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Performance Study of a Novel Solar Solid Dehumidification/Regeneration Bed for Use in Buildings Air Conditioning Systems

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Abstract: In this paper, a novel solar solid dehumidification/regeneration bed has been proposed, and its three regeneration methods, i.e., simulated solar radiation regeneration, microwave regeneration, and combined regeneration of the microwave and simulated solar radiation, were experimentally investigated and compared, as well as the dehumidification performance. The degree of regeneration of the proposed system under the regeneration method combining both microwave irradiation and simulated solar radiation could reach 77.7%, which was 3.77 times higher than that of the system under the simulated solar regeneration method and 1.05 times higher than that of the system under the microwave regeneration. The maximum energy efficiency of the proposed system under the combined regeneration method was 21.7%, while it was only 19.4% for the system under microwave regeneration. All these proved that the combined regeneration method of the simulated solar and microwave radiation not only improved the regeneration efficiency of the system, but also enhanced the energy efficiency. For the dehumidification performance, the maximum transient moisture removal was 14.1 g/kg, the maximum dehumidification efficiency was 68.0% and the maximum speed of dehumidification was 0.294 g/(kg·s) when the inlet air temperature was at 26.09 °C and the air relative humidity was at 89.23%. By comparing the testing results with the semi-empirical results from the Page model, it was indicated that the Page model can predict the regeneration characteristics of the novel solar solid dehumidification/regeneration bed under the combined method of microwave and simulated solar regeneration. The results of this research should prove useful to researchers and engineers to exploit the potential of solar technologies in buildings worldwide.

Keywords: regeneration; microwave; simulated solar radiation; performance; Page model

1. Introduction

Independent temperature-and-humidity-controlled air conditioning systems are being more and more widely used in buildings. The complete air-conditioning cycle of the systems consists of the adsorption process, regeneration process and cooling process, while the regeneration process is the core of the entire cycle. This is because the regeneration process not only affects the dehumidification performance during the adsorption process, but also affects the energy efficiency of the entire system [1,2].

Traditionally, one of the most used regeneration methods for dehumidification materials in buildings' air conditioning systems is by means of the high temperature provided by simulated solar energy [3,4]. Techajunta et al. [5] established an integrated desiccant/collector system which was directly regenerated by solar radiation, and the results proved that silica gel can be regenerated in tropical humid climates by using solar-heated air. Surajitr et al. [6] investigated the regeneration of silica gel desiccant by a solar air heater, and it was found that the average regeneration rate under various weather conditions was 0.19 kg/h per m^2 of the aperture area, and the highest regeneration rate was 0.51 kg/h for one silica gel bed with the air flow rate of 0.007 kg/s. Ram et al. [7] studied the feasibility of the regeneration of solid desiccants by using a solar parabolic dish collector, and the results showed that the maximum regeneration rate was 0.24 kg/h for activated charcoal. Dong et al. [8] designed a solar heating system which combined the technologies of evacuated tube solar air collector and rotary desiccant humidification together, and the experimental and simulation results showed that the solar heating with desiccant humidification was worthwhile when applied to improving the indoor thermal comfort during the heating season. The solar regeneration method can improve the COP of the air conditioning system and is suitable for all dehumidification materials, but it has low regeneration efficiency and consumes a lot of time.

Another commonly-used regeneration method nowadays is called the microwave regeneration, which has been introduced due to its improved regeneration efficiency, shortened regeneration time and little damage to the dehumidification materials [9–11]. Ania et al. [12] compared the regeneration of activated carbon under electric heating and microwave irradiation. They proved that the duration of microwave regeneration was less than that of electric heating, and the adsorption capacity of the activated carbon after the microwave irradiation was greater than that after electric heating. Polaert et al. [13] found that the porous and molecular structure of the adsorbent had little effect on the absorption of microwave energy, while the dielectric properties of the adsorbents played a dominant role in this process. Chao et al. [14] studied the regeneration of granular activated carbon by microwave thermal treatment, and their results also showed that in comparison with the conventional thermal regeneration, microwave regeneration reduced the processing temperature and time. Even though the microwave technology appears to be very successful in the regeneration of solid desiccant, most research cases were demonstrated in a closed microwave oven and have the drawback of non-uniformity in the regeneration process [10,15–17].

In order to resolve the problems of simulated solar regeneration, e.g., low energy efficiency and being time-consuming, and microwave regeneration, e.g., non-uniformity during the process, a combined simulated solar/microwave regeneration method has been proposed. In this paper, a novel solar solid dehumidification/regeneration bed with a generation method which combines microwave irradiation with solar radiation to regenerate the dehumidification materials will be explored. The combined simulated solar/microwave regeneration method was compared with the pure simulated solar radiation regeneration and pure microwave regeneration in the aspects of regeneration effect and regenerative energy consumption. The dehumidification performance of the proposed bed will also be investigated. Then, a mathematical model was put forward to predict the regeneration characteristics of the proposed system under the combined method of microwave irradiation and simulated solar regeneration. This research is expected to improve the regeneration effect of the dehumidification materials and reduce the energy consumption of the regeneration process for building air-conditioning systems.

2. System Description

The proposed solar solid dehumidification/regeneration bed is made of plexiglass and a wooden rectangular container filled with silica gel. The container was separated into five sub-containers by four columns, and each column has two holes, one above the sub-container, and one below the sub-container. A schematic of the proposed system was shown in Figure 1.

The proposed bed can operate under two modes, i.e., dehumidification and regeneration modes. In the dehumidification process (Figure 1a), the outdoor air driven by fans passes through the container with silica gel, and the water vapour in the outdoor air will be absorbed by the silica gel. Then the dehumidified air will be supplied to the building interior. In the regeneration process (Figure 1b), the saturated silica gel will be heated by the simulated solar and microwave radiation, and the water vapour inside the silica gel will be vaporised. The outdoor air driven by the fans passes through the bed. The water vapour contained in the bed will be taken away by the outdoor air, and then the outdoor air will turn into moist air. The moist air will be released to the surroundings, and the silica gel will be regenerated for use.

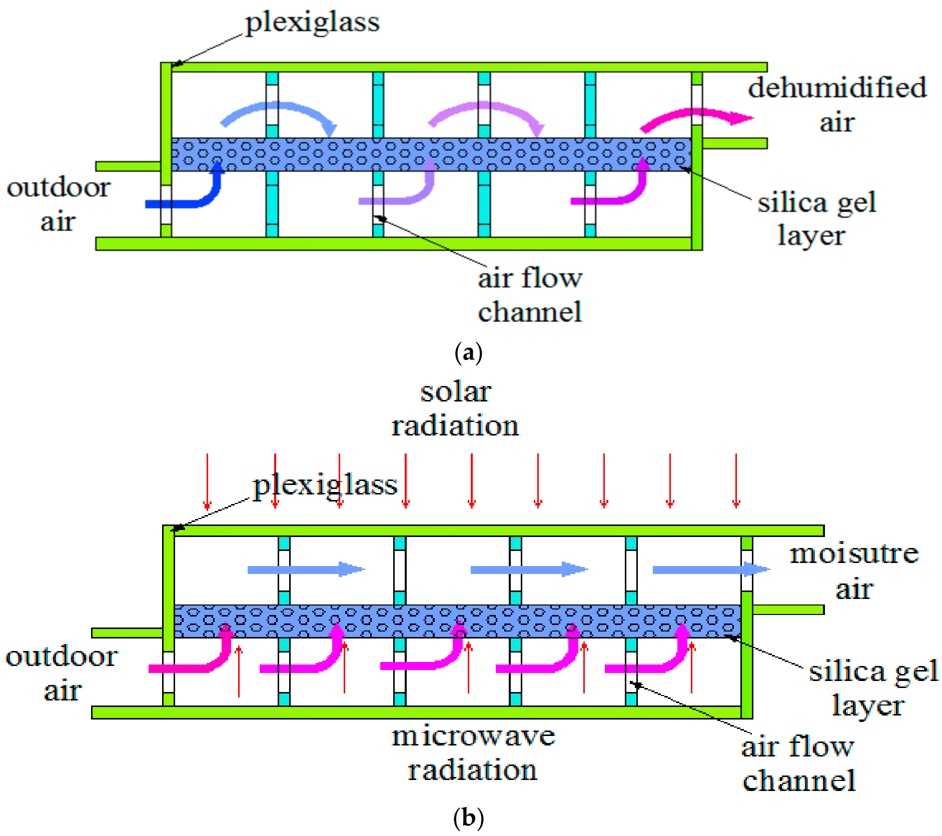

Figure 1. Schematic of the solar solid dehumidification/regeneration bed: (**a**) dehumidification mode; (**b**) regeneration mode.

Independent temperature-and-humidity-controlled air conditioning systems have demonstrated that the novel solar solid dehumidification/regeneration bed designed based on the concept of independent temperature and humidity control is more energy efficient compared with the traditional condensate dehumidification air conditioning systems [1,18,19]. Compared with the conventional dehumidification/regeneration bed, the advantages of the proposed solar solid dehumidification/regeneration bed can be summarized as follows: (1) the proposed bed is composed of five dehumidification sub-containers with thin silica gel layers, which will enhance the dehumidification capacity and reduce the total thickness of the dehumidification layer in conventional air conditioning systems; (2) the structure of the proposed bed is simple in that the dehumidification and regeneration modes could be easily adjusted according to the requirements of the building residents; and (3) the saturated silica gel in the proposed bed will be regenerated using the combined method of solar radiation and microwave irradiation, reducing the energy consumption and cost of operating conventional air conditioning systems in the building.

The proposed solar solid desiccant/regeneration bed, as the main component of the independent temperature-and-humidity-controlled air conditioning systems for buildings, will be structurally simple, easily integrated in the building and have excellent dehumidification effects, regeneration efficiency, and reduced energy consumption and carbon emission.

3. Construction of the Testing Rig

In order to investigate the performance of the proposed bed, a test rig was constructed at the laboratory in the Guangdong University of Technology, China as shown in Figures 2 and 3. The testing rig mainly consisted of a DC air conditioner, solar solid dehumidification/regeneration bed, microwave generator, xenon lamps, electronic scale, multichannel temperature and humidity recorder and a Pitot tube anemometer. The DC air conditioner provides the air flow across the solar solid dehumidification/regeneration bed with controlled temperature and humidity.

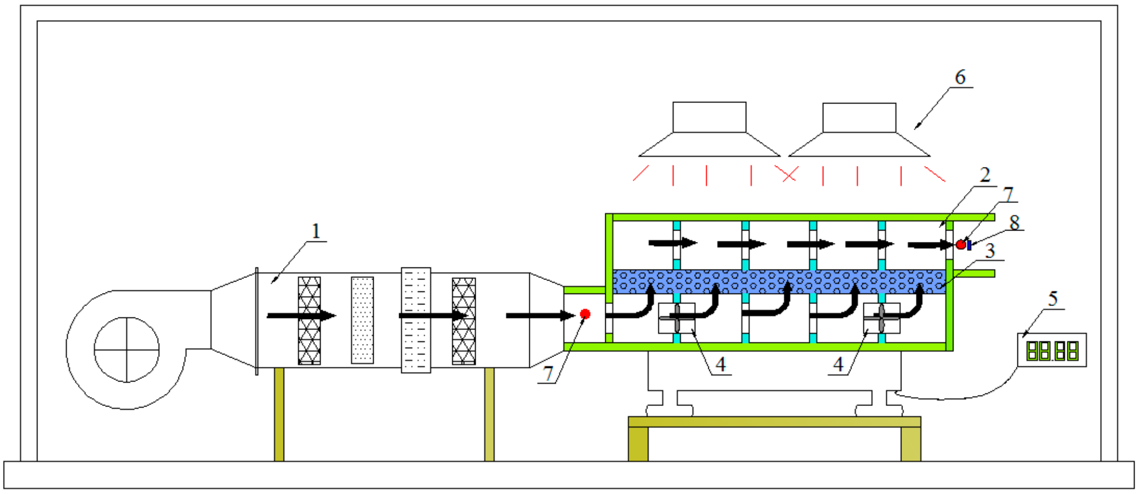

Figure 2. The structure of the test rig: 1—DC air conditioner; 2—solar solid dehumidification/regeneration bed; 3—silica gel; 4—microwave generator; 5—electronic scale, 6—xenon lamps, 7—temperature/humidity sensor, 8—Pitot tube anemometer.

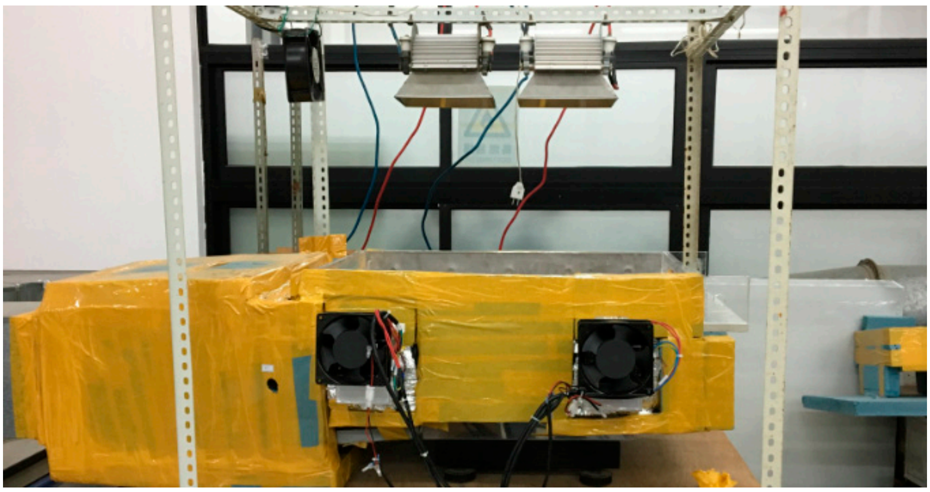

Figure 3. Image of the test rig.

The size of the solar solid dehumidification/regeneration bed (shown in Figure 4) was at 700 mm × 500 mm × 250 mm. The thickness of the silica gel layer was chosen at 50 mm. This was because that the authors in the previous study [20] had measured the temperature of silica gel at different thicknesses under simulated solar radiation conditions, and the results had shown that the temperature of the silica gel at 50 mm thick was 60% of the surface temperature. When the thickness was more than 50 mm, the temperature of the silica gel would be significantly decreased; while when the thickness was less than 50 mm, the silica gel cannot absorb the water contained in the air. The microwave generator providing microwave radiation was mounted on the sides of the bed, and the xenon lamps were fixed above the bed to simulate the sunlight. The electronic scale can measure the weight change of the silica gel during the humidification and regeneration processes of the bed. The multichannel temperature and humidity recorder and Pitot tube anemometer can measure the temperature/humidity of the air and the ambient wind speed, respectively. The performance parameters of each component are listed in Table 1, which indicate that the experimental tests can be conducted within the error range of the test instrument.

Table 1. Performance parameters of each component of the testing rig.

Equipment	Specification	Parameter
DC air conditioner	DW11-50No2. OCS-I	Power: 105 W; voltage: 220 V/50 HZ; current: 0.48 A; air flow volume: 370 m^3/h; static pressure: 400 Pa
Microwave generator	Custom-made	Frequency: 2450 MHz; power: 0–1000 W
Electronic scale	TCS-01	Power supply: 220 V; power: 14 W; maximum weight: 75 kg
Xenon lamps	AHD1000	Wavelength range: 0.2–2 μm; power: 1000 W
Multi-channel temperature monitor	AT4340	Sensor: K-type thermocouple; temperature range: −200–1300 °C; measurement accuracy: ±(0.5% × value + 2); power supply: 220 V ± 10%, 50 Hz ± 2%
Multichannel temperature and humidity recorder	BYCT-TH150B	Temperature range: −40–150 °C; relative humidity range: 20–90%; temperature accuracy: ±0.5 °C
Pitot tube anemometer	VF110	Range: 0–10 m/s; accuracy: 0.01 m/s

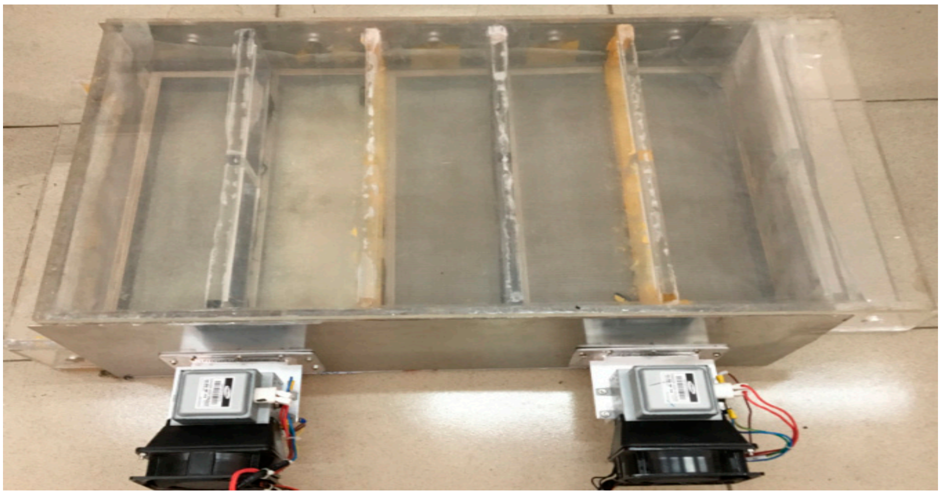

Figure 4. Image of the solar solid dehumidification/regeneration bed.

The testing rig could be operated under two processes:

Regeneration process: Before the testing, the silica gel was placed in a blast oven at atemperature of 120 °C for 8 h to be completely dried and then weighed (mass = 11.312 kg). Then the dried silica gel was placed into the bed, and the moist air controlled by the air conditioner was passed through the silica gel until the mass of the silica gel reached 13.312 kg, which was taken as the saturation of the silica gel with the water vapour from the air fully inside. In the regeneration process, the microwave generator was turned on for 10 min and turned off for 5 min in order to prevent damage to the container, while the xenon lamps were turned on all the time. The weight change of the silica gel was recorded every 15 min through the electronic scale. When the weight of the silica gel no longer changed, the xenon lamps and microwave generator were turned off to finish the testing. For comparison, the regeneration of the bed under the pure simulated radiation and pure microwave radiation (turned on 10 min and turned off 5 min) were tested as well. In these processes, the power consumption for the bed operated under different regeneration methods was also monitored for analyses.

Dehumidification process: Before the testing, the silica gel was placed in the blast oven at the temperature of 120 °C for 8 h, and the dried silica gel was weighted and placed in the bed. Then the air flow channels were closed as seen in Figure 1a, and the air under different conditions (shown in Table 2) provided by the DC air conditioner was passed through the silica gel layer. The weight change of the silica gel was recorded every 10 min through the electronic scale. When the weight of the silica gel no longer changed, the DC air conditioner was turned off to finish the testing.

Table 2. Performance parameters of the testing rig during the dehumidification process.

Condition	Inlet Air Temperature (°C)	Inlet Air Relative Humidity (%)	Inlet Air Humidity Ratio (g/kg)	Mass Flow (kg/s)
1	27.69	81.84	19.24	0.33992
2	26.09	89.23	19.09	0.33992
3	27.66	85.24	20.03	0.33992
4	29.17	81.68	20.98	0.33992

4. Test Results and Analyses

The regeneration performance of the proposed solar solid dehumidification/regeneration bed was evaluated from the aspects of the dry basis moisture content, speed of regeneration, regeneration degree, and energy efficiency. The dehumidification performance of the bed will be studied by analyzing the moisture removal, dehumidification efficiency and speed of dehumidification.

4.1. Dry Basis Moisture Content

Dry basis moisture content refers to the ratio of the mass difference between the silica gel at a timepoint during the regeneration process and at the completely dried state to the mass of the silica gel at the completely dried state [21], which was expressed by Equation (1). Figure 5 presents the variation of the dry basis moisture content of the solar solid dehumidification/regeneration bed under the three regeneration methods.

$$M_\tau = \frac{m_\tau - m_g}{m_g} \quad (1)$$

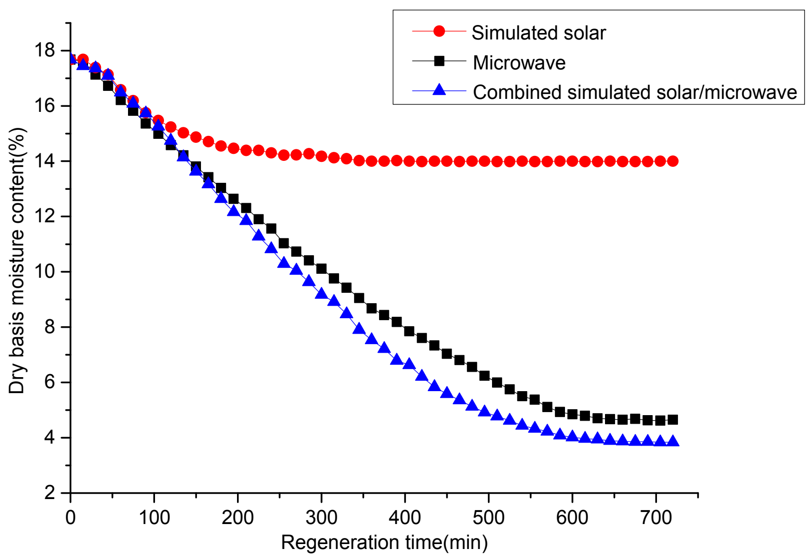

Figure 5. Variation of the dry basis moisture content of the solar solid dehumidification/regeneration bed under the three regeneration methods.

From Figure 5, it can be found that the dry basis moisture content for the three regeneration methods presented similar trends in that it decreased until it reached a relatively stable value. This was because with the increase of the degree of regeneration, the water vapour in the silica gel was reduced and less energy was required for the regeneration, leading to reduced dry basis moisture content. The dry basis moisture content was maintained at 14.02% for the simulated solar regeneration, 4.67% for the microwave regeneration, and 4.01% for the combined simulated solar/microwave regeneration, indicating that amongst the three regeneration methods, more water vapour was regenerated from the solar solid dehumidification/regeneration bed by using the combined method.

4.2. Speed of Regeneration

Speed of regeneration is defined as the ratio of the change of the dry basis moisture content per unit time to the unit time [22], which is described by Equation (2). The variation of the speed of regeneration with time was shown in Figure 6.

$$v = \frac{M_\tau - M_{\tau+\Delta\tau}}{\Delta\tau} \tag{2}$$

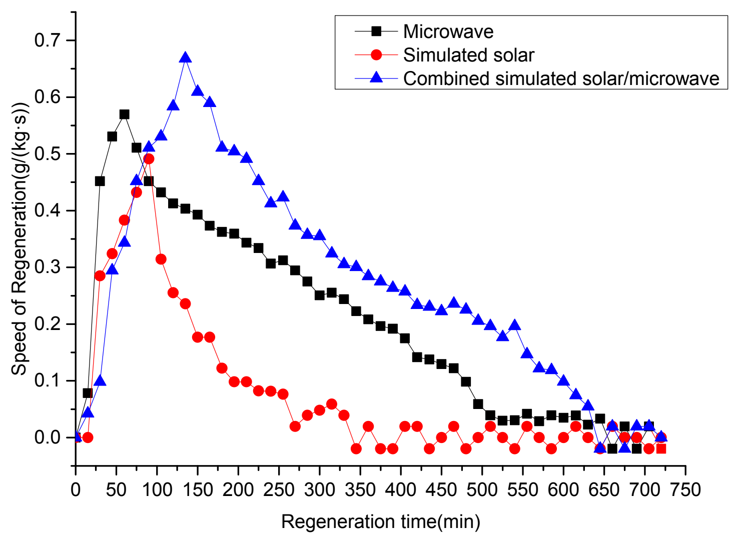

Figure 6. Variation of the speed of regeneration for the solar solid dehumidification/regeneration bed under the three regeneration methods.

From Figure 6, it can be seen that the speed of regeneration under different conditions increased linearly, and then decreased slowly after reaching the maximum. This could be explained by the molecular structure of the water vapour inside the silica gel. At the beginning of the regeneration process, the speed of regeneration increased with the increase of the regeneration energy required for free water molecules, while later the speed of regeneration decreased with the increase of the regeneration energy required for bound water molecules. For the simulated solar radiation conditions, the speed of regeneration reached its maximum at 0.491 g/(kg·s) for the first 90 min. The maximum speed of regeneration under the microwave regeneration method appeared at 60 min with a value of 0.569 g/(kg·s). The maximum speed of regeneration for the combined simulated solar/microwave regeneration method was 0.668 g/(kg·s) corresponding to the first 135 min during the testing. Compared with the pure simulated solar and microwave radiation regeneration methods, the combined method can improve the regeneration effect of the silica gel.

4.3. Degree of Regeneration

The degree of regeneration is the ratio of the mass of the water vapour regenerated in a certain time during the regeneration process to the mass of the water vapour contained in the saturated silica gel when the process starts [22]. The corresponding equation is shown below:

$$R = \frac{W_\tau}{W_0} \tag{3}$$

The variations of the regeneration degree with time are compared in Figure 7, which indicates that the degree of regeneration under the simulated solar radiation, microwave and combined regeneration methods increased and was maintained at 20.7%, 73.5% and 77.7%, respectively. This meant that the combined method could regenerate more water vapour from the silica gel, and therefore improve the dehumidification capacity of the silica gel.

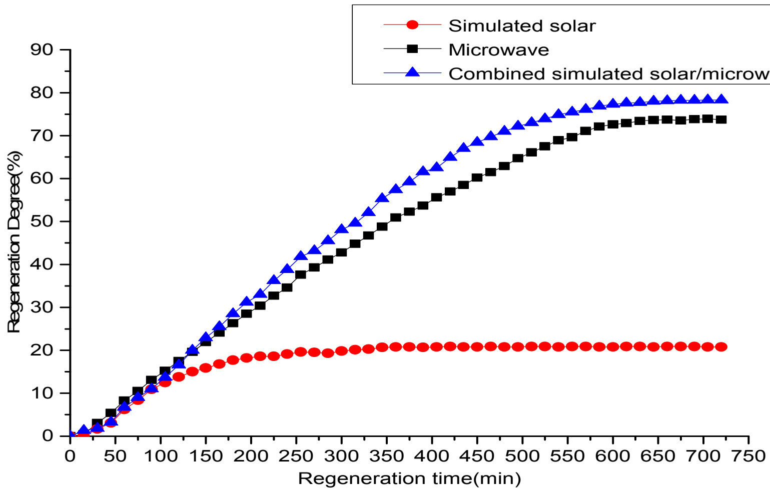

Figure 7. Variation of the regeneration degree for the solar solid dehumidification/regeneration bed under the three regeneration methods.

4.4. Energy Efficiency

The energy efficiency of the testing rig is defined in Equation (4). The energy consumed by the simulated solar radiation was negligible under practical conditions, and therefore, the variation of the energy efficiency with the regeneration degree for the microwave and combined regeneration methods was compared in Figure 8.

$$\eta = \frac{Q_r}{Q_t} = \frac{W_r \cdot \Delta H}{Q_t} \tag{4}$$

From Figure 8, the energy efficiency increased with the increase of the degree of regeneration, reached stability, and then was reduced. There existed a point at 21% of the degree of regeneration where the energy efficiency for the two regeneration methods was equal at 18.6%. When the degree of regeneration was less than 21%, the energy efficiency of the combined method was lower than that of the microwave method, while when the regeneration degree was higher than 21%, the energy efficiency of the combined method was higher than that of the microwave method. This was because that the regeneration process of the silica gel was not only related to the temperature but also to the external pressure. The maximum energy efficiency for the two methods, i.e., microwave and simulated solar/microwave, were 19.4% and 21.7% respectively, meaning that the combined method improved the energy utilisation efficiency during the regeneration process.

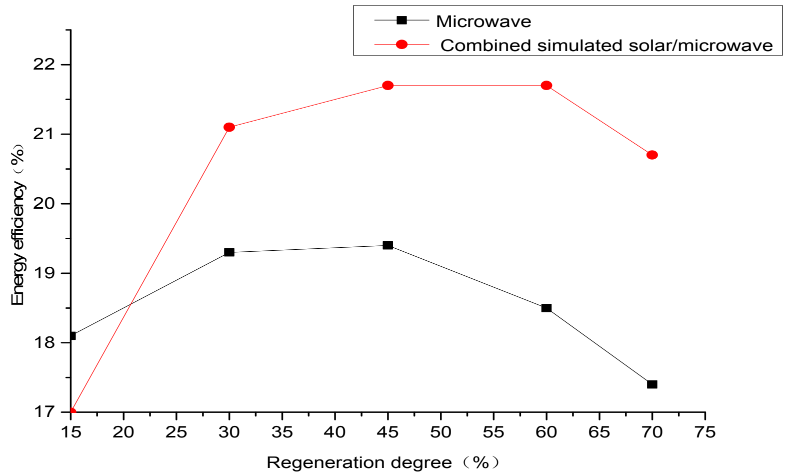

Figure 8. Variation of the energy efficiency with the regeneration degree for the solar solid dehumidification/regeneration bed under the microwave and combined regeneration methods.

4.5. Moisture Removal Performance

The moisture removal is defined as the variation of the humidity ratio between the outlet air and inlet air (Equation (5)). The results are shown in Figure 9 [23].

$$\Delta d = d_{in} - d_{out} \tag{5}$$

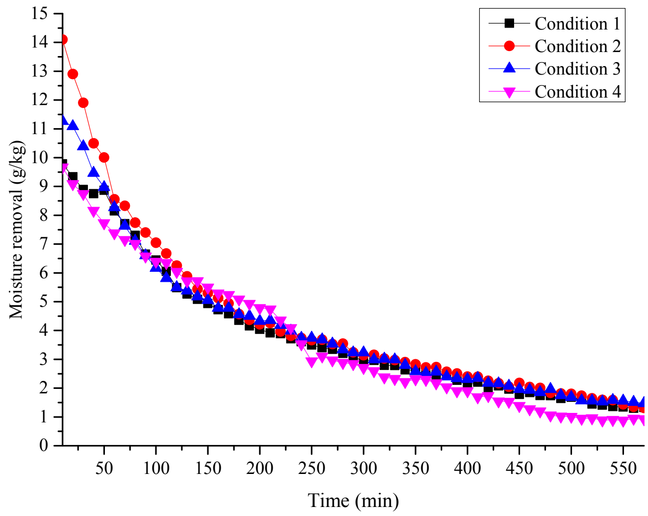

Figure 9. Variation of the moisture removal of the solar solid dehumidification/regeneration bed with time.

Figure 9 shows the variation of the moisture removal at different inlet air temperatures and relative humidities. It was found that the trend of the moisture removal in the four conditions was similar, which was because that with the increase of the water in the silica gel, the water vapour pressure in the silica gel was increased, and therefore the dehumidification capacity was reduced, until the end of the dehumidification process, where the water vapour pressure in the silica gel was the same as that in the air. The maximum moisture removal of 14.1 g/kg was found when the inlet air temperature was at 26.09 °C and the air relative humidity was at 89.23%, and its average moisture removal was also maximum at 4.2 g/kg. This meant that the low temperature and high humidity of the inlet air improved the dehumidification performance.

4.6. Dehumidification Efficiency

The dehumidification efficiency of the system, defined as the ratio of the moisture removal performance to the humidity ratio of inlet air, is shown in Equation (6) and Figure 10 [24]. From Figure 10, it can be found that the maximum dehumidification efficiency, significantly influenced by the temperature of the inlet air, decreased with time. The maximum dehumidification efficiency was 68.0% when the inlet air temperature was at 26.09 °C and the air relative humidity was at 89.23%.

$$\varepsilon_d = \frac{\Delta d}{d_{in}} \tag{6}$$

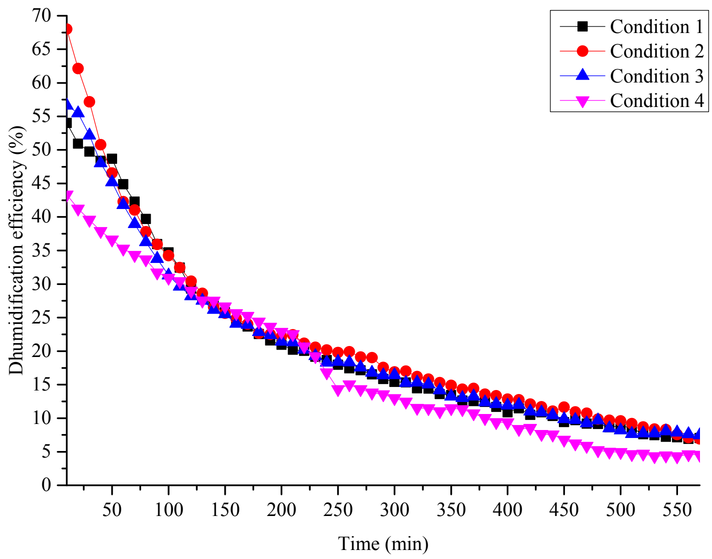

Figure 10. Variation of the dehumidification efficiency of the solar solid dehumidification/regeneration bed with time.

4.7. Speed of Dehumidification

Speed of dehumidification is defined as the ratio of the moisture removal per unit time to the mass, and is described by Equation (7). Figure 11 presents the variation of the speed of dehumidification with time [25]. From the figure it can be seen that the maximum speed of dehumidification occurred at the beginning of the dehumidification process since the water vapour pressure difference between the silica gel and the inlet air was greatest at this stage, resulting in the maximum speed of dehumidification. After that, the speed of dehumidification decreased slowly. The maximum average speed of dehumidification was 0.126 g/(kg·s) when the inlet air temperature was at 26.09 °C and the air relative humidity was at 89.23%.

$$v_d = \frac{\dot{m} \cdot \Delta d}{m_g} \tag{7}$$

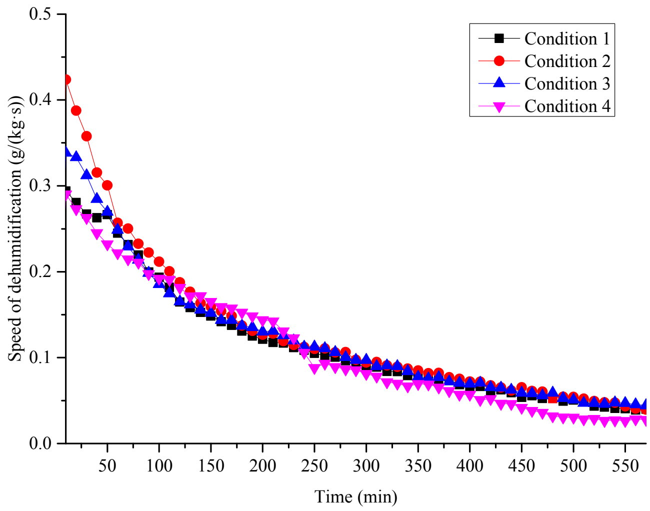

Figure 11. Variation of the speed of dehumidification of the solar solid dehumidification/regeneration bed with time.

5. Comparison with the Previous Models

The moisture ratio is the main parameter used to study the regenerative mathematical model of the dehumidification materials [26], and the calculated moisture ratio (Equation (8)) from the testing results is shown in Figure 12.

$$MR = \frac{M_\tau - M_1}{M_0 - M_1} \tag{8}$$

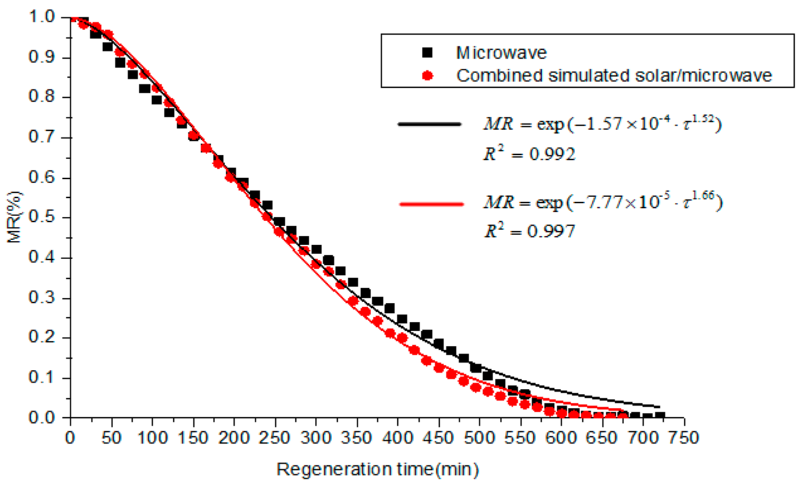

Figure 12. Comparison of the moisture ratio from the testing and semi-empirical Page model results [27].

For comparison, four commonly-used previously-studied regeneration models were selected to simulate the moisture ratio of the silica gel (shown in Table 3) [27–30], and the semi-empirical equations from the testing results are summarised in Table 4. By comparing the results from the testing with the results from the semi-empirical models, it indicated that the Page model could predict the moisture ratio of the silica gel with good agreement with the experimental values.

Table 3. Previous regenerative mathematical models for thin layer silica gel.

Model	Expressions
Lewis model [27]	$MR = \exp(-k \cdot \tau)$
Page model [28]	$MR = \exp(-k \cdot \tau^n)$
Wang and Singh model [29]	$MR = 1 + a \cdot \tau + b \cdot \tau^2$
Two-term model [30]	$MR = a \cdot \exp(-k_0 \cdot \tau) + b \cdot \exp(-k_1 \cdot \tau)$

Table 4. Summary of the semi-empirical equations.

Regeneration Method	Model	Semi-Empirical Equations	R^2
Microwave regeneration	Lewis model [27]	$MR = \exp(-0.0033 \cdot \tau)$	0.9414
	Page model [28]	$MR = \exp(-1.57 \cdot \tau^{1.52})$	0.9926
	Wang and Singh model [29]	$MR = 1 - 0.0023 \cdot \tau + 1.12 \times 10^{-6} \cdot \tau^2$	0.9956
	Two-term model [30]	$MR = 0.57 \cdot \exp(-0.0038 \cdot \tau) + 0.57 \cdot \exp(-0.0038 \cdot \tau)$	0.9577
Combined simulated solar/microwave regeneration	Lewis model [27]	$MR = \exp(-0.0035 \cdot \tau)$	0.9289
	Page model [28]	$MR = \exp(-0.78 \cdot \tau^{1.66})$	0.9973
	Wang and Singh model [29]	$MR = 1 - 0.0024 \cdot \tau + 1.275 \times 10^{-6} \cdot \tau^2$	0.9886
	Two-term model [30]	$MR = 0.584 \cdot \exp(-0.0041 \cdot \tau) + 0.584 \cdot \exp(-0.0041 \cdot \tau)$	0.9534

6. Conclusions

In this paper, a novel solar solid dehumidification/regeneration bed was proposed where three regeneration methods, i.e., simulated solar radiation, microwave irradiation, and combined simulated solar/microwave irradiation, were experimentally investigated, as well as its dehumidification performance, by constructing a test rig in the laboratory at the Guangdong University of Technology, China. The parameters determining the characteristics of the proposed bed, i.e., dry basis moisture content, speed of regeneration, regeneration degree, energy efficiency, moisture removal, dehumidification efficiency, and speed of dehumidification, were evaluated. The regenerative testing results were also compared with the results from the previously studied models to indicate the most appropriate regeneration method for silica gel.

It was found that the speed of regeneration rose linearly and then slowly decreased with maximums of 0.491 g/(kg·s), 0.569 g/(kg·s) and 0.668 g/(kg·s) for the simulated solar radiation, microwave irradiation and combined regeneration methods, respectively. The maximum regeneration degree under the combined regeneration method of both microwave and simulated solar radiation was at 77.7%, which was 3.77 times higher than that for the simulated solar radiation, and 1.05 times higher than that for the microwave irradiation. The maximum energy efficiency for the testing rig under the combined regeneration method was 21.7%, while it was 19.4% for the microwave regeneration. The testing results indicated that the combined simulated solar/microwave regeneration method performed the best among the three regeneration methods. When the inlet air temperature was at 26.09 °C and the air relative humidity was 89.23%, the maximum transient moisture removal was 14.1 g/kg, the maximum dehumidification efficiency was 68.0% and the maximum speed of dehumidification was 0.294 g/(kg·s). By comparing with the previous studies, the semi-empirical Page model equation was established for the moisture ratio of the silica gel, and the results from the semi-empirical Page model were in good agreement with the testing results in the regeneration process.

This study demonstrated that the combination of microwave and simulated solar radiation can improve the regeneration effect and energy efficiency of the regeneration process and reduce the regeneration energy consumption for the proposed solar solid dehumidification/regeneration bed. The next step of this research will study the dehumidification performance of the entire system and the optimisation of the experimental devices, providing an effective theoretical basis for using the system in practical applications.

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Author Contributions: W.Y. conceived and designed the experiments; W.W. performed the experiments; Z.D. and S.H. analyzed the data; X.Z. contributed analysis tools; Z.W. and W.W. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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