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An Energy Flow Analysis of a Solar Desiccant Cooling Equipped with a Honeycomb Adsorber

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Abstract. A solar assisted adsorptive desiccant cooling process has been experimentally tested. This study aimed to investigate an actual performance of the cooling process with a typical configuration (one desiccant wheel, one sensible heat exchanger and two water spray evaporative coolers) driven with solar heated water. The performance was examined in terms of COP_s (thermal coefficient of performance based on solar irradiation), Temperature decrease (temperature difference between outside air and supply air) and cooling effect CE (=enthalpy difference between outside air and supply air) at various operating conditions of regeneration temperature, air condition of ambient air and solar irradiation. Stable irradiation at a clear sky gave the desiccant cooling process a higher dehumidifying performance. Temperature decrease and COP_s in this condition were 10°C and 0.41, respectively. Unstable irradiation at somewhat cloudy made the system lower dehumidifying performance. However, decrease of the cooling performance was comparably small due to buffering effect by thermal storage in the circulating water. At higher humidity condition, the amount of dehumidified water became higher than that dehumidified at low humidity condition due to increasing relative humidity of outside air or effective adsorption capacity of the desiccant rotor. However, resulting temperature decrease in this condition was just 6.9°C. This behavior is mainly due to humidity increase and simultaneous temperature rise in the dehumidified air. In this situation, an effective evaporation in the following water spray evaporative cooler did not occur.

Keywords: desiccant cooling, dehumidification, adsorbent rotor, solar heat, honeycomb adsorbent

1. Introduction

Desiccant cooling processes can be driven with a low temperature heat around 60°C obtained from lower level energy such as waste heat or solar heat instead of electricity. It usually consists of a dehumidifier, sensible heat exchanger and evaporative water spray coolers. It is a promising technology that can be developed as a candidate for non-fron and less electricity cooling from viewpoints of global environment and energy sources. Solar assisted cooling (Waugaman et al., 1993; Halliday et al., 2002) is particularly attractive because it is clean, renewable and has a low cost, and the cooling demand is in phase with availability of solar radiation. After our preparatory investigation using 2 kW system (Kuma et al., 1998), field-test of a 20 kW apparatus

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for solar assisted adsorption desiccant air conditioning has been carried out at Kumamoto University in Japan. In the system, about 4000 m^3/hr of fresh air was dried in a thermal swing honeycomb rotor dehumidifier and cooled by a regenerative heat exchanger and an evaporative cooler. The same amount of return air, which was derived from outside of the test room, was used as a cooling medium in the regenerative heat exchanger, heated in a finned coil heater by hot water circulating through solar heat collectors (48 m^2) and discarded through the honeycomb rotor dehumidifier after desorbing the moisture adsorbed from the supplied air stream. The performance was examined in terms of CE (cooling effect), temperature decrease and COP_s (thermal coefficient of performance) at various operating conditions of regeneration air temperature, temperature/humidity of ambient air etc. There is urgent need for the development of the process considering energy consumption in Asia that is getting larger economically.

2. Experimental

2.1. *Experimental Set-Up of Solar Assisted Desiccant Evaporative Cooling*

The schematic diagram of a test unit of the desiccant cooling process is shown in Fig. 1. The main body of this system, desiccant cooling unit consisted of two blowers, a rotary dehumidifier equipped with a honeycomb adsorbent wheel, a fin coil heater, a rotary heat exchanger and two evaporative coolers. Here, depth of the desiccant wheel was 0.2 m. The hot-water supply unit consisted of twenty-four modules of solar collectors, two water storages as shown in Fig. 1. The total aperture area of the solar collectors was 48 m^2 and the all were trained to the south with an angle of 30 degrees elevation. Approximately 0.5 m^3 of water was charged

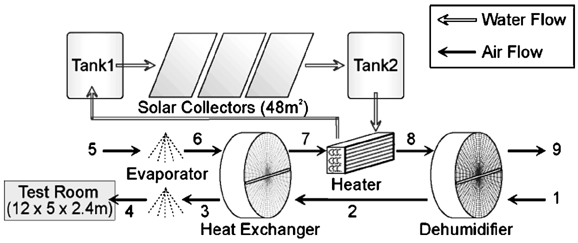

Figure 1. Schematic diagram of the solar assisted desiccant cooling process.

in the heat supply unit as a heat transfer medium. Hot water was circulated through tank 1, solar collectors, tank 2, and fin coil heater in the desiccant cooling process.

Rotation speeds of the dehumidifier and heat exchanger were setup to 25 and 450 rph, respectively. The flow rate of supply air and return air was kept at 1.1–1.2 m^3/s in the whole of experiments reported in this paper and it is corresponding to 2 m/s of the superficial air velocity in front of the adsorbent wheel. Water in the heat supply unit was circulated with a flow rate of 0.025 m^3/min.

All experiments were carried out during continuous nine hours, from 9:00 to 18:00. All of heat supplied to the cooling process was obtained from solar collectors. Considering a detailed discussion, temperature and humidity of air were measured at the positions numbered 1–9 as indicated in Fig. 1.

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 (CE) for this cycle (shown in Fig. 1) is a difference in enthalpy between supply air 4 and ambient air 1. It is the measure of cooling provided and is then calculated as

$$\mathrm{CE} = h_1 - h_4 \tag{1}$$

where h_4 and h_1 are specific enthalpy of moist air for points 4 and 1 respectively.

Thermal coefficient of performance (COP_s) is a ratio of the total cooling power to solar irradiation, and is calculated as

$$\mathrm{COP}_s = \frac{(h_1 - h_4) \times \dot{m}_4}{J \times S} \tag{2}$$

where J and S are solar irradiation at the surface of the collectors and total aperture area of the solar collectors and m_4 is mass flow rate of supply air 4. Here, COP_s does not take account of the consumption of electricity for driving blowers, desiccant wheel, heat exchange wheel and water pumps since amount of consumed electricity is much less comparing with thermal energy supplied to the cooling process.

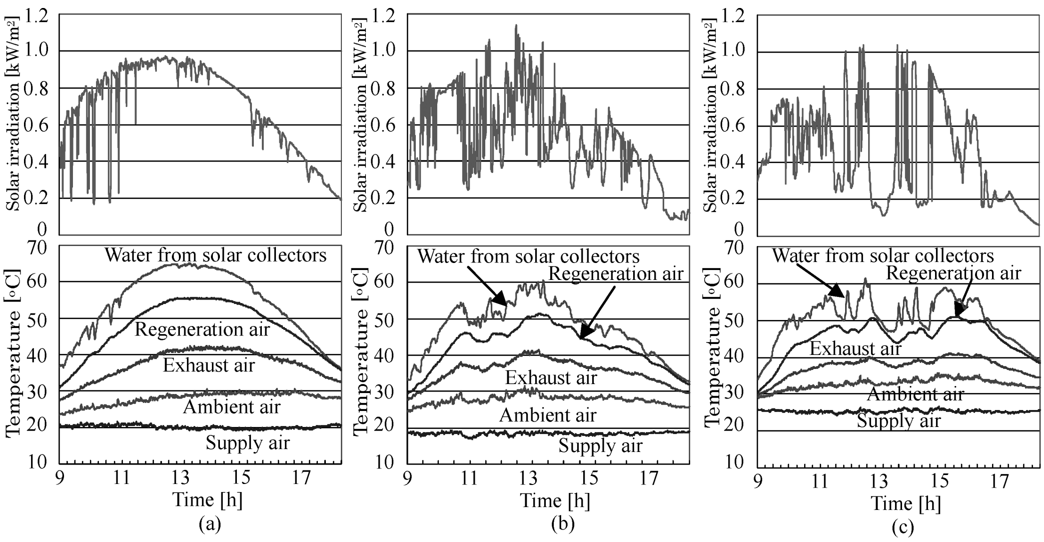

Figure 2. Time variations of solar irradiation, water and air temperatures around the cooling process at (a) stable irradiation/ambient humidity = 9.53g/kg, (b) unstable irradiation/ambient humidity = 9.03 g/kg and (c) unstable irradiation/ambient humidity = 17.7 g/kg.

3. Results and Discussion

3.1. *Time Variations of Solar Irradiation and Temperatures around the Cooling Process*

Figure 2 shows time variations of solar irradiation, water and air temperatures at various ambient conditions. In this section, influences of weather condition and ambient humidity on the cooling behavior are mainly discussed.

3.1.1. Stable Solar Irradiation and Low Humidity. In Fig. 2(a), solar irradiation was stable in daytime. Ambient temperature changed between 25.0 and 29.7°C and averaged ambient air humidity H_1 was 9.53 g/kg. The maximum irradiation 0.97 kW/m^2 was observed at midday. Maximum water temperature supplied from solar collectors 66°C appeared at 13:00 and then regeneration air temperature was 61°C. Supply air temperature changed between 19.7 and 21.1°C during the operating time. At the beginning of the measurement, from 9:00 to 11:00, supply air temperature was somewhat high due to low regeneration temperature. In this time period, solar heat collected at the collectors was consumed to heat both the regeneration air and the circulating water. In the evening, solar irradiation at this period was already quite low as compared with that at midday although the ambient temperature was still high even in the late afternoon toward evening. Therefore, hot water temperature gained at the solar collectors and thus regeneration air temperature decreased as the solar irradiation decreased. However, regeneration air temperature was still kept at 45°C due to buffering effect by thermal storage in circulating water and supply air temperature could be kept at 20°C. Consequently, the thermal storage in the circulating water played an important role to prevent the drastic decrease in the dehumidifying performance at evening time although the effect of heat storage in the test room should be also considered.

3.1.2. Unstable Solar Irradiation and Low Humidity. Solar irradiation sometimes fluctuates dramatically even in a sunny day due to some clouds. Figure 2(b) and (c) show time variations of water and air temperatures around the field test at such a cloudy day. In Fig. 2(b), ambient air temperature changed from 26.5 to 30.3°C and the averaged ambient humidity was 9.03 g/kg. Although solar irradiation was fluctuated between 0.3 and 1.1 kW/m^2 around midday, water temperature was kept constant around 50°C and supply air temperature could be kept at 20°C or below. This behavior is also due to the thermal storage in circulating water. Actually, solar irradiation in the morning was almost stable as indicated in Fig. 2(b) and water temperature circulated in the heat supply system became high. It can produce a suitable buffering effect for the fluctuation of solar irradiation.

3.1.3. Unstable Solar Irradiation and High Humidity. Figure 2(c) shows a result obtained at a high humidity condition. Changes of the circulating water temperature and regeneration air temperature along the solar irradiation had the same manner mentioned in previous sections. However, supply air temperature increased to near 25°C (temperature decrease was just 7°C), against the supply air temperature under 20°C (temperature decrease was over 10°C) obtained at lower humidity conditions. At higher ambient humidity, the adsorption capacity of the adsorbent rotor becomes relatively small and temperature increase in the adsorbent due to heat of adsorption accelerates the decrease of the adsorption capacity. Also, high humidity air released from the heat exchanger does not give a sufficient driving force in the following water spray evaporator. Consequently, supply air temperature and humidity increase in such a high humidity ambient condition. These results show that the performance of the low temperature driven desiccant process strongly depends on ambient humidity. Especially, its cooling performance becomes lower as the ambient humidity increases. At least, stable solar irradiation or higher regeneration temperature is needed to produce a better cooling performance at higher ambient humidity.

3.2. *Effect of Amount of Solar Irradiation*

In this section, the process performance at maximum solar irradiation (12:00–15:00) is mainly discussed.

Influence of the amount of solar irradiation on the cooling effect, regeneration air temperature, COP_s and heat collecting efficiency were summarized in Figs. 3 and 4. At lower solar irradiation, regeneration air temperature could not reach 40°C and suitable cooling performance was not appeared even in lower ambient humidity. This figure implies that the regeneration temperature requested for this kind of adsorbent to produce an effective cooling performance should be higher than 50°C. In other words, this desiccant cooling system can be driven with a low regeneration temperature around 50°C. In Fig. 4, although heat collecting efficiency kept at 0.5 (water temperature gained at the solar collectors varies in proportional to solar irradiation), values of COP_s tend to decrease along with increasing solar irradiation and which is independent of ambient humidity. This behavior indicates the increasing rate of cooling power is less than that of solar irradiation.

Figure 5 shows the effect of solar irradiation on the temperatures and humidities of air in the cooling process. Regeneration air temperature increased along with increasing solar irradiation resulting low humidity in dehumidified air. However, temperature of dehumidified air also increased along with increasing solar irradiation. It is considered that increases of heat of adsorption and heat transfer from the regeneration zone to adsorption zone make the dehumidified air temperature high. As a result, air temperature at the outlet of heat exchanger or water spray evaporator becomes higher.

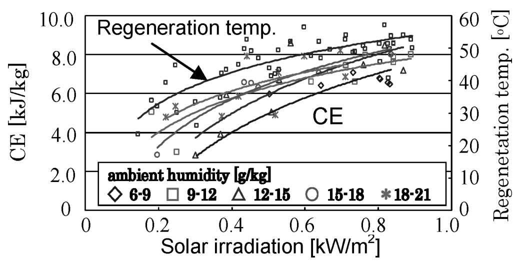

Figure 3. Influence of solar irradiation on the cooling effect and regeneration air temperature.

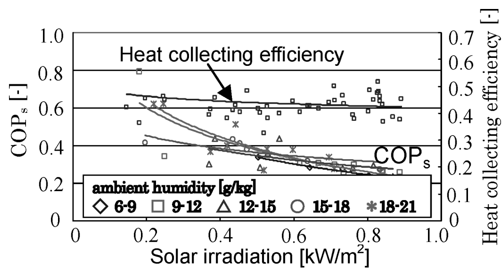

Figure 4. Influence of solar irradiation on COPs and heat collecting efficiency of the Solar collector.

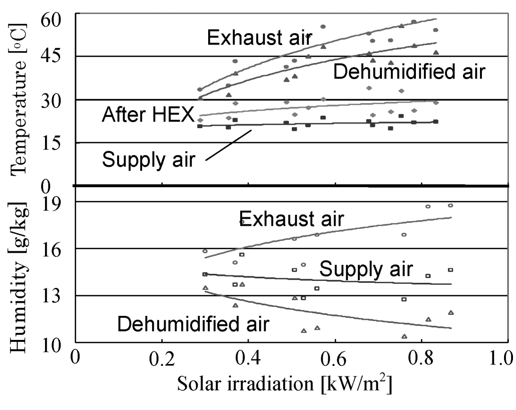

Figure 5. Influence of solar irradiation on temperature and humidity in the cooling process. (ambient humidity = 12–15g/kg).

Therefore, the increasing rate of cooling power is less than that of solar irradiation.

3.3. *Effect of Ambient Humidity*

The cooling performance of this open desiccant cycle strongly depended on ambient air humidity (Kodama et al., 2003). Figure 6 shows influences of ambient air humidity and regeneration air temperature on the dehumidifying performance. Amount of adsorbed water increased along with increasing ambient humidity due to increase of the effective adsorption capacity. This behavior was further accelerated by higher regeneration temperature. However, as can be seen in Fig. 7, temperature difference T_1–T_4 decreased along with increase of ambient humidity and it is independent of regeneration air temperatures. This result also shows that cooling performance becomes lower along with increasing ambient humidity due to temperature increase in the cooling process. Finally, high humidity air can not produce a good evaporation of water and low temperature air in the evaporative cooling process.

Figure 8 shows the effect of the amount of dehumidified water on temperature rise (T_2–T_1) at dehumidified process. Dehumidified air temperature dramatically rises along with the increase of amount of dehumidified water at lower regeneration air temperature. However, this behavior seemed to be disappeared at higher regeneration air temperature (T_8 > 50°C). This figure indicates that the temperature rise in the dehumidified air at the lower regeneration temperature is mainly due to heat of adsorption and the effect of sensible heat transfer in the adsorbent rotor becomes larger when the regeneration temperature is high.

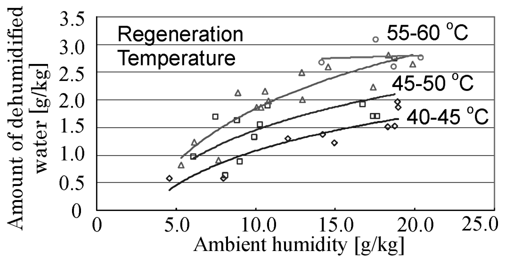

Figure 6. Influence of ambient humidity on amount of dehumidified water.

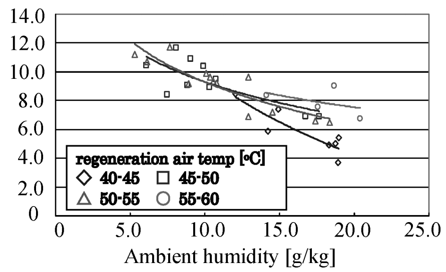

Figure 7. Effect of ambient humidity on temperature difference T_1–T_4.

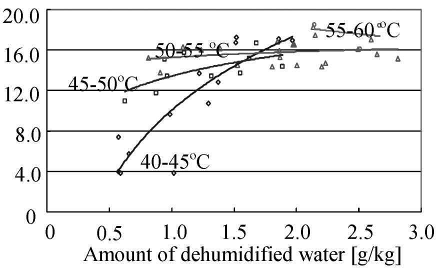

Figure 8. Effect of amount of dehumidified water on temperature rise T_2–T_1.

4. Conclusions

Performance of a solar assisted adsorptive desiccant cooling was investigated from a viewpoint of air temperature, cooling effect and COP_s. At stable solar irradiation, supply air temperature was kept at temperature below 20°C during daytime due to the buffering effect by thermal storage in water circulating in the heat supply system. The same effect was seen in unstable condition and fluctuation of the cooling performance could be prevented. This thermal storage also delays the temperature increase in supply air at late afternoon. However, supply air temperature was increased as the ambient air humidity increased. It was also found that stable solar irradiation (over 0.6 kW/m^2) and high regeneration temperature (over 50°C) is required to produce sufficient cool air.

Effect of the amount of solar irradiation on the process performance was also investigated. The COP_s value decreases with increasing regeneration temperature. It implies cooling performance was not proportional to solar irradiation and the increasing rate of cooling power is less than that of solar irradiation. As the solar irradiation increased, temperature of dehumidified air increased due to increases of heat of adsorption and heat transferred from the regeneration zone to adsorption zone, resulting higher air temperature at the outlet of heat exchanger or water spray evaporator.

It was also found that ambient humidity seriously effects on the cooling performance at lower regeneration temperature. Although the amount of dehumidified water was actually increased with increasing the ambient humidity, it was not proportional to the ambient humidity due to adsorption property (isotherm) of the honeycomb adsorbent. In other words, relative adsorption capacity of the adsorbent rotor becomes small at higher ambient humidity and temperature increase in the adsorbent due to heat of adsorption accelerates the decrease of the adsorption capacity. Also, high humidity air released from the heat exchanger does not give a sufficient driving force in the following water spray evaporator. As a result, simultaneous increases of temperature and humidity cause in supply air. Therefore, additional pre-cooling or pre-dehumidification introduced before the adsorption step must be effective to achieve a sufficient cooling performance even at higher ambient humidity.

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Nomenclature

- H Humidity contained in air (g/kg)
- h Enthalpy of air (kJ/kg)
- J Solar radiation (kW/m^2)
- m Dry air flow rate (kg/s)
- S Total aperture area of solar collectors (m^2)
- T Temperature (°C)

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