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Experimental Study on a Process Design for Adsorption Desiccant Cooling Driven with a Low-Temperature Heat

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Abstract. Among the desiccant cooling process, 2-rotor process consisting of a honeycomb rotor dehumidifier and a sensible heat exchanger is the mainstream of the cooling processes which are practically applied to supermarket, hospital and so on. Most of them are driven with a higher regeneration temperature around 100–140°C obtained from gas-engine heat pump or micro gas turbine generator. However, dehumidifying performance of this typical configuration driven with a low temperature heat is not sufficient for cooling at higher ambient humidity. In this study, 4-rotor desiccant cooling process equipped with a double stage dehumidification was proposed and investigated experimentally. In this process, regeneration temperature around 70°C could produce a sufficient dehumidifying performance at high ambient humidity. Furthermore, the cascade use of hot water inside the cooling cycle was applied and confirmed somewhat lower cooling performance than that operated with parallel supply of hot water. Against this result, COP_r of the former was much higher than that of the latter. Effect of water spray evaporative cooling at the inlet of regeneration air stream on the process performance was also investigated. This evaporative cooling was expected to cause humidity increase in regeneration air reducing the dehumidifying performance of the honeycomb absorber, while the evaporative cooling plays an important role to produce a lower temperature in supply air. Experimental results showed that the amount of dehumidified water at the process without water spray evaporative cooler was actually larger than that of process with water spray evaporative cooler. This behavior was due to increase of humidity or relative humidity in the regeneration air as expected. However, temperature of supply air produced by the process with evaporator was rather lower than that of the other, resulting higher COP value. It was concluded that the evaporative cooler effectively worked at higher regeneration temperature and lower ambient humidity.

Keywords: desiccant cooling, dehumidification, adsorption, evaporative cooling

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1. Introduction

Kyoto Protocol was made to prevent the progress of global warming and we have been required to reduce the CO_2 emission to the 1990 level at least. But the amount of CO_2 emission into the atmosphere of Japan in 2000 became the maximum, which is considered to be a result of the increase of the operation time of air conditioners and heaters. However, people's request is still coexistence of economic growth and reduction of the energy consumption.

Considering these background, desiccant cooling process is one of the most important technologies to be developed from viewpoints of the global environment, energy sources and human health. Desiccant cooling process is an open heat driven cycle consisting of a combination of a dehumidifier, sensible heat exchanger and evaporative water spray cooler. Evaporative water spray cooler is occasionally equipped at the regeneration inlet, process outlet or both positions. Figure 1 shows a schematic diagram of experiment set-up of an adsorptive cooling system. Among the desiccant cooling cycle, adsorptive one can be operated with mild-temperature around 80°C obtained from lower level energy such as waste heat from industries or solar heat, and reducing the consumption of conventional energy. This implies that the desiccant cooling cycle may be useful in solving global problem such as disruption of the ozone layer and the greenhouse effect by its use as an alternative practical air conditioning process. However, 2-rotor desiccant cooling process driven with a low temperature heat cannot work well for the high humidity air since the increase rate of adsorption capacity of the honeycomb rotor is smaller than that of the ambient humidity. Furthermore, in the honeycomb adsorbent, temperature increase in dehumidified air due to released adsorption heat around the upper stream of the air results in smaller driving force for the dehumidification around the down stream of the air. After all, humidity and temperature of the air produced by the conventional 2-rotor desiccant cooling process simultaneously increase with increasing the inlet air humidity, resulting a poor cooling performance in the desiccant cycle.

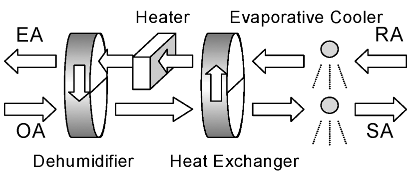

Figure 1. Schematic diagram of the 2-rotor adsorptive cooling system consisting of a honeycomb dehumidifier and sensible heat exchanger. (Evaporative coolers are option.)

Considering these behaviors, pre-dehumidification or pre-cooling step introduced into the position before the adsorption step of the dehumidifier must be effective to maintain a suitable cooling performance of the desiccant cycle even in the high ambient humidity. Therefore, 4-rotor desiccant cooling process equipped with a double stage dehumidification has been proposed and investigated experimentally. Some of those results are reported in this paper. Also, the evaporative cooling at the inlet of the return air stream can produce a lower temperature in supply air and which is often used in the desiccant cooling process. However, detailed discussion about the effect of the evaporative cooling on the overall cooling performance of the desiccant cycle has not been carried out in any articles in spite of the fact that a decrease of the dehumidifying performance due to humidity increase in regeneration air can be easily expected. Therefore, another purpose of this research is to clarify the effect of the evaporative cooling at various air conditions. Finally, newly-proposed 4-rotor desiccant cooling process should be accomplished more taking account of the effect of the evaporative cooling.

2. Double Stage Dehumidification

Low-temperature driven desiccant cooling process consisting of one dehumidifier and one sensible heat exchanger cannot produce a sufficient cooling performance in high humidity region as mentioned above. In this study, 4-rotor desiccant cooling process equipped with a double stage dehumidification was proposed and investigated experimentally.

2.1. Experiment Set-Up

Figure 2 shows a schematic diagram of the experiment set-up of the desiccant cooling process with a double stage dehumidification. It consists of two honeycomb

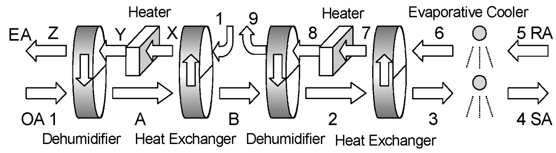

Figure 2. Schematic diagram of the experiment set-up of desiccant cooling process with a double stage dehumidification.

rotary dehumidifiers, two sensible heat exchangers, two heaters and two water flash evaporative coolers. This process is expected to produce a higher dehumidifying performance even in high ambient humidity.

2.2. *Definitions and Calculations*

The technical terms and parameters pertaining to the system performance used in this paper are defined and calculated as follows. Cooling effect is a difference in enthalpy between supply air and return air. It is the measure of cooling provided and is then calculated as

$$CE' = h_5 - h_4 \tag{1}$$

Thermal coefficient of performance (COP_r) is a ratio of the total cooling effect to heat supplied to regeneration air stream, and is calculated as

$$COP_r = \frac{(h_5 - h_4) \times \dot{m}_4}{(h_8 - h_7) \times \dot{m}_8 + (h_Y - h_X) \times \dot{m}_Y} \tag{2}$$

2.3. *Results and Discussion*

2.3.1. Cooling Performance and the Change of Air States in the Cooling Cycle. Figure 3 shows the change of air states in the desiccant cooling process with a double stage dehumidification at the following condition; ambient air condition = 32.4°C and 16.8 g/kg, regeneration temperature = 70°C. In this chart, solid line and dash line respectively indicate the change of air states in the first stage/second stage dehumidification. The first stage performs pre-drying of air. The dehumidified air (A) is cooled down with counter currently supplied ambient air. The pre-dried air (B), which temperature is nearly equal to ambient depending on the temperature efficiency of sensible heat exchanger, is input air for the following (second) stage. The second stage produces cool air for air conditioning. This process can maintain its dehumidification performance even with regeneration temperature 70°C in high ambient humidity. As can be seen in Fig. 3, humidity after second step dehumidifier is 7 g/kg. If the 2-rotor desiccant cooling process is operated at the same ambient air condition, dehumidifying/cooling performance becomes much lower than the process with a double stage dehumidification.

2.3.2. Cascade Use of Hot Water inside the Cooling Cycle. The desiccant cooling process with a double stage dehumidification has some demerits such as its enlarged size. However, by supplying the hot water discharged from the fin coil heater for room side dehumidifier (second stage) to the fin coil heater for ambient side dehumidifier (first stage), water temperature exhausted from this system must be near environment. This means that low-temperature heat around 60°C can be used efficiently in this cooling performance. Therefore, cooling performance of the 4-rotor cycle with a cascade use of hot water is investigated at the following section.

Figure 4 shows influence of the ambient humidity on the cooling effect (CE′) and thermal coefficient of

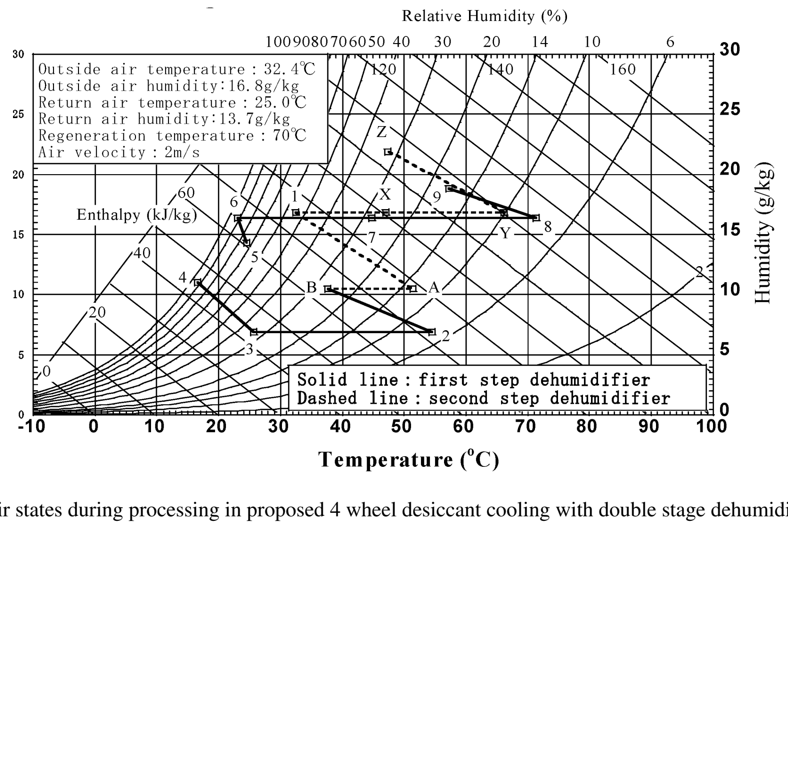

Figure 3. Changes of air states during processing in proposed 4 wheel desiccant cooling with double stage dehumidification.

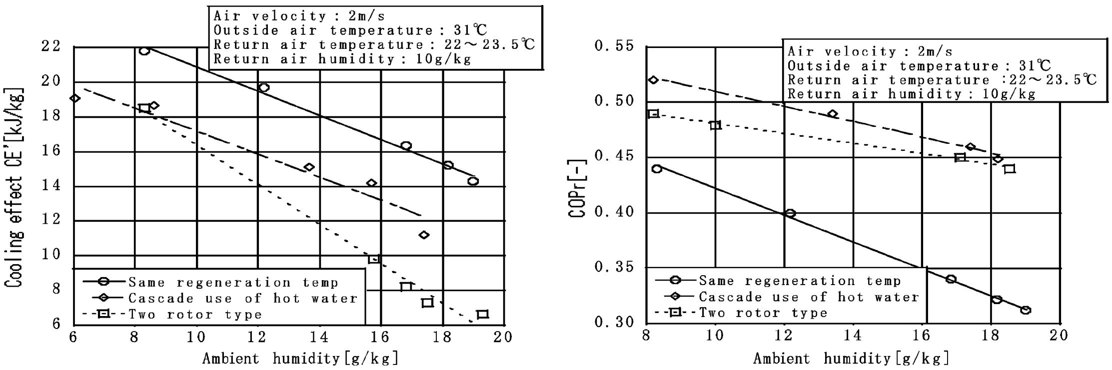

Figure 4. Influence of the ambient humidity on the cooling effect and COP_r produced by various type of the desiccant cycle. (OA and RA flow rates = 2 m/s, OA temperature = 31°C).

performance (COP_r) of the proposed cycle/hot water supply comparing the different configuration/heat supply at the following condition; ambient temperature = 31°C, return air condition = 22–23.5°C, and 10 g/kg, air velocity = 2m/s. The value of CE′ of the process with the internal heat cascading was lower than that of 4-rotor cycle with parallel hot water supply, but higher than that of conventional 2-rotor process. However, cascade use of hot water can be maintaining high performance in high ambient humidity. Thermal coefficient of a performance (COP_r) of the process with the same regeneration temperature using two heat sources is 0.3 to 0.4. However, the cascade use of hot water is 0.45 to 0.5 conventionally at the value of a 2-rotor desiccant cooling process. From this result, process performance of the cooling process with cascade use of hot water is somewhat lower than the same regeneration type. However, COP_r of the process with heat cascading is much higher than the other.

3. Effect of Evaporative Cooling at the Inlet of the Return Air Stream

An evaporative cooling at the inlet of the return air stream has been expected to decrease the dehumidifying performance due to humidity increase in regeneration air, while it plays an important role to produce lower temperature in supply air. In this section, influence of the evaporative cooler on the process performance at various operating condition is discussed.

3.1. Experimental Set-Up

Figure 5 shows a schematic diagram of the experimental set-up. It consists of a honeycomb rotary dehumidifier (adsorbent rotor is 0.32 m in diameter and 0.2 m in width) and a rotary sensible heat exchanger (rotor size is 0.32 m in diameter and 0.2 m in width). Water spray evaporative cooler at the inlet of regeneration air stream was controlled depending on the experimental condition. At the all experiments, both process and regeneration air velocity and both inlet air temperature were respectively kept at 2 m/s, 30°C.

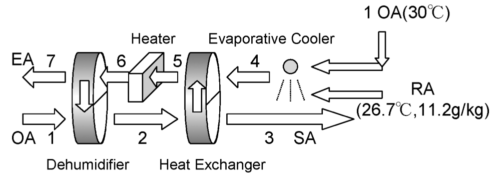

Figure 5. Schematic diagram of the experiment set-up for investigation of the effect of the evaporative cooling.

3.2. Definitions and Calculations

The technical terms and parameters pertaining to the system performance used in this paper are defined and calculated as follows. Cooling effect (CE) for this cycle is a difference in enthalpy between supply air and out air. It is different from Eq. (1) and calculated as

$$CE = h_{\mathrm{OA}} - h_{\mathrm{SA}} \tag{3}$$

Thermal coefficient of performance (COP_m) is also used as an evaluation factor, and which is the ratio of the total cooling effect to heat supplied to regeneration air stream, and is calculated as

$$COP_m = \frac{CE \times \dot{m}_{\mathrm{SA}}}{\text{Input of heat energy}} \tag{4}$$

where the amount of heat energy was calculated from the difference of temperature before and after the heater and mass flow rate of regeneration hot air.

3.3. Results and Discussion

All experiments mentioned in this section were obtained at constant rotation speeds of dehumidifier = 36 rph and the sensible heat exchanger = 16 rpm.

3.3.1. Changes of Air States in the Cooling Cycle. Figure 6 shows changes of air states during processing in the desiccant cycles with/without a water spray evaporative cooler at return air inlet. (Air flow rate = 2m/s, Regeneration air temperature = 70°C, OA/RA condition = 15 g/kg and 30°C; solid/dashed line = with/without evaporative cooling) The amount of dehumidified water of the cycle without water spray evaporative cooler was larger than that of cycle with water spray evaporative cooler. This is due to increase of humidity or relative humidity in the regeneration air 6 as expected before. However, temperature of air 3 of the cycle with evaporative cooler was rather lower than that of the other. This behavior was more realized at higher temperature or lower humidity in the ambient air. On the other hand, a drop in dehumidifying performance due to humidity increase in the regeneration air was compensated by the larger enthalpy reduction in the sensible heat exchanger. In this condition, higher heat exchange efficiency of heat exchanger is rather important to achieve higher process performance. However, it can be expected that this behavior depends on the experimental condition.

3.3.2. Cooling Effect and COP_m. Figure 7 shows influences of the ambient humidity and water spray evaporative cooling at the inlet of the return air stream on the value of CE and COP_m. Ambient humidity changed between 10 and 20 g/kg. The value of CE of the cycle with water spray evaporative cooler was higher than that of the cycle with water spray evaporative cooler at any regeneration temperature in the low ambient humidity region. Water spray evaporative cooler equipped at the inlet of the return air brought the regeneration air 6 humidity increase as described in Fig. 6. However, supply air temperature and its enthalpy became lower. At low regeneration temperature, the value of CE of the cycle with the evaporative cooler becomes smaller as the ambient humidity increases. This behavior can be interpreted as follows; higher air humidity at lower regeneration temperature gives higher relative humidity in the regeneration air resulting smaller effective adsorption capacity in the temperature swing honeycomb dehumidifier. Also, equilibrium amount of adsorbed water at higher relative humidity is expected to be almost constant although which amount is strongly depending on the shape of the adsorption isotherm. As a result, evaporative cooler at the return air inlet becomes more effective at higher regeneration temperature or lower humidity region since larger adsorption capacity is still kept at such air condition. On the other hand, evaporative cooler does not work effectively at the higher humidity because evaporation of water is

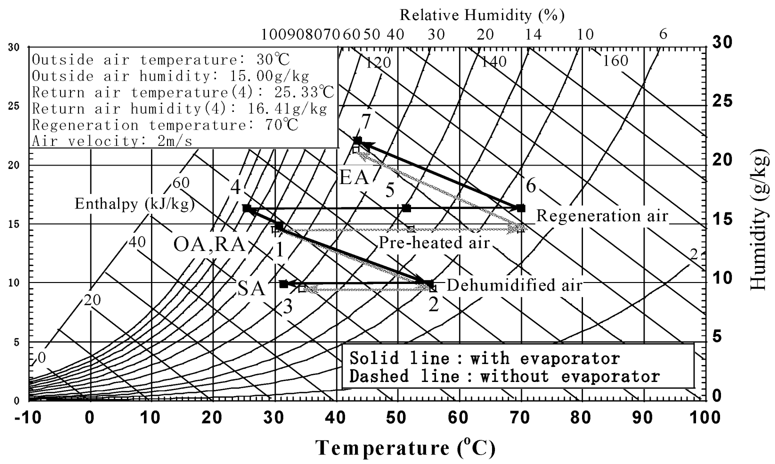

Figure 6. Comparison of air states during processing in the desiccant cycle with/without a water spray evaporator at return air inlet. (Air flow rate = 2 m/s, Regeneration air temperature = 70°C, OA/RA condition = 15 g/kg and 30°C).

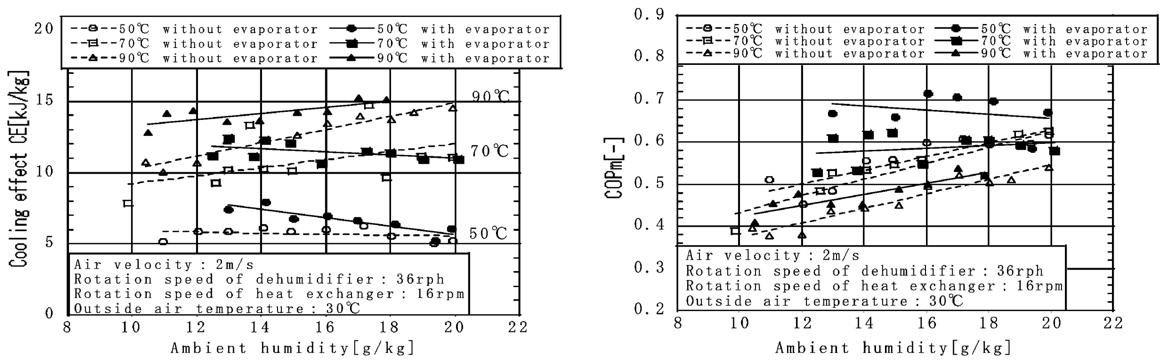

Figure 7. Influences of the ambient humidity and introduction of water spray evaporative cooling into the inlet of the return air stream on the value of CE and COP_m. (OA/RA flow rate = 2 m/s, OA/RA temperature = 30°C).

prevented by the smaller difference in relative humidity between ambient air and its saturation.

The value of COP_m of the cooling cycle with the evaporative cooler is always larger than that of cycle without evaporative cooler although it can be expected that lower temperature return air produced by the evaporative cooling requires the much amount of energy input to heat up the regeneration air to the subject temperature. This means that produced cooling effect by the additional evaporative cooler is larger than the increase of energy input for heating of regeneration air. However, this effect is disappeared at the higher ambient humidity due to decrease of the cooling effect as mentioned the above.

4. Conclusions

Low-temperature driven desiccant cooling process consisting of one dehumidifier and one sensible heat exchanger cannot produce a sufficient cooling performance in high humidity region. In this study, 4-rotor desiccant cooling process equipped with a double stage dehumidification was proposed and investigated experimentally. In this process, regeneration temperature around 70°C could produce a sufficient dehumidifying performance at high ambient humidity. Furthermore, the cascade use of hot water inside the cooling cycle was applied and confirmed somewhat lower cooling performance than that operated with parallel supply of hot water. Against this result, COP_r of the former was much higher than that of the latter.

Sensible/latent heat transfers in a 2-rotor desiccant cooling process have been experimentally discussed to clarify the effect of water spray evaporative cooler at the inlet of return air stream on the process performance. It was found that the cooling performance was accelerated by the additional evaporative cooler since the enthalpy reduction in the sensible heat exchanger was enhanced by a larger temperature difference between both air streams. This behavior was more realized at higher temperature or lower humidity in the ambient air. On the other hand, a drop in dehumidifying performance due to humidity increase in the regeneration air was compensated by the larger enthalpy reduction in the sensible heat exchanger.

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