Research Progress of Fixed Bed Dehumidification System: A Mini Review

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Abstract: In recent years, the fixed bed dehumidification system has received extensive attention. Research shows that the fixed bed can be combined with the vapor compression refrigeration system to replace the traditional air conditioning (A/C) system, improve the dehumidification efficiency of the system and reduce energy consumption of A/C. In this study, the optimization and improvement methods of the fixed bed dehumidifier in recent years are introduced in detail firstly. It points out that adding heating/cooling devices to the fixed bed can greatly improve the dehumidification capacity and efficiency of the system, which is the main method to improve the fixed bed currently; Optimizing the structure of fixed bed is also an effective method, but the current research results have limited improvement on dehumidification performance; Optimizing the regeneration mode of fixed bed can improve the utilization rate of renewable energy and improving the overall dehumidification efficiency of the system, but the research in the direction is still insufficient; The parallel double packed bed structure can ensure the continuous operation of the fixed bed to improve the dehumidification efficiency of the system, but such systems are large in scale and high in cost. Then the dehumidification performances of various systems are summarized and comprehensively compared. Finally, the future optimization and improvement direction of the fixed bed is pointed out.

Keywords: Fixed bed, Dehumidification system, Dehumidification efficiency, Heat and mass exchange.

1. INTRODUCTION

Nowadays, the energy consumption of airconditioning (A/C) system is increasing. In order to reduce energy consumption, the temperature and humidity independent control system are studied, among which the solid dehumidification A/C system is one of the temperature and humidity independent control A/C systems [1]. The solid dehumidification A/C system combines the solid adsorption dehumidification device with traditional refrigeration systems (such as steam compression refrigeration system [2, 3], steam absorption refrigeration system [4, 5]). The dehumidification device realizes humidity control and the refrigeration system realizes temperature control. The solid dehumidification device usually uses low-grade thermal energy as the driving energy, including solar energy [6-8], waste heat [9-12] and so on, which greatly reduces energy consumption and environmental pollution [13]. Solid dehumidification devices can generally be divided into desiccant wheel (DW)[14-15], fixed (packed) bed [16, 17] and desiccant-coated heat exchangers (DCHEs) [18, 19]. The DW can realize continuous dehumidification and regeneration process with compact structure and wide application. However, the DW cannot overcome the influence of the adsorption heat released by the desiccant during the dehumidification process, which would cause the temperature of the desiccant and treated air to rise, increase the irreversible loss of heat and mass transfer process, reduce the dehumidification capacity of the system, and require the high temperature of regenerative heat source [20, 21]. The DCHEs can be coated with a limited amount of desiccant, so the dehumidification capacity is low [22]. The fixed bed dehumidifier has a relatively simple structure, low initial investment and operational cost, a large number of filling desiccants and high dehumidification capacity, so it has become a research hotspot. However, the fixed bed cannot operate continuously, and the contact between the flowing gas and the solid desiccant is weak, resulting in a low heat and mass transfer coefficient of the dehumidification system, which affects the dehumidification efficiency of the system [23, 24].

Therefore, many researches are devoted to improving the design of fixed bed, solving the problems of discontinuous operation of fixed bed and low heat and mass transfer coefficient, so as to improve the dehumidification efficiency of the system [23]. In this study, the optimization and improvement methods of fixed bed dehumidifier in recent years are introduced, the dehumidification performance of each system is comprehensively compared, and the future optimization and improvement direction of fixed bed dehumidifier is pointed out.

2. OPTIMIZATION AND IMPROVEMENT OF FIXED BED

In order to solve the problems of discontinuous operation of fixed bed and low heat and mass transfer

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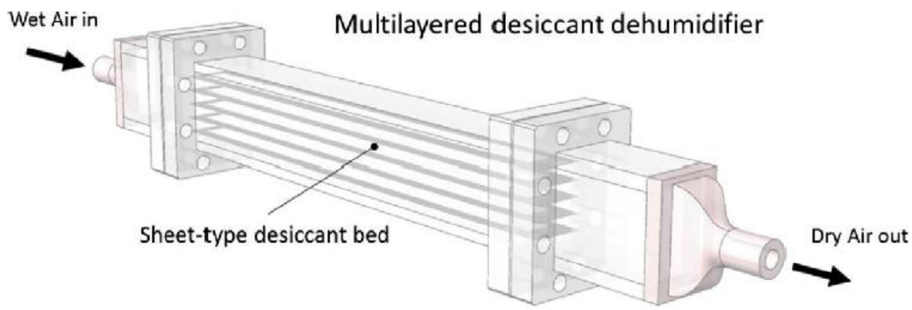
coefficient, the optimization and improvement based on single material packed bed and double material packed bed are made in recent years.

2.1. Single Material Packed Bed

Based on single material packed bed, the heat and mass transfer performance and dehumidification efficiency are improved by optimizing the system structure design. Shamim *et al*. [16] designed a new type of multi-layer fixed bed adhesive free dehumidifier, as shown in Figure **1a**, which used silicon based high-purity spherical gel as adsorbent and combined with the steam compression system to improve the dehumidification efficiency while reducing power



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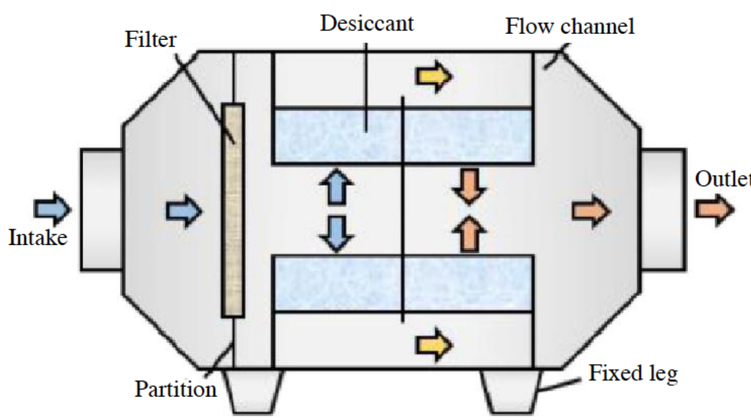

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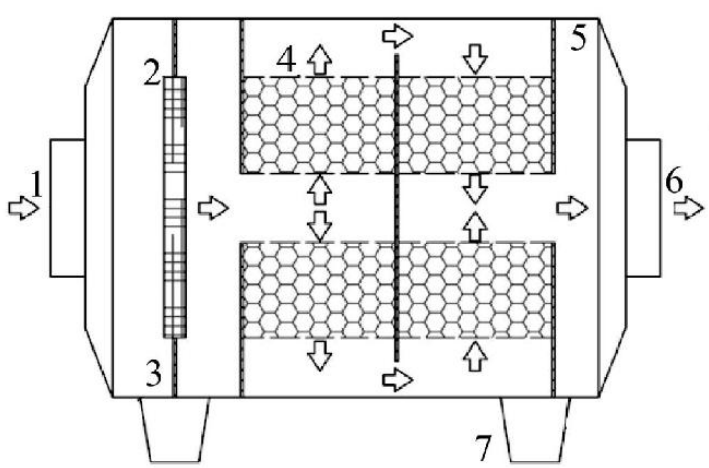
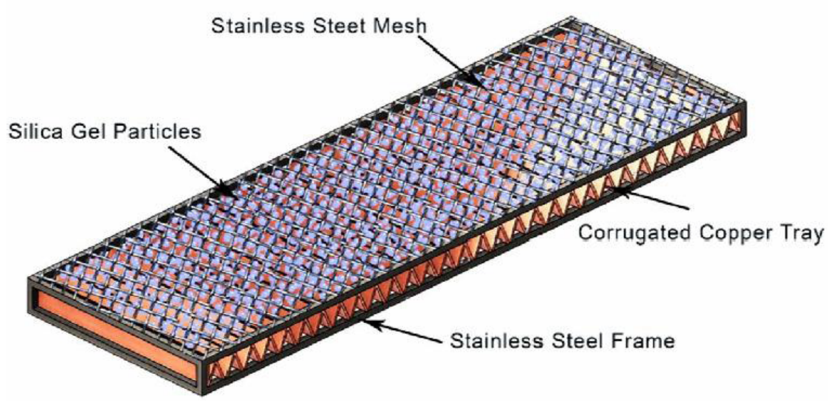


1-Airinlet; 2-Filter fiber layer; 3-Baffle;

4-Double stage solid dehumidification box

(**c**)



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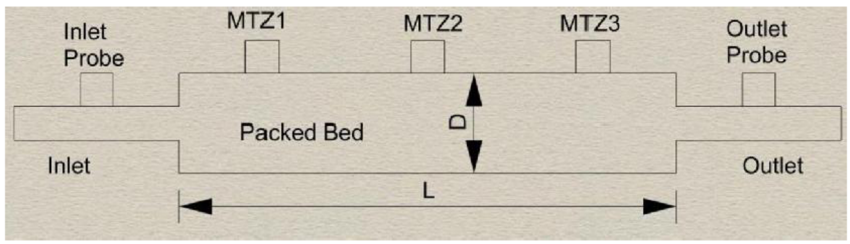
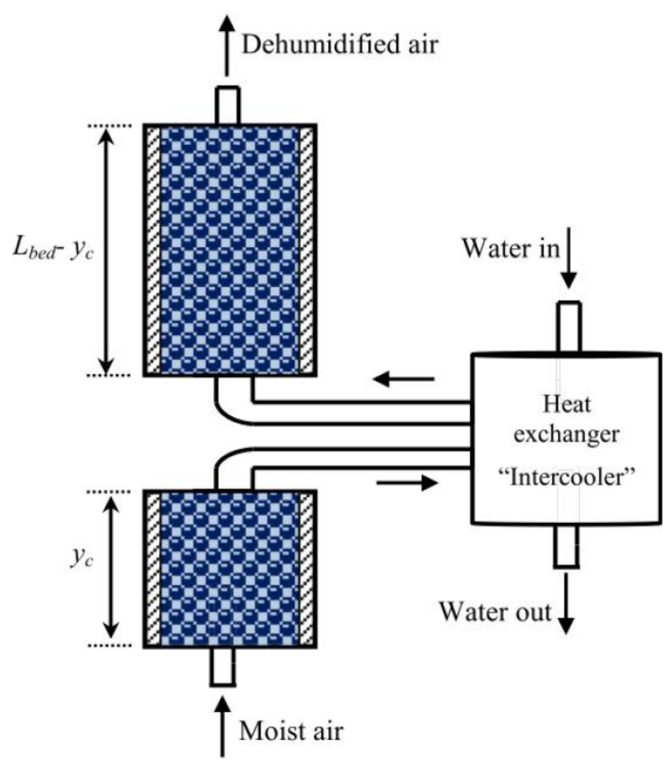


(**e**)

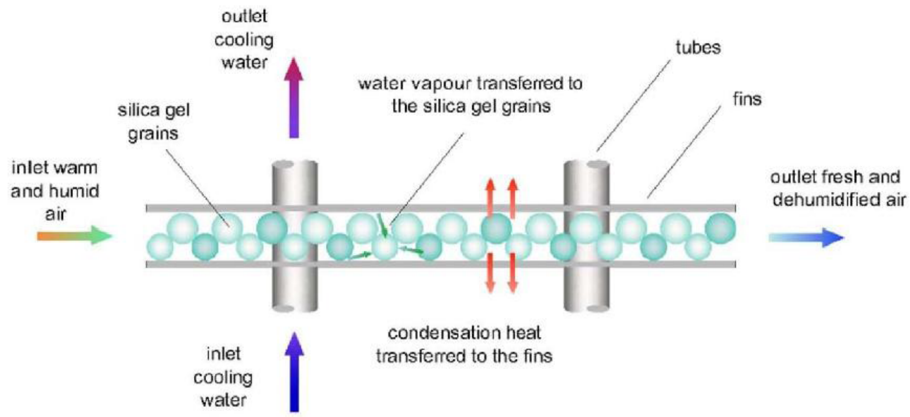
Figure 1: (**a**) Multilayer fixed bed dehumidifier [16], (**b**) Double-stage DDB [22], (**c**) Double-stage solid dehumidifier [25], (**d**) Multi tray packed fixed bed [26], (**e**) Packed bed with Z-annular flow configuration [27].

consumption. When the thickness of bed D was 1 mm, the air velocity v was 0.6 m/s, and the moisture content of inlet air w_0 was 16.5 g/kg, the average dehumidification efficiency of the system in the first 10 mins was 35.96% higher than that of the traditional dehumidifier wheel. When the D was 1 mm and the v was 0.9 m/s, the maximum pressure drop of the device was 20 Pa/m, which was nearly 98% lower than that of the traditional dehumidifier. He *et al*. [22] studied a double-stage desiccant dehumidification box (DDB), as shown in Figure **1b**. Compared with single-stage DDB, the device had stable dehumidification performance. Under the condition of 27.3 ℃ and 62.8% relative humidity (RH), the maximum dehumidification capacity of double-stage DDB was 3.9 g/kg, about 1.44 times of single-stage DDB, and its maximum dehumidification efficiency was 27.8%. Yang *et al*. [25] also studied a double-stage solid dehumidifier, as shown in Figure **1c**. With the condition of 25.2 ℃ and 56.4%~74.9% RH, the maximum dehumidification efficiency of the system was 22.2%, twice of the single-stage solid dehumidifier under the same working condition; The average dehumidification efficiency was 11.1%, 2.8 times of the single-stage solid dehumidifier under the same working condition. Abd-Elhady *et al*. [26] designed a solid dehumidification system with multi tray packing, as shown in Figure **1d**. The system greatly increased the contact area between desiccant and air, and the dehumidification capacity was about 27% higher than that of conventional packed bed. Compared with the conventional DW, the pressure drop of the system was reduced by about 87%, and the energy consumption was significantly reduced. In addition, the moisture absorption of the system could reach about 80% of the saturation state after 2000 s of startup, and the dehumidification rate was greatly improved. Yeboah *et al*. [27] designed a packed bed with Z-annular flow configuration, as shown in Figure **1e**. The structure enhanced the moisture absorption capacity of the packed bed, and the bed temperature was 4.22~5.47 ℃ lower than that of the conventional packed bed, reducing the impact of adsorption heat on the dehumidification performance. However, the end plate of the device blocked the air flow, leading to flow reversal, so its pressure drop was higher than that of the traditional packed bed.

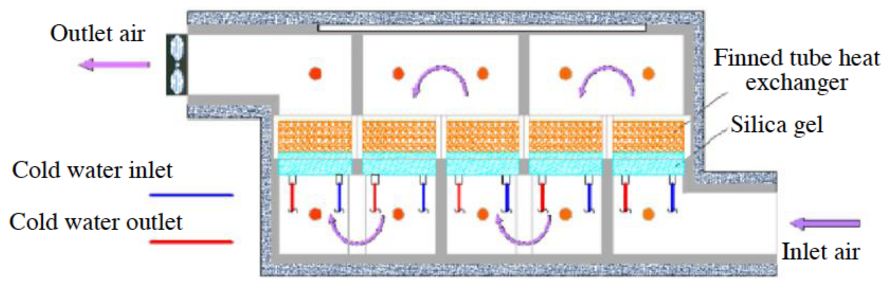
Several researches improved the heat and mass transfer performance and dehumidification efficiency by adding coolers, heaters and other devices to the fixed bed. Ramzy *et al*. [17] added an intercooler in the packed bed to improve the utilization rate of the drying agent at the tail layer of the bed, as shown in Figure **2a**. The dehumidification efficiency of the dehumidifier increased from 41%, 43%, and 47% of the traditional fixed bed to 75%, 79%, and 94% at 1000s under the conditions that the airflow temperature T was 27 ℃, 28 ℃, 27 ℃, and v was 0.8 m/s, 0.68 m/s, and 0.61 m/s, respectively. When the bed length was 0.05~1 m, the best position of intercooler to obtain the maximum total adsorption mass was $0.45<y/L<0.65$, where y was the axial position of the intercooler and L was the bed length. Finocchiaro *et al*. [28] added finned tube heat exchanger to the packed bed. As shown in Figure **2b**, the silica gel was gathered between the fins. The heat exchanger cooled the silica gel during the dehumidification process to reduce the impact of the adsorption zone, so as to improve the dehumidification efficiency of the fixed bed. Long *et al*. [29] added a finned tube heat exchanger to the fixed bed, as shown in Figure **2c**. During the adsorption dehumidification process, the gas flowed through the heat exchanger for cooling and then exchanged heat with silica gel, which could reduce the impact of adsorption heat. At the temperature of 35 ℃ and RH of 75%, the maximum dehumidification capacity of the device was 19.53 g/kg, 1.3 times of the traditional fixed bed. The maximum dehumidification efficiency was 72.3%, increased by 26.4%, and the increase rate was 49.67%; At the temperature of 22 ℃ and RH of 65%, the maximum dehumidification capacity of the device was 7.93 g/kg, 1.4 times of the traditional fixed bed. The maximum dehumidification efficiency was 73.9%, increased by 43.8%, and the increase rate was 145.51%. Yeboah *et al*. [30] combined the helically coiled oscillating heat pipes (HCOHPs) using ethanol, methanol and deionized water as working fluids with the packed bed, as shown in Figure **2d**. HCOHPs was used to eliminate the heat released by the desiccant adsorbed water vapor, thus reducing the temperature of the packed bed and improving the adsorption performance of the desiccant. The results showed that the maximum average bed temperature can be reduced by 14 ℃. However, the heat and mass transfer performance of the system was affected not only by the overall thermal resistance, but by the thermal resistance between the evaporator and vessel wall, so the device needed to be further optimized. Yu *et al*. [31] reduced the impact of adsorption heat by adding water heating and cooling devices to the multi-layer fixed bed non binder dehumidifier to improve the dehumidification efficiency of the system, as shown in Figure **2e**. Under the conditions of T=27 ℃, v=0.9 m/s and w_0=10.01 g/kg and 14.88 g/kg respectively, the maximum dehumidification efficiency of the dehumidifier was 24% and 33% higher than that of the traditional fixed bed. Yang *et al*. [32] connected DN20 water pipes to the fixed bed, and introduced water at different temperatures into water pipes during dehumidification regeneration, reducing the impact of adsorption heat and increasing the regeneration amount, as shown in Figure **2f**. The results showed that under the conditions of T=38 ℃, RH=56% and inlet air flow q=320 m^3/h, the total dehumidification capacity of the system was 520 g when 28 ℃ water was introduced in the dehumidification stage, which was 1.17 times of the conventional system, and its regeneration capacity was 1.12 times of the conventional system. Hung *et al*. [33] designed a desiccant tray with water cooling/heating coils inside to reduce the impact of adsorption heat in the dehumidification process and improve the regeneration efficiency. When T=25~40 ℃, w_0=15~20 g/kg and air mass flow rate q_m was 0.15~0.5 kg/s, the dehumidification performance of the system was improved by 10~40% compared with the conventional system. During regeneration, when the water temperature was 55~75 ℃, the regeneration time could be shortened by 180 mins.



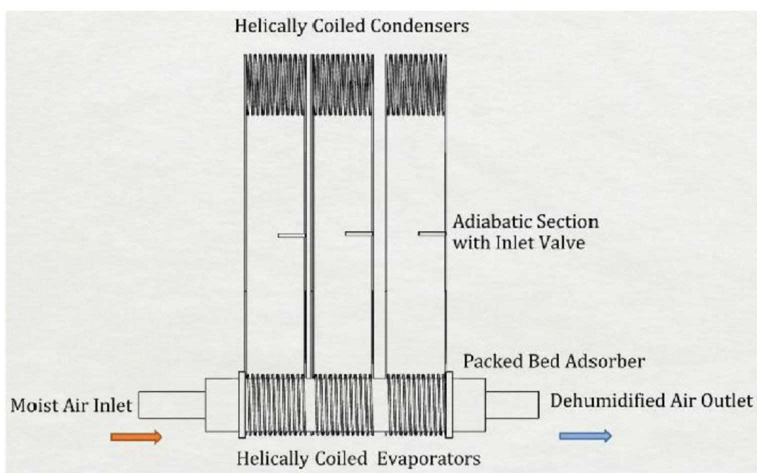
(**a**)


outlet cooling water
water vapour transferred to the silica gel grains
tubes
fins
silica gel grains
inlet warm and humid air
outlet fresh and dehumidified air
condensation heat transferred to the fins
inlet cooling water

(**b**)


Outlet air
Finned tube heat exchanger
Silica gel
Cold water inlet
Cold water outlet
Inlet air

(**c**)


Helically Coiled Condensers
Adiabatic Section with Inlet Valve
Packed Bed Adsorber
Moist Air Inlet
Dehumidified Air Outlet
Helically Coiled Evaporators

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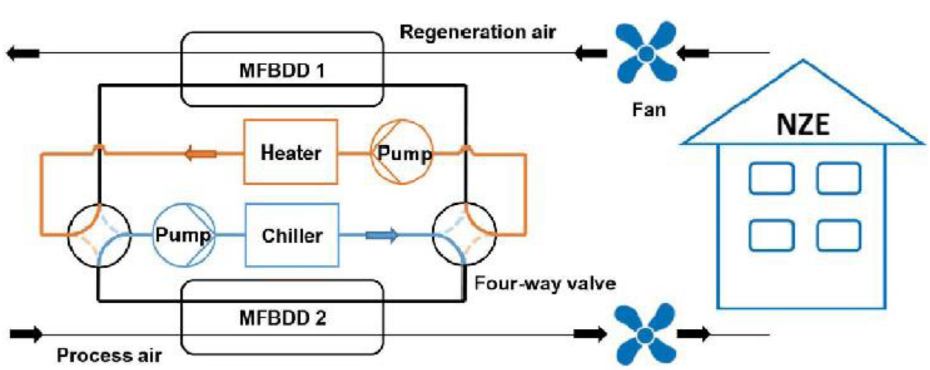
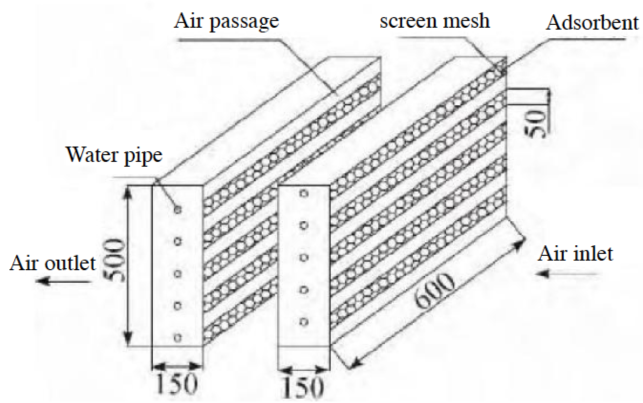

Regeneration air
MFBDD 1
Fan
NZE
Heater
Pump
Pump
Chiller
Four-way valve
MFBDD 2
Process air

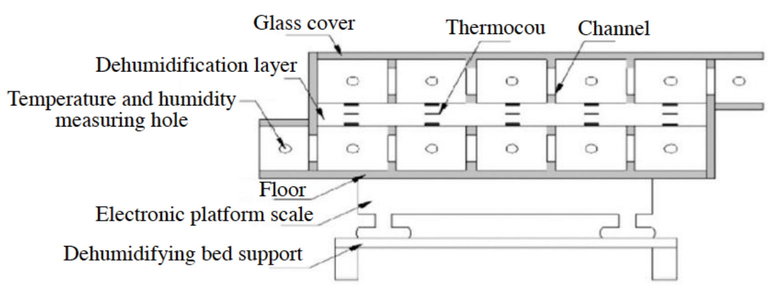
(**e**)



(**f**)

Figure 2: (**a**) Intercooling packed bed [17], (**b**) Cooling packed bed [28], (**c**) Internal cooling solid desiccant bed [29], (**d**) Schematic of the three HCOHPs integrated with the packed bed [30], (**e**) Schematic diagram of air dehumidification system [31], (**f**) Structure diagram of fixed bed with water pipes [32].

Other researches improved the utilization rate of regenerative heat source, reduced the energy consumption of regeneration and improved the dehumidification efficiency by changing the regeneration mode of fixed bed. Yang *et al*. [34] designed a solid desiccant bed with direct solar regeneration, as shown in Figure **3a**. The device carried out the regeneration of desiccant through solar radiation, improved the heat utilization efficiency of solar energy, and reduced the energy consumption of regeneration. Under the conditions of 34.5~35.6 ℃ and 89.8%~90.4% RH, the average dehumidification efficiency of the dehumidification device in the one h was 10.04%, and the average dehumidification capacity was 3.26 g/kg; The maximum dehumidification efficiency was 13.24%, the maximum dehumidification capacity was 4.3 g/kg, and the average effective dehumidification time was 2 h. Yang *et al*. [35] used solar/microwave combined regeneration to improve energy utilization efficiency and reduce regeneration energy consumption, as shown in Figure **3b**. Under the condition of 26.09 ℃ and 89.23% RH, the maximum dehumidification capacity of the dehumidifier was 14.1 g/kg, the maximum dehumidification efficiency was 68%, and the maximum dehumidification rate was 0.294 g/(kg·s).



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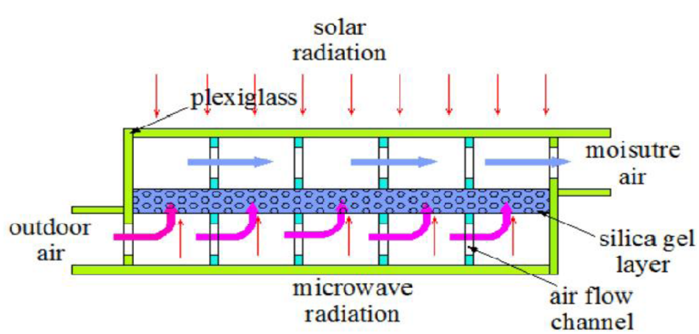
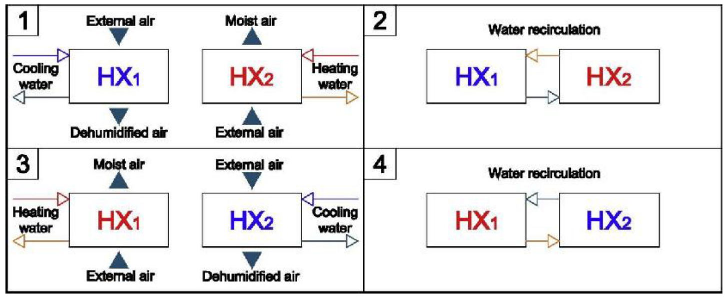


(**b**)

Figure 3: (**a**) Solid desiccant bed with direct solar regeneration [34], (**b**) Solid desiccant bed with solar/microwave combined regeneration [35].

2.2. Double Material Packed Bed

In view of the discontinuous operation of fixed bed, a common improvement method is to use parallel double packed bed structure.



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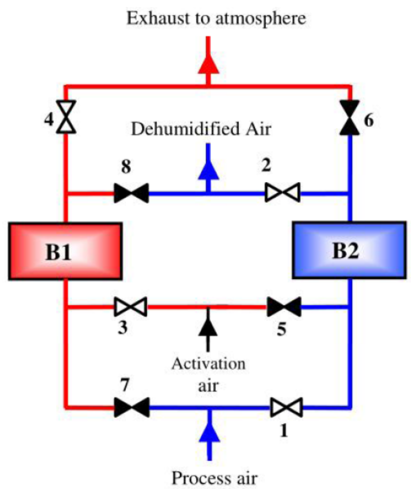

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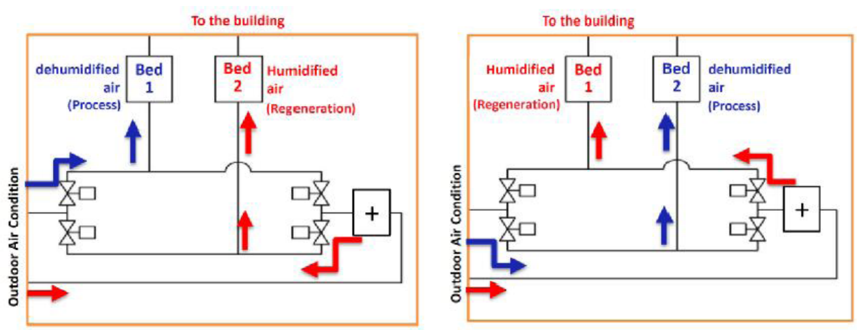

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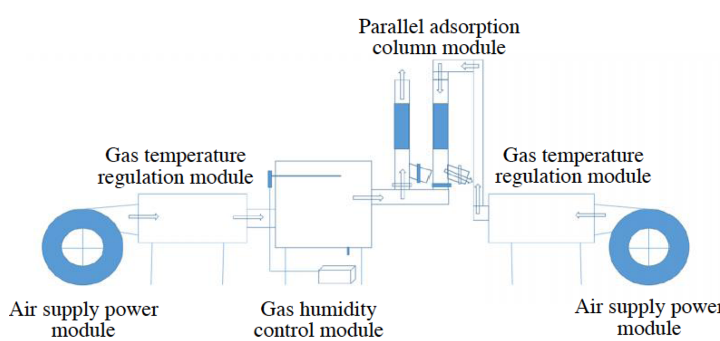

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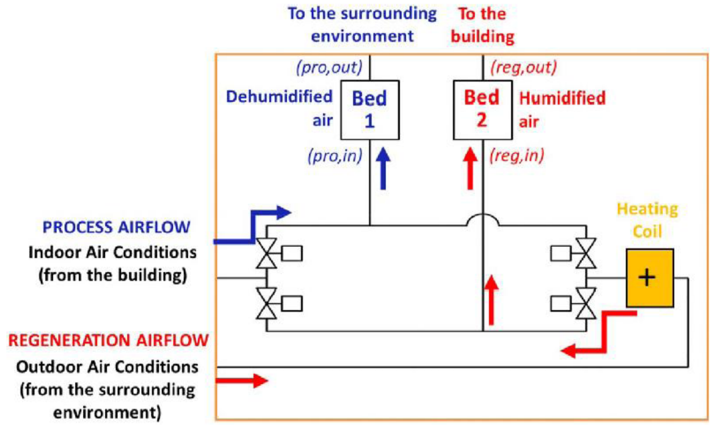

(e)

Figure 4: (**a**) Circulation diagram of fixed bed based on two finned tube heat exchangers (HX1, HX2) [36], (**b**) Dehumidification system based on two silica gel packed beds and eight control valves [37], (**c**) Humidity control system based on two silica gel packed beds [38], (**d**) System diagram of parallel fixed bed [39], (**e**) Humidity control system based ontwo cylindrical packed beds [40].

Pistocchini *et al*. [36] designed a fixed bed dehumidification system based on two finned tube heat exchangers, and its operational diagram was shown in Figure **4a**. The system reduced the gas supply temperature by implementing the quasi isothermal adsorption and desorption processes. On the premise of ensuring the dehumidification rate, the system could maintain a constant air flow direction during the adsorption-desorption phases. When the fin spacing was 4 mm, under the conditions of T=28.1 ℃ and w_0=13.8 g/kg, the average dehumidification capacity of the system was 7.3 g/kg, the coefficient of performance (COP) was 0.43, and the energy efficiency ratio (EER) was 33.1. Ramzy *et al*. [37] designed a dehumidification system consisting of two desiccant beds and eight control valves, as shown in Figure **4b**. Under the conditions of w_0=18 g/kg and v=0.75 m/s, when the required outlet moisture content was less than 12 g/kg, the cycle efficiency of the dehumidification system was 0.27. In addition, when the particle size of silica gel was 2 mm, under the condition of w_0=18 g/kg and v=0.75 m/s, if the inlet air at 50 ℃ was pre-cooled to 25 ℃ in advance, the circulating efficiency of the system could be increased from 0.26 to 0.33. Cazzaniga *et al*. [38] designed a humidity control system consisting of two silica gel packed beds. As shown in Figure **4c**, two kinds of airflow (regeneration and cooling) alternately passed through each bed layer, and the system could provide the required humidification capacity under the outdoor conditions with temperature of 0 ℃ and moisture content of 3.4 g/kg. The disadvantage was that if the outdoor conditions became worse (high temperature and low humidity ratio), the outlet regeneration temperature would be higher than 30 ℃, causing discomfort to the human body. Zhao [39] designed a parallel adsorption/desorption column structure. As shown in Figure **4d**, two adsorption columns performed adsorption and desorption respectively, ensuring the continuous operation of the fixed bed. Under the conditions of T=40℃, w_0=29.74 g/kg, q=150 m^3/h, the maximum dehumidification capacity of the system was 4.496 g/kg, and its effective dehumidification time was 140 mins. At the regeneration temperature of 90 ℃, the system could complete regeneration within 20 mins. Antonellis *et al*. [40] built a humidity control system with two cylindrical beds filled with spherical silica gel beads and four directional valves, as shown in Figure **4e**. Through the position change of the four directional valves, the process and regeneration airflow alternately passed through the two beds to ensure the continuous operation of the system. When the return air temperature of the building was 20 ℃ and the humidity content was 5.8 g/kg, the air humidity supplied to the building could increase from 1.5 g/kg to 5.3~6.1 g/kg, and its regeneration temperature was about 60 ℃.

Based on the above research results, Table **1** gives a brief summary, from which the difference of dehumidification performance of various fixed bed devices can be seen, providing a certain reference value for future research on the fixed bed.

3. CONCLUSION AND PERSPECTIVE

The energy consumption of A/C is increasing day by day. The goal is to reduce the energy consumption of A/C and improve the system efficiency. The traditional

Table 1: Comparison of Dehumidification Performance of Fixed Beds Devices [16-17, 22, 25, 29, 31-36, 39]

Type of fixed beds	Optimization method	Eenvironment condition	Maximum dehumidification capacity/($g\cdot kg^{-1}$)	Maximum dehumidification efficiency	Increase rate of maximum dehumidification efficiency	Average dehumidification capacity/($g\cdot kg^{-1}$)	Average dehumidification efficiency	Increase rate of average dehumidification efficiency	Reference
Single material packed bed	Optimization of fixed bed structure	D=1 mm、v=0.6 m/s、w_0=16.5 g/kg	-	-	-	7.07	42.85%	35.96%	[16]
		T=27.3 ℃、RH=62.8%	3.9	27.8%	44%	-	-	-	[22]
		T=25.2℃、RH=56.4%~74.9%	-	22.2%	100%	-	11.0%	180%	[25]
	Addition of cooling/heating device	T=27 ℃、v=0.8 m/s	-	-	-	-	75%	82.93%	[17]
		T=28℃、v=0.68 m/s	-	-	-	-	79%	83.72%	
		T=27℃、v=0.61 m/s	-	-	-	-	91%	100%	
		T=35 ℃、RH=70%	19.53	72.3%	49.76%	-	-	-	[29]
		T=22℃、RH=65%	7.93	73.9%	145.51%	-	-	-	
		T=27 ℃、v=0.9 m/s、w_0=10.01 g/kg	-	-	24%	-	-	-	[31]
		T=27 ℃、v=0.9 m/s、w_0=14.88g/kg	-	-	33%	-	-	-	
		T=38 ℃, RH=56%、q=320 m^3/h	-	-	-	-	-	17%	[32]
		T=25~40 ℃, w_0=15~20 g/kg、q_m=0.15~0.5kg/s	-	-	-	-	-	10-40%	[33]
	Optimization of regeneration mode	T=34.5~35.6℃、RH=89.8%~90.4%	3.26	10.04%	-	4.3	13.24%	-	[34]
		T=26.09 ℃、RH=89.23%	14.1	68%	-	-	-	-	[35]
Double material packed bed	Parallel double packed bed structure	T=28.1 ℃、w_0=13.8g/kg	-	-	-	7.3	-	-	[36]
		T=40 ℃、w_0=29.74 g/kg、q=150 m^3/h	4.496	-	-	-	-	-	[39]

A/C dehumidification system consumes a lot of energy and has low operating efficiency. Solid adsorption dehumidification provides a new direction for the research of dehumidification system. In this study, the optimization and improvement methods of fixed bed dehumidifier in recent yearsare introduced in detail, and the dehumidification performances of various devices are comprehensively compared. The summary is as follows:

1. Adding the heating/cooling devices to the fixed bed is still the mainstream optimization method at present, which can greatly improve the heat and mass transfer characteristics of the system, and greatly improve the dehumidification capacity and efficiency of the system. Among the above systems, the maximum dehumidification capacity can reach 19.53 g/kg, the maximum dehumidification efficiency can reach 73.9%, and the average dehumidification efficiency can reach 91%.

2. The structure optimization of fixed bed is also a hotspot research direction. The mass transfer

characteristics of the optimized fixed bed have been greatly improved. In the above research results, the average dehumidification capacity of the system can reach 7.07 g/kg, the average dehumidification efficiency can reach 42.85%, and the increase rate of average dehumidification efficiency can reach 180%.

3. At present, there is little research on the regeneration method of fixed bed. The main method is to use solar energy and microwave for regeneration. Optimizing the regeneration method can improve the regeneration efficiency, and the overall dehumidification efficiency of the system to a certain extent. The maximum dehumidification efficiency of the system can reach 68%.

4. The parallel double packed bed structure can ensure the continuous operation of the fixed bed and improve the dehumidification efficiency of the system. The average dehumidification capacity of the system can reach 7.3 g/kg. However, such systems are bulky and costly.

In the future, adding heating/cooling devices to the fixed bed is still an effective method. However, for different systems, the specific location of the heating/cooling devices and the specific temperature of the heating/cooling loads to be studied. For the structure of fixed bed, there are few optimization methods at present, and the improvement of dehumidification capacity and efficiency of the optimized system is limited. More optimized structures need to be studied by researchers. At present, the regeneration mode of fixed bed is still dominated by solar energy, and the feasibility of other regeneration modes and the coupling of regeneration modes need to be studied. The parallel double packed bed structure can ensure the continuous operation of the system, but the structure is large in volume and high in cost, so the structure needs to be optimized to reduce the occupied space and cost.

NOMENCLATURE

D Thickness of fixed bed (mm)

T Inlet air temperature (℃)

v Inlet air velocity (m/s)

y The axial position of the intercooler (mm)

L Length of fixed bed (mm)

w_0 Moisture content of inlet air (g/kg)

q Inlet air volume flow (m^3/h)

q_m Inlet air mass flow (kg/s)

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