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Performance of a Multipass Honeycomb Adsorber Regenerated by a Direct Hot Water Heating

AKIO KODAMA*
Division of Innovative Technology and Science, Graduate School of Natural Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan
kodama@t.kanazawa-u.ac.jp

NAOKI WATANABE, TSUTOMU HIROSE AND MOTONOBU GOTO
Department of Applied Chemistry and Biochemistry, Kumamoto University, Kumamoto 860-8555, Japan

HIROSHI OKANO
Seibu Giken Co., Ltd., Koga, Fukuoka 811-3134, Japan

Abstract. A multi-pass honeycomb rotary adsorber has been proposed to achieve a low temperature heat driven desiccant cooling process. This multi-pass honeycomb rotary adsorber has a sandwich arrangement of honeycomb shaped adsorbent blocks and aluminum passages. In the regeneration step, hot water flows in the passages heating the honeycomb adsorbent. Simultaneously, outside air is co-currently supplied to the adsorbent layer to discharge the desorbed water vapor. On the other hand, adsorption heat caused in the adsorption step can be removed by cool air which is counter-currently passing through inside of the passages to keep the sufficient adsorption capacity/rate. The vaporization heat of water remaining in the passages also accelerates the cooling of the adsorbent rotor. Dehumidifying performance of the above mentioned adsorber has been investigated under various operating conditions, which are air velocity of each sector, temperature of hot water and so on. It was confirmed that the adsorber could be regenerated by direct hot water heating and removal of adsorption heat generated in the adsorption step achieved the semi-isothermal dehumidification. It was also found that lower temperature heat around 50°C was still effective in regeneration of the adsorbent rotor although the same temperature air was needed to discharge the desorbed water vapor. At the moment, detailed investigations including the influence of heat transfer between honeycomb rotor and aluminum passage are being carried out to improve the dehumidifying performance.

Keywords: desiccant cooling, dehumidification, adsorption, heat of adsorption

1. Introduction

Desiccant cooling process is particularly attractive because there are abundant resources of low temperature waste heat, which is discharged from distributed power generation and various cogenerations. Especially a desiccant dehumidification system using a honeycomb adsorbent rotor can supply cooling air with mild-temperature waste heat around 80°C. Popularization of this process accelerates the application of solar heat and industrial waste heat and, as a result, electricity consumption and carbon-dioxide emission can be cut down. This system is ambient air introduction/humidity conditioning system. If it is located in such place requiring large amount of ventilation, for example school, laboratory and factory, energy consumption will be greatly decreased.

Widespread use of PEFC (Polymer Electrolyte Fuel Cell) is anticipated in the governmental energy policy of Japan in future and the associated technique of

*To whom correspondence should be addressed.

high efficiency energy utilization with waste heat is required to be explored. Actually, desiccant cooling system using a gaseous waste heat discharged from micro gas turbine/gas engine generator has been already commercialized and a sufficient dehumidifying performance has been achieved with those high temperature waste heats. However, such high temperature can not be expected in the waste heat from PEFC because its operation temperature is less than 100°C. Moreover, water cooling is adopted in PEFC since the heat exchanger in such small generators should be highly efficient and compact. Therefore, waste heat is converted to hot water (secondary cooling water) around 50–60°C, slightly higher than ambient air temperature. Although adsorbents in the conventional dehumidifier are ordinary regenerated by hot air supplied from an auxiliary heater, a direct hot water heating/regeneration attempted here becomes an effective regeneration way in using such a low temperature heat considering heat losses at the heating apparatus. Furthermore, the temperature rise of adsorbent caused by adsorption heat influences negatively on adsorption equilibrium resulting low dehumidifying performance and this behavior is observed in adiabatic adsorption process. Because this adverse affect accelerates with decreasing regeneration temperature, the adsorption is required to proceed in isothermal situation by removal of adsorption heat through heat exchange. In this work, a multi-pass honeycomb rotary dehumidifier was developed to remove adsorption heat and cool adsorbent in adsorption step. Operation parameters are evaluated in terms of their influence on the dehumidifying performance (Kodama et al., 2002).

In terms of the adsorption of water vapor into honeycomb adsorber, adsorption heat is as much as the evaporation heat of water and the amount adsorbed is often uniquely related to relative humidity. The change of air state in dehumidification process is indicated in a humidity chart. Figure 1 shows a comparison of the change of air state in the adiabatic process with the isothermal one in an ideal dehumidifier with negligible mass transfer resistance. Since the relative humidity of dehumidified air cannot be lower than that of the regeneration hot air, the lowest humidity of dehumidified air is given by point P in the adiabatic adsorption and point P^* in the isothermal adsorption in Fig. 1 (Kodama et al., 1995, 2001, 2003). When the ambient air shown by point F (30°C, 20 g/kg) is dehumidified with regeneration air of 50°C in the isothermal adsorption, the humidity of air obtained is shown by point $P2^*$ which

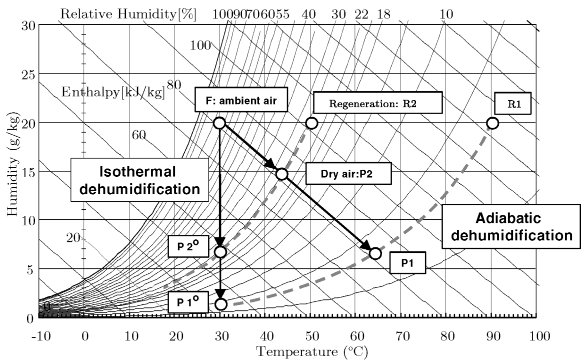

Figure 1. The change of air state in an ideal dehumidifier.

is comparable air dehumidified with regeneration air of 90°C in the adiabatic adsorption. Thus the isothermal adsorption is very important.

2. Experimental

2.1. Multi-Pass Honeycomb Rotary Adsorber

A schematic diagram of the multi-pass honeycomb rotary adsorber is shown in Fig. 2. The multi-pass honeycomb rotary adsorber is 0.3 m in diameter and 0.2 m in height. Area ratio (adsorption zone/desorption zone) is 1:1. The area of honeycomb adsorbent is 60% for sectional area of this rotor.

This adsorber has sandwich structure of alternate arrangement of honeycomb zeolite blocks and passages made of aluminum. In desorption side, in the regeneration step, hot water flows in passages for heating the honeycomb adsorber. Simultaneously, outside air is co-currently supplied to the adsorbent layer for discharging the desorbed water vapor. On the other hand, in the adsorption step, adsorption heat generated can be removed by passing air through the passages, increasing the adsorption capacity/rate. The evaporation of water remaining in the passages also accelerates the cooling of the adsorbent rotor.

A schematic diagram of a rotary dehumidifier with a multi-pass honeycomb adsorber is shown in Fig. 3. In this process, the direction of feed air stream is counter-current flow for that of regeneration air, cooling air and hot water.

Adsorption isotherm of the honeycomb adsorbent used in this study is shown in Fig. 4, which was measured at 25–60°C (298–333 K). In this temperature region, the adsorption isotherm is almost independent of

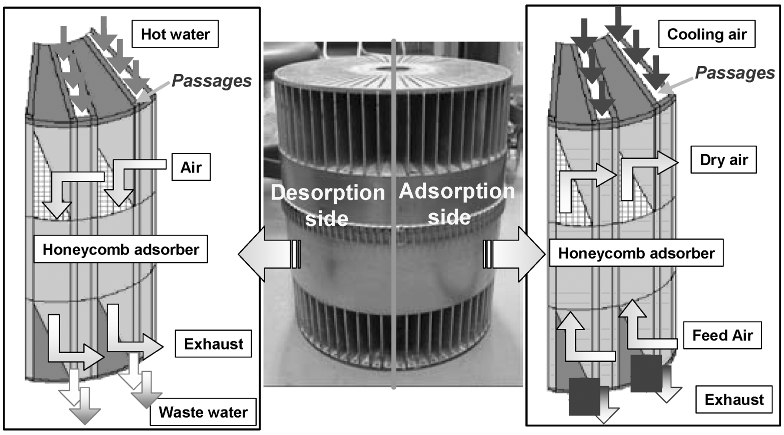

Figure 2. Schematic diagram of a multi-pass honeycomb rotary adsorber regenerated by a direct hot water heating.

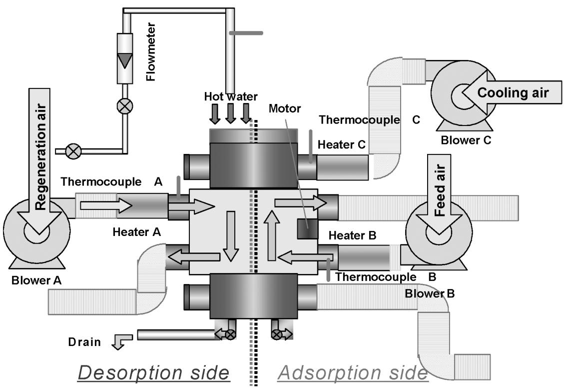

Figure 3. Schematic diagram of process configuration of the multi-pass honeycomb rotary dehumidifier.

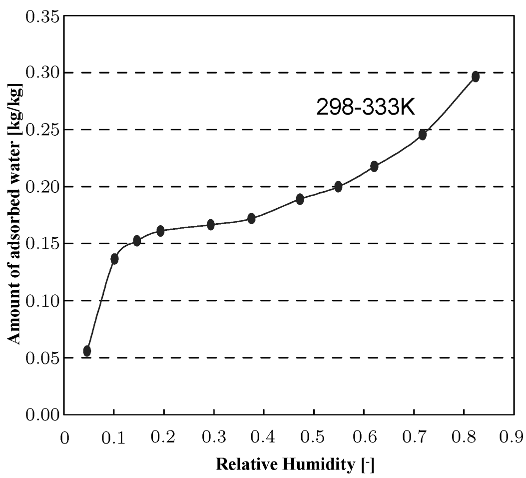

Figure 4. Adsorption isotherm of water vapor onto the honeycomb adsorbent used in this study.

temperature and any hysterisis loop at desorption step is not observed.

2.2. *Experimental Operations*

In whole of this paper, temperatures of feed air and cooling air were kept at 32°C. The flow rate of hot water was approximately kept at 1 kg/min. Rotation speed of the rotor, flow rates of feed and regeneration air, temperature of hot water and regeneration air were set at the desired values. Temperature and humidity of feed air, dehumidified air and exhaust air were measured by humidity sensor (Vaisala HMP series), dew point meter (General Eastern) and thermocouples. Experimental results are shown in the humidity chart to make a detailed discussion.

3. Results and Discussion

3.1. *Regenerated by Heated Air*

In the regeneration step, only regeneration air heated was supplied to the honeycomb adsorbent. In the adsorption step, feed air was supplied to the adsorbent layer and cooling air was simultaneously supplied into aluminum passages to cool down the adsorbent. Figure 5 shows the influence of the regeneration air temperature and the effect of cooling air on the dehumidifying performance. This figure shows that temperature of regeneration air (45–60°C) didn't affect dehumidifying performance and the temperature of dehumidified air increases with increasing temperature

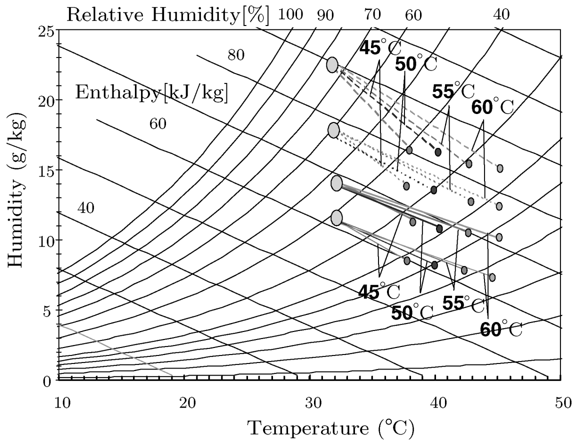

Figure 5. Influence of temperature of regeneration air and the effect of cooling air on the dehumidifying performance. (Flow rates of feed air, regeneration air and cooling air are 1 m/s, 2 m/s and 3 m/s, respectively. Temperatures of feed air and cooling air are the same temperature of 32°C. Rotation speed of rotor is 6 rph.)

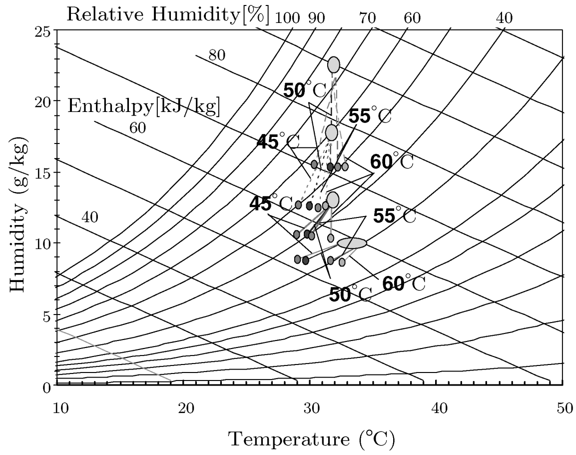

Figure 6. Influence of the temperature of hot water on the dehumidifying performance. (Flow rates of feed air, regeneration air, cooling air and hot water are 1 m/s, 2 m/s, 3 m/s and approximately 1.0 kg/min, respectively. Temperatures of feed air, regeneration air and cooling air are the same temperature of 32°C. Rotation speed of rotor is 6 rph.)

of regeneration air. However, dehumidification process approached toward iso-enthalpy or decreasing enthalpy in these experimental conditions. This result shows the adsorption heat can be effectively removed by the cooling air. Moreover, this result is interpreted by adsorption isotherm shown in Fig. 4. The adsorption isotherm shows that the amount of adsorption in high humidity is lager than that in middle humidity.

3.2. Regenerated by Hot Water Heating

In the regeneration step, only hot water was supplied to aluminum passages for regenerating the honeycomb adsorbent. Figure 6 shows the influence of the temperature of hot water on the dehumidifying performance. In terms of feed air (32°C, 22 g/kg), this figure shows a satisfactory dehumidifying performance could be obtained with even 45°C hot water to regenerate. Also, temperature of the dehumidified air was almost the same to that before adsorption. Particularly for the feed air (32°C, 10 g/kg), the temperature of dehumidified air decreased approximately by 4°C. This result shows that the honeycomb adsorbent in the adsorption step was effectively cooled by both the evaporation heat of water remaining in the passages and the cooling air itself. Therefore, the isothermal adsorption can be feasible with hot water for regenerating honeycomb adsorbent. Moreover, the influence of the feed humidity shown in this figure is similarly interpreted as described in Section 3.1.

3.3. Regenerated by Hot Water and Air Heating

3.3.1. Influence of Flow Rate of Cooling Air. In the regeneration step, hot water was supplied to aluminum passages and the heated regeneration air was supplied to the honeycomb adsorbent. Figure 7 shows the influence of the flow rate of cooling air on the dehumidifying performance. A better result of removing adsorption heat or preventing the temperature increase in the adsorbent was obtained by increasing the flow rate of cooling air. However, much faster velocity of the cooling air seems to be required to achieve the "isothermal effect".

3.3.2. Influences of Temperatures of Hot Water and Regeneration Air. Figure 8 shows influences of temperature of hot water and regeneration air on the dehumidifying performance. When the honeycomb adsorbent was regenerated by hot water only (see Fig. 6), low humidity feed air was not sufficiently dehumidified. However, Fig. 8 shows that the dehumidifying performance was improved by simultaneous supply of hot water and heated air for the regeneration. This result implies that the adsorbent was effectively regenerated by this regeneration way. Unfortunately, temperature increase in the dehumidified air was more remarkable since the adsorbent layer and aluminum passages were well heated by much amount of heat

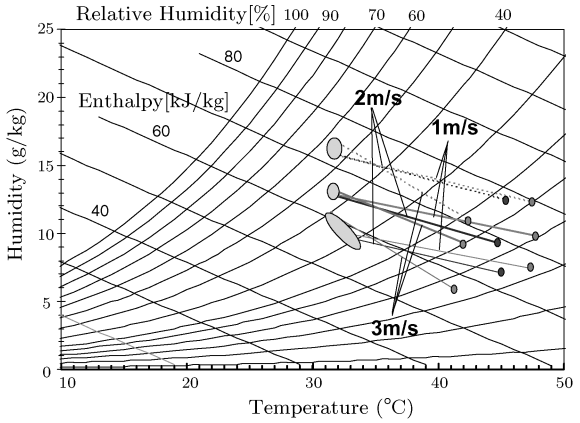

Figure 7. Influence of the flow rate of cooling air on the dehumidifying performance. (Flow rates of feed air, regeneration air and hot water are 1 m/s, 2 m/s and approximately 1.0 kg/min, respectively. Temperatures of feed air, regeneration air, cooling air and hot water are 32°C, 60°C, 32°C, 60°C respectively. Rotation speed of rotor is 6 rph).

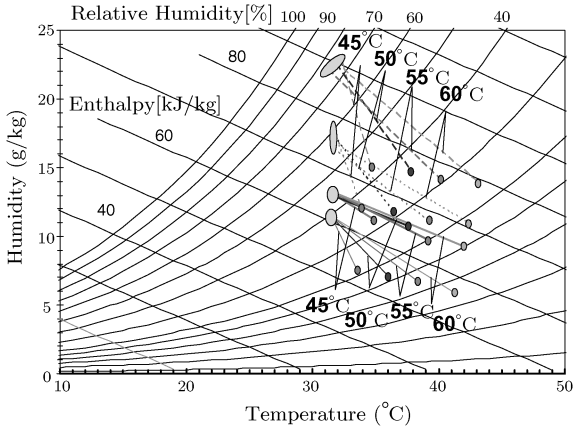

Figure 8. Influence of the temperature of hot water on the dehumidifying performance. (Flow rates of feed air, regeneration air, cooling air and hot water are 1 m/s, 2 m/s, 3 m/s and approximately 1.0 kg/min, respectively. Temperatures of feed air and cooling air are the same temperature of 32°C. Rotation speed of rotor is 6 rph).

supply. This temperature increase is one of difficulties to achieve the isothermal adsorption which gives high dehumidifying performance.

3.4. *Comparison of the Multi-Pass Honeycomb Rotor with the Conventional One*

Figure 9 shows the comparison of dehumidification behavior between the multi-pass honeycomb rotor and the conventional honeycomb rotor. In both case, regeneration temperature was 60°C and their rotation speeds of rotor were set to each optimal value. Here, the optimal rotation speed of the multi-pass adsorber is three times slower than that of the conventional rotor. This behavior indicates that the adsorption capacity of the multi-pass honeycomb adsorber can be enhanced by cooling of the rotor or removal of the adsorption heat. Actually, higher value of its optimal rotation speed was expected at the beginning of this work. However, it has not been achieved yet since heat capacity of the proposed rotor increased due to its complicated structure. Anyhow, the dehumidifying performance of the multi-pass honeycomb rotor was 1.3 times higher than that of the other in spite of the fact that cross-sectional area of adsorbent part of the multi-pass honeycomb rotor is 40% smaller than that of the conventional honeycomb rotor. Moreover, the temperature of dehumidified air by the conventional honeycomb rotor was 8°C higher than that by the multi-pass honeycomb rotor. This result shows that the honeycomb adsorbent was efficiently regenerated by hot water flowing through the passages. In the adsorption step, temperature increase in the adsorbent or decrease of dehumidifying performance was prevented with the additional cooling accelerated by the evaporation of remaining water to cooling air stream.

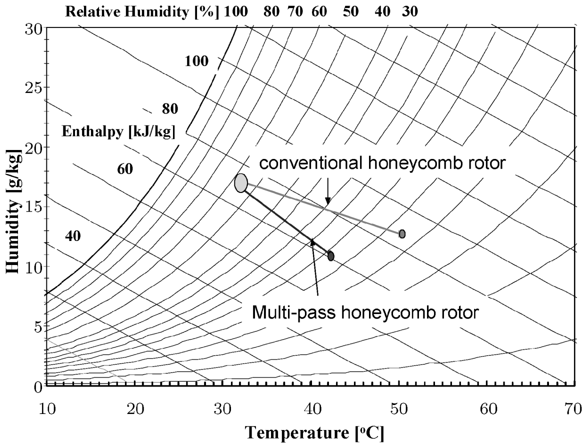

Figure 9. Comparison of dehumidification behavior between the multi-pass honeycomb rotor and the conventional one. [Multi-pass honeycomb rotor] Flow rates of feed air, regeneration air, cooling air and hot water are 1 m/s, 2 m/s, 3 m/s and approximately 1.0 kg/min, respectively. Temperatures of feed air, regeneration air, cooling air and hot water are 32°C, 60°C, 32°C and 60°C, respectively. Rotation speed of rotor: 6 rph (Conventional rotor) Flow rates of feed air and regeneration air are the same velocity of 1 m/s. Temperatures of feed air and regeneration air are 32°C and 60°C, respectively. Rotation speed of rotor: 18 rph).

4. Conclusion

A multi-pass honeycomb rotary dehumidifier was developed and investigated at various operating conditions. It was confirmed that the adsorber could be regenerated by direct hot water heating and removal of adsorption heat achieved the semi-isothermal dehumidification. It was also found that lower temperature heat around 50°C was still effective in regeneration of the adsorbent rotor although the same temperature air was needed to discharge the desorbed water vapor. However, observed dehumidifying performance was much lower than that we expected. Things should be investigated are physicochemical properties of the adsorbent suitable for the adsorber, optimal operating condition, reduction of heat transfer resistance in the adsorber and so on. Furthermore, the fact that the dehumidification behavior at our target regeneration temperature (45∼50°C) is quite sensitive to the adsorbent properties, operating condition and feed/regeneration air conditions should be carefully considered.

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