

A Theoretical Study of Heat and Mass Transfer in Water Vapor Desorption using Both Microwaves and Hot Air

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Abstract— In order to improve performance of desiccant air-conditioners, a desiccant air-conditioner system using both microwaves and hot air is proposed in this study. The heat and mass transfer phenomena of water vapor desorption in zeolite packed bed assuming an adsorption rotor section of the desiccant air-conditioning system is theoretically examined, and the effectiveness of water vapor desorption using both microwaves and hot air by comparing with experimental results is discussed. The analysis results of the temperature and desorption amount in the packed bed showed a comparatively good match with the corresponding experimental results, and the experimental considerations were backed up theoretically. Furthermore, the thermal efficiency of a standard with the same desorption amount of desorption using both microwaves and hot air is higher than hot air desorption, and the thermal efficiency ratio (thermal efficiency of desorption using both microwaves divided by thermal efficiency of hot air desorption) reaching a maximum of 1.35 times.

Keywords— Desiccant Air Conditioning System; Heat transfer; Desorption; Microwave; Zeolite

I. INTRODUCTION

Desiccant air-conditioner systems which can independently control temperature and humidity using the adsorption/desorption phenomenon are positioned as equipment employing low-temperature exhaust heat which can operate with low temperature heat sources at $\leq 100^{\circ}\text{C}$. For beneficial use of waste heat, there is a strong need for development to improve their performance. As part of that, it is essential to improve the performance of the rotor-type adsorption unit (adsorption rotor) which is the key component of a desiccant air-conditioner system. These systems generally use corrugated adsorption rotor type adsorption units in which the adsorbent is impregnated into ceramic fiber paper, or similar material. The system is employed in which part of the rotor cross-section is taken to be the adsorption zone, and the other part the desorption zone. And water vapor

adsorption/desorption operation is carried out by continuously circulating outside moist air and return dry air to the respective zones. To secure a satisfactory air treatment volume with this system, the area ratio of the air flow section must be considerably large. Therefore, the adsorption capacity per unit volume of the rotor is small, and this is regarded as a factor inhibiting greater compactness and higher performance of the equipment. Incidentally, the porosity and adsorbent filling density in adsorption rotors with honeycomb of ceramic fiber paper impregnated with 60 wt% adsorbent is estimated to be ≥ 0.7 and $\leq 10 \text{ kg/m}^3$, respectively. Therefore, the adsorption rotor volume is estimated to be ≥ 5 times the volume of an adsorption unit for an adsorption type heat pump using the same capacity. Also, hot air and/or heating with a heater are used in desorption (regeneration) operation. The decrease of the desorption rate caused by the slow heating rate of the adsorbent and the high heat loss to the outside of the heated material unavoidably leads to increased rotor size and energy consumption. For these reasons, the authors proposed and experimentally verified the effectiveness of a desiccant air-conditioning system using heating with both microwaves and hot air, and newly incorporating microwave heating for desorption of adsorbed water. Specifically, in water vapor desorption using both microwaves and hot air, the results suggested that there is an excess desorption effect of 1.6–2.0 times compared to hot air desorption [1–3], and that the treated air volume can be increased by 1.25 times, or the rotor cross-sectional area can be reduced by 0.8 times, compared to conventional adsorption rotors [4]. Thus, in this research, a study is carried out to establish rational design guidelines for desiccant air-conditioning systems using heating with both microwaves and hot air.

A number of studies have been conducted regarding development of higher performance adsorption rotors, in areas such as: 1) improving performance of the adsorbent used, and 2) increasing the adsorption/desorption rate. In particular, 1)

involves developing adsorbent with a large difference in absorption/desorption amount (effective adsorption amount) in the humidity range of desorption operation. A group led by Kakiuchi et al. [5] has reported new development of a functional adsorbent material (FAM) composed of aluminophosphate, improvement of silica rotor dehumidification performance by 11–22% using FAM-Z02 in low-temperature regeneration at 50–70°C [6]. Furthermore, Shimooka et al. [7] have reported the ability to regenerate at a lower temperature than FAM-Z02 by using FAM-Z05. By using the impregnating method of silica in activated carbon pores [8] and the acid treatment method of activated carbon [9], the authors showed a maximum increase of 3.4 times over silica gel in the effective adsorption amount. For approach 2), Shimooka et al. [7] have reported that higher speed adsorption/desorption than the adsorption rotor type can be achieved using a direct heating/cooling type adsorption unit in which FAM is coated onto a heat exchanger plate. Kubota et al. [10] has applied three types of silica gel in a microwave heating experiment. The result shows that silica gel RD exhibited the maximum microwave heating effect. In addition, studies have been conducted on analytic prediction of performance under the hot air supply conditions of a desiccant air-conditioner [11–17]. Miyazaki et al. [18] have conducted analysis of the regeneration process using microwave heating. They reported that regeneration performance using microwave heating is comparable with using high-temperature air. However, almost no work has been done on heat and mass transfer of the adsorption units using heating with both microwaves and hot air.

In this research, the modeling and dynamic analysis of heat and mass transfer in water vapor desorption using both microwaves and hot air was carried out. More specifically, as the first stage, the authors looked at adsorption units incorporating a zeolite-packed bed in a previous study [4], developed a simulation model for heat and mass transfer in the desorption process, and based on the validity of the model, examined desorption performance taking as parameters the air humidity, hot air supply temperature, and microwave irradiation intensity in the isohumic adsorption/desorption conditions.

II. HEAT AND MASS TRANSFER MODEL FOR WATER VAPOR ADESORPTION USING BOTH MICROWAVES AND HOT AIR

Fig. 1 shows a schematic diagram of an adsorption column, which was used on water vapor desorption using both microwaves and hot air in the previous study [4]. The adsorption unit is a glass cylindrical tube, and its center part is filled with zeolite. This adsorption unit is inside a microwave waveguide, and the zeolite packed bed is located at the center part of the waveguide. Air for desorption is introduced to the packed bed, which has been heated to the specified temperature by the micro heater at the top part of the packed bed. Temperature of the sample section is directly measured, 1 point above the packed bed air intake (T1), 2 points in the radial direction at the top part of the packed bed (T2, T3), 2 points in the radial direction at the bottom part of the packed bed (T4, T5), and 1 point below the air outlet of the packed bed (T6). Air humidity is measured at the inlet and outlet of adsorption unit.

Fig. 2 shows the heat and mass transfer model for the desorption process in the adsorbent packed bed as shown in Fig. 1. Hot air at the packed bed intake (Q_{gas} (W)) and microwaves from the packed bed sides (Q_{MW} (W)) are supplied to the adsorbent packed bed as heating energy, and consumed by the sensible heat (Q_s (W)) and desorption heat (Q_{des} (W)) of the adsorbent. At the same time, a part of heating energy is radiated from the sides of the adsorption unit (Q_{side} (W)), and the remaining energy (Q_{out} (W)) flows out from the lower part of the packed bed. During this interval, water vapor in the adsorbent moves toward the particle surface direction, and flows out from the bottom part of the packed bed, accompanied by the main unit flow. Table 1 shows the specifications of the adsorption unit and adsorbent.

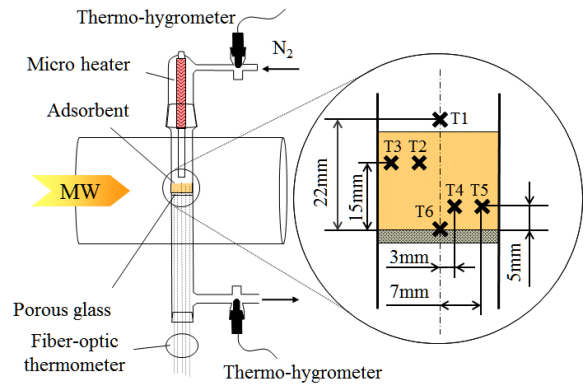


Fig. 1 Schematic diagram of adsorption column

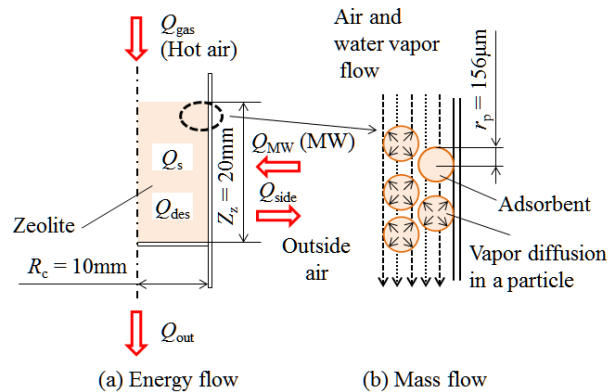


Fig. 2 Schematic diagram of energy and mass flow in the packed bed

TABLE 1 SPECIFICATIONS OF THE ADSORPTION UNIT AND ADSORBENT

| Adsorbent | Zeolite 13X |
|-----------------------------|-------------|
| Packed bed thickness, Z_p | 20mm |
| Packed bed radius, R_c | 10mm |
| Particle radius, r_p | 156µm |
| Frequency of microwave, f | 2450MHz |

The following assumptions were established to analytically solve this model:

- Water vapor desorption using both microwaves and hot air is expressed with a two-dimensional cylinder model.
- Adsorbent particles are spherical particles with a uniform particle diameter.

- Temperature is uniform in an infinitesimal volume of the packed bed.
- Temperature in adsorbent particles is uniform.
- Water vapor transfer in adsorbent particles can be expressed with surface diffusion.
- Microwave electric field intensity is uniform in the packed bed.
- Diffusion based on the difference in water vapor concentration in the packed bed can be ignored.

The heat and mass balance equation for the desorption process of this system, under the above assumptions, is expressed as follows.

Heat balance equation:

$$\left\{ \varphi_G C_{p,G} + (1 - \varepsilon) \rho C_{p,B} \right\} \frac{\partial T}{\partial \theta} = \lambda \left(\frac{\partial^2 T}{\partial Z^2} + \frac{\partial^2 T}{\partial R^2} + \frac{1}{R} \frac{\partial T}{\partial R} \right) - u \rho_G C_{p,G} \frac{\partial T}{\partial Z} + P + \rho \Delta H \frac{\partial \bar{q}}{\partial \theta} \quad (1)$$

$$C_{p,B} = C_{p,A} + q C_{p,W} \quad (2)$$

Mass balance equation:

$$\frac{\partial C}{\partial \theta} = -u \frac{\partial C}{\partial Z} + (1 - \varepsilon) \rho \frac{\partial \bar{q}}{\partial \theta} \quad (3)$$

$$\frac{\partial q}{\partial \theta} = D_A \left(\frac{\partial^2 q}{\partial r^2} + \frac{2}{r} \frac{\partial q}{\partial r} \right) \quad (4)$$

$$\bar{q} = \frac{3}{r_p^3} \int_0^{r_p} r^2 q dr \quad (5)$$

Initial conditions:

$$\theta = 0, 0 \leq Z \leq Z_z, 0 \leq R \leq R_c; T = T_{\text{initial}}, C = C_{\text{initial}} \quad (6)$$

$$\theta = 0, 0 \leq r \leq r_p; q = q_{\text{initial}} \quad (7)$$

Boundary conditions:

$$Z = 0, Z = Z_z; \frac{\partial T}{\partial Z} = 0, \frac{\partial C}{\partial Z} = 0 \quad (8)$$

$$R = 0; \frac{\partial T}{\partial Z} = 0, \frac{\partial C}{\partial Z} = 0 \quad (9)$$

$$R = R_c; \lambda \frac{\partial T}{\partial Z} = h(T - T_{\text{out}}), \frac{\partial C}{\partial Z} = 0 \quad (10)$$

$$r = 0; \frac{\partial q}{\partial r} = 0 \quad (11)$$

$$r = r_p; -D_A \rho \frac{\partial q}{\partial r} = k_F a_v (C_s - C) \quad (12)$$

Where, C (kg/m^3), h ($\text{W}/(\text{m}^2 \cdot \text{K})$) and q (kg/kg) are vapor concentration, heat transfer coefficient and adsorption amount, respectively. Subscript A, B, G, out, s and W are indicate adsorbent, packed bed, fluid, outside surface and water, respectively.

The calculation was carried out by applying the forward difference method to the above differential equations. In this calculation, the accurate desorption amount was found beforehand by a trial-and-error method assuming the desorption amount from the adsorbent. More specifically, the steps were: 1) The amount calculated from the temperature and water vapor concentration in the packed bed is set the maximum desorption amount, when the supplied heat is consumed by sensible heat only; 2) Calculate the temperature and the bulk water vapor concentration in the packed bed, taking as a tentative desorption amount an amount at or below the maximum desorption amount in 1). Next, in step 3), the desorption amount is calculated by solving the mass balance equation in the particle, using this bulk water vapor concentration of fluid as a standard, and when the difference between this desorption amount and the assumed desorption amount is less than 1.0%, the value is confirmed as the accurate desorption amount.

Table 2 shows the analysis conditions for heat and mass transfer in the packed bed and Table 3 shows the values used in the analysis. Here, the value indicated in the previous study [4] was used for the desorption heat ΔH . The diffusion coefficient D_A was determined by equation (13) [19]. The adsorption rate constant (k_{s,a_p} (1/s)) was determined from the actual measurement value of the zeolite adsorption rate using a high-precision vapor adsorption measurement system (BELSORP-aqua3, made by MicrotracBEL).

$$k_{s,a_p} = \frac{15 D_A}{r_p^2} \quad (13)$$

Table 2 Analysis Conditions For Heat And Mass Transfer In The Packed Bed

| | |
|---|-----------|
| Initial temperature, T_{initial} | 30 °C |
| Relative humidity (30°C), φ | 16-55 %RH |
| Hot air heating temperature, T_G | 55-100 °C |
| Outside temperature, T_{out} | 30 °C |
| Microwave intensity, M_W | 0-100 W |
| Flow rate (Superficial velocity), u | 0.106 m/s |

TABLE 3 The Values Used In The Analysis

| | |
|---|--|
| Desorption heat, ΔH | 3900 kJ/kg |
| Diffusion coefficient, D_A | $1.8 \times 10^{-11} \text{ m}^2/\text{s}$ |
| Effective thermal conductivity, λ | 0.08 W/(m·K) |
| Porosity of packed bed, ε | 0.646 |
| Specific heat of adsorbent, $C_{p,A}$ | 758 J/(kg·K) |
| Density of adsorbent, ρ | 1132 kg/m ³ |

The effective thermal conductivity in the packed bed (λ) was set as the actual measurement value of zeolite 13X by Hirasawa et al. [20]. The heat transfer coefficient (h) between the adsorption column side and the atmosphere was estimated using the following equation [21].

$$Nu = 0.0387(GrPr)^{\frac{1}{4}} \quad (14)$$

Where, Nu , Gr and Pr are Nusselt number, Grashof number and Prandtl number, respectively.

The mass transfer coefficient k_F (1/s) between the particle surface and the bulk fluid was estimated using the following equation [22].

$$\frac{k_F}{u} Sc^{\frac{2}{3}} = 1.77 \left[\frac{Re}{(1-\epsilon)} \right]^{-0.44} \quad (15)$$

Where, Sc , Re are Schmidt number and Reynolds number, respectively.

Microwave input P (W/m³) was calculated using the following equation, by assuming input of microwave irradiation field with the electric field intensity (E (V/m)) standard, same with the previous study [4].

$$P = \frac{5}{9} f E^2 \epsilon_r \tan \delta \cdot 10^{-10} \quad (16)$$

Where, ϵ_r is relative permittivity and $\tan \delta$ is dielectric loss angle. The loss coefficients ($\epsilon_r \tan \delta$) are taken from the literature [23]. The loss coefficient of zeolite is 0.25, and the loss coefficient of water is 12.3–3.1 (25–85 °C).

III. RESULTS AND DISCUSSION

In order to check the validity of the analysis model indicated in this study, the calculation results in this work of desorption amount and temperature in the packed bed was compared with experimental results in the previous study [4]. Fig. 3 and Fig. 4 show temperature and total adsorption ratio inside the packed bed with time at Case 1 and Case 2, respectively. The calculation conditions of Case 1 is at $T_G = 55^\circ\text{C}$ after attaining adsorption equilibrium under conditions with hot air temperature of ($T_{\text{initial}} =$) 30°C , air humidity ($\phi =$) 40%RH, while Case 2 is under condition of heating using both microwaves and hot air with heating at $T_G = 55^\circ\text{C}$ and irradiation with microwaves ($M_w =$) 50W. In addition, Figs. 5 and 6 show adsorbent sensible heat (Q_s), desorption heat (Q_{des}), heat radiation at the outer side of packed bed (Q_{side}), and total heat balance at Case 1 and Case 2, respectively. The following shows the calculation equations for each consumed heat of the packed bed.

$$Q_s = (M_A C_{p,A} + M_W C_{p,W}) \frac{dT}{d\theta} \quad (16)$$

$$Q_{\text{des}} = M_A \Delta H \frac{dq_{\text{des}}}{d\theta} \quad (17)$$

$$Q_{\text{side}} = hA(T - T_{\text{out}}) \quad (18)$$

Where, A (m²), M (kg) and q_{des} (kg/kg) are wall surface area of packed bed, mass and desorption amount, respectively.

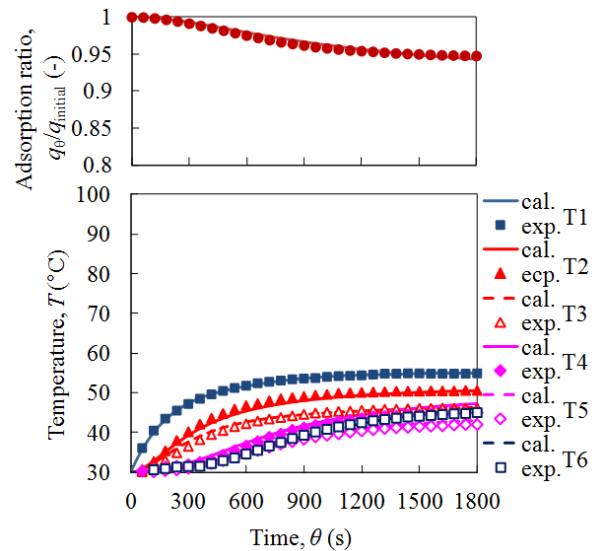


Fig. 3 Changes in temperature and adsorption ratio with time at $T_G = 55^\circ\text{C}$ and $\phi = 40\%$ (Case 1)

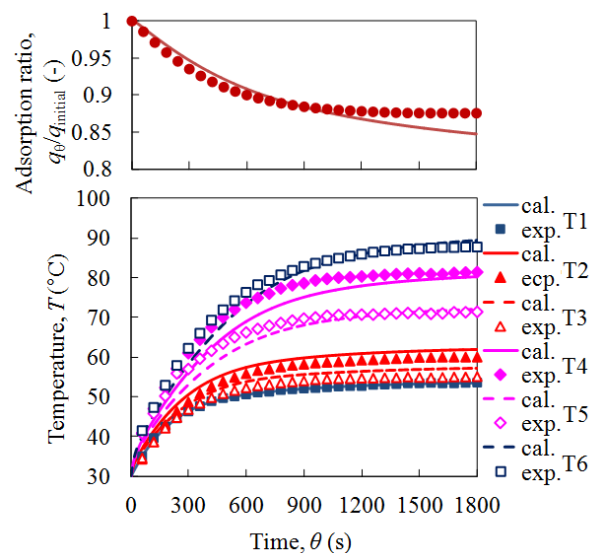


Fig. 4 Changes in temperature and adsorption ratio with time at $T_G = 55^\circ\text{C}$, $\phi = 40\%$ and $M_w = 50\text{W}$ (Case 2)

The calculation results of adsorption ratio and temperature in the packed bed match well with experimental results at Case 1 and Case 2 (as shown Figs. 3 and 4), respectively. Furthermore, the calculation results of each consumed heat and the overall heat balance with time (Figs. 5 and 6) almost match the trend of experimental results. Therefore, this analysis method can be regarded as almost adequate. The experimental considerations relating to changes in temperature and adsorption amount, described in the experimental results of the previous study [4], can also be regarded as logically supported. In Case 2, the calculation results of adsorption ratio change were slightly lower than experimental results after 1000s. This is due to the fact that the Clausius-Clapeyron equation obtained from actually measured isotherms up to 15–45°C for calculation of the desorption amount were also applied to temperature larger than 45°C. Even if these results changed with T_G , ϕ and M_w conditions, the tendencies were confirmed to be similar.

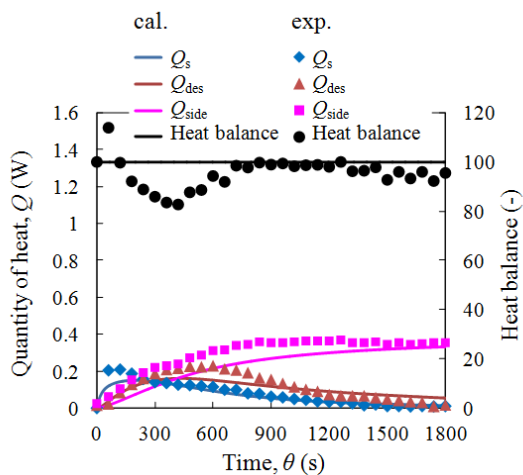


Fig. 5 Changes in heat consumption and heat balance at $T_g = 55^\circ\text{C}$ and $\phi = 40\%$ (Case 1)

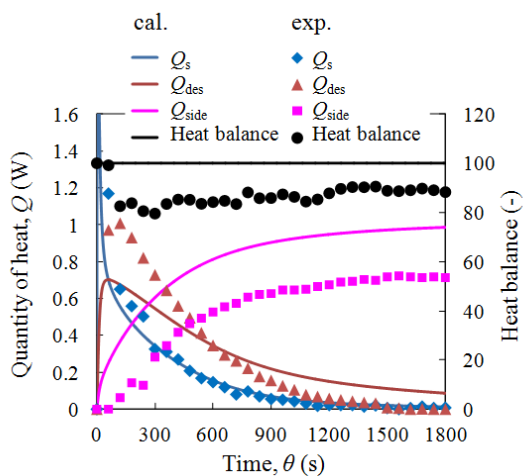


Fig. 6 Changes in heat consumption and heat balance at $T_g = 55^\circ\text{C}$, $\phi = 40\%$ and $M_w = 50\text{W}$ (Case 2)

The validity of this analysis has been confirmed as above-mentioned. In light of this, the following section considers the temperature behavior and desorption behavior in the packed bed in Case 1 and Case 2. In addition, the effectiveness of desorption using both microwaves and hot air were verified.

Specifically, the thermal efficiency was compared under a wide range of humidity conditions.

A. Temperature distribution and adsorption amount distribution in the packed bed

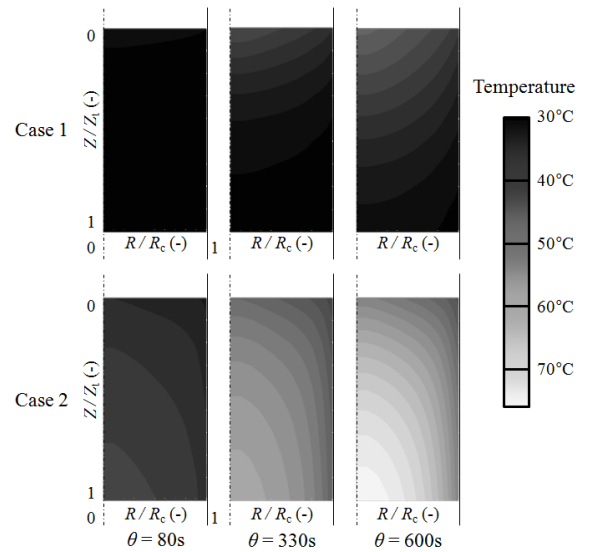


Fig. 7 Change in temperature distribution in the packed bed with time

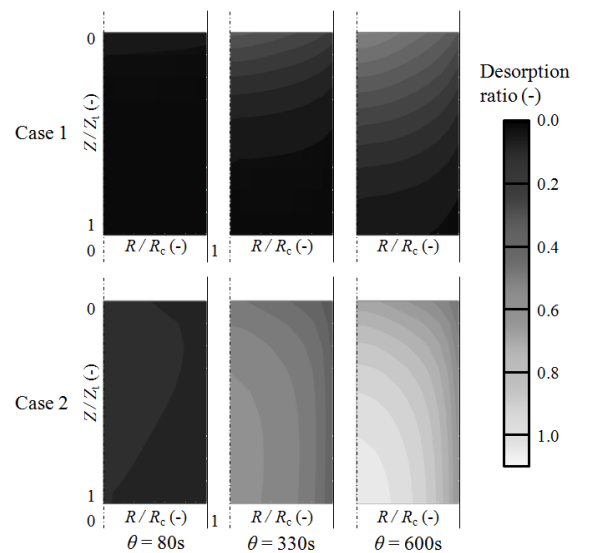


Fig. 8 Change in desorption ratio distribution in the packed bed with time

In order to clarify the desorption state in Case 1 and Case 2, Figs. 7 and 8 show the calculation results of temperature distribution and desorption ratio distribution at time of ($\theta =$) 80s, 330s, and 600s. The calculation conditions of Case 1 and Case 2 is same as Figs. 3 and 4. In Case 1, the temperature rises from the top and axial center parts of the packed bed (as shown Fig. 7). The desorption progresses together with temperature rise (as shown Fig. 8). However, even at $\theta = 600\text{s}$, the desorption ratio at the top and bottom of the packed bed are 50% and 0.0% for the equilibrium adsorption amount difference of $T_G = 30^\circ\text{C}$ and $T_G = 55^\circ\text{C}$ at $\phi = 40\%\text{RH}$ ($q_{30^\circ\text{C}}, 40\%\text{RH} - q_{55^\circ\text{C}}, 40\%\text{RH} = 0.04 \text{ kg/kg}$), respectively. In Case 2, in contrast, there is a marked increase in temperature of the

packed bed from the initial stage of heating in comparison with Case 1. This temperature rises from the center part in the axial direction. The temperature around measurement point T4 exceeds T_G at $\theta = 270$ s. The desorption ratio corresponds to this temperature rise, and becomes higher than 1 at the axial direction center of the bottom part of the packed bed at $\theta = 600$ s. In Case 2, it is shown that the temperature of the packed bed rises quickly due to the microwave irradiation, and desorption occurs at higher speed than in Case 1.

B. Effectiveness of water vapor desorption using both microwaves and hot air

In order to confirm the effectiveness of water vapor desorption using both microwaves and hot air, the temporal thermal efficiency η defined by the following equation was used as a desorption effect indicator.

$$\eta = \frac{Q_{des,\theta}}{Q_{s,\theta} + Q_{des,\theta} + Q_{side,\theta}} \quad (19)$$

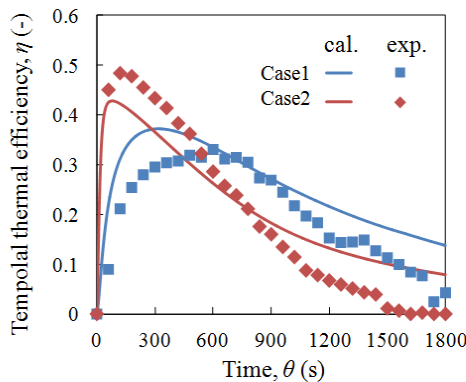


Fig. 9 Change in temporal thermal efficiency with time

Fig. 9 shows the η value for Case 1 and Case 2 obtained from the calculation results, together with the experimental results in the previous study [4]. In both Case 1 and Case 2, the thermal efficiency η_{cal} in calculation increases after the start of desorption, reaches the maximum thermal efficiency $\eta_{cal,MAX}$, and then decreases. The arrival time at $\eta_{cal,MAX}$ in Case 2 is shorter than in Case 1. The $\eta_{cal,MAX}$ in Case 2 is higher than in Case 1. In Case 2, η_{cal} is larger than in Case 1 from the initial stage of desorption up until 300s, and after that the two swap positions. These changes in η_{cal} match the trend of the thermal efficiency η_{exp} in the experiment, and this suggests that it is possible to examine by taking η as a standard for performance evaluation of a desiccant air-conditioner using heating with both microwaves and hot air. Therefore, the following discusses the effectiveness of water vapor desorption using both microwaves and hot air by using the η value as an index when microwave intensity, and desorption air temperature/humidity are varied. The thermal efficiency in the packed bed η_θ at the same desorption amount defined by the following equation was used for the comparison discussion.

$$\eta_\theta = \frac{\sum_{\theta=0}^{\theta_i} Q_{des,\theta}}{\sum_{\theta=0}^{\theta_i} (Q_{s,\theta} + Q_{des,\theta} + Q_{side,\theta})} \quad (20)$$

Here, θ_i is the desorption time of Case 2 for reaching the same desorption amount at $\theta = 1800$ s in Case 1. Also, the desorption amount at $\theta = 1800$ s in Case 1 differs depending on the T_G and ϕ value, but for the purpose of simplification in this study, η_θ was calculated at $q_{des} = 0.0165$ kg/kg in Case 1 with $T_G = 55^\circ\text{C}$, $\phi = 16\%$ RH, and $\theta = 1800$ s.

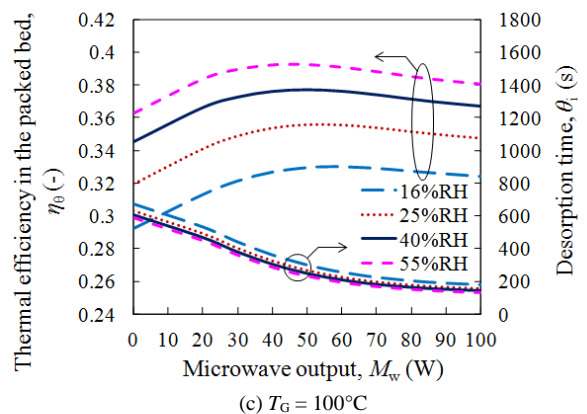
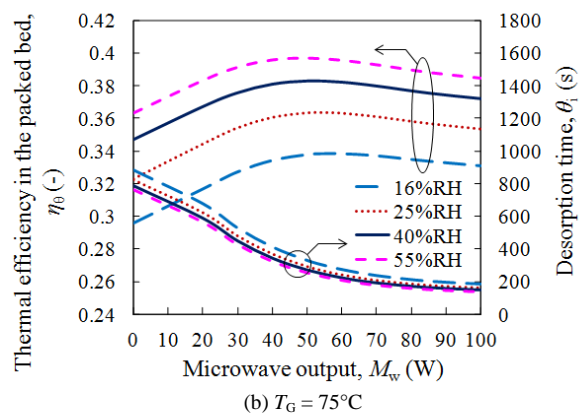
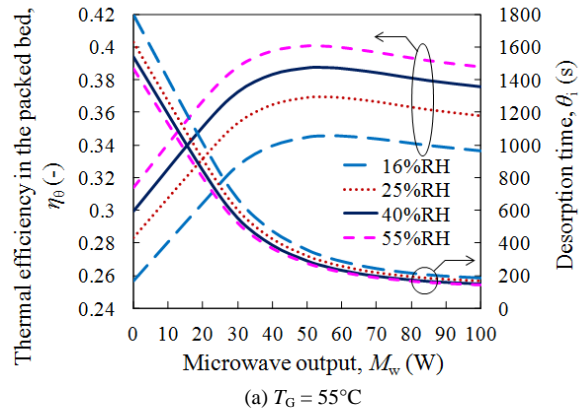


Fig. 10 Effect of microwave output on thermal efficiency in the packed bed and desorption time

Figs. 10(a), (b), and (c) show the relationship of η_θ and M_w under conditions of $\phi = 16\text{--}55\%$ RH (30°C) and $T_G = 55^\circ\text{C}$, 75°C and 100°C , respectively. Values of θ_i are also shown in the figures. The value of η_θ at Case 2 ($M_w > 0$) is larger than Case 1 ($M_w = 0$), does not depend on T_G and ϕ . The value of η_θ is increased as M_w increases, reaches the maximum value at $M_w = 40\text{--}60$ W, and then decreases somewhat. The value of η_θ increases together with the increase in ϕ , and this increase is almost proportional to increase in ϕ . At M_w where η_θ is maximal, there is a tendency to increase together with decreasing ϕ . Also, θ_i decreases together with the rise in T_G

and the increase in M_w . Thus, looking at the maximum value $\eta_{\theta,MAX,Case2}$ of η_{θ} , Fig. 11 shows the ratio of this value divided by $\eta_{\theta,Case1}$, i.e., $\eta_{\theta,MAX,Case2}/\eta_{\theta,Case1}$. In all cases, the value of $\eta_{\theta,MAX,Case2}/\eta_{\theta,Case1}$ is larger than 1, and increases together with decreases in T_G and ϕ . This suggests that water vapor desorption using both microwaves and hot air enables use of low-temperature hot air, and is effective for promoting desorption under a low adsorption amount conditions.

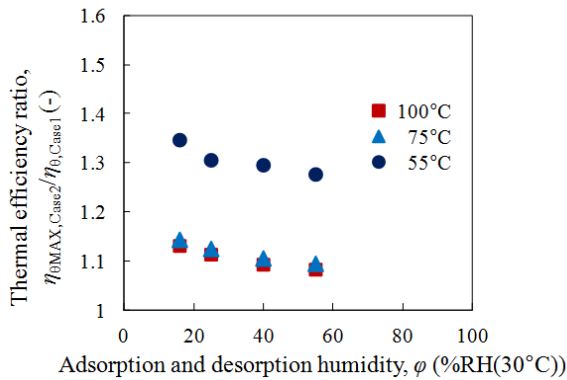


Fig. 11 Relationship between thermal efficiency ratio and humidity

IV. CONCLUSION

In order to design a desiccant air-conditioner with high thermal efficiency using heating with both microwaves and hot air, a theoretical study was conducted on heat and mass transfer in the desorption process for adsorption units with a zeolite-packed bed. The main findings were as follows.

- The calculation model was developed for water vapor desorption using both microwaves and hot air. Validity of the analysis was shown by a comparison of analysis results and actual measurement results, and experimental considerations relating to temperature and adsorption amount changes were also backed up theoretically.
- Effectiveness of water vapor desorption using both microwaves and hot air was evaluated, using as an indicator the thermal efficiency of desorption. Thermal efficiency of this dual-use desorption is higher than hot air desorption, and a promoting effect of desorption can be expected under low-temperature heat condition and a low adsorption amount condition.

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