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Performance Analysis of Two-Stage Solid Desiccant Densely Coated Heat Exchangers

Kun-Ying Li [1], Win-Jet Luo [1,*], Bo-Yi Tsai [2] and Yean-Der Kuan [2]

[1] Graduate Institute of Precision Manufacturing, National Chin-Yi University of Technology, Taichung 41170, Taiwan; likunying@ncut.edu.tw

[2] Department of Refrigeration, Air Conditioning and Energy Engineering, National Chin-Yi University of Technology, Taichung 41170, Taiwan; wsx0988568821@yahoo.com.tw (B.-Y.T.); ydkuan@ncut.edu.tw (Y.-D.K.)

* Correspondence: wjluo@ncut.edu.tw; Tel.: +886-42392-4505 (ext. 2960)

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Abstract: In this study, silica gel and sodium polyacrylate desiccants are coated onto a finned tube heat exchanger (Desiccant Coating Heat Exchanger, DCHE), which can absorb the vapor in the process air for dehumidification. In the experiments, the desiccant is coated on fins using the dense coating method, which causes the fixed fin area to be coated with greater amounts of desiccants for a better dehumidification performance. This study discusses the dehumidification performances of a single stage DCHE and two-stage DCHEs in series under different relative humidity conditions of the inlet process air and different regeneration water temperatures. The results show that the thermal coefficient of performance (COP_{th}) of the DCHEs for the two desiccants prepared by the dense coating method is better than that of DCHEs with the general immersing coating method by a factor of 2–2.4. The two-stage DCHEs in series have a lower supply humidity ratio than a single stage DCHE at different inlet humidity levels, and they can be used in the industry when a special low humidity manufacturing process is required. The overall dehumidifying capacities of two-stage series-connected DCHEs at regeneration temperatures of 50 °C and 70 °C are approximately twice as high as those of a single stage DCHE. The COP_{th} value of a single stage or two stages increases with an increase in the inlet humidity of the process air. The COP_{th} values of the sodium polyacrylate single stage and two-stage DCHEs are 1–1.3 times greater than those of the silica gel single stage and two-stage DCHEs at a high inlet air humidity. Finally, the effects of different regeneration water temperatures on the performance of DCHEs are investigated. With an increase in the regeneration water temperature, the COP_{th} value, dehumidifying capacity and regeneration capacity of single stage or two-stage DCHEs increase as well.

Keywords: dehumidification; dense coating method; solid desiccant; thermal coefficient of performance; two-stage DCHE

1. Introduction

According to statistical analyses of relevant meteorological data in Taiwan [1], the climate in Taiwan is under high temperature and high humidity climatic conditions throughout the entire year. Hot and high humidity weather conditions bring many inconveniences to people's production and lives. With the development of society and the economy, people have increasingly higher requirements for life comfort, and the demand for dehumidification is intensifying [2]. In addition, documents and archives, tobacco, the military industry, medicine, biotechnology and other departments, as well as underground or semi underground buildings, all require dehumidification for different reasons. Especially under the goal of "saving energy and reducing carbon", the demand and efficiency of dehumidification technology promotion is becoming increasingly important [3].

In many industrial sectors, the production quality and precision in some manufacturing processes strongly depends on the humidity conditions in the process air. For materials such as paper or hygroscopic materials, changes in humidity may cause fiber expansion or contraction and make the surface of the paper uneven or the size of the paper change [4]; it can even cause the paper to be incorrectly conveyed to the printing machine. The paper manufacturing process sometimes has to be conducted under controlled humidity conditions. In the steel industry, dehumidification of the combustion air in high-temperature steelmaking furnaces can reduce coke, increase the efficiency of steelmaking and improve the quality of steel [5,6].

In addition to industrial production, the more important significance of dehumidification lies in the impact on people's living environments. As per guidelines of the ASHRAE handbook, the relative humidity of the air in the building should be maintained at 30% to 60% [7]. This makes air conditioning systems a necessary facility for regulating the indoor thermal environment of buildings. During the operation of an air conditioning system, the dehumidification of the process air is a high energy-consuming process. The vapor content in the air is very small, and the air contains only dozens of grams of water vapor. However, the latent heat of vaporization of water is very high. The electric power consumption in the dehumidification process accounts for approximately 20–40% of the total power consumption of air conditioning systems [8].

Currently, the common use for air dehumidification in air conditioning systems is to use a cooler to cool down the temperature and reduce the humidity of the process air [9]. To meet the dehumidification requirements, the temperature of the process air after cooling and the dehumidification coils often have to drop to a very low temperature. However, in order to meet the temperature demand of the air-conditioning space, it is often necessary to reheat the dehumidified air in order to meet the requirements of the supply air temperature, which results in an unnecessary waste of energy [10]. Therefore, in recent years the concept of "cooling and dehumidification split" has been proposed in the development of air-conditioning equipment; that is, the use of individual dehumidification and cooling units to attain cooling and dehumidification effects. Via the split and independent treatments for the process air, the operational performance of the cooling unit can be boosted, and operational power consumption can be reduced. Therefore, the development of more efficient and energy-saving dehumidification technology is beneficial for reducing carbon dioxide emissions and increasing the environmental protection and the thermal comfort of human beings in air conditioning space.

Dehumidification refers to the process of reducing the water vapor content from the process air. Generally, dehumidification methods can be divided into the following types: The first is to use the cooling and dehumidification method, which cools the process air down and the vapor in the process air condenses into liquid via a cooling media with a temperature less than the dew point temperature [11]. The second method is to use the strong hygroscopic property of water-soluble solutions, such as diethylene glycol, lithium chloride, calcium chloride, and lithium bromide, to attain the dehumidification effect for the process air. The third is to use the strong hygroscopic effect of solid desiccants, such as silica gel, activated carbon, molecular sieve, and alumina gel, to attain the dehumidification effect for the process air. The above methods can be combined in an integrated air conditioning system [12].

Liquid dehumidification is a method that uses certain hygroscopic solutions to absorb vapor in the process air and dehumidifies the air. The liquid dehumidification solutions that are currently widely used in air conditioning systems include calcium chloride ($CaCl_2$), lithium chloride (LiCl) solution, etc. [13]. In recent years, this liquid dehumidification method has been adopted in the military, medicine, electronic component production processes and other areas.

The solid dehumidification method involves using solid desiccants such as silicone, activated carbon, a molecular sieve, alumina and other materials with strong hygroscopic properties to dehumidify the process air. There are generally two types of solid desiccant dehumidification units, i.e., fixed and rotary solid desiccant dehumidifiers. The fixed type dehumidifier adopts a periodic switching between the dehumidification and regeneration processes to achieve an intermittent moisture absorption and regeneration effects. However, the rotary wheel type dehumidifier [14] uses the rotation of a desiccant coating wheel to achieve continuous dehumidification and regeneration effects. Thus, it is widely used in industry. In the dynamic operation of the rotary wheel dehumidifier, the sorption heat released in the dehumidification process increases the temperature of the desiccant and significantly reduces the hygroscopic capacity. Thus, the irreversible loss of the entire process is large and can worsen the operational efficiency [15].

For composite solid desiccant materials, two or three different desiccants with different weight percentages are usually synthesized to become composite solid desiccant materials. Zhang et al. [16] investigated the dehumidification effects of desiccants of silica gel, $CaCl_2$, and composite desiccant (silica-$CaCl_2$), and found that, by coating the composite desiccant of silica-$CaCl_2$, the sorption ability is greater than that with silica gel desiccant and an equilibrium state can be attained within a short period of time. Chen et al. [17] developed a new composite desiccant material composed of silica gel, polyacrylic acid and Sodium polyacrylate with a weight percentage ratio of 10:1:1. It was determined that, under an environment of 25 °C and RH 70%, the sorption ability of the composite material is greater than that of silica gel by 41%. Zheng [18] coated a carbon-based composite desiccant on a Desiccant Coating Heat Exchanger (DCHE) and built a mathematical model to predict the performance of the dehumidification unit. Their simulation results showed that more moisture can be absorbed by DCHEs coated with the composite desiccant. Jia et al. [19] developed a rotating wheel cooling system with a composite solid desiccant that can be activated with a lower regeneration temperature. From the experimental results, the vapor removal of the developed system can be greater than that of a silica gel rotating wheel system by 20–40%. Chang et al. [20] investigated the switching time effect on the dehumidification performance of the DCHEs coated with desiccants of silica gel and sodium polyacrylate, respectively, for process air with different temperatures and humidity levels. It was determined that the DCHE coated with sodium polyacrylate possesses superior vapor sorption ability compared to that of silica gel coating DCHE, especially under the high humidity conditions of process air. Moreover, by adapting the corresponding recommended switching times in the sorption and regeneration processes, the thermal performance of the DCHEs can be enhanced by 10–14% under the operating conditions in the study.

Solid desiccant coated on a fin-tube heat exchanger is treated as a good method for space dehumidification for buildings, and the performances of DCHEs with different coating solid desiccants have been investigated in the literature. Regarding dehumidification applications in industry, the demands for supply air with a low humidity is required widely. For low humidity supply air via DCHE, DCHEs arranged in series for process air may be a good approach for attaining low humidity requirements. However, in the literature the performance of DCHEs arranged in series has never been investigated in detail. To understand the dehumidification effects and the corresponding thermal performance of DCHEs arranged in series, this study conducted several experiments to investigate the vapor sorption amounts, the vapor removal ability per unit mass of desiccant, the vapor removal ability per unit contact area and the corresponding thermal performance of two stages of DCHEs with solid coating desiccants of silica gel and sodium polyacrylate in a series arrangement under different inlet process air humidity conditions and different regeneration water temperatures, compared to those of single stage DCHE. Moreover, the desiccant coating methods on the performances of DCHEs were also investigated.

2. Experimental Equipment Construction and Dehumidification Theory

2.1. Experimental Equipment

Figure 1 shows the configuration of the dehumidification effect measurement for a single stage DCHE. Process air with a constant temperature and constant humidity is supplied to the measurement chamber with a constant flow rate. A constant water flow rate of 7 L/min is evenly distributed into the single stage DCHE. The introduced process air first passes through a filter in order to maintain a stratified and stable flow field inside the measurement chamber. The DCHE is then installed behind the filter at a distance of 475 mm and six temperature and humidity sensors along the cross sections of the measurement chamber in front of and behind the DCHE are designed with distances of 240 mm and 260 mm in order to detect the temperature and humidity conditions of the processed air before and after the DCHE. For the DCHE, hot water for the regeneration process and the cooling water can be alternatively introduced into DCHE with a constant flow rate via a three-way valve. Two temperature sensors are used to measure the water temperature before and after passing through the DCHE.

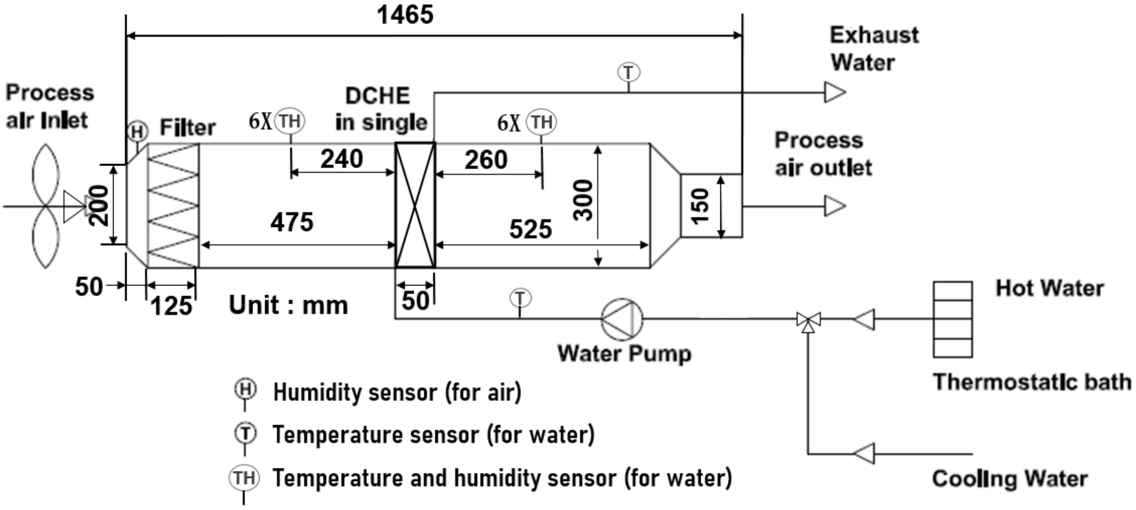


Figure 1. The configuration of the dehumidification effect measurement for a single stage Desiccant Coating Heat Exchanger (DCHE).

Figure 2 shows the configuration of the dehumidification effect measurement for the two-stage DCHEs in series. The measurement chamber configuration for the two-stage DCHEs is similar to that for the single stage DCHE. Process air with a constant temperature and constant humidity is supplied to the measurement chamber with a constant flow rate. The water piping for two-stage DCHEs system is designed in parallel. A constant water flow rate of 14 L/min is evenly distributed into the two DCHEs, which then merges and exhausts. Two DCHEs are installed behind the filter at a distance of 475 mm and the distance between the two DCHEs is 30 mm. Two temperature sensors are designed to detect the inlet water temperature and the outlet water temperature for each DCHE, in order to understand the heat transfer effect for each DCHE.

Uncertainties in measuring any physical quantity are always presented due to instrumental, physical and human inadequacies [21]. Uncertainty analysis is the procedure employed to assess the uncertainty from measured variables with known values of uncertainties. In this study, the experimental influencing factors and corresponding uncertainties in the experiments include: (1) Programmable constant temperature and humidity system errors are 0–100 °C ± 0.3 °C and 10–98% RH ± 3% RH; (2) Low temperature constant temperature sink error is −20–100 °C ± 0.1 °C; (3) Precision electronic scale error is 0–210 g ± 0.001 g; (4) Electric heating plate error is 0–350 °C ± 1 °C; (5) Data recorder error is ±0.002%; (6) Temperature and humidity probe error are −40–85 °C ± 0.1 °C and 0–100% RH ± 0.8% RH; (7) Anemometer error is 1–80 m/s ± 3%; (8) Liquid flow meter error is 1.5–20 L/min ± 2%. The uncertainty of instruments in this study is shown in Table 1.

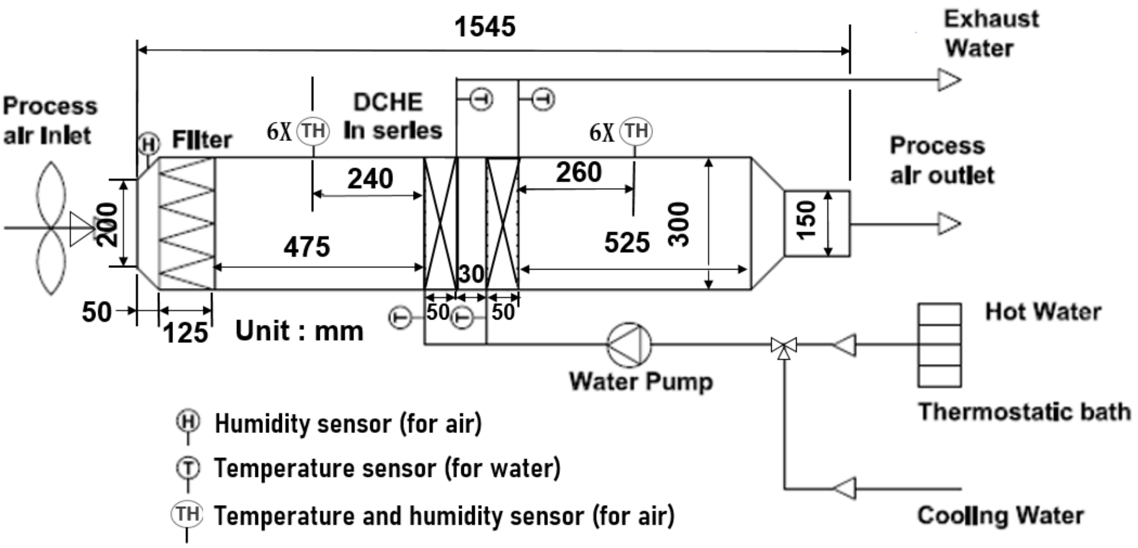


Figure 2. Configuration of the dehumidification effect measurement for the two-stage DCHE.

Table 1. Uncertainty of instruments.

	Instrument	Type	Uncertainty
1	Programmable constant temperature and humidity system	150-00-SP-SD	Temperature 0–100 °C ± 0.3 °C Humidity 10–98% RH ± 3% RH
2	Constant temperature sink	D-620	−20–100 °C ± 0.1 °C
3	Precision electronic scale	TB-214	0–210 g ± 0.001 g
4	Electric heating plate	HP-303D	0–350°C ± 1 °C
5	Data recorder	GL-840M	±0.002%
6	Temperature and humidity probe	HC2-IC302	Temperature −40–85 °C ± 0.3 °C Humidity 0–100% RH ± 0.8% RH
7	Anemometer	TES-3142	1–80 m/s ± 3%
8	Liquid flow meter	NW20-NTN	1.5–20 L/min ± 2%
	Uncertainty of calculated quantity		Uncertainty range
A	M_{vap}		−2.2% to 2.2%
B	G_{vap}		−2.2% to 2.2%
C	G_{vg}		−4.2% to 4.2%
D	G_{va}		−6.5% to 6.5%
F	COP_{th}		−3.7% to 3.7%

Using J. Kline's [21] measurement uncertainty, this study performed an error analysis of the experimental results based on the propagation of the uncertainties equation derived by Kline and McClintock (1953). The test errors of the moisture removal rate (M_{vap}), the vapor sorption or desorption amounts by the DCHE/DCHEs (G_{vap}), sorption ability (G_{vg}), the vapor sorption or desorption ability per unit area of DCHE or DCHEs (G_{va}) was determined by dividing the vapor sorption or desorption amounts (G_{vap}) and COP_{th} were found to be ±2.2%, ±2.2%, ±4.2%, ±6.5% and ±3.7%, respectively.

2.2. Dehumidification Effect

The moisture removal rate (M_{vap}) of the single stage DCHE and the two-stage DCHEs can be obtained by calculating the humidity ratio differential value at the inlet and outlet of the DCHE/DCHEs and the mass flow rate of the process air, as shown in Equation (1).

$$M_{vap} = \dot{m}_a \left(W_{a,out} - W_{a,in} \right), \tag{1}$$

where $\dot{m}_a$ is the mass flow rate of the process air, and $W_{a,in}$ and $W_{a,out}$ denote the inlet and outlet humidity ratios of the process air.

The vapor sorption or desorption amounts by the DCHE/DCHEs (G_{vap}) can be determined by Equation (2):

$$G_{vap} = \int_0^{\tau} \left|M_{vap}\right| dt, \tag{2}$$

where τ is the period for the vapor sorption or desorption process.

The vapor sorption or desorption ability per unit mass of the desiccant (G_{vg}) is determined by dividing the vapor sorption or desorption amounts (G_{vap}) by the weight of the desiccant, as shown in Equation (3):

$$G_{vg} = \frac{G_{vap}}{g_{des}}, \tag{3}$$

where g_{des} is the mass of the desiccant coated on DCHE or DCHEs.

The vapor sorption or desorption ability per unit area of DCHE or DCHEs (G_{va}) is determined by dividing the vapor sorption or desorption amounts (G_{vap}) by the total contact area of the DCHE or DCHEs, as shown in Equation (4):

$$G_{va} = G_{vap}/A_{fin}, \tag{4}$$

where A_{fin} is the total area of the fins of DCHE or DCHEs.

The average thermal performance COP_{th}, which indicates the overall energy efficiency of DCHE or DCHEs, is defined as the ratio of the total energy exchange of the processed air in an effective dehumidification process ($Q_{cooling}$) over the average heat exchange of water in an effective regeneration process (Q_{reg}), and can be expressed as Equation (5):

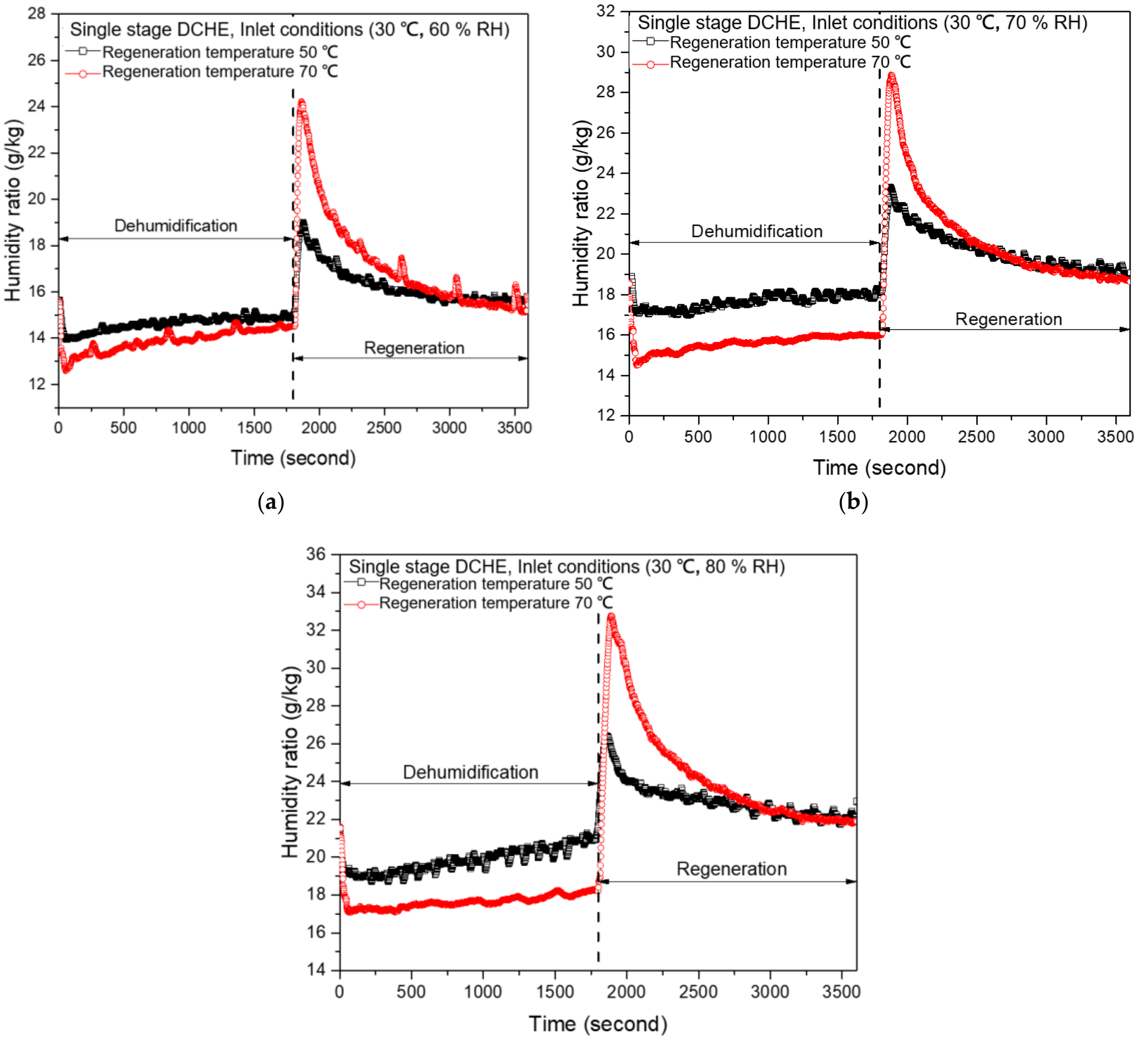
$$COP_{th} = \frac{\int_0^{\tau} \dot{m}_a \times (h_{a,out} - h_{a,in})dt}{\int_0^{\tau} \dot{m}_{water} \times C_{p,\,w} \times \left(T_{h,out} - T_{h,in}\right)dt} \tag{5}$$

where $\dot{m}_a$ and $\dot{m}_{water}$ are the mass flow rate of the process air and the regeneration hot water across, respectively, in kg/s, $h_{a,in}$ and $h_{a,out}$ are the enthalpies of the process before and after the DCHE or DCHEs, respectively, in kJ/kg, and C_p is the specific heat of the regeneration hot water at a constant pressure in kJ/kg K. $T_{h,in}$ and $T_{h,out}$ are the temperatures of the hot water supply to and exhausting from the DCHE, respectively.

3. Results and Discussions

3.1. Performance Analysis of Single Stage DCHE and Two Stage DCHEs with Different Desiccant Coating Methods

Figure 3 illustrates the humidity ratio variations of the process air behind the single stage DCHE with dense coating desiccant of silica gel under different inlet humidity ratios of process air at regeneration water temperatures of 50 °C and 70 °C, respectively. It can be seen that, during the dehumidification process with an inlet air temperature of 30 °C, the cooling water with a temperature of 25 °C is introduced into the DCHE and the vapor in the process air is absorbed by the desiccant due to the vapor pressure difference between the process air and the desiccant. At the beginning of the dehumidification process, the humidity ratio of the process air behind the DCHE decreases sharply from its initial value to a minimum value, and then gradually increases until the end of the dehumidification process. The time for the dehumidification process is 30 min. At the end of the dehumidification process, the humidity ratio value of the process air behind the DCHE does not return to its initial value, which means that the silica gel desiccant does not attain a saturation state after the dehumidification process period of 30 min.



(**a**) (**b**)

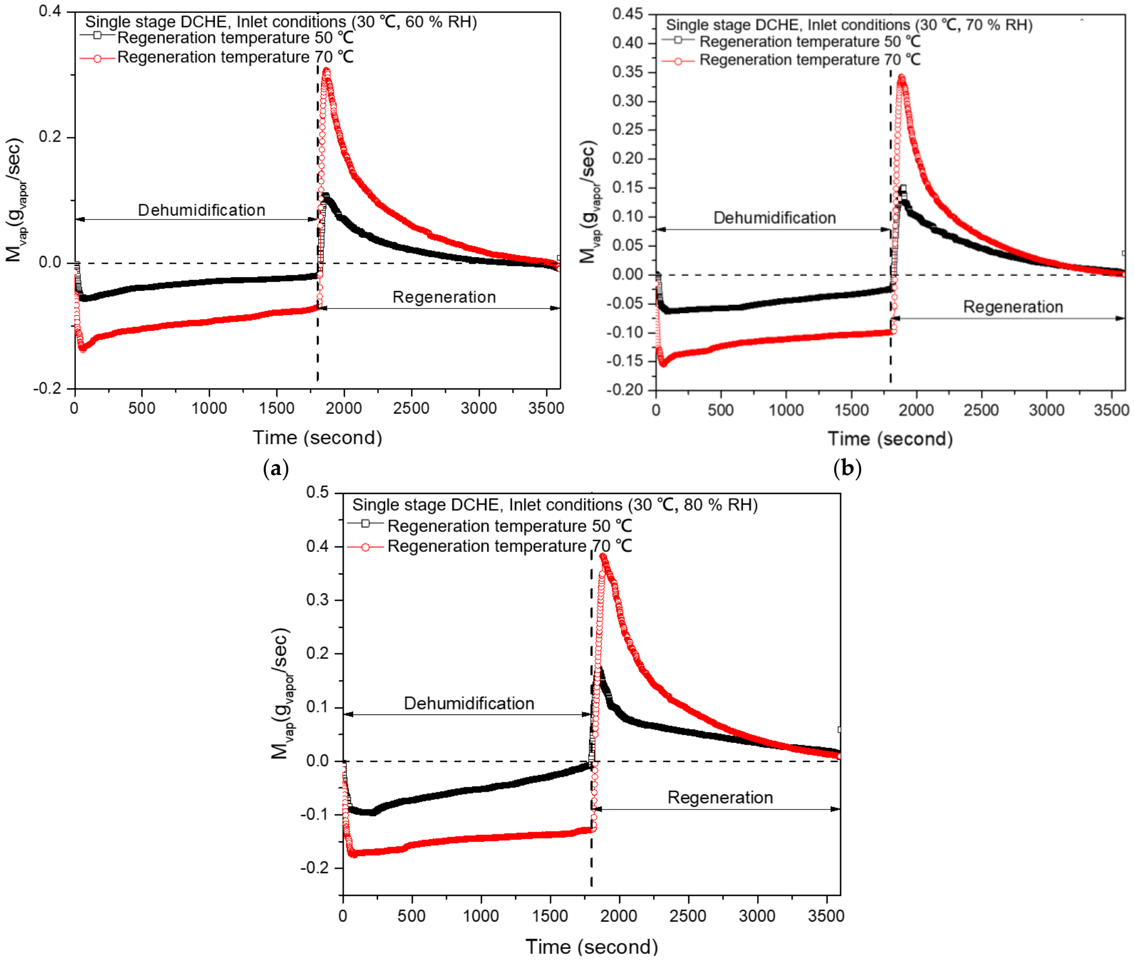
(**c**)

Figure 3. The humidity ratio variations of the process air behind the single stage DCHE with a dense coating desiccant of silica gel under different inlet humidity ratios of process air at the regeneration water temperatures of 50 °C and 70 °C; (**a**) 30 °C/60% RH; (**b**) 30 °C/70% RH; (**c**) 30 °C/80% RH.

After the dehumidification process, the regeneration water, with temperatures of 50 °C or 70 °C, is introduced into the DCHE alternatively in order to heat the silica gel desiccant of the DCHE. The heat gain of the desiccant results in a greater vapor pressure of the desiccant, which makes the vapor eject into the process air from the desiccant. Similarly, at the beginning of the regeneration process, the humidity ratio of the process air behind the DCHE increases by leaps and bounds from its initial lower value to a maximum value, which then quickly decreases until the end of the regeneration process. The time for the regeneration process is 30 min as well. At the end of the regeneration process, the humidity ratio value of the process air behind the DCHE can almost equal the humidity ratio of the process air before the DCHE, which means that the silica gel desiccant no longer ejects vapor to the process air after a regeneration process period of 30 min.

From the figure, it can be seen that, with a regeneration water temperature of 70 °C, a higher maximum humidity ratio of the process air behind the DCHE can be attained compared to the case with a regeneration water temperature of 50 °C under the same inlet process air conditions, which means that more vapor can be ejected into the process air and more vapor can be absorbed by the desiccant in the dehumidification process, as well as with a higher regeneration water temperature.

Figure 4 illustrates the vapor removal rates from the process by the single stage DCHE with a dense coating desiccant of silica gel under different inlet humidity ratios of the process air at regeneration water temperatures of 50 °C and 70 °C, respectively. It can be seen that, during the dehumidification process, with the cooling water introduced into the DCHE, the vapor removal rates attain their minimum values at the beginning of the dehumidification process, which indicates that much vapor is absorbed by the desiccant. Then, the vapor removal rates gradually increase until the end of the dehumidification process. At the end of the dehumidification process, the vapor removal rates do not approach zero, which means that the silica gel desiccant does not attain a saturation state after a dehumidification process period of 30 min.



(**a**)

(**b**)

(**c**)

Figure 4. The vapor removal rates from the process by the single stage DCHE with a dense coating desiccant of silica gel under different inlet humidity ratios for the process air at the regeneration water temperatures of 50 °C and 70 °C; (**a**) 30 °C/60% RH; (**b**) 30 °C/70% RH; (**c**) 30 °C/80% RH.

In the regeneration process, regeneration water with temperatures of 50 °C or 70 °C is introduced into the DCHE alternatively. Similarly, at the beginning of the regeneration process, the vapor removal rates by DCHE increase by leaps and bounds from initial lower values to maximum values, then quickly decrease until the end of the regeneration process. At the end of the regeneration process, the vapor removal rates by the DCHE almost approach zero, which means that the silica gel desiccant no longer ejects vapor to the process air after the regeneration process.

From the figure, it can be seen that, with a regeneration water temperature of 70 °C, a higher vapor removal rate can be attained compared to the case with a regeneration water temperature of

50 °C under the same inlet process air conditions, which means that more vapor can be ejected into the process air and more vapor can be absorbed by the desiccant in the dehumidification process, as well as with a higher regeneration water temperature.

In this study, the desiccants of the silica gel and sodium polyacrylate were evenly and densely coated onto the surfaces of the fin-tube heat exchangers, respectively. Using the previous desiccant coating method, the fine-tube heat exchangers were immersed in the desiccant-water solutions with different weight percentages in order to make the desiccants cling onto the surfaces of the heat exchangers by the binder. Then, the coated heat exchangers were placed in a high temperature oven for several hours to obtain a fully dry desiccant layer on the surfaces of the fins of the heat exchangers. However, the amounts of desiccants coated on the surfaces of the heat exchangers are difficult to control and, sometimes, fewer amounts of desiccants were coated onto the surfaces of the heat exchangers, which may worsen the sorption and desorption efficiencies of the desiccants due to the invalid heat loss between the fin surface and the process air stream during the sorption and desorption processes. In this study, a layer of binder with a constant thickness of 2–6 μm was coated onto the surface of each fin sheet of the fine-tube heat exchanger with a spraying process. Then, the desiccant was evenly and densely distributed onto the surface of each fin sheet with a single layer of desiccant, one-by-one. The coated fin sheets were placed in a high temperature oven to dry for several hours. Finally, the coated fine sheets were brought to a heat exchanger manufacturing company to conduct the fabrication processes, including mechanical tube expansion, welding and leakage detection, etc. Using this desiccant coating method, the amount of coating desiccant on the fine surface of the exchanger can be greatly increased and high density and uniform distributions of the coating desiccant on each fin sheet can be assured. The thickness of the fin sheet is 0.1 mm and the gap of fins is 5 mm. The coating thicknesses of silica gel layer and sodium polyacrylate layer are in ranges of 0.8–1.0 mm and 3–5 mm, respectively.

Table 2 illustrates the amounts of desiccants of silica gel and sodium polyacrylate coated onto the fin-tube heat exchangers, respectively. In comparison to the amount of desiccant coated on the fine-tube heat exchanger by the conventional method, the amount of silica gel desiccant and polyacrylate desiccant coated onto the fine-tube heat exchanger can be enhanced by 3.28 times and 2.57 times by using the densely coating method, respectively.

Table 2. Vapor sorption and desorption amounts of the fin-tube heat exchangers coated with desiccants of silica gel and sodium polyacrylate by the two coating methods under different humidity conditions for the processing air within 30 min.

Sorption and Desorption Amount (G_{vap}) of DCHEs with Different Coating Methods (Unit: Gram)						
	30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
	Sorption amount	Desorption amount	Sorption amount	Desorption amount	Sorption amount	Desorption amount
Densely silica coating DCHE	60.29	40.55	86.75	75.81	95.66	93.30
Immersing silica coating DCHE	3.35	3.33	3.93	3.90	4.54	4.53
Densely polyacrylate coating DCHE	34.66	31.48	69.81	70.08	109.50	150.08
Immersing polyacrylate coating DCHE	2.45	2.44	3.98	3.99	4.11	4.12

Table 2 illustrates the vapor sorption and desorption amounts of the fin-tube heat exchangers coated with desiccants of silica gel and sodium polyacrylate via the two coating methods under different humidity conditions of the processing air within 30 min, respectively. At a temperature of 30 °C, the vapor sorption and desorption amounts of the two desiccants by the two coating methods increase with an increase in the humidity of the processing air. When the relative humidity is 80%, using the dense coating method the vapor sorption amounts of the desiccants of silica gel and polyacrylate can attain values of 95.66 g and 109.5 g, respectively, and the vapor desorption amounts of the desiccants of silica gel and polyacrylate can attain values of 93.3 g and 150.08 g, respectively. However, using the immersing coating method, the vapor sorption amounts of the desiccants of silica gel and polyacrylate can attain values of 4.54 g and 4.11 g, respectively, and the vapor desorption amounts of the desiccants of silica gel and polyacrylate can attain values of 4.53 g and 4.12 g, respectively. Regarding the vapor sorption and desorption amounts by the two coating methods, the vapor sorption and desorption amounts using the densely coating method can be 13–15 times higher than those using the immersing method. Due to the greater amounts of desiccants coated on the surface of the fin-tube heat exchangers when using the dense coating method, the vapor sorption and vapor desorption amounts of the desiccants are much greater than those obtained by using the immersing coating method.

Table 3 illustrates the vapor sorption and desorption abilities (G_{vap}/g_{des}) of the fin-tube heat exchangers coated with desiccants of silica gel and sodium polyacrylate using the two coating methods under different humidity conditions of the processing air within 30 min. The vapor sorption and desorption abilities of both desiccants gradually increase with an increase in the relative humidity and, at a higher relative humidity condition, the vapor sorption and desorption amounts of sodium polyacrylate desiccant are higher than those of silica gel. However, at lower relative humidity conditions, the vapor sorption and desorption amounts of silica gel are greater. For vapor sorption/desorption capacity per unit gram of desiccant, because the density of sodium polyacrylate is quite light compared to silica gel, the weight of sodium polyacrylate coated on the fine-tube heat exchanger is smaller; however, the porosity (85%) of sodium polyacrylate is much greater than that (50–65%) of silica gel. Thus, the vapor sorption/desorption abilities per unit gram of sodium polyacrylate are always much greater than those of silica gel under different relative humidity conditions. Under the same temperature and relative humidity conditions, the vapor sorption/desorption abilities per unit gram of both desiccants using the dense coating method are greater than those obtained using the immersing coating method, because the invalid heat lost and the heat transfer efficiency in the sorption and desorption processes are less than those in the dense coating method. In Table 4, the vapor sorption/desorption amounts per square centimeter of the two desiccants are shown as well. Due to the dense desiccant distributions on the fin-tub heat exchanger, the vapor sorption/desorption amounts per square centimeter of both desiccants using the dense coating method are much greater than those obtained using the immersing coating method.

Table 3. Vapor sorption and desorption abilities (G_{vg}) of the fin-tube heat exchangers coated with desiccants of silica gel and sodium polyacrylate obtained by the two coating methods under different humidity conditions of the processing air within 30 min.

Sorption and Desorption Amount per Gram (G_{vap}/g_{des}) of DCHEs with Different Coating Methods (Unit: Gram/Gram)						
	30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
	Sorption amount	Desorption amount	Sorption amount	Desorption amount	Sorption amount	Desorption amount
Densely silica coating DCHE	0.0646	0.0435	0.0930	0.0812	0.1025	0.1000
Immersing silica coating DCHE	0.0238	0.0236	0.0279	0.0277	0.0322	0.0322
Densely polyacrylate coating DCHE	0.0895	0.0813	0.1802	0.1809	0.2826	0.3874
Immersing polyacrylate coating DCHE	0.0349	0.0348	0.0569	0.0571	0.0588	0.0586

Table 4. The vapor sorption and desorption amount per unit area (G_{va}) of the fin-tube heat exchangers coated with desiccants of silica gel and sodium polyacrylate using the two coating methods under different humidity conditions of the processing air within 30 min.

Sorption and Desorption Amount per Unit Area (G_{va}) of the Fin-Tube Heat Exchangers Coated with Desiccants of Silica Gel and Sodium Polyacrylate Obtained Using the Two Coating Methods under Different Humidity Conditions of the Processing Air within 30 min (G_{va} = (G_{vap}/cm^2))						
	30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
	Sorption amount	Desorption amount	Sorption amount	Desorption amount	Sorption amount	Desorption amount
Densely silica coating DCHE	0.0125	0.0084	0.0180	0.0157	0.0198	0.0193
Immersing silica coating DCHE	0.000335	0.000333	0.000393	0.00039	0.000453	0.000454
Densely polyacrylate coating DCHE	0.0034	0.0030	0.0067	0.0068	0.0106	0.0145
Immersing polyacrylate coating DCHE	0.000241	0.000240	0.000392	0.000394	0.004056	0.000405

Regarding the thermal coefficients of performance of both desiccants by the dense and immersing coating methods in Table 5, due to the higher heat transfer efficiencies between the desiccants and the cooling/heating water in the sorption/desorption processes obtained by the dense coating method, the thermal performances of the heat exchangers via the dense coating method under the same temperature and relative humidity conditions are almost 2 times greater than those obtained via the immersing coating method. The thermal performances of both desiccants are gradually increasing with an increase in the relative humidity condition because the larger vapor pressure difference between the process air and the desiccant under a higher humidity condition leads to the higher sorption efficiency of the desiccant during the sorption process. When the relative humidity of the process air is 80%, the thermal performances of silica gel and sodium polyacrylate with a dense coating method can attain higher values of 0.629 and 0.572, respectively.

Table 5. Thermal coefficients for the performance of both desiccants using the dense and immersing coating methods.

The COP_{th} of both Desiccants Obtained by the Dense and Immersing Coating Methods in 30 min						
	30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
	Sorption amount	Desorption amount	Sorption amount	Desorption amount	Sorption amount	Desorption amount
Densely silica coating DCHE	0.5272	0.5524	0.6292	0.5272	0.5524	0.6292
Immersing silica coating DCHE	0.2104	0.2575	0.2697	0.2104	0.2575	0.2697
Densely polyacrylate coating DCHE	0.4605	0.5244	0.5722	0.4605	0.5244	0.5722
Immersing polyacrylate coating DCHE	0.1928	0.2801	0.2860	0.1928	0.2801	0.2860

3.2. Performance Comparison of Single Stage DCHE and Two Stage DCHEs Densly Coated with Silica Gel

Table 6 compares the vapor sorption/desorption amounts, abilities and amount per contact area of the single stage DCHE and two-stage DCHEs in series, densely coated with silica gel and at a regeneration water temperature of 50 °C. It can be seen that the vapor sorption/desorption amounts, abilities, and amount per contact area of the single stage DCHE and the two-stage DCHEs are increased with an increase in the relative humidity ratio of the process air. The silica desiccant-coated amount in single DEHE is 933.18 g and the coated amounts in two-stage DCHEs are 933.18 g and 948.76 g, respectively. For the vapor sorption amounts at different RH values, the two-stage DCHEs can absorb approximately 2.16–2.68 times the vapor from the process air using the coated silica gel desiccant due to having twice the contact area in the two-stage DCHEs. However, for the vapor sorption ability per desiccant unit weight, due to different silica gel desiccant weight amounts coated on the DCHEs, the vapor sorption abilities per unit desiccant weight in the two-stage DCHEs are greater than those in the single stage DCHE by 1.07–1.33 times. For a vapor sorption amount per unit area, the vapor sorption amount per unit contact area in the two-stage DCHEs are greater than those in the single stage DCHE by 1.06–1.33 times. The reasons for greater vapor sorption amounts per unit desiccant weight and per unit contact area in the two-stage DCHEs are that the flow circulations occurring in the region between the two DCHEs may retard the flow motion of the process air, enlarge the pressure drop of the process air, extend the heat and mass transfer time between the process air and desiccants and enhance the vapor sorption effect in the second stage DCHE.

Table 6. The vapor sorption/desorption amounts, abilities and amounts per contact area of the single stage DCHE and two-stage DCHEs in series, densely coated with silica gel at a regeneration water temperature of 50 °C.

The Single Stage DCHE and Two-Stage DCHEs in Series, Densely Coated with Silica Gel at a Regeneration Water Temperature of 50 °C						
	30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
	Sorption	Desorption	Sorption	Desorption	Sorption	Desorption
Vapor sorption/ desorption amount of DCHE (G_{vap} unit: gram)	60.29	40.55	86.75	75.81	95.66	93.30
Vapor sorption/ desorption amount of DCHEs (G_{vap} unit: gram)	161.91	101.36	187.31	183.98	244.99	243.34
Vapor sorption/ desorption amounts per contact area of DCHE (G_{va} unit: gram/cm^2)	0.0125	0.0084	0.0180	0.0157	0.0198	0.0193
Vapor sorption/ desorption amounts per contact area of DCHEs (G_{va} unit: gram/cm^2)	0.0166	0.0104	0.0192	0.0189	0.0251	0.0250
Vapor sorption/ desorption amounts per unit desiccant of DCHE (G_{vg} unit: gram/gram)	0.0646	0.0435	0.0930	0.0812	0.1025	0.1000
Vapor sorption/ desorption amounts per unit desiccant of DCHEs (G_{vg} unit: gram/gram)	0.0860	0.0539	0.0995	0.0978	0.1301	0.1293

Table 7 illustrates the vapor sorption/desorption amounts, abilities and amount per unit contact area of the single stage DCHE and two-stage DCHEs in series, densely coated with silica gel at a regeneration water temperature of 70 °C. For the vapor sorption amounts at different RH values, the two-stage DCHEs can absorb approximately 1.26–1.52 times of vapor from the process air by the coated silica gel desiccant, which are less than those at a generation temperature of 50 °C. However, in comparison to the case at a generation temperature of 50 °C, the vapor sorption amount per unit desiccant weight and per unit contact area of the two-stage DCHEs are less than those in the single stage DCHE at a generation temperature of 70 °C. The reasons for greater vapor sorption amounts per unit desiccant weight and per unit contact area in the single stage DCHEs at a generation temperature of 70 °C are that more vapor in the process air being absorbed by the first stage DCHE causes lower humidity process air to enter the second stage DCHE, which results in the vapor sorption effect by the second stage DCHE being less than those of the two-stage DCHEs at a generation temperature of 50 °C.

Table 7. The vapor sorption/desorption amounts, abilities, and amount per contact area of the single stage DCHE and two-stage DCHEs in series, densely coated with silica gel at a regeneration water temperature of 70 °C.

The Single Stage DCHE and Two-Stage DCHEs in Series, Densely Coated with Silica Gel at a Regeneration Water Temperature of 70 °C						
	30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
	Sorption	Desorption	Sorption	Desorption	Sorption	Desorption
Vapor sorption/ desorption amount of DCHE (G_{vap} unit: gram)	172.83	117.02	211.71	128.88	267.75	178.04
Vapor sorption/ desorption amount of DCHEs (G_{vap} unit: gram)	227.42	117.99	321.86	198.33	438.56	225.55
Vapor sorption/ desorption amounts per contact area of DCHE (G_{va} unit: gram/cm^2)	0.0358	0.0242	0.0438	0.0267	0.0554	0.0368
Vapor sorption/ desorption amounts per contact area of DCHEs (G_{va} unit: gram/cm^2)	0.0233	0.0121	0.0330	0.0203	0.0450	0.0231
Vapor sorption/ desorption amounts per unit desiccant of DCHE (G_{vg} unit: gram/gram)	0.1852	0.1254	0.2269	0.1381	0.2869	0.1908
Vapor sorption/ desorption amounts per unit desiccant of DCHEs (G_{vg} unit: gram/gram)	0.1208	0.0627	0.1710	0.1054	0.2330	0.1199

3.3. Performance Comparison of Single Stage DCHE and Two Stage DCHEs Densly Coated with Sodium Polyacrylate

Table 8 compares the vapor sorption/desorption amounts, abilities and amount per contact area of the single stage DCHE and two-stage DCHEs in series, densely coated with sodium polyacrylate at a regeneration water temperature of 50 °C. It can be seen that the vapor sorption/desorption amounts, abilities and amount per contact area of the single stage DCHE and two-stage DCHEs increase with an increase in the relative humidity ratio of the process air. The sodium polyacrylate desiccant coating amount in a single DEHE is 387.42 g and the coating amount in two-stage DCHEs are 387.42 g and 493.12 g, respectively. For the vapor sorption amounts at different RH values, the two-stage DCHEs can absorb approximately 2.47–2.84 times the vapor from the process air using the coated sodium polyacrylate desiccant due to having twice the contact area in two-stage DCHEs. However, for the vapor sorption ability per desiccant unit weight, due to the different sodium polyacrylate desiccant weight amounts coated on the DCHEs, the vapor sorption abilities per unit desiccant weight in two-stage DCHEs are greater than those in the single stage DCHE by 1.09–1.25 times. For a vapor sorption amount per unit area, the vapor sorption amount per unit contact area in two-stage DCHEs is greater than those in the single stage DCHE by 1.26–1.44 times. The reasons for greater vapor sorption amounts per unit desiccant weight and per unit contact area in the two-stage DCHEs are that the flow circulations occurring in the region between the two DCHEs may retard the flow motion of the process air, enlarge the pressure drop of the process air, extend the heat and mass transfer time between the process air and desiccants and enhance the vapor sorption effect in the second stage DCHE.

Table 8. The vapor sorption/desorption amounts, abilities, and amount per unit contact area of the single stage DCHE and two-stage DCHEs in series, densely coated with sodium polyacrylate at a regeneration water temperature of 50 °C.

The Single Stage DCHE and Two-Stage DCHEs in Series, Densely Coated with Sodium Polyacrylate at a Regeneration Water Temperature of 50 °C						
	30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
	Sorption	Desorption	Sorption	Desorption	Sorption	Desorption
Vapor sorption/ desorption amount of DCHE (G_{vap} unit: gram)	34.66	31.48	69.81	70.08	109.50	150.08
Vapor sorption/ desorption amount of DCHEs (G_{vap} unit: gram)	98.35	79.98	184.91	134.10	270.17	229.77
Vapor sorption/ desorption amounts per contact area of DCHE (G_{va} unit: gram/cm^2)	0.0034	0.0030	0.0067	0.0068	0.0106	0.0145
Vapor sorption/ desorption amounts per contact area of DCHEs (G_{va} unit: gram/cm^2)	0.0049	0.0040	0.0092	0.0066	0.0134	0.0114
Vapor sorption/ desorption amounts per unit desiccant of DCHE (G_{vg} unit: gram/gram)	0.0895	0.0813	0.1802	0.1809	0.2826	0.3874
Vapor sorption/ desorption amounts per unit desiccant of DCHEs (G_{vg} unit: gram/gram)	0.1116	0.0908	0.2010	0.1523	0.3068	0.2609

Table 9 illustrates the vapor sorption/desorption amounts, abilities and amount per unit contact area of the single stage DCHE and two-stage DCHEs in series, densely coated with sodium polyacrylate at a regeneration water temperature of 70 °C. For the vapor sorption amounts at different RH values, the two-stage DCHEs can absorb approximately 1.28–1.59 times the vapor from the process air by using the coated sodium polyacrylate desiccant in comparison to the single stage DCHE, which is less effective than those at a generation temperature of 50 °C. However, compared to the case at a generation temperature of 50 °C, the vapor sorption amount per unit desiccant weight and per unit contact area of the two-stage DCHEs are less than those in the single stage DCHE at a generation temperature of 70 °C. The reasons for greater vapor sorption amounts per unit desiccant weight and per unit contact area in the single stage DCHEs at a generation temperature of 70 °C are that more vapor in the process air being absorbed in the first stage DCHE causes lower humidity process air to enter the second stage DCHE, which results in the vapor sorption effect caused by the second stage DCHE being less than those of the two-stage DCHEs at a generation temperature of 50 °C.

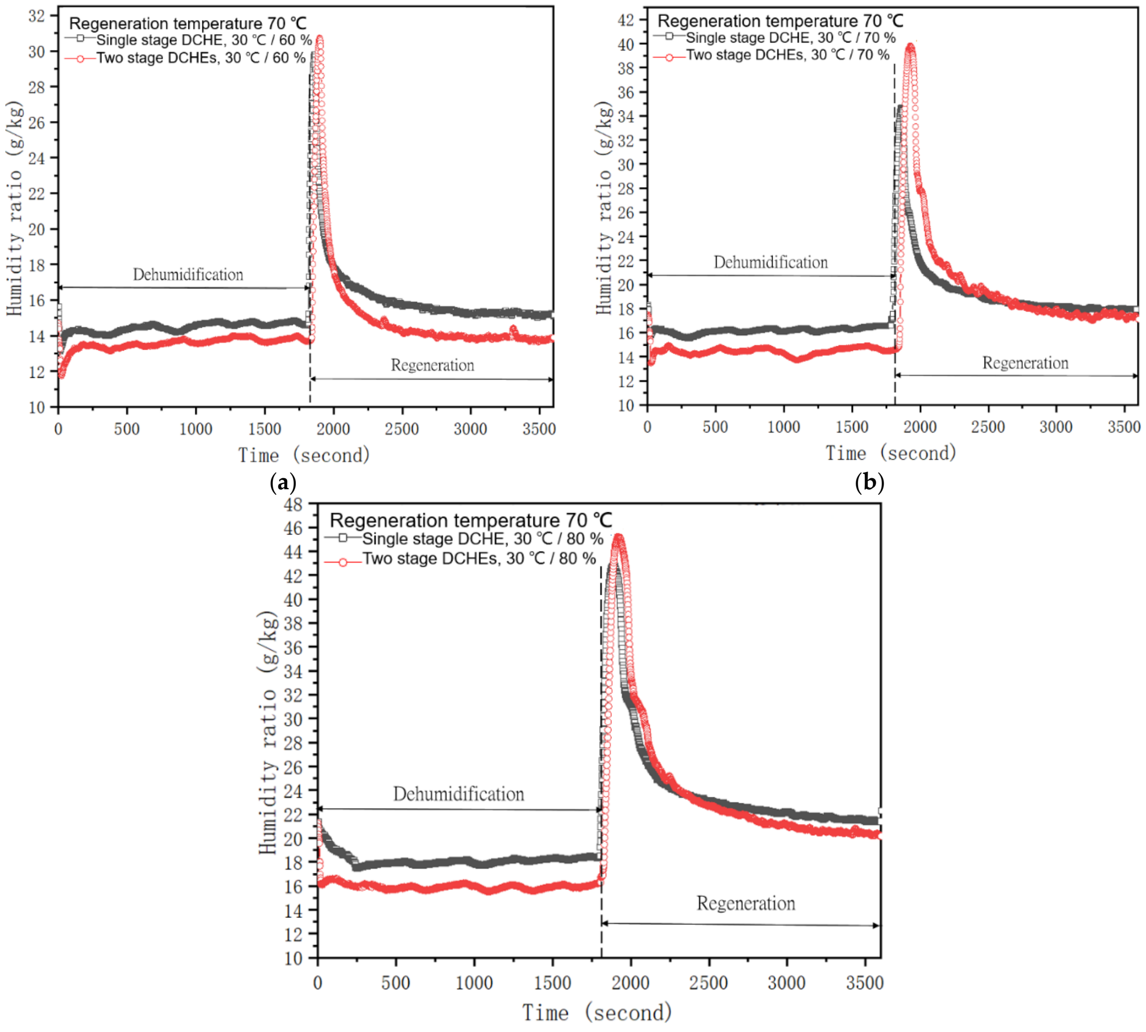
Table 9. The vapor sorption/desorption amounts, abilities and amount per unit contact area of the single stage DCHE and two-stage DCHEs in series, densely coated with sodium polyacrylate at a regeneration water temperature of 70 °C.

The Single Stage DCHE and Two-Stage DCHEs in Series, Densely Coated with Sodium Polyacrylate at a Regeneration Water Temperature of 70 °C						
	30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
	Sorption	Desorption	Sorption	Desorption	Sorption	Desorption
Vapor sorption/ desorption amount of DCHE (G_{vap} unit: gram)	108.59	69.50	168.19	105.03	268.96	176.22
Vapor sorption/ desorption amount of DCHEs (G_{vap} unit: gram)	138.91	103.82	264.96	182.06	346.99	252.83
Vapor sorption/ desorption amounts per contact area of DCHE (G_{va} unit: gram/cm^2)	0.0237	0.0152	0.0368	0.0230	0.0588	0.0385
Vapor sorption/ desorption amounts per contact area of DCHEs (G_{va} unit: gram/cm^2)	0.0150	0.0112	0.0287	0.0197	0.0376	0.0274
Vapor sorption/ desorption amounts per unit desiccant of DCHE (G_{vg} unit: gram/gram)	0.2803	0.1794	0.4341	0.2711	0.6942	0.4549
Vapor sorption/ desorption amounts per unit desiccant of DCHEs (G_{vg} unit: gram/gram)	0.1578	0.1179	0.3009	0.2068	0.3940	0.2871

Figure 5 compares the outlet humidity ratio of the process air of the single stage DCHE and two-stage DCHEs under different inlet conditions at the regeneration water temperatures of 70 °C. From the figure, it can be seen that, with the two stage arrangement of DCHEs, the outlet humidity ratio of the process air in the dehumidification process can attain to a lower value in comparison to that of the case with single stage DCHE. The outlet average humidity ratio can be reduced from 14.6 g/kg to 13.6 g/kg under the inlet conditions of 30 °C/60% RH, from 16.3 g/kg to 14.7 g/kg under the inlet conditions of 30 °C/70% RH, from 18.2 g/kg to 16.1 g/kg under the inlet conditions of 30 °C/80% RH. It can be found that, with the increase in inlet relative humidity, the reduction of outlet humidity ratio of the process air increases as well.

3.4. Thermal Performance Comparison of Single Stage DCHE and Two Stage DCHEs with Silica Gel and Sodium Polyacrylate

Table 10 indicates the coefficient of thermal performance (COP_{th}) of the single stage DCHE and two-stage DCHEs in series with silica gel and sodium polyacrylate under different inlet humidity levels for the process air and supplied regeneration water temperatures. For the single stage of silica gel and sodium polyacrylate DCHE, the COP_{th} values of the two DCHEs gradually increase with an increase in the inlet humidity of the process air at the same supplied regeneration water temperatures. The COP_{th} values of the two-stage DCHEs rise with an increase in the supplied regeneration water temperature at the same inlet temperature and humidity of the process air.



(**a**) (**b**) (**c**)

Figure 5. Comparison of the single stage DCHE and two-stage with a dense coating desiccant of sodium polyacrylate under different inlet humidity ratios for the process air at the regeneration water temperatures of 70 °C; (**a**) 30 °C/60% RH; (**b**) 30 °C/70% RH; (**c**) 30 °C/80% RH.

Table 10. The coefficient of thermal performance (COP_{th}) of the single stage DCHE and two-stage DCHEs in series with silica gel and sodium polyacrylate under different inlet humidity levels of the process air and supplied regeneration water temperatures in 30 min.

The Coefficient of Thermal Performance (COP_{th}) of the Single Stage DCHE and Two-Stage DCHEs in Series with Silica Gel and Sodium Polyacrylate under Different Inlet Humidity Levels of the Process Air and Supplied Regeneration Water Temperatures in 30 min.							
		30 °C/60% RH		**30 °C/70% RH**		**30 °C/80% RH**	
		Silica gel	sodium polyacrylate	Silica gel	sodium polyacrylate	Silica gel	sodium polyacrylate
50 °C	DCHE	0.5272	0.4605	0.5524	0.5244	0.6292	0.5722
	DCHEs	0.5157	0.4787	0.5303	0.5523	0.5651	0.6490
70 °C	DCHE	0.8137	0.7582	0.8391	0.8683	0.8493	0.9317
	DCHEs	0.4288	0.5423	0.5949	0.6017	0.6052	0.7271

Under the conditions of higher inlet humidity levels of process air and regeneration water temperatures, for the two-stage DCHEs of silica gel and sodium polyacrylate, the COP_{th} values of the two-stage DCHEs gradually increase with an increase in the inlet humidity of the process air, as well as the supplied regeneration water temperature.

Higher COP_{th} values of the two-stage sodium polyacrylate DCHE are present under higher inlet humidity levels of process air and regeneration water temperatures.

In terms of the COP_{th} values of single stage DCHE and the two-stage DCHEs of the two desiccants, at a generation water temperature of 70 °C, the COP_{th} values of the single stage DCHE are greater than those of the two-stage DCHEs at the same inlet humidity of the process air. For the two-stage DCHEs, after passing through the first stage DCHE, the reduced humidity of the process air may cause a worse dehumidification effect of the second DCHE. Thus, the COP_{th} values of the two-stage DCHEs are lower than that of the single stage DCHE. However, at a generation water temperature of 50 °C, the deviations of the COP_{th} values between the single stage DCHE and the two-stage DCHEs are not apparent. At a regeneration water temperature of 50 °C, the dehumidification effect by the first stage DCHE is less than that at a regeneration temperature of 70 °C, and the flow circulations between the two DCHEs may extend the heat and mass transfer time, which may enhance the vapor sorption/desorption effect and increase the energy consumption of the supplied water. Thus, at a generation water temperature of 50 °C, the deviations of the COP_{th} values between the single stage DCHE and the two-stage DCHEs are not apparent. Comparing the thermal performances of the two desiccants of silica gel and sodium polyacrylate, the sodium polyacrylate possesses a higher thermal performance under higher humidity conditions. However, under lower humidity conditions, the thermal performance of silica gel is better.

4. Conclusions

In this study, the performances of two stages of DCHEs arranged in series and coated with solid coating desiccants of silica gel and sodium polyacrylate, respectively, were investigated in order to understand the dehumidification effects and corresponding thermal performance of DCHEs. Several experiments were conducted to investigate the characteristics of the vapor sorption amounts, the vapor removal ability per unit mass of desiccant, the vapor removal ability per unit contact area and the corresponding thermal performance of single stages DCHE and two-stage DCHEs coated with solid desiccants of silica gel and sodium polyacrylate under different inlet process air humidity conditions and different regeneration water temperatures. Moreover, the desiccant coating methods' effects on the performances of DCHEs were also investigated. Based on the experimental results, the following conclusions are obtained.

1. Using the dense desiccant coating method on the heat exchanger, the absorption capacity of the desiccants can be greatly boosted and the thermal coefficient of performance can be greatly enhanced due to a higher thermal utility and less heat loss in the dehumidification and regeneration processes.
2. Using the two-stage DCHEs, a lower outlet humidity of the process air can be attained compared to the single stage DCHE.
3. The total vapor absorption amounts of the two-stage DCHEs are greater than those of the single stage DCHE by more than a factor of 2. Because the stay time of the process air between the first stage DCHE and the second stage DCHE and the velocity of the process air decrease, there is more time for the desiccants to undergo vapor absorption; thus, the absorption effect of the desiccant can be raised.
4. With the increase in the inlet humidity of the processed air, the water vapor pressure difference between the processed air and the desiccant rises and total heat exchange of the processed air in dehumidification process, $Q_{cooling}$, increases as well. With the regeneration water temperature rise, the water vapor pressure difference between the desiccant and the processed air increases, meaning more water content in the desiccant is ejected into the processed air. This is beneficial to

the water vapor absorption of the desiccant in the dehumidification process. Therefore, for single stage DCHE and two-stage DCHEs, the COP_{th} value increases with an increase in the inlet humidity of the processed air and the regeneration water temperature.

5. The absorption effect of sodium poly is better than silica gel under a higher inlet humidity of process air.

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Nomenclature

A_{fin}	Total area of the fins of DCHE/DCHEs	G_{vap}	Vapor sorption/desorption amounts
COP_{th}	Coefficient of thermal performance	g_{des}	Mass of the desiccant coated on DCHE/DCHEs
C_p	Specific heat	$h_{a,out}$	Enthalpies of the process after of DCHE/DCHEs
C_w	Sorption ability	$h_{a,\ in}$	Enthalpies of the process before of DCHE/DCHEs
G_{vg}	Vapor sorption/desorption amounts per unit desiccant	$\dot{m}_{water}$	Mass flow rate of water
G_{va}	Vapor sorption/desorption amounts per unit area of DCHE/DCHEs	$\dot{m}_a$	Mass flow rate of air
M_{vap}	Moisture removal rate	$T_{h,out}$	Temperatures of water exhaust from DCHE
Q_{reg}	Average heat exchange of water in an effective regeneration process	$W_{a,out}$	Humidity ratio of process air inlet
$Q_{cooling}$	The ratio of the total energy exchange of the processed air in an effective dehumidification process	$W_{a,in}$	Humidity ratio of process air inlet
RH	Relative humidity	τ	Period for vapor sorption or desorption
$T_{h,in}$	Temperatures of water supply to DCHE		

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