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Numerical Simulation of a Dehumidification / Humidification Performance of a Desiccant Rotor using Pore Size Controlled Material Regenerated by Low Grade Thermal Energy

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ABSTRACT

A desiccant rotor and its applied system have a lot of potential to utilize waste thermal energy for humidity control demand. A co-generation system supplies waste heat of which temperature is around 60°C. It needs to develop a high efficiency rotor regenerated by such a low-grade thermal energy. The aim of the study is to evaluate the dehumidification performance of the rotor. It was clarified that the dehumidification rate changes steeply with the regeneration temperature. A suitable regeneration temperature to obtain proper dehumidification rate was 55°C for the rotor I, 45°C for the rotor II and 80°C for silica gel, and a suitable regeneration temperature to obtain dried air and to convert thermal energy effectively was 55°C for the rotor I, 35°C for the rotor II and 45°C for silica gel in a short length rotor. A suitable rotor length is designed with a consideration of residence time near 0.2s.

1. INTRODUCTION

In refrigeration and air conditioning systems, a development of temperature and humidity independent control technology is necessary from a standpoint of rational energy utilization and a comfortable environment control. Recently, demand of the humidity control has increased rapidly to have a comfortable space and a safety for a food processing plant. Humid air is super cooled to be controlled humidity as a conventional method, and then a heating coil controls the air temperature. A desiccant air conditioning system controls temperature and humidity independently. If the waste heat is available for the regeneration heat of a desiccant rotor, it is operated with relatively less thermal energy. Therefore, it is recognized as a method for reducing the environmental load. Desiccant air conditioning system driven by low-grade thermal energy (near-ambient temperature waste heat) sources will be utilized for super markets, food-processing sites, hospitals, those can provide a lot of waste thermal energy (Hamamoto *et al.*, 2002a, 2005).

Desiccant air conditioning system is mainly composed of desiccant rotor, heat exchanger, cooling and heating coils. Desiccant rotor is generally honeycomb body impregnated with adsorbent. The system performance practically will depend on a desiccant rotor performance. There are reviews on the desiccant systems (for example, Waugaman *et al.*, 1993), and performance analysis and experimental study of dehumidification rotor (for example, Jurinak and Mitchell, 1984, Bulck *et al.*, 1986, Charoensupaya and Worek, 1988, Kodama *et al.*, 1995, Kodama and Hirose, 2001). The performance of a dehumidification rotor depends on adsorbent characteristics, flow rate of process air and revolution speed of desiccant rotor. A potential evaluation of desiccant air conditioning system combined a conventional refrigerator and desiccant dehumidifier was conducted to clarify energy saving performance (Dhar and Singh, 2001) with the consideration of regional climate condition (Khalid and Nabbl, 2001).

Recently, co-generation system such as fuel cell technology supplies waste heat of which temperature is around 60°C. It needs to develop a high efficiency rotor regenerated by such a low-grade thermal energy. The evaluation of the rotor with numerical method was performed, and it was reported that (1) there was an optimized regeneration temperature reaching the maximum of the dehumidification performance, (2) the optimum adsorption zone angle and rotor length was increased with the rise of regeneration temperature, (3) the influence of a hysteresis curve of adsorption characteristics and an equivalent mass transfer coefficient on the rotor performance was not negligible (Hamamoto *et al.* 2007a). However, the results were not fully discussed considering the measured equivalent heat and mass transfer coefficients and the disadvantage hysteresis curve. The aim of the study is to evaluate the dehumidification performance of rotor having some different equilibrium adsorption characteristics using a dynamic rotor simulation. It is discussed that (1) how much the suitable temperature to obtain proper dehumidifying capacity is, (2) how much an optimized regeneration temperature reaching the maximum of the dehumidification efficiency is, and (3) how long the suitable rotor length reaching the maximum of the efficiency is.

2. THEORETICAL ANALYSIS

2.1 Outline of the Analysis Model and Method

Figure 1 shows a cross section view of a desiccant rotor element, which is honeycomb body. It is composed of a porous material sheet impregnated with adsorbent. Heat and mass are transferred simultaneously in the each cylindrical path. For simplicity of this element in this study, the element is treated as a flat plate divided into airflow path and adsorbent bed. The path in the axis of airflow is divided into some small elements. In the element, heat and mass transfer between air and adsorbent bed are treated, based on the following assumptions; (1) Pressure and airflow rate are constant. (2) Heat and mass in the airflow path are transferred one-dimensionally in the airflow direction. (3) Heat and mass transfer of airflow direction in the adsorbent bed are negligible. (4) Temperature and amount of adsorbed water distributions in the each adsorbent bed element are uniform (Hamamoto *et al.*, 2002a).

Governing equations are composed of mass conservation in the airflow path and the adsorbent bed, adsorption rate, energy conservation in the airflow path and the adsorbent bed as listed in the Table 1. Heat and mass transfer coefficients between air and adsorbent bed, adsorption equilibrium and heat of adsorption are considered (Hamamoto *et al.*, 2002b). Adsorption equilibrium as shown in Equation (6) is given as a function of relative humidity on the surface of adsorbent rotor. Figure 2 shows three different adsorption equilibrium curves silica gel rotor and two kinds of the pore size controlled adsorbent rotor.

Calculations are performed on each element along with a direction of airflow path. Then the calculations of a whole rotor are performed with following method. A whole rotor is divided into small elements in the direction of rotation. An element is calculated during the rounding through the adsorption and desorption zone. Inside of an element, above-mentioned calculations in the direction of airflow are performed. This rounding calculation is continued reaching a steady state of the rotor. Counter airflow is considered between adsorption and desorption zone. Inlet air conditions of each zone are constant. Averaged outlet air temperature and humidity of each zone are calculated. And also, amount of adsorbed or desorbed water in a whole rotor is calculated (Hamamoto *et al.*, 2002a). A validity of the model had been discussed (Hamamoto *et al.* 2003). It gave a rational result for the dehumidifying performance.

2.2 Boundary Conditions and Physical Properties

The inlet air temperature T_{adin}, T_{dein} and humidity x_{adin}, x_{dein} to the rotor are given as the boundary condition. The initial temperature, humidity and amount of adsorption are given arbitrarily. Table 2 shows the physical properties and input data. Dry air density ρ_{a} is given a constant because the temperature difference of a rotor between inlet and outlet is relatively small compared with conventional system. The overall heat and mass transfer coefficient k_b and α_{s} of the adsorbent rotor was reported (Hamamoto *et al.* 2007b), those value are input.

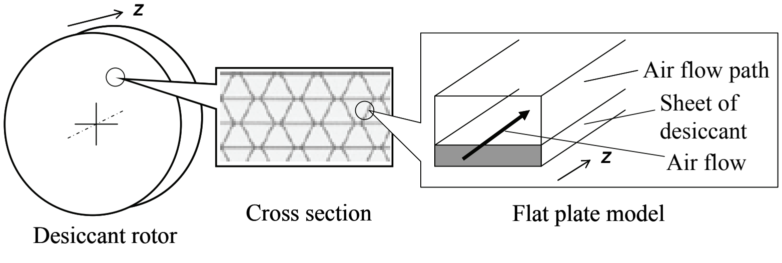


Figure 1: Rotor element and flat plate model

Table 1: Governing equations

Mass balance	$\rho_a \frac{\partial x}{\partial t} + \rho_a u_a \frac{\partial x}{\partial z} + \frac{a_b}{a_a} \rho_b \frac{\partial q}{\partial t} = 0$	(1)
Adsorption rate	$\frac{\partial q}{\partial t} = \frac{k_b}{a_b}(q^* - q)$	(2)
Heat balance in the air side	$\rho_a c_{pa} \frac{\partial T_a}{\partial t} + \rho_a u_a c_{pa} \frac{\partial T_a}{\partial z} + \frac{q_s}{a_a} = 0$	(3)
Heat balance in the bed	$\rho_b c_{pb} \frac{\partial T_b}{\partial t} = \rho_s \frac{\partial q}{\partial t} q_h + \frac{q_s}{a_b}$	(4)
Heat transfer between the air and the bed	$q_s = \alpha_s (T_a - T_b)$	(5)
Equilibrium adsorption	$q^* = f(\varphi) = f(x, T_b)$	(6)

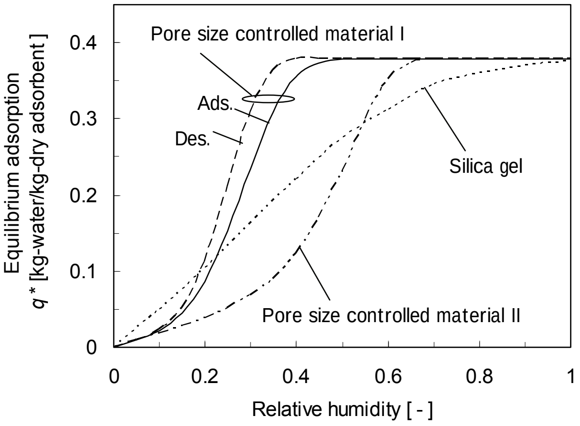


Figure 2: Equilibrium adsorption

Table 2: Input data

T_{adin}	(°C)	24	N	(rph)	10	
x_{adin}	(kg/kg’)	0.0112	ρ_{a}	(kg/m^3)	1.2	
T_{dein}	(°C)	35-75	ρ_{b}	(kg/m^3)	383	
x_{dein}	(kg/kg’)	0.0112	$k_{b\mathrm{ad}}, k_{b\mathrm{de}}$	(m/s)	$7\mathrm{x}10^{-5}$	
u_{ad}	(m/s)	0.1, 1.0	α_{s}	(W/m^2/K)	33	
u_{de}	(m/s)	1.0	q_{h}	(kJ/kg)	2700	
D_{rot}	(m)	0.55	L	(m)	0.02-1.0	
D_{bos}	(m)	0.04	c_{pa}	(J/kg/K)	1006	
$\theta_{\mathrm{ad}}, \theta_{\mathrm{de}}$	(°)	180	c_{pb}	(J/kg/K)	$c_{\mathrm{pbd}} + q c_{\mathrm{pw}}$	$=921+4180q$

3. INDEX FOR PERFORMANCE EVALUATION

3.1 Dehumidifying rate

Dehumidifying (Adsorption) rate ΔM is evaluated with Equation (7). It denotes an amount of adsorbed/desorbed water vapor per hour. It also means humidifying rate.

$$\Delta M = \rho_a u_{ad} \frac{\pi (D_{rot}^2 - D_{bos}^2)}{4} (x_{adin} - x_{adout}) \times 3600 \tag{7}$$

The ratio of the dehumidifying rate to mass of adsorbent rotor $\Delta M/m_{ads}$ is important for an evaluation of the dehumidifying capacity. If the adsorbing potential is used effectively, the ratio increases. It contributes to the rotor design for minimization.

3.2 Dehumidification Efficiency of Humidity

Dehumidification efficiency of humidity η_x is evaluated with Equation (8). It denotes the ratio of a difference of absolute humidity between inlet x_{adin} and outlet x_{adout} to a difference between the inlet humidity x_{adin} and the adiabatic ideal humidity x_{adiout} that is corresponding to dehumidify adiabatically to the relative humidity of desorption inlet air. The efficiency shows the performance of dehumidifying air dryness. If the operating and design condition to supply dry air is suitable, the efficiency increases.

$$\eta_x = \frac{x_{adin} - x_{adout}}{x_{adin} - x_{adiout}} \tag{8}$$

3.3 Dehumidification Efficiency of Relative Humidity

Dehumidification efficiency of relative humidity η_φ is evaluated with Equation (9). It denotes the ratio of a difference of relative humidity between inlet and outlet to a difference of inlet relative humidity between adsorption and desorption zone. The efficiency shows an energy conversion performance. If the thermal energy having regeneration airflow in desorption zone can be used effectively for dehumidification, the efficiency increases.

$$\eta_\varphi = \frac{\phi_{adin} - \phi_{adout}}{\phi_{adin} - \phi_{dein}} \tag{9}$$

3.4 Dehumidification Efficiency of Temperature

Dehumidification efficiency of temperature η_T is evaluated with Equation (10). It denotes the ratio of a difference of air temperature between outlet T_{adout} and inlet T_{adin} to a difference of inlet air temperature between adsorption T_{adin} and desorption T_{dein}. The efficiency shows the temperature effectiveness of the desiccant rotor. If the sensible heat is exchanged strongly and it is far from a condition of adiabatic process, the efficiency increases.

$$\eta_T = \frac{T_{adout} - T_{adin}}{T_{dein} - T_{adin}} \tag{10}$$

3.5 Maximum Amount of Dehumidifying for a Cycle

The value Δq^*_{max} denotes the difference of equilibrium adsorption at the inlet air condition between adsorption and desorption process as shown in Figure 3. It increases with the rise of regeneration temperature T_{de}. Silica gel and pore size controlled material II have a large dehumidifying potential at the low regeneration temperature. Pore size controlled material I can adsorbed well water vapor above the temperature of 50°C.

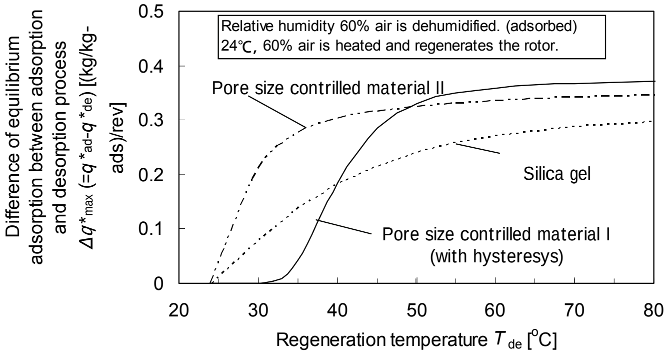
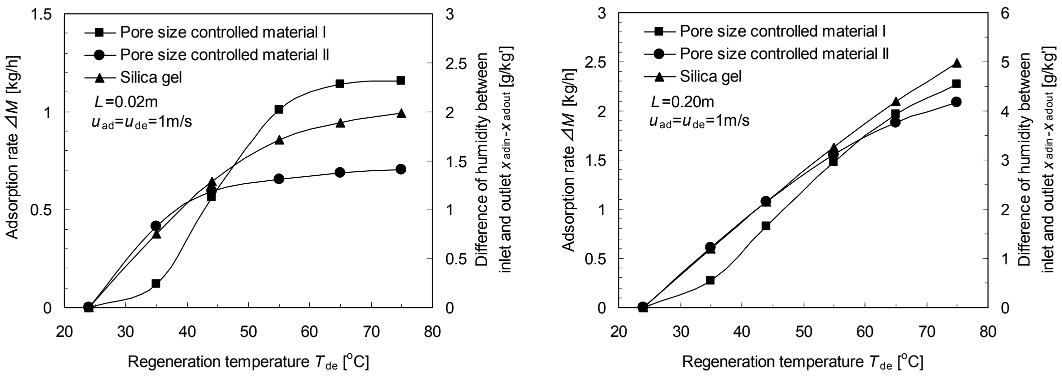


Figure 3: Maximum amount of dehumidifying for a cycle

4. RESULTS AND DISCUSSION

4.1 Influence of regenerative temperature on the dehumidifying rate and capacity

Figure 4 shows an adsorption (dehumidifying) rate ΔM at 0.02 and 0.20m of the rotor length L, and it shows a difference of humidity between inlet and outlet of the rotor corresponding to the *ΔM*. It was seen that the rate of all material increases with the regeneration temperature. A silica gel and pore size controlled rotor II has better performance at very low regeneration temperature in the figure 4(a). However, pore size controlled rotor I rises up steeply at the temperature of 45°C, the rotor I has good performance above this temperature. It was confirmed that a suitable regeneration temperature to obtain proper dehumidification rate was 55°C for the rotor I, 45°C for the rotor II and 80°C for silica gel in a short length rotor. While in the figure 4(b), it is not seen the large difference of the rate among them, and the rate increases with the regeneration temperature almost lineally. Therefore, the suitable temperature is much higher than in a case for short length rotor. Not shown here but, it does not appear the increase of the rate even if the rotor length is increased to 0.50m. Furthermore, the rate decreased slightly when the rotor length was increased to 1.0m. Figure 5 shows the ratio of the dehumidifying rate to mass of adsorbent rotor $\Delta M/m_{\mathrm{ads}}$. It was clarified that a short length rotor can use the adsorption potential effectively. It was suggested that several short length rotor should be used to obtain an adsorption rate instead of using a long length rotor. However, if it needs more dried air, it will be made a sacrifice of rotor size.



(a) L=0.02 m (b) L=0.20 m

Figure 4: Influence of regeneration temperature on the adsorption rate

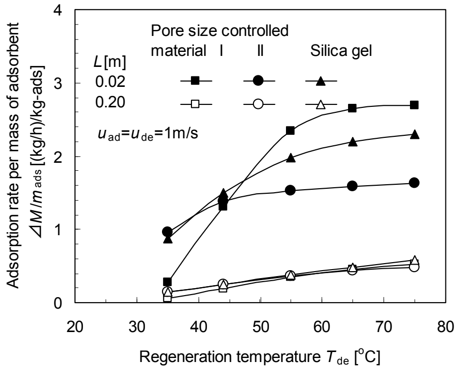


Figure 5: Influence of regeneration temperature on the dehumidifying capacity

4.2 Influence of regenerative temperature on the supply air condition

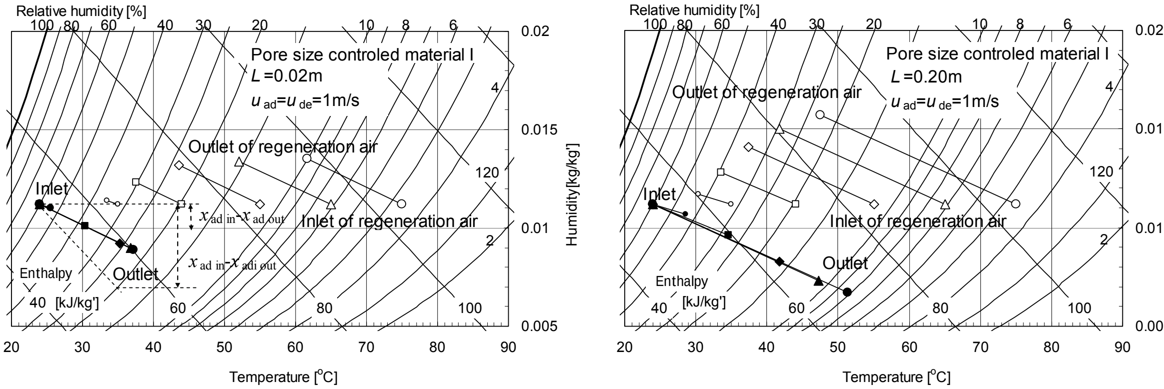
Figure 6 shows the supply air humidity and temperature in each regeneration temperature condition. If dried air is needed at the outlet. It should be used a long length rotor. Figure 7 shows the dehumidification efficiency of humidity η_x. It was seen that the rate of all material has a maximum value that is around 30% in the figure 7(a). A silica gel and pore size controlled rotor II has better performance at very low regeneration temperature. It was confirmed that a suitable regeneration temperature to obtain dried air effectively was 55°C for the rotor I, 35°C for the rotor II and 45°C for silica gel in a short length rotor. It was seen that the efficiency of silica gel increased slightly, that of material I reached maximum and material II was almost constant in the figure 7(b). The averaged value is around 50% in the long length rotor at 50°C. It is important to consider the rotor length for obtaining the dried air. It implies that multi stage adsorption process with short length rotor of pore size controlled material is effective when the regeneration process is performed at low temperature.

4.3 Influence of regenerative temperature on the dehumidification efficiency of energy conversion

Figure 8 shows the dehumidification efficiency of relative humidity η_φ and that of temperature η_T. It was confirmed that a suitable regeneration temperature to convert thermal energy effectively was 55°C for the rotor I, 35°C for the rotor II and 45°C for silica gel in a short length rotor. It was observed that the efficiency of the relative humidity is almost 90% at 55°C for all material in the long length rotor. The efficiency of temperature that is a temperature effectiveness of the desiccant rotor shows around 30% in short length rotor and 60% in long one at 55°C. It seems that they decrease with the increase of regeneration temperature. Therefore, it is examined that the sensible heat exchange is relatively strong and it is difficult to operate the process adiabatically, when the regeneration is performed by low-grade thermal energy.

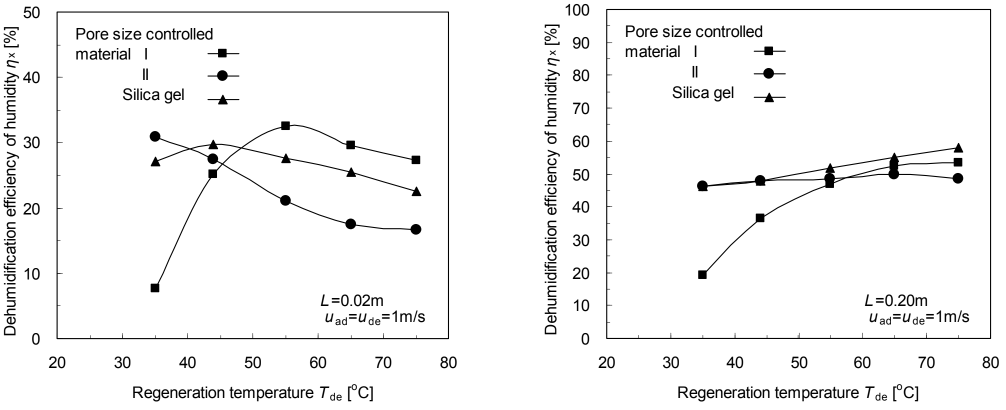
4.4 A Suitable Rotor Length for Low Regeneration Temperature

Rotor length and airflow velocity is a kind of the significant parameters. Residence time L/u_{ad} is derived from non-dimensional governing equation. Figure 9 shows the influence of residence time in the adsorption process. It was confirmed that a suitable residence time to obtain proper dehumidification rate is 0.2s at 44°C of the regeneration temperature in the figure 9(a). The rate per mass of adsorbent decreased with the increase of residence time in the figure 9(b).Dehumidification efficiency of humidity has a maximum point. The value reached about 50% even if the regeneration temperature is only 44°C and material is the rotor I, when the air flow velocity u_{ad}=0.1m/s,u_{de}=1.0m/s and the length of rotor is 0.02m (short length rotor) in the figure9(c). It is examined that suitable rotor length is designed with a consideration of residence time.



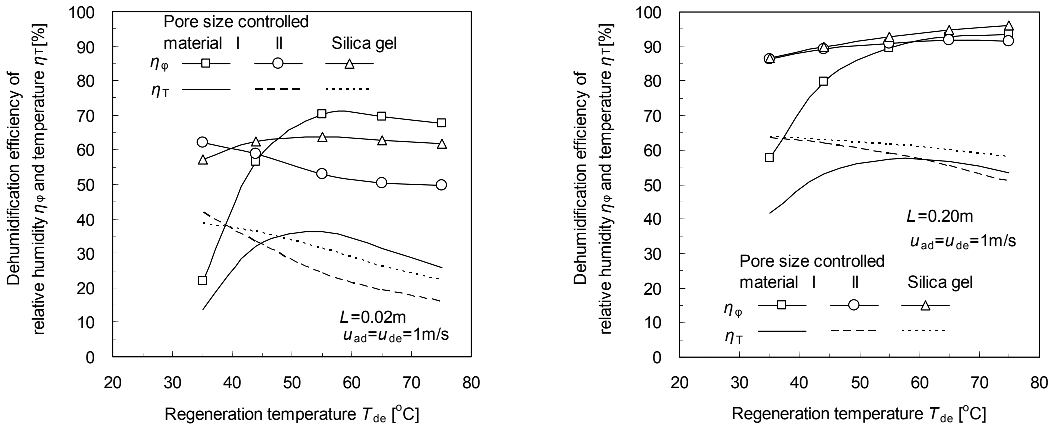
(a) L=0.02 m (b) L=0.20 m

Figure 6: Humidity and temperature conditions of the supply and regeneration air



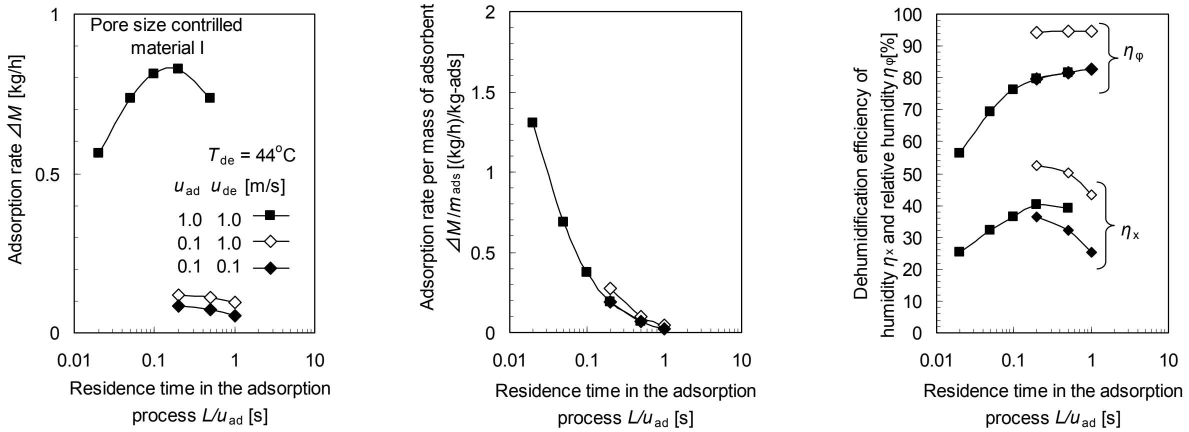
(a) L=0.02 m (b) L=0.20 m

Figure 7: Influence of regeneration temperature on the dehumidification efficiency of humidity



(a) L=0.02 m (b) L=0.20 m

Figure 8: Influence of regeneration temperature on the dehumidification efficiency of relative humidity and temp.



(a) Adsorption rate (b) Adsorption rate per mass of adsorbent (c) Dehumidification efficiency

Figure 9: Influence of residence time in the adsorption process

5. CONCLUSIONS

In a development of a high efficiency rotor regenerated by a low-grade thermal energy, the study evaluates the dehumidification performance of rotor having some different equilibrium adsorption characteristics using a dynamic rotor simulation. Following points are clarified with a constant rotor speed.

- A suitable regeneration temperature to obtain proper dehumidification rate was 55°C for the rotor I, 45°C for the rotor II and 80°C for silica gel in a short length rotor (L=0.02m), and in a long rotor (L=0.20m), the temperature is much higher than in a case for a short one.
- A suitable regeneration temperature to obtain dried air and to convert thermal energy effectively was 55°C for the rotor I, 35°C for the rotor II and 45°C for silica gel in a short length rotor. In the long length rotor, the averaged value is around 50% for dried air and 90% for energy conversion at 50°C. They are larger than those of the short one.
- It is effective to introduce the multi stage adsorption process with short length rotor of pore size controlled material, and it is difficult to operate the process adiabatically when the regeneration is performed at low temperature.
- A suitable residence time to obtain proper dehumidification rate and its efficiency is 0.2s at 44°C of the regeneration temperature. The value reached about 50% even if the regeneration temperature is only 44°C and material is the rotor I, when the air flow velocity u_{ad} is 0.1m/s, u_{de} is1.0m/s and the length of rotor is 0.02m. A suitable rotor length is designed with a consideration of residence time near 0.2s.

NOMENCLATURE

a	thickness	(m)	φ	relative humidity	(%)
c_p	specific heat	(kJ/kg/K)	η	dehumidification efficiency	(%)
D	rotor diameter	(m)	θ	zone angle	(^{o})
k_b	equivalent mass transfer coefficient	(m/s)	ρ	density	(kg/m^3)
L	rotor length	(m)		**Subscripts**	
N	rotor speed	(rph)	a	air	
q	amount of adsorbed water	(kg/kg)	ad	adsorption	
q_h	heat of adsorption	(kJ/kg)	adi	adiabatic	
q_s	heat transfer rate	(W/m^2)	ads	adsorbent	
q^*	equilibrium adsorption	(kg/kg)	b	adsorbent bed	
T	temperature	(^{o}C)	bos	boss of rotor	
t	time	(s)	de	desorption	
u	velocity	(m/s)	in	inlet	
x	humidity	(kg/kg')	max	maximum	
z	location in the direction of airflow	(m)	out	outlet	
α_s	heat transfer coefficient	(W/m^2/K)	rot	rotor	

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