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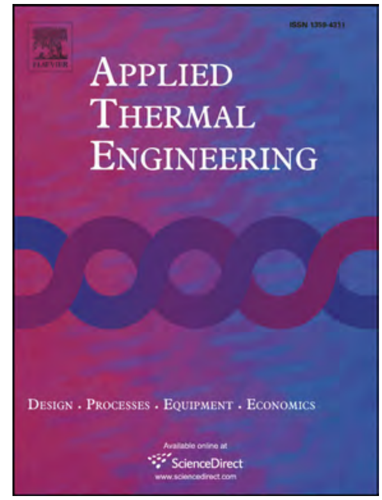

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Performance Investigation of Regenerative Total Heat Exchanger with Periodic Flow

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Abstract

This study proposes a new regenerative type of the periodic total heat exchanger system, which consists of four centrifugal fans and two fixed wheels. The total heat exchanger, which operates periodically to replace the rotation of the fixed wheel in conventional design, can save more energy from motors. The fixed wheels alternately store and release energy using the heat and moisture storage materials of aluminum and silica gel. The operation periods are 2 minutes, 3 minutes, 4 minutes, 6 minutes, and 8 minutes. The results show that under the temperature and humidity ratio differences of 10°C and 4 g/kg between indoors and outdoors, the operating period of 3 minutes has the best performance of sensible heat effectiveness, latent heat effectiveness, and total heat effectiveness. When the temperature and humidity differences increase, the optimal operating period becomes shorter. In order to increase heat effectiveness, adding another high temperature and low moisture air for regeneration in the total heat exchanger increases the latent heat effectiveness, but the sensible heat effectiveness decreases.

Keywords: Periodic total heat exchanger, Storage material, Operation period

Nomenclature

h enthalpy (kJ/kg)

˙ mass flow rate (kg/s)

$\dot{Q}$ heat transfer rate (W)

RH relative humidity(%)

T temperature (◦C)

ω humidity ratio (g/kg)

Greek symbol

ε effectiveness

Subscripts

EA exhaust air

L latent heat

max maximum

min minimum

OA outdoor air

OS flow from outdoor air to supply air

RA return air

S sensible heat

SA indoor supply air

T total heat

1. Introduction

As quality of life increases, indoor air quality has received more attention. For a comfortable and healthy indoor environment, ventilation is essential, but large amounts of energy must be consumed to condition outdoor air. Thus, total heat exchangers that recover energy from exhaust air have been designed to reduce the energy needs of buildings and improve indoor air quality. There are two types of classifications for total heat exchangers: the recovery type and the regenerative type. The recovery type exchanges heat at the same time, but the regenerative type exchanges heat at a different time, as shown in Figures 1(a) and 1(b). Most studies have focused on correlations or the materials used for the total heat exchanger [1–10]. Zhang [11] proposed total heat exchangers under uncertainties are optimized by reliability-based single-loop genetic algorithm. Sabek [12] presented total heat exchanger is experimentally investigated, and numerically validated. The variation of membrane surface and/or flow velocity has an important impact on the activation and clogging times. Min [13] discussed four methods to evaluate the performance of a membrane-type total heat exchanger. They are the numerical method with consideration of moisture adsorption heat, the numerical method with no consideration of that heat, the effectiveness-NTU method with consideration of that heat, and the effectiveness-NTU method with no consideration of that heat.

Yang [14] first proposed the periodic total heat exchanger, composed of a fixed-plate heat exchanger, two flow passages, and four centrifugal fans. This recovery-type total heat exchanger has a double flow circuit heat exchange device. By the control of four fans, the device can pump fluids in different flowing directions, so that the heat exchange device possesses a double flow circuit for periodic positive and reverse directional pumping. Chang [15] and colleagues investigated the usage of different energy storage materials in the recovery type of periodic total heat exchanger to enhance the device's performance. Three types of energy storage materials were installed and investigated: activated carbon, aluminum, and a mixture of activated carbon and aluminum. The results showed that adding activated carbon to the device increases latent heat effectiveness by 17.3%. Installing aluminum results in an increase of 15.1% in sensible heat effectiveness. Finally, among the three types of energy storage materials, the device with activated carbon had the best performance, increasing the total heat effectiveness up to 11.7%. For this study, a periodic total heat exchanger based on a regenerative and rotary-type concept was constructed. Fixed wheels were made of the heat and moisture storage materials of aluminum and silica gel, which can store and release energy alternately. These wheels were installed at the center of each flow passage to enhance the thermal performance of the device.

In this work, the total heat exchanger operates periodically to replace the rotation of the fixed wheel. The total heat exchanger uses double flow circuit heat exchange. During the half-period, one fan drives air through one fixed wheel for adsorption and the other fan, operating in the opposite direction, induces air through the other fixed wheel for desorption. In the next half-period, both air flow directions are reversed by the other two fans. The total heat exchanger was tested with various operating periods and different temperature and humidity ratios between indoors and outdoors, and the influence of the additional high temperature air added in the storage materials to influence the effectiveness were discussed.

2. Experiment research

2.1. Experiment set-up

Figures 2(a), (b), and (c) give a schematic figure and photographic views of the experiment set-up and inside contracture, which consists of an ameliorative periodic total heat exchanger device, temperature and humidity control devices, and measuring instruments. The fixed wheel located in each flow passage is made of aluminum material with a large number of channels. Also, the silica gel is coated with the surface of aluminum material. The dimension of fixed wheel is 20 cm in length and 25cm in diameter. The photographic view of fixed wheel is shown in Figure 2(d). In contrast to a traditional rotary-type total heat exchanger, the periodic total heat exchanger has four centrifugal fans to form a double flow circuit for periodic operation, which is illustrated in Figure 2. In each process, there are only two fans running at the same time. When fans 2 and 4 are working (red arrows), the outdoor air enters the device from vent 3, and the supply air flows indoors from vent 2; the return air enters the device from vent 1, and the exhaust air is then discharged from vent 4. Similarly, when fan 1 and fan 3 are working (blue arrows), the outdoor air enters the device from vent 4, and the supply air flows indoors through vent 1; the return air enters the device from vent 2, and the exhaust air is then discharged from vent 3.

Two groups of simulating apparatus are used to maintain the desired conditions of the indoor and outdoor air. To simulate specific conditions of indoor air, the air first passes through a cooling coil, which uses a chiller to keep water cold, to reach the target of the condensation dehumidification. The dry cold air then passes through a heating coil, which uses a constant temperature water bath to maintain hot water, to achieve the desired condition. Similarly, outdoor air is simulated using the combination of a heating coil and a humidifier. Measured variables in these experiments include temperature, humidity ratio, and flow rate of air at inlet and outlet points of the flow passages, as shown in Figure 2. The data collected to evaluate the performance indices mentioned above are measured by temperature transmitters, humidity transmitters, and vane anemometers. The manufacturers and models of the instruments are listed in Table 1. Based on the uncertainty analysis proposed by ISO standards [16], the uncertainties of temperature, humidity, and flow velocity measurement are ±0.2◦C, ±2% and ±1.5%, respectively.

2.2. Experiment parameters

Because the capacity of the energy storage material is relevant to the device's operating duration, the operating period was the dominant parameter. The operation periods are 2 minutes, 3 minutes, 4 minutes, 6 minutes, and 8 minutes. For example, in the case of a 4-minute operation period, the running of fans 2 and 4 at the same time was a positive operation, while running fans 1 and 3 was a negative operation. Positive operation and negative operations each lasted 4 minutes, and each process was carried out two times. Therefore, the total duration of one test run was 16 minutes.

2.3. Performance indices

To investigate the performance of the periodic total heat exchanger, effectiveness was adopted as an important index. According to the ASHRAE STANDARD [17], sensible, latent, and total heat transfer effectiveness are defined as follows:

$$\varepsilon_s = \frac{Q}{Q_{max}} = \frac{\dot{m}_{OS}(T_{OA} - T_{SA})}{\dot{m}_{min}(T_{OA} - T_{RA})} \quad (1)$$

$$\varepsilon_l = \frac{Q}{Q_{max}} = \frac{\dot{m}_{OS}(\omega_{OA} - \omega_{SA})}{\dot{m}_{min}(\omega_{OA} - \omega_{RA})} \quad (2)$$

$$\varepsilon_t = \frac{Q}{Q_{max}} = \frac{\dot{m}_{OS}(h_{OA} - h_{SA})}{\dot{m}_{min}(h_{OA} - h_{RA})} \quad (3)$$

In these models, $\dot{m}_{os}$ is the mass flow rate of outdoor and supply air and $\dot{m}_{min}$ is the fluid with the minimum mass flow rate from inlet of outside air or return air. T, ω, and h represent the temperature, absolute humidity ratio, and the enthalpy, respectively, and the subscripts of OA, SA and RA are the states of outdoor air, indoor supply air and return air, respectively.

3. Results and discussion

Given that the two flow passages are symmetrical and the total heat exchanger is the regenerative type rather than the recovery type, the performance of the total heat exchanger is studied in one flow passage, as shown in Figure 3. The total heat exchanger was tested with different temperature and humidity ratios between indoors and outdoors, and the influences of the high temperature gas added in the storage materials to regeneration were discussed.

3.1 Ameliorative periodic total heat exchanger with energy storage material

Figure 4 shows the temperature and relative humidity of the total heat exchanger for the 3-minute operating period when the temperature and humidity ratio differences between the indoor and outdoor environments were maintained close to the fixed values of 10℃ and 4 g/kg, respectively. The fixed values of 10 ◦C and 4 g kg^{-1} are the temperature and relative humidity differences between supplied air and returning air. The data of temperature and relative humidity have similar values and regular trends in each period of positive and negative operation, which means that heat and moisture achieved a balanced state. The average temperature, relative humidity, and enthalpy of outside air, supply air, return air, and exhaust air are listed in Table 2. The mass flow rates of outside air and return air are 0.133kg/s and 0.132 kg/s, respectively. The high-temperature, humid outside air flows through the storage materials, which adsorb the heat and moisture. The temperature and humidity of the outside air decreases, and it becomes supply air. After the fan operation changes, the low-temperature, less humid return air flows through the storage materials, releasing their heat and moisture to the air. The return air then becomes exhaust air. In the 3-minute period, the total heat exchanger finishes one cycle of behavior.

Figure 5 shows an increase in effectiveness from periods of 2 minutes to 3 minutes and a decrease from periods of 3 minutes to 8 minutes; the sensible, latent, and total heat effectiveness show the same trends. The average temperature, relative humidity, and enthalpy of outside air, supply air, return air and exhaust air are listed in Table 2. During shorter periods, the energy-storing materials undergo regeneration and temperature decrease without adsorbing enough heat and moisture beforehand, thus reducing effectiveness. During longer periods, the material adsorbs enough heat and moisture to reach a saturated state, meaning the effectiveness gradually decreases. There is a limit to the adsorption. The optimal period time is 3 minutes for the total heat exchanger to be most effective. Moreover, from our previous study[18], motors were not needed to drive the wheels of periodic total heat exchanger systems, so the power consumption of the periodic systems was lower than that of rotary type total heat exchanger systems. Thus, the periodic device does not need additional energy consumption for the rotary mechanism, increasing its application life and ease of maintenance.

3.2 Influence of different temperature and humidity ratios for periodic total heat exchanger

The thermo-physical properties of the total heat exchanger at the temperature and humidity ratio differences of 15℃ and 8 g/kg during different operating periods are listed in Table3. Table 4 shows the heat effectiveness of the total heat exchanger for different operating periods when the temperature and humidity differences between the indoor and outdoor environments change. As the temperature and humidity differences increase for the operating period of 3 minutes, the effectiveness of all the heat exchanges decrease. This is because the regeneration-type heat exchanger processes the heat exchange at a different time. Thus, when the temperature difference is high, the heat stored at the fixed wheel is easy to dissipate. The sensible heat effectiveness is also lower. For the latent heat effectiveness, when the humidity ratio difference increases, the fixed wheel cannot easily adsorb all moisture in a short time. When the temperature difference is larger, the fixed wheel cannot regenerate easily because its temperature is higher. In this case, each heat effectiveness is better in the operating period of 2 minutes because the heat and mass transfer abilities increase at larger temperature and humidity differences between indoor and outdoor environments. The behaviors of adsorption and regeneration can be achieved in a shorter time. If the period time is longer, performance becomes worse and the device consumes more energy.

3.3 Influence of installing high temperature and low moisture air to regeneration after return air or outside air flows.

Based on the temperature and humidity ratio differences of 10°C and 4 g/kg in Table 4, the optimal operating period is 3 minutes. The sensible heat effectiveness is 80%, but the latent heat effectiveness is 52%. The latent heat effectiveness is lower because low temperature and moisture air is easy to regenerate to the state of saturated humidity. There is a adsorption limit to the adsorption materials. Even if the air is not at the state of saturated humidity, the relative humidity of low temperature air increase due to the moisture regenerated from adsorption material. Therefore, if the required relative humidity control is higher, adding high temperature and low moisture air for regeneration is a solution after return air or outside air enters into the storage materials, as shown in Figure 6(a) and (b). Compared to the original design, with an operating period of 3 minutes at the temperature and humidity ratio differences of 15℃ and 8 g/kg, the air quality of the indoor environment and heat effectiveness when adding additional high temperature, low moisture air after return air or outside air to influence the effectiveness are shown in Table 5. When air quality is required to be high, adding additional high temperature and low moisture air flow after return air can not only dry out the moisture on the surface of the storage material, but it can also remove the dirty indoor air from the total heat exchanger. Thus, as outside air enters the total heat exchanger, the moisture is easily adsorbed by the storage material. Compared with the original design, the latent heat effectiveness will increase. The shortcoming is that the sensible heat effectiveness would decrease because the temperature of the storage material would be increased by the addition of the high temperature air. Thus, the outside air could not effectively decrease in temperature. Adding additional high temperature, low moisture air after outside air to the regeneration process could result in better latent heat effectiveness compared with original design because the storage material is regenerated by high temperature, low moisture air. Although the temperature of the storage material is cooled by the return air, the sensible heat effectiveness would still decrease. Compared with the regeneration using return air in the original design in Table 5, this method for installing high temperature and low moisture air to regeneration after outside air can result in medium performance for both sensible and latent heat effectiveness. The shortcoming is that the air quality would be low. Because the return air exhausts, the dirty quality of the air particles would coat the storage material. When outside air enters indoors, the air quality would become worse, compared with adding high temperature, low moisture air to regeneration with return air. This method is not suitable for a healthy environment.

4. Conclusion

In this paper, the total heat exchanger, which operates periodically to replace the rotation of the fixed wheel in conventional design, can save more energy from motors. Energy storage materials were added in the periodic total heat exchanger to improve its performance. A series of experiments were conducted to investigate the new design, and the results indicated three main findings. First, under the temperature and humidity ratio differences of 10℃ and 4 g/kg, the best performance of each heat effectiveness is at the operating period of 3 min. Sensible heat effectiveness is the highest value at 80%. This level of effectiveness is similar to that of commercial products. Second, when the temperature and humidity differences increase, the optimal operating period becomes shorter. Third and finally, adding high temperature, low moisture air to regeneration in the total heat exchanger increases latent heat effectiveness but decreases sensible heat effectiveness.

5.Acknowledgements

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Figure captions:

Figure. 1. Schematic view of a periodic total heat exchanger: (a) recovery type and (b) regenerative type

Figure. 2. (a) Schematic figure of total heat exchanger with performance test and measurement points. (b) Photographic view of the experiment set-up. (c) Photographic view of the inside of the total heat exchanger. (d) Photographic view of fixed wheels of total heat exchanger.

Figure. 3. Schematic figure of the total heat exchanger in one flow passage

Figure. 4. Performance of the periodic total heat exchanger for a 3-minute operating period: (a) variations in temperature at the measuring points; (b) variations in relative humidity at the measuring points.

Figure 5. Performance of the periodic total heat exchanger for different operating periods

Figure 6. Schematic figure of adding high temperature and low moisture air for regeneration

Table captions:

Table1. The manufacturers and models of the instruments

Table2. The thermo-physical properties of total heat exchanger at the temperature and humidity ratio differences of 10 ℃ and 4 g/kg under different operating periods.

Table3. The thermo-physical properties of total heat exchanger at the temperature and humidity ratio differences of 15 ℃ and 8 g/kg under different operating periods.

Table4. The heat effectiveness of the total heat exchanger for different operating period when the temperature and humidity differences between the indoor and outdoor environments.

Table5. The air quality of indoor environment and heat effectiveness under installing high temperature and low moisture air to regeneration with return air or outside air

Table1. The manufacturers and models of the instruments

	Manufacturer	Model
Temperature transmitters	YOKOGAWA	K type
Humidity transmitters	LUTRON	HT-305
Vane anemometers	TESTO	0635-1049

Table2. The thermo-physical properties of total heat exchanger at the temperature and humidity ratio differences of 10 ℃ and 4 g/kg under different operating periods

Operating period: 2 min	OA	SA	RA	EA
T_{ave}(℃)	33.6	25.8	22.3	25.4
ω_{ave}(g/kg)	15.2	14.4	11.3	11.5
H_{ave}(kJ/kg)	72.7	62.7	51.1	54.8
Operating period: 3 min	OA	SA	RA	EA
T_{ave}(℃)	35.8	27.8	25.8	28.6
$\omega_{ave}(g/kg)$	15.6	13.9	12.3	11.9
$H_{ave}(kJ/kg)$	76.0	63.4	57.4	59.1
Operating period: 4 min	OA	SA	RA	EA
T_{ave}(℃)	34.9	28.6	25.9	30.3
ω_{ave}(g/kg)	14.7	13.0	11.4	11.5
H_{ave}(kJ/kg)	72.7	62.0	55.2	60.0
Operating period: 6 min	OA	SA	RA	EA
T_{ave}(℃)	35.4	28.6	25.5	29.3
W_{ave}(g/kg)	15.5	14.0	12.3	12.0
H_{ave}(kJ/kg)	75.3	64.7	56.9	60.2
Operating period: 8 min	OA	SA	RA	EA
T_{ave}(℃)	35.6	29.1	25.4	30.5
ω_{ave}(g/kg)	18.4	16.7	14.8	14.2
H_{ave}(kJ/kg)	83.0	72.0	63.3	67.1

Table3. The thermo-physical properties of total heat exchanger at the temperature and humidity ratio differences of 15 ℃ and 8 g/kg under different operating periods

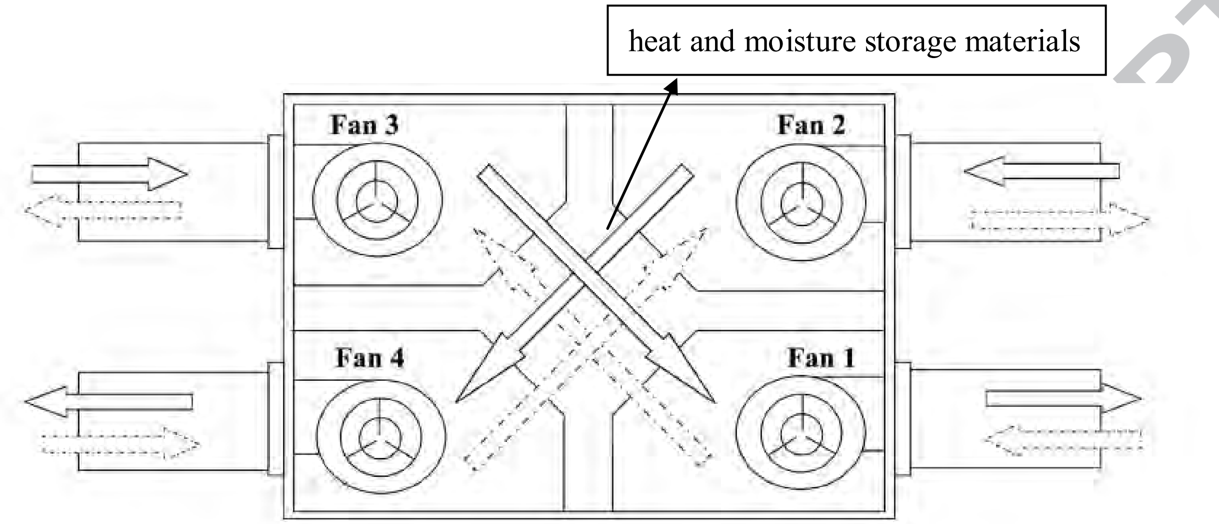
Operating period: 2 min	OA	SA	RA	EA
T_{ave}(℃)	40.0	28.4	24.6	32.5
ω_{ave}(g/kg)	23.9	20.2	16.1	15.9
H_{ave}(kJ/kg)	101.7	80.1	65.0	73.5
Operating period: 3 min	OA	SA	RA	EA
T_{ave}(℃)	38.9	28.5	24.5	32.5
ω_{ave}(g/kg)	23.6	20.9	16.4	15.7
H_{ave}(kJ/kg)	99.9	82.0	66.5	72.8

Table4. The heat effectiveness of the total heat exchanger for different operating period when the temperature and humidity differences between the indoor and outdoor environments

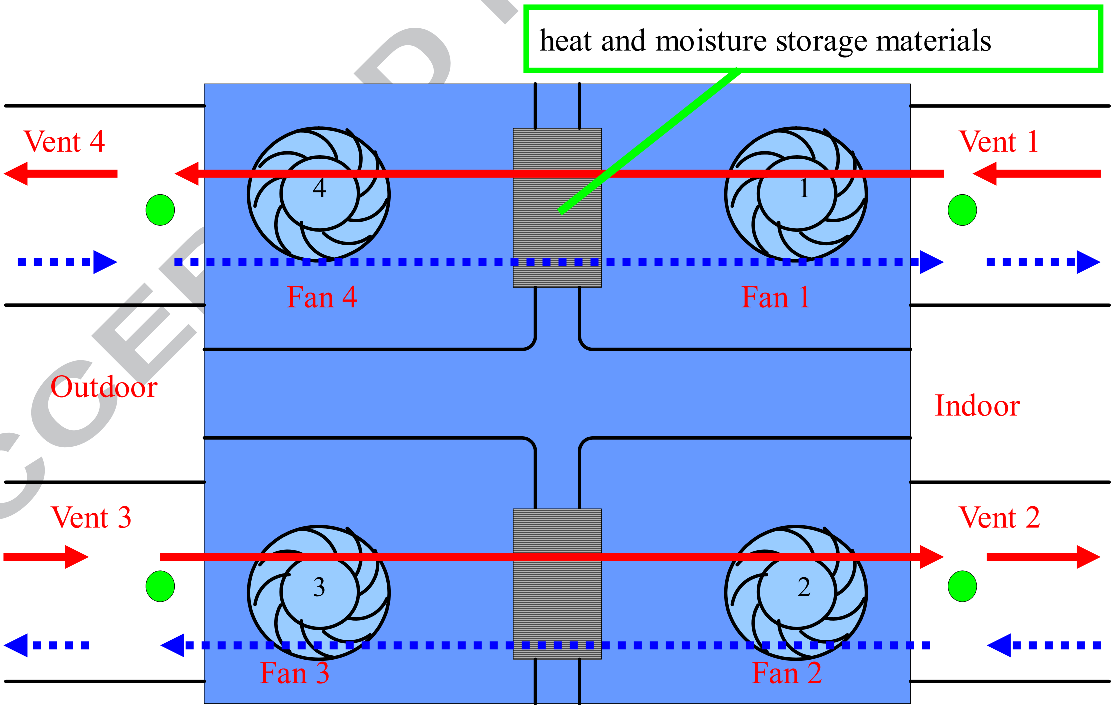
	Temperature differences: 10℃ Humidity differences :4g/kg			Temperature differences: 15℃ Humidity differences :8g/kg	
	2min	3min	4min	2min	3min
Sensible heat effectiveness	69%	80%	70%	75%	72%
latent heat effectiveness	21%	52%	51%	47%	38%
total heat effectiveness	46%	68%	61%	59%	54%

Table5. The air quality of indoor environment and heat effectiveness under installing high temperature and low moisture air to regeneration with return air or outside air

	Air quality	The sensible heat effectiveness	The latent heat effectiveness
Original design without installing high temperature and low moisture air	Medium	High	Low
installing high temperature and low moisture air to regeneration after return air flows	High	Low	High
installing high temperature and low moisture air to regeneration after outside air flows	Low	medium	medium

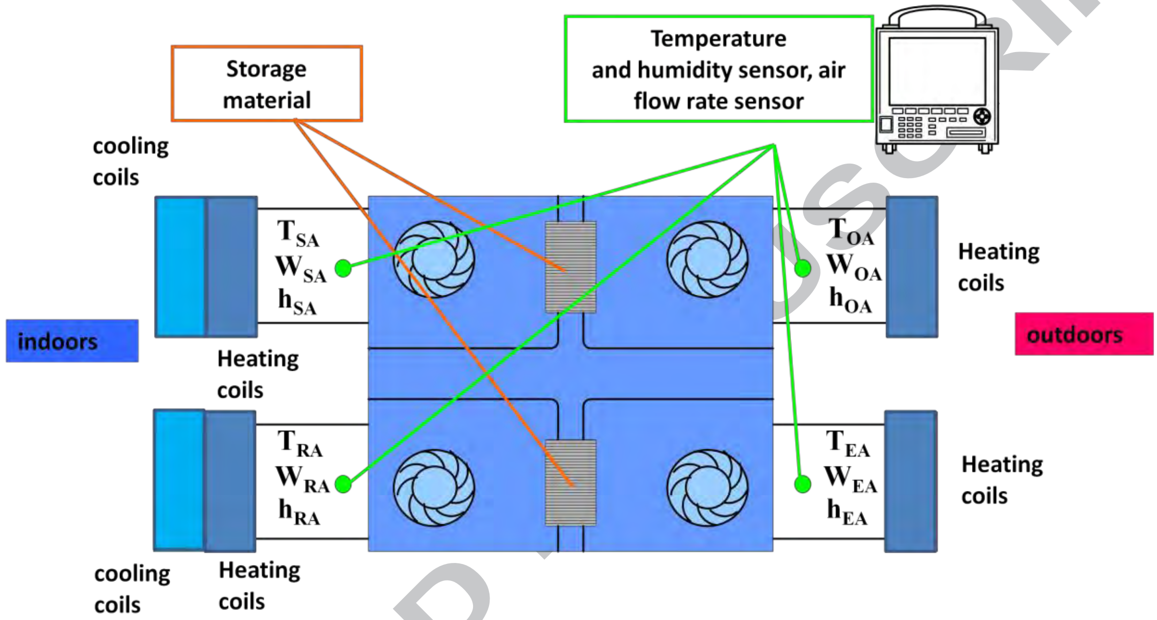


(a) recovery type

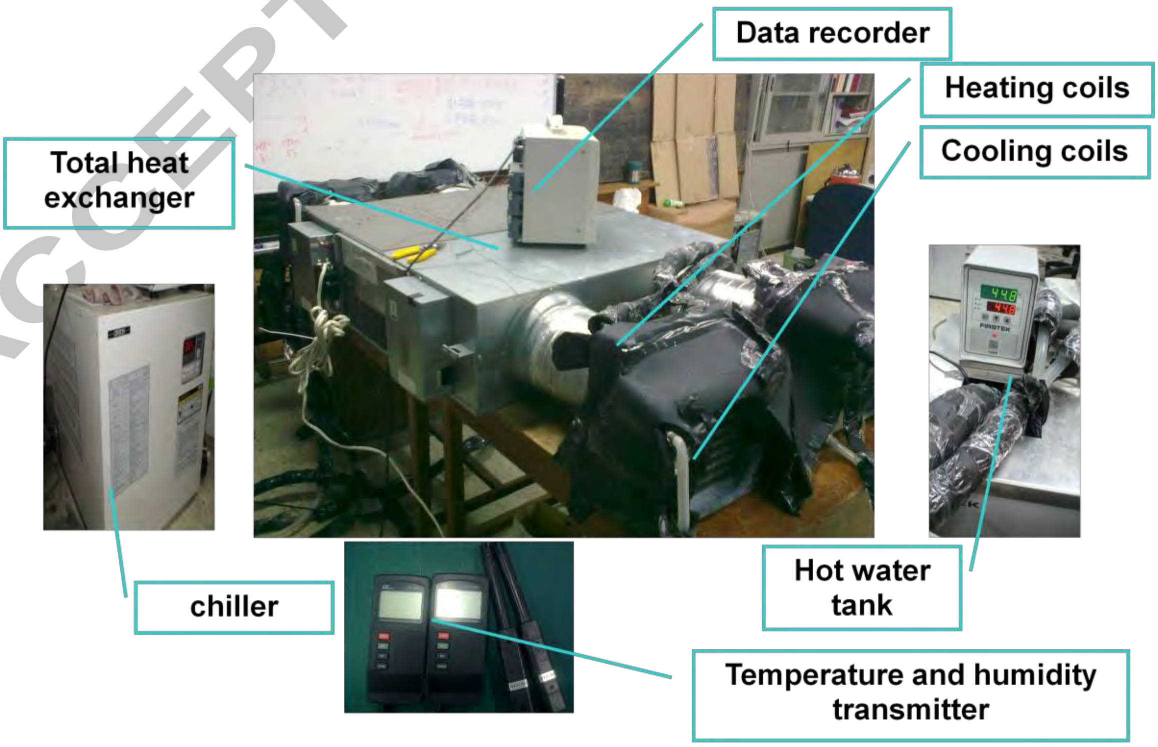


(b) regenerative type

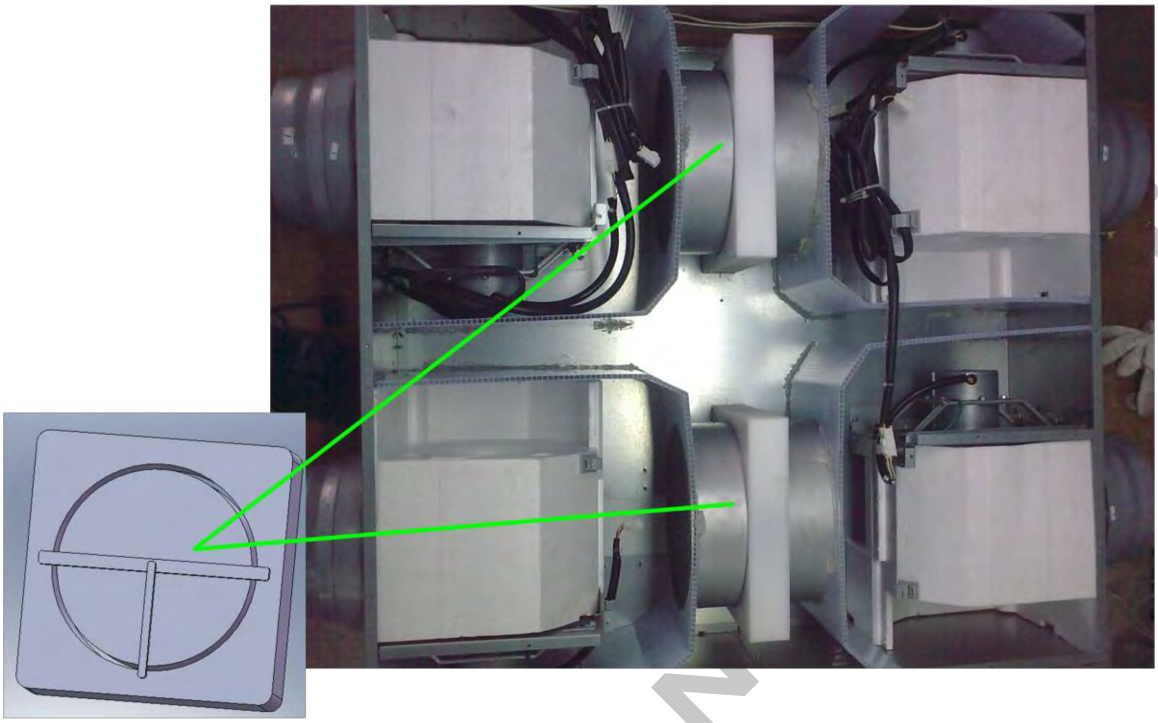
Figure 1. Schematic view of a periodic total heat exchanger: (a) recovery type and (b) regenerative type


Storage material
Temperature and humidity sensor, air flow rate sensor
cooling coils
T_SA W_SA h_SA
T_OA W_OA h_OA
Heating coils
indoors
outdoors
Heating coils
T_RA W_RA h_RA
T_EA W_EA h_EA
Heating coils
cooling coils
Heating coils

(a)


Data recorder
Heating coils
Cooling coils
Total heat exchanger
chiller
Hot water tank
Temperature and humidity transmitter

(b)



(c)

(d)

Figure 2. (a) Schematic figure of total heat exchanger with performance test and measurement points. (b) Photographic view of the experiment set-up. (c) Photographic view of the inside of the total heat exchanger.(d) Photographic view of fixed wheels of total heat exchanger.

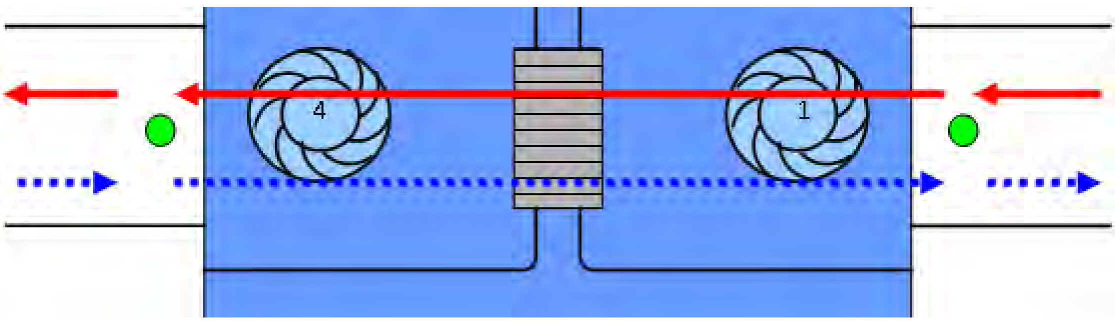
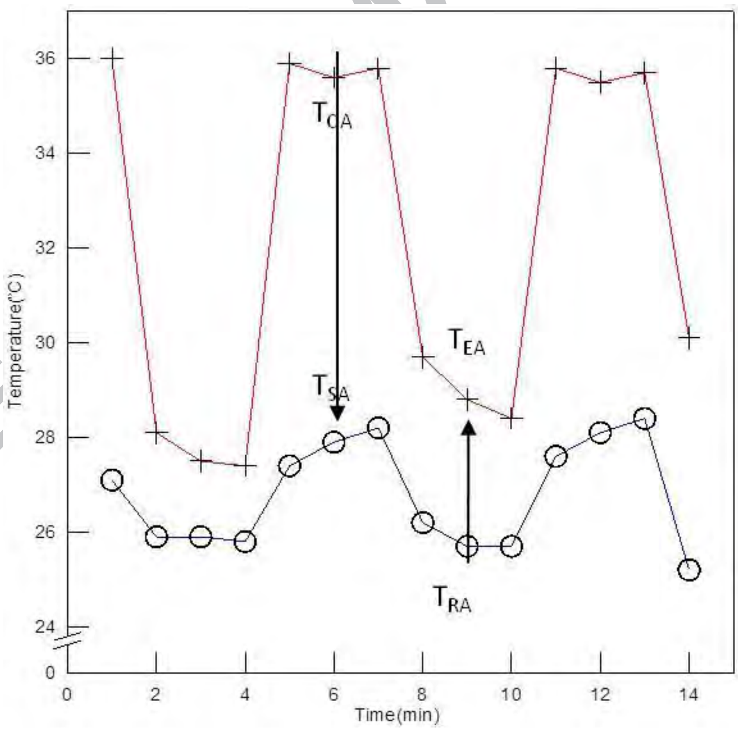
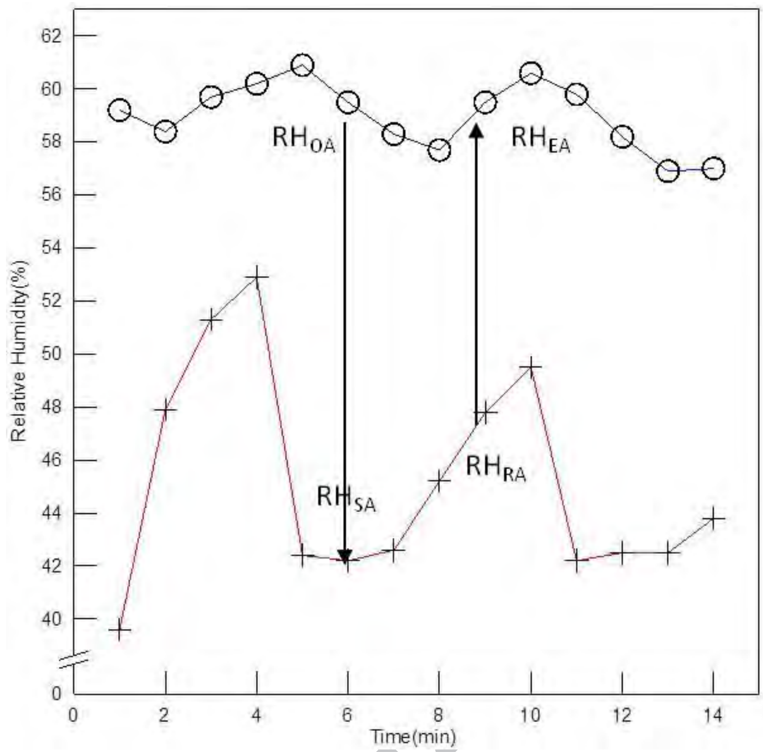


Figure 3. Schematic figure of the total heat exchanger in one flow passage



(a) temperature



(b) relative humidity

Figure 4. Performance of the periodic total heat exchanger for a 3-minute operating period: (a) variations in temperature at the measuring points; (b) variations in relative humidity at the measuring points.

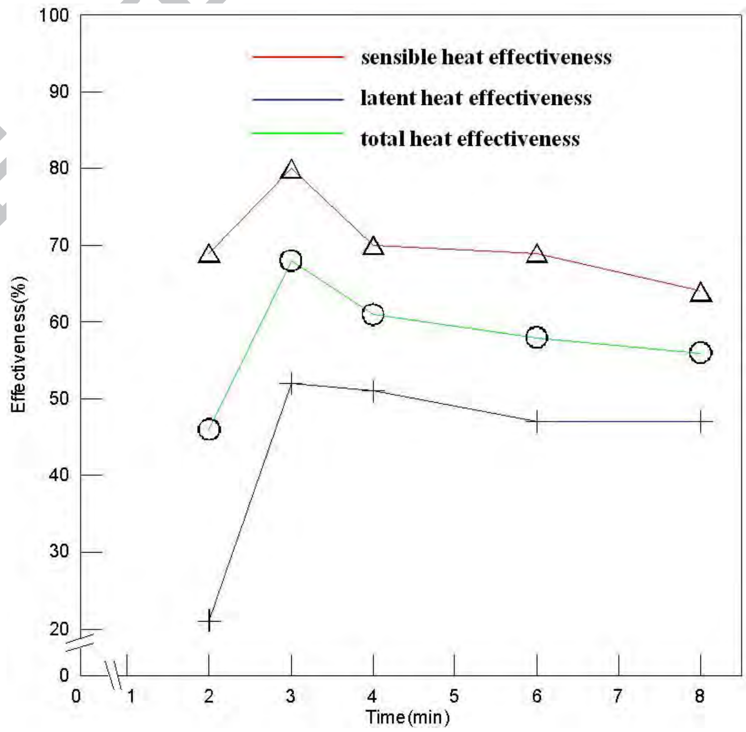
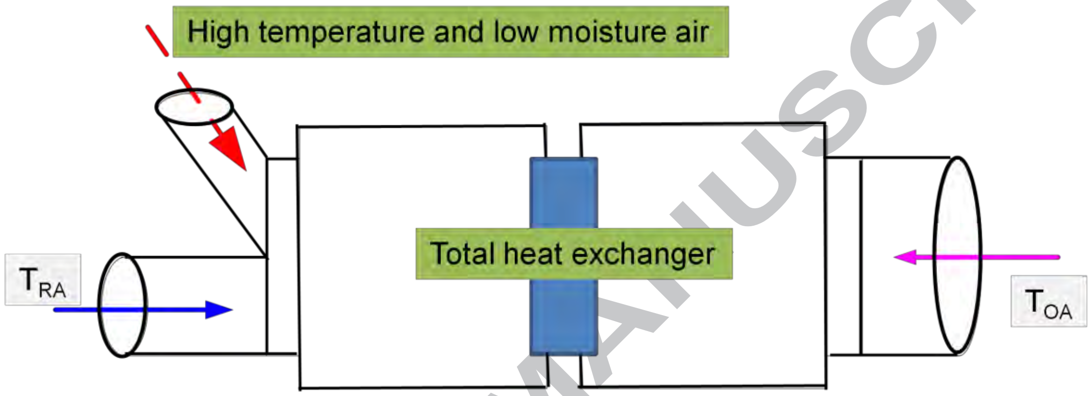
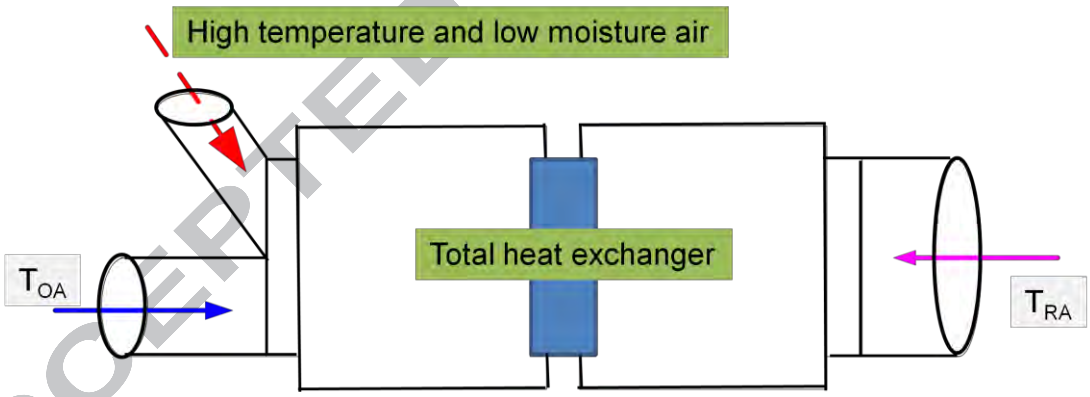


Figure 5. Performance of the periodic total heat exchanger for different operating periods



(a)



(b)

Figure 6. Schematic figure of adding high temperature and low moisture air for regeneration

1. This study investigates of regenerative total heat exchanger with periodic flow.
2. Effects of operating periods are studied.
3. Effectiveness of total heat exchanger is adopted as an important index.