silica gel + sodium polyacrylate	Filling form	30	70	50	–	2.2

$$\dot{W}_{\mathrm{th}} = \dot{m}_{\mathrm{reg}} \cdot c_r \cdot \left(t_4 - t_3\right)$$

$$COP_{\mathrm{th}} = \frac{\dot{Q}_{\mathrm{c}}}{W_{\mathrm{th}}}$$

$$\varphi_{\mathrm{abs}} = \frac{\omega_1 - \omega_2}{\omega_1 - \omega_{2,\mathrm{ideal}}}, \omega_{2,\mathrm{ideal}} \to 0$$

$$\varphi_{\mathrm{reg}} = \frac{\omega_5 - \omega_4}{\omega_4}$$

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{c}}}{\dot{E}_{\mathrm{reg}} + \dot{E}_{\mathrm{fan}} + \dot{E}_{\mathrm{DW}}}$$

$$\mathrm{DCOP} = \frac{h_{\mathrm{v}}.\left(\omega_1 - \omega_2\right)}{\gamma\left(h_4 - h_5\right)}, h_v = 2250\,\mathrm{kJ\,kg^{-1}}$$

$$\gamma = \frac{q_{\mathrm{process}}}{q_{\mathrm{regeneration}}} \times 100\%$$

$$E_s = \frac{t_2 - t_1}{\gamma\left(t_4 - t_3\right)}$$

Assuming there are no airflow losses and neglecting pressure drops: $\dot{m}_{\mathrm{ven}} = \dot{m}_1 = \dot{m}_3 = \dot{m}_{\mathrm{reg}}$.

RDWCS' analysis, which feeds the regeneration part from solar energy

$$W_{\mathrm{reg}} = \omega_5 - \omega_4$$

$$\dot{m}_{\mathrm{ven}} = \frac{HL}{\omega_3 - \omega_2}$$

$$\Delta h = h_1 - h_2$$

$$M_{\mathrm{abs}} = \dot{m}_1\left(\omega_1 - \omega_2\right)$$

$$M_{\mathrm{reg}} = \dot{m}_1\left(\omega_5 - \omega_4\right)$$

$$\dot{Q}_c = \dot{m}_3 \cdot \Delta H$$

$$\dot{W}_{th} = A.G$$

$$COP_{th} = \frac{\dot{Q}_c}{W_{th}}$$

$$\varphi_{\mathrm{abs}} = \frac{\omega_1 - \omega_2}{\omega_1 - \omega_{2,\mathrm{ideal}}}, \omega_{2,\mathrm{ideal}} \to 0$$

$$\varphi_{\mathrm{reg}} = \frac{\omega_5 - \omega_4}{\omega_4}$$

$$\mathrm{COP} = \frac{\dot{Q}_c}{E_{\mathrm{reg}} + E_{\mathrm{fan}} + E_{\mathrm{DW}}}, E_{\mathrm{reg}} \to 0$$

$$\mathrm{DCOP} = \frac{h_{\mathrm{v}}.\left(\omega_1 - \omega_2\right)}{\gamma\left(h_4 - h_5\right)}, h_v = 2250\,\mathrm{kJ\,kg^{-1}}$$

$$\gamma = \frac{q_{\mathrm{process}}}{q_{\mathrm{regeneration}}} \times 100\%$$

$$E_s = \frac{t_2 - t_1}{\gamma\left(t_4 - t_3\right)}$$

$$\eta = \frac{\dot{m}_3.C_r.\left(T_2 - T_3\right)}{A.G}$$

Assuming there are no airflow losses and neglecting pressure drops: $\dot{m}_{\mathrm{ven}} = \dot{m}_1 = \dot{m}_3 = \dot{m}_{\mathrm{reg}}$.

Experimental studies on rotary desiccant wheel systems

Ge et al. [143] present an experimental investigation of a novel two-stage rotary desiccant cooling system utilising a silica gel-haloids composite desiccant, as shown in Fig. 13. The study aimed to evaluate the system's performance under various conditions and provide practical application data. The TSRDC system employs two desiccant wheels in series, each followed by a sensible heat exchanger to cool the process air and preheat the regeneration air.

The experiments were conducted under three typical environmental conditions. Performance was evaluated using moisture removal (D) and thermal coefficient of performance (COP_{th}). Key findings include:

Low Regeneration Temperature: The TSRDC system demonstrated a low regeneration temperature requirement, ranging from 65 to 80 °C. This is a significant advantage for energy efficiency.

High COP_{th}: The system achieved a high COP_{th}, indicating effective energy utilisation for cooling. While specific values aren't provided in this abstract, the paper emphasises the high COP_{th} as a critical result.

Fig. 13 Two-stage rotary desiccant wheel system [143]

Fig. 14 Rotary desiccant wheel system integrated with solar energy [63]

Performance under Varying Conditions: The study tested the system under different environmental conditions, providing insights into its adaptability.

Kabeel [63] investigates a solar-powered air-conditioning system incorporating a unique rotary honeycomb desiccant wheel as shown in Fig. 14. The study focuses on the performance of this system, particularly the regeneration and absorption processes within the desiccant wheel.

The system comprises a solar air heater, a rotary desiccant wheel, and a heat exchanger. The solar air heater, filled with a porous aluminium foil, heats the air for regeneration. The desiccant wheel, constructed from iron wire mesh coated with a calcium chloride solution, handles dehumidification.

The system demonstrates high effectiveness in the regeneration process, removing significant moisture from the desiccant wheel. The study provides empirical equations relating removed moisture to airflow rate at solar noon.

Empirical equations are also derived for wheel effectiveness as a function of airflow rate for both regeneration and absorption processes. These equations allow for performance prediction under varying operating conditions.

The study analyses the influence of solar radiation intensity on system performance. Higher solar radiation leads to improved regeneration, as expected.

The experiments explore the impact of airflow rate on both regeneration and absorption. Optimal airflow rates are identified for maximising system performance.

Su et al. [131] present an experimental investigation of an innovative dehumidification system designed for enclosed cabins, addressing the challenges of high temperature and humidity, as shown in Fig. 15. The system integrates a pre-cooling stage and a recirculated regenerative rotary desiccant wheel.

The system tackles the limitations of conventional air-conditioning dehumidification systems, which often struggle with high energy consumption in challenging environments. The pre-cooling stage reduces the load on the desiccant wheel, while the recirculation design optimises regeneration efficiency.

A dedicated test rig was constructed to evaluate the system's performance under various operating conditions. The setup allows for precise control and measurement of critical parameters, including regeneration airflow ratio, regeneration air temperature, process air temperature and humidity, and pre-cooling temperature.

While the abstract doesn't provide specific numerical results, it highlights the following key aspects:

The experiments validated the feasibility of the proposed system, demonstrating its effectiveness in dehumidifying enclosed cabin environments.

The study aimed to determine the optimal operating conditions for maximising dehumidification capacity. The full paper likely contains specific data and analysis regarding this optimisation.

The experiments investigated the impact of various parameters on system performance. The full text likely presents detailed results showing the influence of regeneration airflow ratio, regeneration air temperature, process air temperature, humidity level, and pre-cooling temperature on dehumidification capacity and energy efficiency.

Ma et al. [144] experimentally investigated a desiccant wheel dehumidification system's performance under low-humidity conditions, as shown in Fig. 16, aiming for a supply air dew point below 0 °C. Their key findings include:

The system achieved a lower process outlet humidity ratio (0.002 kg kg^{-1}) at lower inlet humidity ratios (0.004 kg kg^{-1} and 0.006 kg kg^{-1}) compared to higher inlet humidity ratios

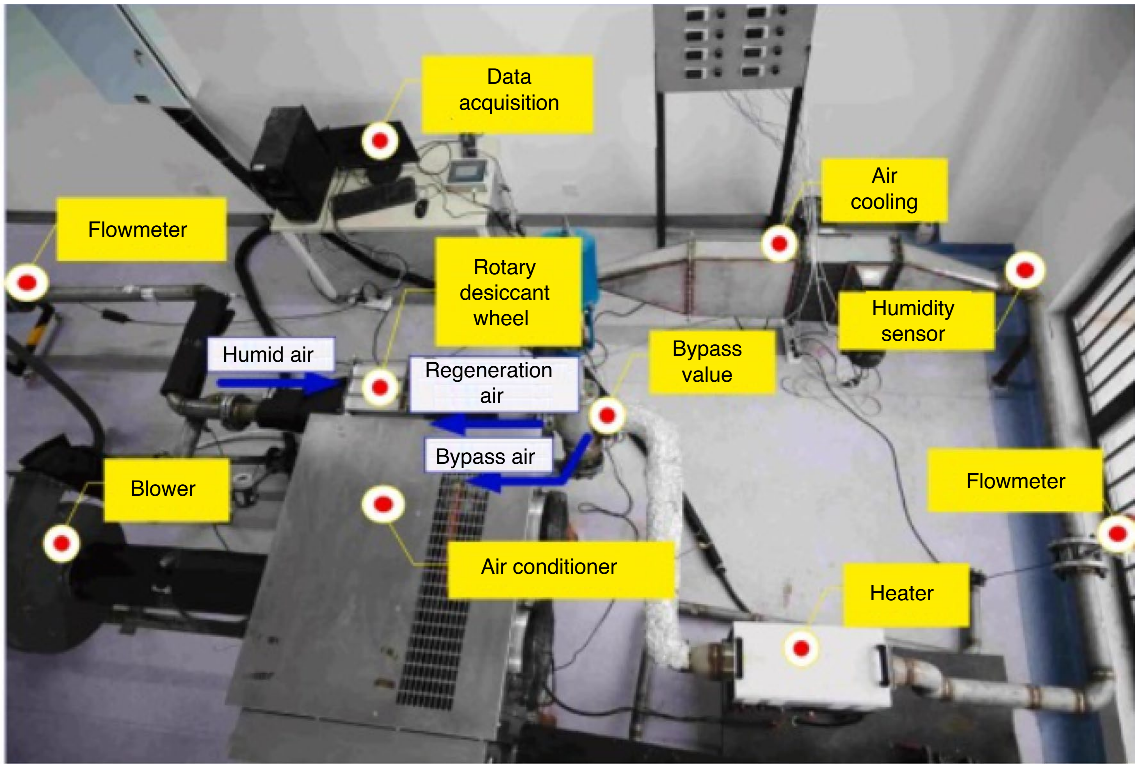

Fig. 15 Pre-cooling and regenerative rotary desiccant wheel system [131]

Fig. 16 Rotary desiccant wheel system [144]

(0.008 kg kg^{-1} and 0.010 kg kg^{-1}). This indicates improved relative dehumidification capacity at lower humidity levels.

Increasing the regeneration temperature from 40 to 60 °C resulted in a decrease in the process outlet humidity ratio, demonstrating enhanced dehumidification performance. However, this also led to a higher surplus temperature rise, affecting overall system effectiveness. For example, at an inlet humidity ratio of 0.006 kg kg^{-1}, increasing the regeneration temperature from 40 to 60 °C decreased the outlet humidity ratio by approximately 0.0005 kg kg^{-1} but increased the surplus temperature rise by roughly 0.6 °C.

The study analysed the system's thermodynamic effectiveness using the surplus temperature rise parameter. Lower regeneration temperatures generally resulted in lower surplus temperature rises, indicating better effectiveness. For instance, at an inlet humidity ratio of 0.006 kg kg^{-1} and a regeneration temperature of 40 °C, the surplus temperature rise was around 0.4 °C, while at 60 °C, it increased to approximately 1.0 °C.

The research compared deep dehumidification with normal dehumidification processes, finding differences in parameter sensitivity and thermodynamic effectiveness. Specifically, the sensitivity of the dehumidification performance to changes in regeneration temperature was higher in deep dehumidification compared to normal dehumidification. Similarly, the surplus temperature rise was generally higher in deep dehumidification, suggesting lower thermodynamic effectiveness.

Aziz et al. [145] conducted a combined numerical and experimental investigation of a desiccant cooling system utilising metal–organic framework materials, as shown in Fig. 17. Motivated by the limitations of conventional desiccant materials like silica gel, the study explored the potential of MOFs, known for their high porosity and water uptake capacity, to enhance system performance. The experimental setup involved a desiccant wheel integrated with an evaporative cooler. The authors developed a numerical model to simulate the system's behaviour and validated it against experimental measurements. Their findings highlighted the superior performance of MOFs compared to traditional desiccants, demonstrating improved moisture removal and cooling capacity. The study provides valuable insights into the potential of MOFs for enhancing desiccant cooling systems and offers a validated numerical model for further research and development in this area.

Rambhad et al. [146] present an experimental investigation focusing on the impact of four different silica gel desiccant wheel combinations on indoor air quality as shown in Fig. 18. The study aimed to evaluate the performance of composite desiccant wheels composed of silica gel with lithium chloride, molecular sieve 5A, and a combination of all three, comparing them to a standard silica gel desiccant wheel. The researchers measured and compared key performance parameters, including adsorption and regeneration rates, under various operating conditions. Their results demonstrated that the composite desiccant wheel incorporating silica gel, lithium chloride, and molecular sieve 5A exhibited the highest adsorption and regeneration rates, significantly outperforming the other configurations. Specifically, the composite wheel achieved an 85.5% improvement in adsorption rate and a 14% increase in regeneration rate compared to the silica gel-only wheel. This study highlights the potential of composite desiccant wheels for enhancing dehumidification performance and improving indoor air quality.

Ge et al. [147] have investigated the efficacy of a silica gel desiccant wheel in simultaneously removing both moisture and contaminants from air streams. Their experimental work explored the performance of the desiccant wheel under a range of operating conditions, focusing on the effects of varying airflow velocity and wheel rotation speed. The study specifically targeted the removal of formaldehyde and toluene, two prevalent indoor air pollutants, while concurrently assessing dehumidification performance.

The silica gel desiccant wheel demonstrated considerable effectiveness in moisture removal. At an airflow velocity of 0.5 m s^{-1} and a rotation speed of 10 rpm, the wheel achieved an average moisture removal effectiveness of 75%. However, this effectiveness decreased to 60% when the airflow velocity was increased to 1.0 m s^{-1} while maintaining the same rotation speed. A similar trend was observed when the rotation speed was increased to 20 rpm at the lower airflow velocity of 0.5 m s^{-1}, resulting in a reduction in effectiveness to 68%.

Formaldehyde removal by the desiccant wheel was also substantial. Under the baseline conditions of 0.5 m s^{-1} airflow velocity and 10 rpm rotation speed, the average formaldehyde removal effectiveness was 65%. Increasing the airflow velocity to 1.0 m s^{-1} led to a decrease in effectiveness to 52%. A smaller reduction to 60% was observed when the rotation speed was increased to 20 rpm while keeping the airflow velocity at 0.5 m s^{-1}.

The desiccant wheel also proved effective in removing toluene. At the baseline operating conditions, the average toluene removal effectiveness reached 72%. A slight decrease to 68% was observed when the airflow velocity was increased to 1.0 m s^{-1}. The impact of increasing the rotation speed to 20 rpm was minimal, with the effectiveness remaining at approximately 70%.

The study's findings highlight the potential of silica gel desiccant wheels for integrated humidity and contaminant control in indoor environments. The results emphasise the importance of optimising operating parameters, such as airflow velocity and wheel rotation speed, to achieve maximum performance for specific applications.

Angrisani et al. [148] have investigated the performance of a silica gel desiccant wheel integrated into a hybrid desiccant HVAC system. The system incorporates an advanced desiccant air handling unit, an electric chiller, a natural gas-fired boiler, and a microcogenerator. Uniquely, the desiccant wheel's regeneration utilises low-temperature thermal energy recovered from the microcogenerator. The research focuses on the impact of key thermal–hygrometric parameters, including outdoor air humidity ratio, outdoor air temperature, and regeneration air temperature, on the desiccant wheel's performance. Measurements were taken of the thermal–hygrometric properties of the process air exiting the rotor and the desiccant wheel's effectiveness. Finally, with the regeneration temperature set at its maximum available value of 65 °C, the study assesses the ventilation and internal latent loads the desiccant wheel can manage, comparing these to required values for various cities globally and as a function of outdoor thermal–hygrometric conditions.

Yamaguchi et al. [71] have presented a combined numerical and experimental performance analysis of rotary desiccant wheels. The schematic representation of the experimental study is shown in Fig. 19.

The study demonstrates that incorporating the entrance region effect leads to more accurate pressure drop predictions.

Humidity and Temperature Distributions: It effectively predicts outlet humidity and temperature distributions, with average relative errors of 3.3% for humidity ratio

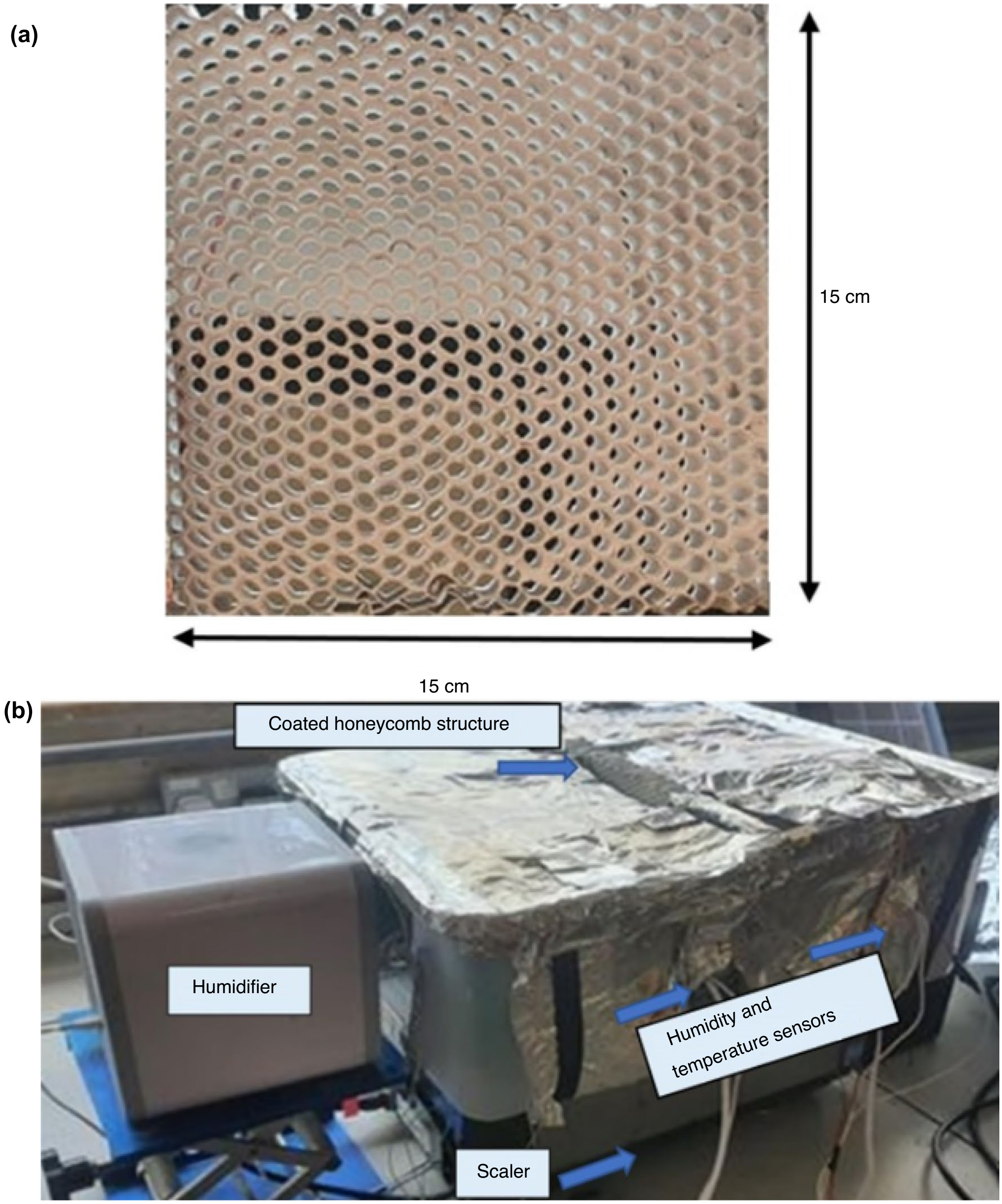

Fig. 17 **a** Honeycomb structure of the metal–organic framework, **b** rotary desiccant wheel system where metal–organic frameworks are tested [145]

difference and 10.8% for temperature difference compared to experimental measurements.

The study investigated the effects of regeneration air inlet temperature, air superficial velocity, and wheel thickness on desiccant wheel performance. The numerical predictions showed good agreement with the experimental results.

Angrisani et al. [112] have explored the performance characteristics of a silica gel desiccant wheel under typical summer conditions in Southern Italy (32 °C temperature and 15 g kg^{-1} humidity ratio), utilising a relatively low regeneration temperature of 65 °C. Their research specifically examined the influence of rotational speed on several key performance indicators, including dehumidification effectiveness,

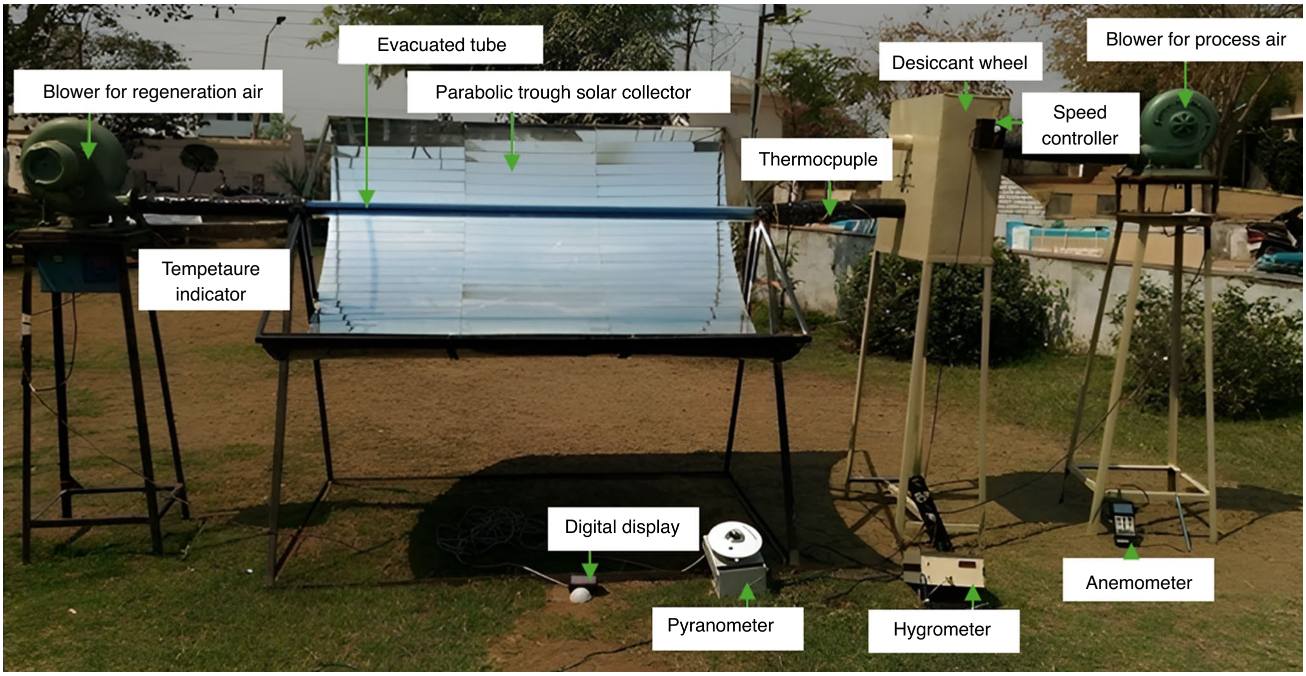

Fig. 18 Rotary desiccant wheel system [146]

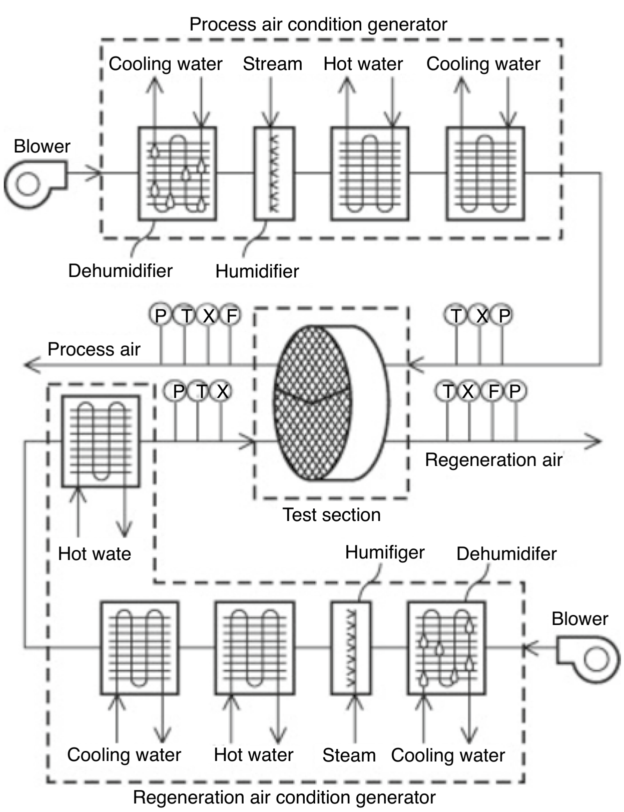

Fig. 19 Schematic representation of the experimental study [71]

dehumidification coefficient of performance, and sensible energy ratio. The optimal rotational speed for maximum dehumidification effectiveness varied depending on the specific operating conditions. For instance, it increased from 7 to 10 revolutions per hour (rev h^{-1}) as the inlet humidity ratio rose from 8.63 to 11.1 g kg^{-1}, and similarly increased from 6 to 10 rev h^{-1} with a rise in regeneration temperature from 45 to 65 °C. Furthermore, the optimal speed rose from 5 to 9 rev h^{-1} as the ratio of regeneration airflow to process airflow increased from 0.50 to 1.11. Conversely, the optimal speed decreased from 8 to 6 rev h^{-1} as the inlet temperature increased from 25.6 to 34.3 °C. The highest dehumidification effectiveness was generally observed within a rotational speed range of 0.50–0.60. In contrast, the optimal rotational speed for maximising the dehumidification coefficient of performance remained relatively consistent at 6–7 rev h^{-1}, showing little dependence on the varying operating conditions, with the maximum DCOP typically falling within the range of 0.50–1.50. The sensible energy ratio exhibited a monotonic increase with rotational speed, irrespective of other operating parameters, within the range of 0.40 to 0.90. The findings of this study underscore the critical role of rotational speed optimisation in achieving efficient desiccant wheel performance, particularly in its impact on the cooling load within hybrid air-conditioning systems. Specifically, the authors highlight the potential for reducing the sensible energy ratio and cooling load, thereby enhancing overall system efficiency, by strategically lowering the rotational speed when dehumidification requirements are less demanding.

The performance of rotary desiccant wheel systems has been experimentally validated by numerous researchers in terms of efficiency, cost, sustainability, and scalability. One such comprehensive experimental study was conducted by Cuce et al., [149] which investigated the thermal performance of a low-cost and eco-friendly rotary RDWS employing recycled materials. The system, equipped with a 2-cm-thick silica gel desiccant wheel, was tested under various regeneration temperatures and fan speeds to determine optimal operating conditions. The measurements revealed a maximum dehumidification coefficient of performance of 0.312 at a regeneration temperature of 50 °C and a fan speed of 2 m s^{-1}. Additionally, the moisture removal and release rates were determined for different operating conditions. At a regeneration temperature of 60 °C, the moisture removal/release rates were reported to be 4.55/1.16 kg^{-1}(d.a.) and 3.97/0.42 kg^{-1}(d.a.) for fan speeds of 2 and 4 m s^{-1}, respectively. This recent practical investigation serves as a strong justification for the promising performance characteristics of RDWSs.

Conclusions

Rotary desiccant wheel systems are emerging as a transformative technology for energy-efficient and sustainable climate control in smart buildings. Their ability to effectively manage humidity while utilising low-grade energy sources positions them as a compelling alternative to conventional HVAC systems. This review has highlighted key advancements driving the potential of RDWSs in revolutionising building energy management.

The incorporation of renewable energy into RDWSs provides an opportunity to reduce the carbon footprint of building operations. Solid desiccant wheel technology presents an energy-efficient alternative to traditional dehumidification systems, especially when coupled with solar thermal energy or waste heat sources for the regeneration process [54]. This approach reduces the energy demands for desiccant wheel operation, contributing to the overall sustainability of the system. Similarly, the use of CO_2 heat pumps within closed-loop desiccant systems has shown significant energy savings potential, highlighting the feasibility of coupling innovative technologies to enhance the energy performance of RDWSs [150]. The employment of advanced materials, such as silica gel composites and polymer coatings, further improves the moisture absorption and energy efficiency of RDWSs.

Silica gel composites, as desiccants, are often compared based on their water vapour absorption capacity and their performance under varying temperature and humidity conditions. The advantages of molecular sieves over silica gel in high-temperature, low-humidity environments due to their crystalline pore structure are highlighted in recent reports. The importance of considering equilibrium capacity, which represents the amount of moisture a desiccant can adsorb at a specific temperature and relative humidity, crucial for packaging applications is also underlined. For applications like desiccant films in packaging, the practice of dispersing silica gel and other desiccants within polymer matrices, influencing the material's water vapour absorption, permeability, and mechanical properties, is described. Other performance metrics include adsorption/desorption kinetics, regeneration temperature, and longevity. Comparing silica gel composites requires specifying the intended application and the relevant performance criteria. For example, using desiccant materials in dehumidification and cooling systems, emphasising their potential for cost and energy savings compared to traditional air-conditioning is discussed in several studies.

Cost analysis for silica gel composites must consider raw material costs, manufacturing processes, and potential long-term operational costs. It is noted that while molecular sieves have a higher unit cost, their superior adsorption capabilities might make them more cost-effective overall. Manufacturing costs can vary depending on the complexity of the composite structure and the incorporation method. For example, creating desiccant films involves dispersing silica gel within a polymer matrix, adding to the production cost.

Durability is a crucial factor determining a desiccant material's lifespan and effectiveness. It is shown that silica gel derived from rice husk ash improved the mechanical behaviour of cement pastes, indicating potential durability benefits in construction applications. The wet/dry cycling durability of cement mortar composites reinforced with micro and nanoscale cellulose pulps, demonstrating that hybrid composites with high nanofibrillated cellulose content could maintain or even improve properties after ageing is investigated in different studies. The addition of silica in different applications such as PLA and its nanocomposites can influence the biodegradation process, suggesting a role of silica in enhancing material durability under specific environmental conditions. For desiccant materials in packaging assessments involve evaluating the material's resistance to degradation under various temperature and humidity levels. For construction materials, assessing freeze–thaw resistance, water resistance, and chemical resistance is essential for ensuring long-term performance.

While demonstrating remarkable energy savings and environmental benefits, RDWS technology faces ongoing challenges in optimising design parameters, including rotational speed, desiccant material composition, and regeneration methods. Continued research and experimental investigations are crucial for addressing these limitations and enabling widespread adoption across diverse applications.

Looking ahead, the integration of cutting-edge technologies, such as advanced thermodynamic modelling and the incorporation of metal–organic frameworks, promises further enhancements in RDWS efficiency and performance. As global demand for sustainable and intelligent climate control solutions intensifies, RDWSs are poised to play a pivotal role in shaping the next generation of smart building infrastructure, paving the way for a more sustainable and energy-efficient built.

Author's contributions Pinar Mert Cuce involved in investigation, methodology, supervision, conceptualisation, writing—review & editing. Yusuf Nadir Yilmaz took part in writing—review & editing. Erdem Cuce involved in formal analysis, writing—review & editing, conceptualisation, methodology, supervision, validation.

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Declarations

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