Study on the adsorption and purification performance of runner with different staged regeneration modes

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Abstract. In this paper, the hierarchical regeneration mode of three-zone, four-zone and two-stage regeneration of the wheel is firstly determined. Silica gel is selected as the adsorbent, and toluene is selected as the VOC pollutant. Visual Basic software is used to establish the coupling adsorption model of heat, humidity and VOC pollutants in the staged-regeneration wheel. The dehumidification and VOC adsorption performance of the graded regenerated wheel with different influencing factors were compared, and the variation rules of the dehumidification and toluene adsorption concentration of the staged-regeneration wheel with different influencing factors were analyzed. The results show that, when the regeneration energy consumption of the runner is the same, the dehumidification capacity of the two-stage runner is the highest, the concentration of toluene adsorbed by the three-zone runner is the highest, and the dehumidification capacity and the concentration of pollutants adsorbed by the two-zone runner are the lowest. When the capacity of dehumidification is the same, the regeneration energy consumption of two-stage runner is the lowest, and the regeneration energy consumption of two-zone runner is the highest. With the increase of adsorption capacity, the lower the regeneration temperature is, the more significant the energy saving effect will be. When the capacity of dehumidification is the same, the concentration of pollutants adsorbed by the runner in the three regions is the highest. In addition, with the increase of air entrance temperature and humidity, the dehumidification capacity of the two-stage runner changes the most, and the adsorption concentration of toluene of the two-stage runner changes the most. When the concentration of toluene in the treatment zone was different, it had no effect on the dehumidification effect of the runner, and the concentration of toluene adsorbed by the runner in the third zone changed the most.

1. Introduction

With the continuous advancement of science and technology and the rapid development of society in China, the level of national economy has been improved in recent years, and people's living and working environment have also undergone significant changes. In addition to daily life, people's working environment has gradually tended to be mainly indoor. Studies have shown that people spend more time than 87\% \cite{1} of the whole day in indoor space, accounting for most of the proportion. Therefore, in order not to affect people's health and work efficiency, the indoor environment requirements of modern buildings are constantly improving, and gradually pursue to make people more comfortable living and working environment.
As an air conditioning system with new operating mode, the runner dehumidification air conditioning system can not only meet the requirements of indoor temperature and humidity, but also absorb indoor VOC, which has been paid more and more attention [2, 3]. Runner dehumidifier has strong dehumidification capacity, large dehumidification capacity, and continuous operation [4]. Continuous, humidity controllable, compact structure, energy saving and material saving etc. However, the regeneration process of adsorbent requires higher temperature, which is also the main energy consumption in the process of dehumidification and purification of runner. The graded regeneration method has been proven to reduce the regeneration temperature requirements of the runner and improve the thermal performance of the system. Collier and Cohen [5] put forward the hierarchical graded regeneration runner dehumidification air conditioning system. Its principle is to add a preheating zone before the regeneration zone and use silica gel as desiccant. Through simulation and experimental research, the system can significantly improve the COP of the air conditioning system. Scholars of Shanghai Jiaotong University [6, 7] proposed two kinds of two-stage runner dehumidification system. Because of the different regeneration and treatment zones of the runner, it is divided into TSDC system and OTSDC system. The results show that the regeneration temperature of the two systems obviously decreases when the treatment air entrance conditions are the same, and the thermal COP of the two systems are both above 1.0. Schultz [8] used direct solar radiation to regenerate the desiccant, and the results showed that the system had a lower COP than the system using hot air to regenerate the desiccant. Han Wang [9] puts forward a new technology which combines the graded regeneration runner with evaporative cooling technology. Compared with the general composite air conditioning system, the regeneration energy consumption of the new composite air conditioning system is reduced by about 42% and the COP is increased by about 78%. Jia Chunxia [10] made a desiccant rotor using a silica-based composite desiccant material, and experimentally analyzed the dynamic and steady-state dehumidification characteristics of the desiccant rotor dehumidifier. The experimental results show that the dehumidification advantage of the composite runner is more obvious in low humidity climate conditions. For purification, Hines [11] et al. tested the adsorption effect of different adsorbents, and selected polar molecules such as water, toluene, formaldehyde, 1,1,1-trichloroethylene and non-polar molecules such as carbon dioxide and radon, which proved that silica gel has the ability to absorb water and other molecules simultaneously. Aristov [12] respectively prepared composite adsorbents modified with CaCl₂ silica gel and modified silica gel with Li Br. The prepared adsorbents were used in air intake devices, and their adsorption properties and amounts were experimentally tested. The regeneration temperature of the adsorbent is lower than 90°C, which can greatly reduce the consumption of regeneration heat energy. Wei Zhang [13] utilizes the ability of silica gel to adsorb water and other molecules at the same time. Using silica gel as desiccant, the adsorption capacity of silica gel runner to indoor VOC pollutants was verified by experiments. In this paper, Visual Basic software is used to establish the coupled adsorption model of heat, humidity and VOC pollutants in the graded regeneration runner. For different staged regeneration modes, the dehumidification capacity and VOC adsorption performance of the runner under different influencing factors were compared.

2. Establishment of model

2.1. Establishment of physical model

The traditional dehumidification runner is divided into two zones: dehumidification zone and regeneration zone. In order to reduce the renewable energy consumption of runners and improve the energy utilization rate, the dehumidification runners in this paper adopt the hierarchical regeneration mode, which are three-zone runners, four-zone runners and two-stage runners composed of two ordinary runners.

The specific regional division is shown in figure 1. The three-zone runner is mainly divided into three parts: dehumidification zone, preheating regeneration zone and heating regeneration zone, which can realize energy cascade utilization and reduce high-grade energy consumption. For the four-zone and
two-stage runner, it is mainly composed of dehumidification zone and regeneration zone. For the four-zone and two-stage runners, it mainly consists of dehumidification zone and regeneration zone. This dehumidification method with intermediate cooling can make the runner close to isothermal dehumidification and increase the dehumidification capacity of the runner. Assuming that all air passages in the runner have the same specifications, the flow direction of treated air and regenerated air is reverse flow.

When the entrance air state is stable, the heat and mass transfer state of the runner in any air passage in the same radial direction is the same, and at different times when the runner rotates, each airflow passage must pass through the same state, the Lagrangian coordinate system is established by taking any airflow passage of the runner as the research object, and the working state of the entire runner at a certain moment is described by using a state of the airflow passage at different times in one rotation cycle.

**Figure 1.** The zone division of desiccant staged-regeneration wheel.

### 2.2. Establishment of mathematical model

- **Energy conservation equation in air**

  \[
  \frac{\partial \theta}{\partial \tau} + \alpha \frac{\partial \theta}{\partial \phi} + \frac{m_i \partial \theta}{\partial z} = \frac{aF_v(t_d - \theta)}{\rho_i \omega f_s(C_{pm} + D\theta + C \cdot C_{pm})}
  \]  
  \[ (1) \]

- **Water mass conservation equation in air**

  \[
  \frac{\partial D}{\partial \tau} + \alpha \frac{\partial D}{\partial \phi} + \frac{m_i \partial D}{\partial z} = \frac{k \cdot F_v}{\rho_i \omega f_s} (D_d - D)
  \]  
  \[ (2) \]

- **VOC mass conservation equation in air**

  \[
  \frac{\partial C}{\partial \tau} + \alpha \frac{\partial C}{\partial \phi} + \frac{m_i \partial C}{\partial z} = \frac{k \cdot F_v}{\rho_i \omega f_s} (G - C)
  \]  
  \[ (3) \]

- **Energy conservation equation of adsorbent and matrix materials**

  \[
  \frac{\partial t_i}{\partial \tau} + \alpha \frac{\partial t_i}{\partial \phi} = \frac{\lambda_i (1 - f_i)}{M_i C_{pm} + M_d(C_{pm} + WC_{pm} + SC_{pm})} \frac{\partial^2 t_i}{\partial z^2} = \frac{aF_v(t - t_i) + k_i F_v (D - D_i)}{M_i C_{pm} + M_d(C_{pm} + WC_{pm} + SC_{pm})}
  \]  
  \[ (4) \]

- **Equation of water mass conservation on adsorbent surface**

  \[
  \frac{\partial W}{\partial \tau} + \alpha \frac{\partial W}{\partial \phi} - D_w (1 - f_i) \frac{\partial^2 W}{\partial z^2} = \frac{k_i F_v}{M_d} (D - D_i)
  \]  
  \[ (5) \]
VOC mass conservation equation on adsorbent surface
\[
\frac{\partial S}{\partial \tau} + \omega \frac{\partial S}{\partial \phi} - D_{ev} (1 - f_j) \frac{\partial^2 S}{\partial z^2} = \frac{k_v F_v}{M_a} (C - G)
\]  
(6)

Adsorption equilibrium equation of moisture and VOC in runner
\[
D_d = \frac{0.622 \cdot \varphi \cdot P_s}{B - \varphi \cdot P_s}
\]  
(7)
\[
\varphi = \frac{W \cdot R}{W_{max} \left[ 1 - \frac{W(1 - R)}{W_{max}} \right]}
\]  
(8)
\[
S = H_i \cdot G \cdot \rho_i
\]  
(9)

2.3. Preliminary validation of the model
At present, the experimental research on the graded regenerative runner only stays in the dehumidification stage, and the VOC adsorption characteristics of the graded regenerative runner are not available. In order to preliminarily verify the reliability of the model, only the dehumidification capacity of the graded regenerative runner is verified. For four-zone and two-stage runners, the values of air state parameters and physical parameters input in the program are given in reference [14]. The values of specific parameters are shown in table 1.

**Table 1.** The parameters of the body and the adsorbent in the four-zone and wheel.

| Various parameters of the runner |   |
|-------------------------------|---|
| Treat air entrance moisture content (g/kg) | 14.3 |
| Regeneration air entrance moisture content (g/kg) | 14.5 |
| Runner thickness (m) | 0.1 |
| Runner diameter (m) | 0.4 |
| Runner speed (r/h) | 8 |
| Processing temperature (°C) | 35 |
| Processing air flow rate (m/s) | 2.5 |
| Regenerated air velocity (m/s) | 2.5 |
| Specific heat of silica gel at constant pressure (J/kg·K) | 921 |
| Density of silica gel (kg/m^3) | 1201 |
| Specific heat of ceramic matrix at constant pressure (J/kg·K) | 880 |
| Density of ceramic matrix (kg/m^3) | 625 |
| Specific heat of lithium chloride at constant pressure (J/kg·K) | 3000 |
| Volume ratio of lithium chloride in compound desiccant | 15 |
| Pore size of composite adsorbent (mm) | 4 |
| Proportion of airflow passage to cross-sectional zone | 0.816 |

Because the adsorbent in the paper is silica gel and the adsorbent in the literature is composite desiccant, the physical properties of the adsorbent, such as its comprehensive density, constant pressure specific heat capacity and thermal conductivity, are simulated. The simulated results are compared with the experimental results, and the results are shown below.
Figure 2. The experimental value and analog value of dehumidification capacity at the regeneration temperature variation of four-zone wheel.

The above figure shows the experimental and simulation results of four-zone runner dehumidification at different regeneration temperatures. From the figure, we can see that the difference between simulation and experiment is very small. When the regeneration temperature is 80°C, the corresponding error is the largest. The difference is about 0.413 g/kg. After calculation, it is 5.51%, and the error is controlled within 10%. This shows that although the characteristics of VOC adsorption are taken into account in the model, the effect of dehumidification is not significant, it is in the acceptable range, the mathematical model is basically accurate.

For the two-stage runner, the parameters in reference [14] are taken as follows: the moisture content of treated air entrance is 15 g/kg, the moisture content of regenerated air entrance is 11 g/kg, and the regeneration temperature is 70°C. The physical parameters of the other parts of the runner are shown in table 1. The simulated results are compared with the experimental results. The results are as follows:

Figure 3. The experimental value and analog value of dehumidification capacity at the entrance temperature variation of two-staged wheel.
The figure above shows the experimental and simulated results of dehumidification capacity of two-stage runners at different entrance temperatures in the dehumidification zone. As can be seen from the figure above, when the entrance temperature is 31°C, the corresponding error is the largest. The difference between the results is about 0.76 g/kg. After calculation, it is 8.83%. The error is controlled within 10%. The model meets the accuracy requirements. Therefore, the mathematical model established is basically accurate.

3. Comparative analysis of runner performance under different staged regeneration modes

3.1. The value of initial parameters
For different staged graded regeneration runners, the dehumidification and adsorption performance of the runners are also different. For the convenience of comparison, this paper refers to the air heat and humidity parameters in reference [15], and simulates them as standard operating conditions. VOC pollutants choose toluene. In order to make the research meaningful, the concentration of toluene entering the room should be higher than that in the room. Referring to China's indoor air quality standards, the concentration of toluene should not be higher than 0.2 mg/m³ in all indoor air pollutants. Therefore, the toluene concentration of imported air in this paper is 500 μg/m³. The specific parameters are as shown in table 2.

| Table 2. Table of wheel value under standard condition. |
|----------------------------------------------------------|
| **Runner thickness (m)** | Two-zone | Three-zone | Four-zone | Two-stage |
| Runner speed (r/h)       | 0.2      | 0.2        | 0.2       | 0.2       |
| Specific heat of adsorbing materials (J/kg·k) | 921      | 921        | 921       | 921       |
| Import humidity of treated air (g/kg) | 13       | 13         | 13        | 13        |
| entrance temperature of treated air (°C) | 30       | 30         | 30        | 30        |
| VOC concentration at import for air treatment (μg/m³) | 500      | 500        | 500       | 500       |
| entrance humidity of regenerated air (g/kg) | 13       | 13         | 13        | 13        |
| entrance temperature of regenerated air (°C) | 70       | 70         | 70        | 70        |
| entrance temperature of preheated air (°C) | —        | 45         | —         | —         |
| entrance humidity of preheated air (g/kg) | —        | 13         | —         | —         |
| Secondary entrance temperature of treated air (°C) | —        | —         | 40        | —         |
| Secondary entrance humidity of treated air (g/kg) | —        | —         | 9         | —         |
| VOC concentration at secondary import of treated Air (μg/m³) | —        | —         | 200       | —         |
| Air handling capacity (m³/h) | 150      | 150        | 150       | 300       |
| Air volume of regenerated air (m³/h) | 50       | 100        | 50        | 100       |
| Preheated air volume (m³/h) | —        | 50         | —         | —         |
| Handling Air Speed (m/s) | 1.78     | 2.67       | 3.56      | 3.55      |
| Wind speed of regenerated air (m/s) | 1.78     | 2.67       | 3.56      | 3.55      |
| Preheated air velocity (m/s) | —        | 2.67       | —         | —         |
| Processing zone Angle (°) | 270      | 180        | 135       | 270       |
| Angle of regeneration zone (°) | 90       | 120        | 45        | 90        |
3.2. Performance comparison of runners under different staged regeneration modes

Through simulation, the outlet air temperature, humidity and VOC toluene concentration of regenerated runners under standard conditions are obtained. In order to analyze the adsorption characteristics of runners more intuitively, a comparative analysis between runners is needed. In order to facilitate comparison, the parameters of air state in the simulation process are as follows: the entrance temperature of the treatment zone is 30℃, the entrance humidity is 13 g/kg, the entrance toluene concentration is 500 μg/m³; the entrance temperature of the regeneration zone is 70℃, the entrance humidity is 13 g/kg, and the entrance toluene concentration is 10 μg/m³. The dehumidification capacity and VOC concentration of the runner are compared.

3.2.1. Comparison of dehumidification capacity and toluene adsorption concentration at the same regeneration temperature.

The figure below shows the comparison of dehumidification capacity between the runner and the two-zone runner under different staged regeneration modes with the same regeneration energy consumption. According to the graph, the dehumidification capacity of two-stage runner is 3.48 g/kg, that of three-stage runner is 5.49 g/kg, that of four-stage runner is 5.78 g/kg, and that of two-stage runner is 5.84 g/kg.

![Figure 4](image)

Figure 4. The dehumidification capacity of the wheel under the same regeneration temperature.

For the four-zone and two-stage runners, when the adsorbent adsorbs water, it releases heat of adsorption, and the temperature of treated air increases. When the air temperature rises to a certain extent, the mass transfer coefficient decreases and the dehumidification process slows down.

For two-zone and three-zone runners, because of the existence of a preheating zone in three-zone runners, the consumption of high-grade energy is reduced, the temperature of adsorbent is lowered, and the equilibrium vapor partial pressure of air on adsorbent surface is lowered.

When the entrance humidity of the treated air is the same, the partial pressure difference between the treated air and the surface air of the adsorbent increases, and the driving force of dehumidification increases.

Therefore, the dehumidification capacity of the three-zone runner is larger than that of the two-zone runner, and the dehumidification capacity of the two-zone runner is the smallest.
It can be seen that although the toluene concentration of the second zone runner is the lowest, it can also meet the toluene concentration limit specified in the standard. Because the content of pollutants in the air is less than one thousandth of the moisture content, VOC concentration in the air is very low.

The mass transfer process of pollutants is similar to that of water. The adsorption effect of runner on VOC pollutants in air depends on the desorption time of adsorbent in regeneration zone. On the treatment side, adsorbents absorb moisture and pollutants from the air and then send them to the regeneration zone.

On the regeneration side, high temperature air flowing through the runner will take away most of the water and pollutants on the adsorbent surface, but there are also a small capacity of water and pollutants remaining on the adsorbent surface due to limited time and low regeneration temperature. At the same time, because regenerated air preferentially desorbs the water on the adsorbent surface, the regeneration time needed to satisfy the simultaneous adsorption of water and pollutants on the runner is relatively longer, in order to ensure that the pollutants on the adsorbent surface achieve better desorption effect and keep the adsorption effect unchanged. Increasing the residence time of the runner in the regeneration zone can be achieved by reducing the rotating speed of the runner or increasing the angle of the regeneration zone.

On the one hand, because of the preheating zone of the three-zone runner, the desorption time is longer. On the other hand, because the three-zone runner has the smallest dehumidification capacity, the adsorbent has more time to desorb and regenerate, so the concentration of pollutants adsorbed by the three-zone runner is the highest.

3.2.2. Comparison of regeneration temperature and adsorption toluene concentration at the same dehumidification volume. The below figure shows the regeneration temperature and the concentration of toluene adsorbed by the runner at different dehumidification rates.

When the dehumidification capacity is 4 g/kg, the regeneration temperature of the two-zone runner is 78℃, the adsorption toluene concentration is 403 μg/m^3; the regeneration temperature of the three-zone runner is 55.5℃, and the adsorption toluene concentration is 487 μg/m^3; the regeneration temperature of the four-zone runner is 55℃, the adsorption toluene concentration is 431 μg/m^3; the
regeneration temperature of the two-stage runner is 54.5°C, and the adsorption toluene concentration is 457 μg/m³; the regeneration energy consumption of three-zone, four-zone and two-stage runners is 28.8%, 29.5% and 30.1% less than that of two-zone runners respectively.

![Figure 6. The regeneration temperature of wheel under the same dehumidification.](image)

![Figure 7. The adsorb toluene capacity of the wheel under the same dehumidification.](image)

Under the condition of 4.5 g/kg dehumidification, the regeneration temperature of the two-zone runner is 86°C, the concentration of toluene adsorbed is 419 μg/m³, the regeneration temperature of the three-zone runner is 61°C, the concentration of toluene adsorbed is 489 μg/m³, the regeneration temperature of the four-zone runner is 59.5°C, the concentration of toluene adsorbed is 438 μg/m³, and
the regeneration temperature of the two-stage runner is 58.5°C, the concentration of toluene adsorbed is 464 μg/m³. The regeneration energy consumption of three-zone, four-zone and two-stage runners is 29.1%, 30.8% and 32.0% less than that of two-zone runners, respectively. Under the condition of 5 g/kg dehumidification, the regeneration temperature of the two-zone runner is 92°C, the concentration of toluene adsorbed is 430 μg/m³, the regeneration temperature of the three-zone runner is 65°C, the concentration of toluene adsorbed is 491 μg/m³, the regeneration temperature of the four-zone runner is 63.2°C, the concentration of toluene adsorbed is 446 μg/m³, and the regeneration temperature of the two-stage runner is 62°C. The concentration of toluene is 472 μg/m³. The regeneration energy consumption of three-zone, four-zone and two-stage runners is 29.3%, 31.3% and 32.6% less than that of two-zone runners, respectively.

For a certain graded runner, with the increase of dehumidification, the energy-saving effect of the graded runner is more significant than that of the two-zone runner. With the increase of desiccant capacity, the greater the relative humidity of air on the adsorbent surface, the greater the equilibrium vapor partial pressure of air on the adsorbent surface, the greater the power of mass transfer between the adsorbent and the regenerated air, the better the desorption effect and the lower the growth rate of regeneration temperature, so the greater the desiccant capacity, the better the energy-saving of the runner.

With the increase of dehumidification, the lower the regeneration temperature is, the slower the growth rate of regeneration temperature is. In other words, the greater the capacity of dehumidification, the more remarkable the energy-saving effect of two-stage runner is than that of four-zone runner, and the more remarkable the energy-saving effect of four-zone runner is than that of three-zone runner. Because when the temperature and humidity of air entrance are the same, the vapor partial pressure of wet air remains unchanged. With the increase of dehumidification capacity, the relative humidity of air on adsorbent surface increases, the equilibrium vapor partial pressure on adsorbent surface increases, which reduces the vapor partial pressure difference between treated air and adsorbent surface, and makes the dehumidification rate lower and lower. The higher the regeneration temperature, the higher the exchange rate between the air and the adsorbent. The temperature of the adsorbent is $T_{\text{two-zone}} > T_{\text{three-zone}} > T_{\text{four-zone}}$, and the saturated water vapor partial pressure $P_{\text{two-zone}} > P_{\text{three-zone}} > P_{\text{four-zone}}$, the equilibrium water vapor partial pressure difference between the treated air and the adsorbent surface air is $P_{\text{two-zone}} < P_{\text{three-zone}} < P_{\text{four-zone}} < P_{\text{two-stage}}$. Therefore, the dehumidification effect of the two-stage runner is promoted, so in order to achieve the same dehumidification effect, the growth rate of the regeneration temperature required for the two-zone runner is the largest. Therefore, for the graded regenerative runners in different modes, the regeneration rate of the three-zone runners is the largest, the energy-saving effect is the slowest, the growth rate of the two-stage runners is the smallest, and the energy-saving effect is the most significant.

In terms of purification, the concentration of toluene adsorbed by three-zone runner is the highest, while that by two-zone runner is the lowest. For the adsorption process of pollutants, the adsorption characteristics are similar to those of the above analysis. When the capacity of dehumidification is the same, the adsorption capacity of adsorbent is mostly affected by the regeneration time, because the regeneration angle of the three-zone runner is the largest and the desorption time is the longest, so the higher the concentration of adsorbed pollutants. In addition, when the VOC concentration and other state parameters of the treated air in the runner remain unchanged, the regeneration temperature of the runner increases with the increase of dehumidification, which enhances the desorption effect between the regenerated air and the adsorbent surface, so the ability of the runner to adsorb pollutants increases.

As can be seen from the figure above, the increase speed of toluene concentration in the two-zone runner is the largest, while that in the three-zone runner is smaller than that in the four-zone runner and the two-stage runner. From the above analysis, with the increase of dehumidification, the ability of runner to adsorb pollutants increases. The higher the concentration of adsorbent adsorbing pollutants, the higher the partial pressure of adsorbent surface compounds. As a result, the absorptive potential energy of treated air and adsorbent surface decreases, and the driving force of adsorption decreases. So, the concentration of toluene adsorbed by three-zone runner increases slowly.
4. Analysis of influencing factors on dehumidification and purification performance of runner

4.1. Effect of treatment air entrance temperature

As can be seen from the figure below, the dehumidification capacity of the runner decreases with the increase of the entrance air temperature in the treatment zone.

When the entrance temperature of treated air rises, the heat transfer between air and adsorbent surface decreases, which leads to the increase of adsorbent surface temperature and the increase of saturated vapor partial pressure on adsorbent surface.

As a result, the partial pressure difference between the treated air and the surface air of the adsorbent decreases, and the adsorption effect becomes worse, so the dehumidification capacity of the runner becomes lower and lower.

With the increase of entrance air temperature, the change of dehumidification capacity of two-stage runner is greater, and the change of dehumidification capacity of two-zone runner is the smallest.

![Figure 8](image-url)

**Figure 8.** The dehumidification capacity of wheel under the different entrance temperature of processing zone.

When the entrance temperature of treated air rises, the saturated vapor partial pressure on the adsorbent surface increases; the smaller the dehumidification capacity, the greater the relative humidity of treated air, the closer the partial pressure of water vapor in air is to saturation, and the greater the difference between the partial pressure of water vapor on the air and the adsorbent surface, the greater the driving force of water transfer, and the greater the removal of water vapor partial pressure, the decrease of humidity is inversely proportional, so the lower the dehumidification, the slower the dehumidification decreases.
As can be seen from the above figure, the concentration of toluene adsorbed by the runner decreases with the increase of the entrance air temperature in the treatment zone. When the entrance temperature of the treated air rises, the surface temperature of the adsorbent increases, which increases the equilibrium concentration of the adsorbent surface, reduces the potential energy of the treated air and the adsorbent surface and weakens the mass transfer process, so the lower the concentration of the adsorbent adsorbing toluene.

With the increase of entrance temperature of treated air, the concentration of toluene adsorbed by three-zone runner changed the least and that by two-zone runner changed the most. When the entrance temperature of treated air rises, the concentration of toluene adsorbed by runner decreases, and the concentration of toluene in treated air increases.

When the regenerated air state remains unchanged, the higher the concentration of toluene adsorbed, the more sufficient the adsorbent desorption is, the lower the equilibrium concentration of toluene on the adsorbent surface is, thus, the greater the concentration difference between the treated air and the adsorbent surface, the stronger the adsorbent's ability to adsorb pollutants. Therefore, the higher the concentration of toluene adsorbed by the runner, the slower the reduction rate is.

4.2. Treatment of the effect of air entrance humidity.
As can be seen from the figure below, the dehumidification capacity of the runner increases with the increase of air humidity at the entrance of the treatment zone.

When the entrance temperature of treated air is unchanged, the increase of entrance air humidity will increase the partial pressure of water vapor in the air, so that the differential pressure of water vapor on the surface of air and adsorbent will also increase, and the adsorption effect will be better, so the dehumidification capacity will be higher and higher.
Figure 10. The dehumidification capacity of wheel under the different entrance humidity of processing zone.

With the increase of entrance air humidity, the dehumidification capacity of two-stage runner changes the most and that of two-zone runner changes the least. When the entrance humidity of treated air rises, the dehumidification capacity of runner increases, which decreases the partial pressure of water vapor in treated air. The smaller the dehumidification capacity, the lower the heat released by adsorbent in runner, the lower the average temperature of adsorbent surface, and the lower the saturated partial pressure of water vapor on adsorbent surface, therefore, the smaller the difference of partial pressure of water vapor between treated air and adsorbent surface air is, the smaller the driving force of dehumidification is. Therefore, with the increase of humidity at the entrance of treated air, the lower the dehumidification capacity is, the slower the change rate is.

Figure 11. The adsorb toluene capacity of wheel under the different entrance humidity of processing zone.
As can be seen from the figure above, the concentration of toluene adsorbed by runner decreases with the increase of air humidity at the entrance of the treatment zone.

When the humidity of the treated air entrance increases, the capacity of dehumidification of the runner increases, the heat released by the adsorbent increases, the average temperature of the adsorbent increases, and the equilibrium concentration of pollutants on the adsorbent surface increases. As a result, the adsorption potential energy of treated air and adsorbent surface decreases and the mass transfer process is weakened, so the concentration of toluene adsorbed becomes lower and lower.

With the increase of air entrance humidity, the concentration of toluene adsorbed by the three-zone runner changed the least and the two-zone runner changed the most. When the humidity of air entrance increases, the concentration of toluene adsorbed by runner decreases, and the concentration of toluene in treated air increases.

When the regenerated air state remains unchanged, the higher the concentration of toluene adsorbed, indicating that the more adequately adsorbent desorption, the lower the equilibrium concentration of toluene on adsorbent surface. Thus, the greater the concentration difference between the treated air and the adsorbent surface, the stronger the adsorbent's ability to adsorb pollutants. Therefore, the higher the concentration of toluene adsorbed by the runner, the slower the reduction rate is.

4.3. Effect of entrance temperature of regenerated air

As can be seen from the figure above, the dehumidification capacity of the runner increases with the increase of the entrance temperature of regenerated air.

When the moisture content in the air remains unchanged, when the entrance temperature of regenerated air rises, the partial pressure of water vapor in the air does not change, but at the same time the partial pressure of saturated water vapor increases, which makes the relative humidity of regenerated air smaller, enhances the purification effect of regenerated air, and thus increases the ability of adsorbent to absorb water. Therefore, the dehumidification capacity of the runner is getting higher and higher.

![Figure 12](image-url)

**Figure 12.** The dehumidification capacity of wheel under the different entrance temperature of regeneration zone.

With the increase of entrance temperature of regenerated air, the change of dehumidification capacity of two-stage runner is the biggest and that of two-zone runner is the smallest.
When the entrance temperature of regenerated air rises, the partial pressure of water vapor in the air remains unchanged; the greater the dehumidification capacity, the higher the saturated partial pressure of water vapor in the adsorbent, which increases the partial pressure difference between regenerated air and the surface air of the adsorbent.

The desorption effect is obvious, thus enhancing the driving force of water transfer in the treatment zone. So, the faster the capacity of dehumidification increases.

![Figure 13. The adsorb toluene capacity of wheel under the different entrance temperature of regeneration zone.](image)

As can be seen from the above figure, the concentration of toluene adsorbed by runner increases with the increase of air temperature at the entrance of regeneration zone.

When the entrance temperature of regenerated air rises, the equilibrium concentration of pollutants on the adsorbent surface rises, and the adsorbent is fully regenerated, that is, the concentration of pollutants on the adsorbent surface decreases, thus increasing the adsorption potential energy on the treated air and adsorbent surface and accelerating the mass transfer process, so the concentration of adsorbent adsorbing toluene is increasing.

With the increase of the entrance temperature of regenerated air, the concentration of toluene adsorbed by the three-zone runner changed the least and that by the two-zone runner changed the most. When the entrance temperature of the regeneration air rises, the concentration of toluene adsorbed by the runner becomes higher and higher, the concentration of toluene in the air decreases, and the partial pressure of the compound decreases.

The greater the concentration of adsorbent adsorbing pollutants, the larger the partial pressure of the adsorbent surface compound, the smaller the adsorption potential energy between the treatment air and the surface air of the adsorbent, and the smaller the driving force of adsorption, the slower the increase.

4.4. Effect of regeneration air entrance humidity
As can be seen from the figure below, the dehumidification capacity of the runner decreases with the increase of the humidity of the regenerated air entrance.
Figure 14. The dehumidification capacity of wheel under the different entrance humidity of regeneration zone.

When the entrance temperature of regenerated air is unchanged, the higher the humidity of regenerated air is, the higher the relative humidity is, and the greater the partial pressure of water vapor in air. When the partial pressure of saturated water vapor on the adsorbent surface is unchanged, the differential pressure of water vapor between regenerated air and the air on the adsorbent surface becomes smaller, which leads to the deterioration of desorption ability. As the humidity of regenerated air increases, the dehumidification capacity of runner becomes lower and lower. With the increase of the humidity of the regenerated air entrance, the dehumidification capacity of the two-stage runner varies the most, and that of the two-zone runner varies the least. When the entrance humidity of regenerated air increases, the relative humidity of regenerated air increases, and the partial pressure of water vapor in air also increases. The smaller the dehumidification capacity, the lower the heat released by adsorbent in the runner, the lower the average surface temperature of adsorbent, and the lower the saturated vapor partial pressure on the surface of adsorbent. Therefore, the smaller the partial pressure difference between the regenerated air and the adsorbent surface is, the smaller the driving force of the desorption process is, and the slower the desorption speed is, so the desiccant capacity of the runner is reduced.

As can be seen from the figure below, the concentration of toluene adsorbed by the runner increases with the increase of air humidity at the entrance of the regeneration zone. When the humidity of regenerated air increases, the desiccant capacity of runner decreases, the average temperature of adsorbent surface decreases, and the equilibrium concentration of pollutants on adsorbent surface decreases, thus increasing the adsorption potential energy between treated air and adsorbent surface, so the concentration of toluene adsorbed by runner becomes higher and higher. With the increase of entrance humidity of regenerated air, the concentration of toluene adsorbed by three-zone runner changed the least, and that by two-zone runner changed the most. When the entrance humidity of regenerated air increases, the concentration of toluene adsorbed by runner increases, the concentration of toluene in air decreases, and the partial pressure of compounds decreases. The higher the concentration of pollutants adsorbed by adsorbents, the higher the partial pressure of compounds on the adsorbent surface, the less the adsorption potential energy between the treated air and the adsorbent surface air, and the less the driving force of adsorption, so the slower the speed of adsorbing pollutants on the runner.
4.5. Effect of toluene concentration at air entrance
As can be seen from the below figure, with the increase of toluene concentration at the entrance of the dehumidification zone, the dehumidification capacity of the runner remains basically unchanged. Because the adsorbent occupies the main position in the process of adsorbing water and VOC, that is, the adsorbent adsorbs water preferentially, so the change of VOC concentration in air has little effect on dehumidification.
As can be seen from the figure above, the concentration of toluene adsorbed by the runner increases with the increase of toluene concentration at the entrance of the treatment zone.

When the temperature and humidity of the treated air entrance remain unchanged, the increasing concentration of imported toluene will increase the adsorption potential energy of the treated air and the adsorbent surface, which will increase the concentration of the adsorbed toluene. In addition, the concentration of toluene adsorbed by silica gel was proportional to the entrance concentration of toluene, and the concentration of toluene adsorbed by three-zone runner changed most.

According to the results of reference [12], when the concentration of indoor pollutants meets the range specified in the Air Quality Standard, the adsorption capacity of the runner does not reach saturation, then the adsorption characteristics of the adsorbent materials on the runner remain unchanged. From the above analysis, under the same conditions, the concentration of toluene adsorbed by the three-zone runner is the largest, so the change speed of the concentration of toluene adsorbed is the largest.

5. Conclusion
In this paper, toluene is chosen as pollutant to study. According to the established mathematical model, the changes of graded regeneration runners in different stages are compared with those in the second zone when the dehumidification capacity (regeneration temperature) is the same.

At the same time, for different staged graded regeneration runners, the dehumidification capacity and VOC adsorption performance of the runners under different influencing factors are compared, and the variation law of the runners under different influencing factors is analyzed.

The main conclusions are as follows:

- when the renewable energy consumption of the runner is the same, the two-stage runner has the largest dehumidification capacity, the three-zone runner has the highest concentration of toluene, and the two-zone runner has the lowest dehumidification capacity and the concentration of pollutants adsorbed. When the dehumidification capacity is the same, the regeneration energy consumption of the two-stage runner is the lowest and that of the two-zone runner is the highest, and the lower the regeneration temperature is, the more remarkable the energy saving effect is. When the capacity of dehumidification is the same, the concentration of pollutants adsorbed by the three-zone runner is the highest, and with the increase of the capacity of dehumidification, the ability of the runner to adsorb pollutants increases. The higher the concentration of pollutants adsorbed by the runner, the slower the increase rate is.
With the increase of the entrance air temperature of the runner, the desiccant capacity of the adsorbent becomes lower and lower. The desiccant capacity of the two-stage runner changes the most and that of the two-zone runner changes the least. At the same time, the concentration of toluene adsorbed by the runner decreases more slowly, and that of the three-zone runner decreases the fastest, and that of the two-zone runner. With the increase of the humidity of the process air entrance, the dehumidification capacity of the runner is getting larger and larger, among which the change of the two-stage runner is the largest, the change of the runner of the second zone is the smallest; the concentration of the toluene adsorbed by the runner is getting lower and lower, and the toluene of the third zone is adsorbing toluene. The change in concentration was minimal, and the concentration of toluene adsorbed in the second zone is the largest.

With the increase of regenerated air temperature, the desiccant capacity of runner is getting higher and higher. The desiccant capacity of two-stage runner changes the most, and that of two-zone runner changes the least. The concentration of toluene adsorbed by runner is getting higher and higher, and the concentration of toluene adsorbed by three-zone runner changes the least and that of two-zone runner changes the most. As the humidity of regenerated air increases, the dehumidification capacity of runner decreases. The two-stage runner has the greatest change and the two-zone runner has the smallest change. The concentration of toluene adsorbed by runner is getting higher and higher, among which the concentration of toluene adsorbed by three-zone runner has the smallest change and that of toluene adsorbed by two-zone runner has the greatest change. Therefore, according to the specific requirements of indoor environment, appropriate regeneration temperature should be selected to reduce the regeneration energy consumption of runners.

When the toluene concentration in the runner treatment zone is different, the desiccant capacity of the graded regeneration runner remains basically unchanged, and the concentration of toluene adsorbed by the runner becomes higher and higher. The concentration of toluene adsorbed by the runner in the three regions is the highest, and the concentration of toluene adsorbed by the runner is also the largest.

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