Heat Transfer during Microwave-Assisted Desorption of Water Vapor from Zeolite Packed Bed

ゼオライト充填層におけるマイクロ波による水蒸気脱着の熱移動挙動

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Abstract　This study attempted to quantify the effect of microwave-assisted desorption of water vapour from a zeolite packed bed. Specifically, an experiment was carried out comparing water vapor desorption using hot air and microwave heating. In the experiment, the temperature in the zeolite packed bed and humidity at the inlet and outlet of the adsorption column were measured. Then, the heat transfer behavior was quantified by calculating the heat balance of a zeolite packed bed, and the effect of microwave irradiation was examined. The results showed that microwave heating is effective for desorption at the beginning.

1. Introduction

A typical adsorptive desiccant humidity conditioner mainly consists of a rotary dehumidifier and heat exchanger that can be driven by low-temperature heat sources, such as waste heat below 100°C. Therefore, desiccant air conditioners are effective as low-temperature waste heat utilization equipment. However, the desiccant humidity conditioner desorption process was found to increase energy consumption and decrease the desorption rate. This problem is being discussed, and optimization of the adsorption–desorption process is being examined by researchers in the desiccant air-conditioning field, but no general solution has yet been achieved.[1-3] This article proposes a hot air heating and microwave irradiation-type hybrid desiccant humidity conditioner.

Applying microwave irradiation as the regeneration heat source of the adsorbent is one strategy to combat the problems mentioned above. Microwave irradiation has the great advantage of direct and[1] rapid heating of a material. Microwaves can heat an adsorbent containing adsorbed water without heating the surrounding air.[4-6] The temperature inside a porous material during drying is higher than the temperature of its surface during microwave heating.[7] In addition, microwaves are effective for uniform heating[8] and can maintain the quality of the product.[9,10] Some reports also suggest efficient energy utilization using microwaves.[11,12] Consequently, processes based on microwaves are currently considered to be promising rapid desorption technology compared to conventional methods.

Some studies have been conducted on the effectiveness of microwave irradiation. Wang et al. suggested an effective diffusivity model of whole fruit Chinese jujube that made microwave drying effective.[13] Mihoubi and Bellagi developed a mathematical model describing heat and mass transfer of combined convective-microwave drying in a clay sample and reported that the temperature rose quickly in the beginning stages of simulated drying.[14]

Some studies have examined the application of microwave heating to adsorbent regeneration for desiccant air conditioning. Ohgushi and Nagae investigated the microwave heating and dehydration characteristics of various zeolites saved as reusable desiccants for home use and reported that a mixture of Na–X and Ca–X was useful for preventing thermal runaway.[15] With regard to the durability of zeolite mixtures against microwave heating,

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they also indicated a 1.3 % decrease in water adsorptivity after repeated microwave irradiation.[16] Miyazaki et al. used a simulation to examine the effects of the switching time and irradiation timing on the performance of microwave irradiation.[17] They reported that timing the microwave irradiation to follow immediately after the regeneration process was advantageous.[17] Kubota et al. reported that both the desorption ratio at desorption equilibrium and the initial desorption rate were found to increase linearly with microwave power.[18]

The authors of the present article carried out the following studies. In past research,[19] zeolite was considered as the adsorbent, because it shows strong water vapor desorption capability; the microwave irradiation effect was examined for water-vapor desorption by zeolite 13X. The desorption speed at microwave heating of 800 W was found to increase by five times or less, and the overplus desorption effect for microwave heating desorption was 1.6–2.0 times that of hot air heating desorption. The availability of desiccant humidity was also suggested for this method. In a previous study,[20] the desorption effect of microwave irradiation was found to be better than that of hot air heating for all zeolites. The effect of the heat source temperature decreased, and the increase in desorption speed was confirmed for microwave irradiation; however, an efficient irradiation method using microwaves is as yet unrealized.

In order to establish a reasonable design standard for a hot air heating and microwave irradiation-type hybrid desiccant humidity conditioner, this study attempted to quantify the microwave heating effect. Specifically, an experiment was carried out comparing water vapor desorption using hot air and microwave heating. The heat transfer behavior was quantified by calculating the heat balance of a zeolite packed bed, and the effect of microwave irradiation was examined.

2. Experiment

2.1 Adsorbent

In this experiment, zeolite DF-9 (13X-type, average particle size: 230 μm, average pore size: 0.8 nm) (Union Showa K.K., Japan) was used as the adsorbent. Figure 1 shows the water vapor adsorption/desorption isotherms measured at different temperatures (30 and 45 °C). The adsorption amount increased sharply below the relative pressure (p/p_0) of 0.05. The adsorption decreased with increasing adsorption temperature, and the adsorption and desorption hysteresis attributed to the difference in temperature was very small. The adsorption and desorption heats were calculated by this result using the Clausius–Clapeyron equation. The adsorption and desorption heats were calculated according to the following equation[21]:

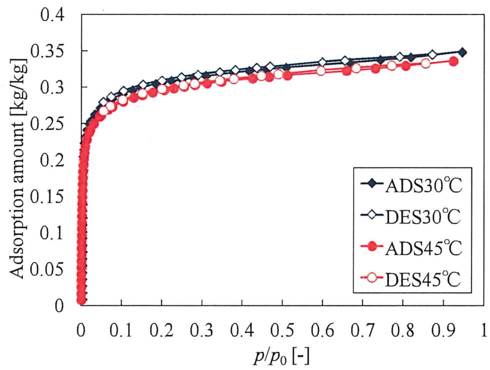

Fig. 1 Adsorption/desorption isotherms for zeolite

Table 1 Dependence adsorption amount of adsorption/desorption heats

q_{ads} [kg/kg]	ΔH_{ads} [kJ/kg]	ΔH_{des} [kJ/kg]
0.29	3280	3480
0.30	3250	3440
0.31	3240	3410
0.32	3210	3310
0.33	3070	3250

$$\Delta H = \frac{\ln\left(\frac{P_2}{P_1}\right)R}{\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \qquad (1)$$

The calculation results are shown in Table 1. The adsorption and desorption heats decreased with increasing adsorption, and the desorption heat was larger than the adsorption heat. The desorption heat was used to calculate the heat balance in the zeolite packed bed.

2.2 Experimental apparatus and method

Figure 2 shows a schematic diagram of the experimental apparatus. The experimental apparatus consisted of a microwave irradiator, adsorption column, evaporator, waveguide, microwave absorber (dummy load), and temperature-controlled room.

The irradiated microwaves (frequency: 2450 MHz) passed the 110-mm-diameter cylindrical waveguide (TE11 mode)

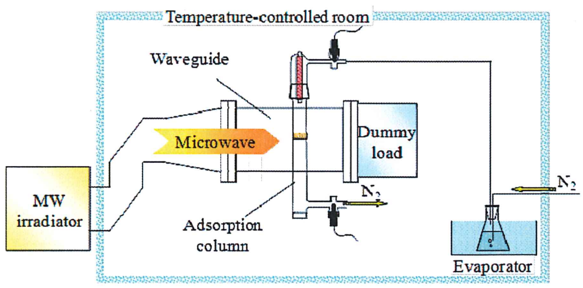

Fig. 2 Schematic diagram of experimental apparatus

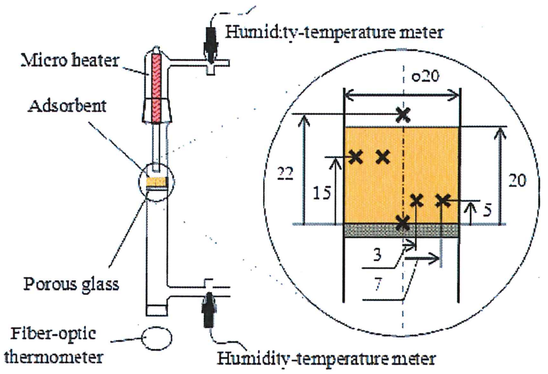

Fig. 3 Schematic diagram of adsorption column

through the rectangular waveguide (TE01 mode) to be finally absorbed by the microwave absorber. The adsorption column was vertically set at a position of 130 mm from the cylindrical waveguide inlet. The electric field strength of the microwaves was at the maximum at this position. Figure 3 shows a schematic diagram of the adsorption column. Humidity–temperature meters (measurement accuracy ±1.5 °C, ±3 % relative humidity; PosiTector DPM, DeFelsko Corp.) were installed on the inlet and outlet of the adsorption column. The amounts of adsorption and desorption were calculated from the measured temperature and humidity. The temperature in the zeolite packed bed was measured by a fiber-optic thermometer (measurement accuracy ±0.5 °C; FL-2000, Anritsu Meter Co., Ltd.). The temperature measurement points in zeolite packed bed are shown by the "x" marks in Fig.3. The zeolite packed bed (packed bed thickness: 20 mm; 5.0 g) in the adsorption column was set in the cylindrical waveguide center. A micro heater was inserted above the zeolite packed bed. The hot air temperature was adjusted by using the micro heater to heat the circulation gas.

The water vapor desorption experiment took place over 30 min and was performed under the following conditions. The adsorption process was induced by circulating N_2 gas at 30 °C and a relative humidity of 40 % to the adsorption column at 0.106 m/s. After adsorption equilibrium was reached, the desorption process was induced by circulating N_2 gas under the same conditions as those of the adsorption process. The desorption process was carried out by hot air heating or combined hot air and microwave heating to compare with the microwave irradiation effect. The process was performed under the following conditions: hot air heating of 30–100 °C and microwave irradiation heating at a microwave output of 30–100 W. In the experiment, the temperature in the zeolite packed bed and humidity at the inlet and outlet of the adsorption column were measured at 1-min intervals.

3. Experimental results and discussions

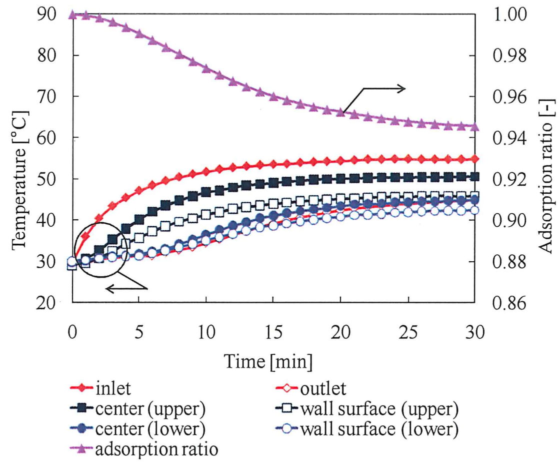

Fig. 4 Time history of temperature and adsorption ratio in the desorption experiment (inlet hot air temperature 55 °C)

3.1 *Temperature and desorption behavior*

Figure 4 shows the time history of the temperature and adsorption ratio in the hot air desorption experiment (inlet hot air at 55 °C). Figure 5 shows the results for the experiment combining hot air with microwave desorption (inlet hot air at 55 °C and microwave output of 50 W). Table 2 shows the adsorption ratio and temperature difference after 30 min compared to the initial values.

The following hot air desorption experiment results are shown in Fig. 4 and Table 2. In the hot air experiment, the inlet temperature immediately rose after the start of the experiment, where as the temperature in the packed bed rose slowly. The temperature change between the initial value and 30 min later was greatest at the inlet and became smaller at the outlet of packed bed. For the lower outlet temperature in the packed bed, the temperature rise was slow between the start of the experiment and 5 min later. In addition, there was a temperature difference in the radial direction of the packed bed. The change in adsorption ratio

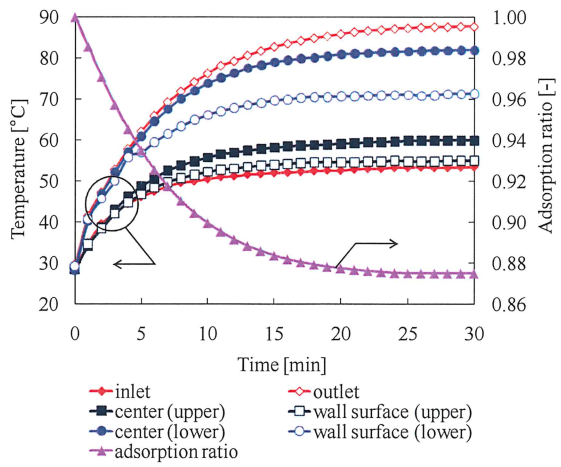

Fig. 5 Time history of temperature and adsorption ratio in the desorption experiment (inlet hot air temperature 55 °C and microwave output of 50 W)

Table 2 Adsorption ratio and temperature difference 30 min after the start of the experiment compared to the initial values

		Temperature change between the initial values and 30 min after the start of the experiment [°C]						Adsorption ratio [-]
		Inlet	Center (upper)	Wall surface (upper)	Center (lower)	Wall surface (lower)	Outlet	
Hot air	55°C	25.1	21.1	16.8	15.2	12.4	15.0	0.946
	75°C	45.0	39.8	31.4	29.4	24.1	27.2	0.899
	100°C	68.2	59.3	46.7	43.7	36.3	41.7	0.850
Hot air and microwave	55°C + 30 W	23.5	26.2	21.5	32.2	24.6	32.2	0.922
	55°C + 50 W	24.7	31.4	26.6	52.8	42.1	58.0	0.875
	55°C + 100 W	24.0	30.6	21.8	92.6	75.2	97.4	0.800
	75°C + 50 W	42.7	45.6	37.1	63.7	48.9	67.0	0.844

was small between the start of the experiment and 2 min later. These results were due to the fact that hot air heating is indirect heating.

The following results for the combined hot air and microwave desorption experiment are shown in Fig. 5 and Table 2. The temperature in the packed bed rose rapidly from the start of the experiment. The temperature inside the packed bed became higher at the outlet of the packed bed and was higher than the inlet hot air temperature. The temperature difference was also in the radial direction of the packed bed, similar to the hot air experiment. The adsorption ratio greatly decreased from the start of the experiment. These results were due to the fact that microwave heating is direct heating.

Therefore, the temperature rose faster with microwave combination heating than with hot air heating. In terms of the change in adsorption ratio, the desorption rate was also faster with microwave combination heating than with hot air heating. These tendencies were observed from the start of the experiment. The results clearly indicate that the microwaves quickly reached the zeolite packed bed and were absorbed. Even if these results changed with the hot air temperature and microwave output conditions, the tendencies were confirmed to be similar.

3.2 *Heat consumption of the zeolite packed bed*

The heat transfer of this experimental system can be expressed as shown in Fig. 6. The heat balance equation of this system is as follows:

$$Q_{\mathrm{in}} - Q_{\mathrm{out}} = Q_{\mathrm{s}} + Q_{\mathrm{des}} + Q_{\mathrm{side}} \tag{2}$$

Q_{in} is defined by the presence or absence of microwave irradiation:

$$Q_{\mathrm{in}} = Q_{\mathrm{gas}} \quad \text{(Hot air experiment)} \tag{3}$$

$$Q_{\mathrm{in}} = Q_{\mathrm{gas}} + Q_{\mathrm{MW}} \quad \text{(Microwave experiment)} \tag{4}$$

Each quantity of heat is then calculated according to the following Eqs. (5)–(9).

$$Q_{\mathrm{gas}} = Q_{\mathrm{out}} = \dot{m}h \tag{5}$$

$$Q_{\mathrm{MW}} = \left(\frac{P_{\mathrm{w}} M_{\mathrm{w}}}{\rho_{\mathrm{w}}} + \frac{P_{\mathrm{z}} M_{\mathrm{z}}}{\rho_{\mathrm{z}}} \right) \tag{6}$$

$$Q_{\mathrm{s}} = \left(M_{\mathrm{w}} C_{pw} + M_{\mathrm{z}} C_{pz} \right) \frac{dT_{\mathrm{p}}}{d\theta} \tag{7}$$

$$Q_{\mathrm{des}} = M_{\mathrm{z}} \Delta H_{\mathrm{des}} \frac{dq_{\mathrm{des}}}{d\theta} \tag{8}$$

$$Q_{\mathrm{side}} = \lambda A_{lm} \left(\frac{T_{\mathrm{center}} - T_{\mathrm{wall}}}{r_{\mathrm{wall}} - r_{\mathrm{center}}} \right) \tag{9}$$

In addition, the heat loss of microwaves (P) was calculated according to the following expression[22]:

$$P = \frac{5}{9} f E^2 \varepsilon_r \tan\delta \cdot 10^{-10} \tag{10}$$

The loss coefficients ($\varepsilon_r \tan\delta$) are taken from the literature.[22] The loss coefficient of zeolite is 0.25, and the loss coefficient of water is 12.3–3.1 (25–85 °C). The field intensity (E), or the equipment eigenvalue, was calculated experimentally by heating water. After the water was poured into the same location in the zeolite packed bed, the water was heated by

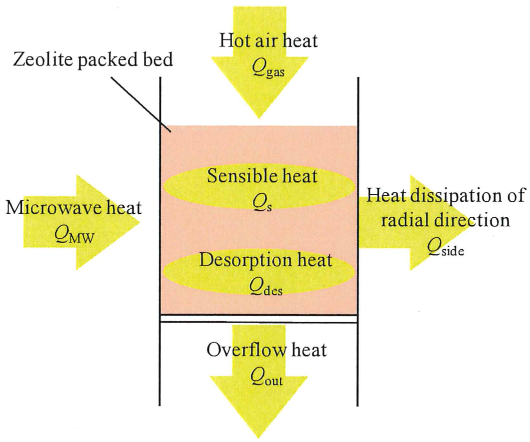

Fig. 6 Heat consumption of the zeolite packed bed

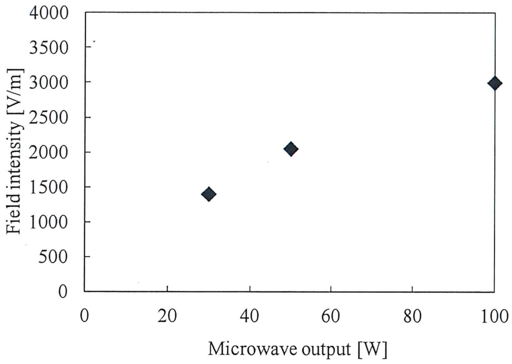

Fig. 7 Calculated field intensity versus microwave output

microwave irradiation for a given length of time. P was calculated from the rise in temperature, amount of evaporation, and heat discharge of the water. P obtained in the water heating experiment was used to evaluate E. E as calculated in the experiment is shown in Fig. 7. E increased with increasing microwave output. The effective thermal conductivity in the packed bed was calculated from the temperature gradient in the radial direction for the steady state reached in the hot air desorption experiment.

3.3 Microwave irradiation effect

Figure 8 shows the calculation results for each heat consumption and the heat balance for the hot air experiment with an inlet temperature of 55 °C. Q_s reached its maximum 1 min after the start of the hot air experiment and decreased thereafter. Q_{des} reached its maximum about 8–10 min after the start and decreased thereafter. Q_{side} increased after the start of the experiment and became dominant in the latter half of the experiment. The sensible heat consumption and desorption heat consumption showed different tendencies in the hot air experiment. The heat balance for the 30 min experiment was about 90–95 %. In the hot air heating experiments, the time difference for the maximum values arrivals of the sensible heat and desorption heat consumption was large. All of these results

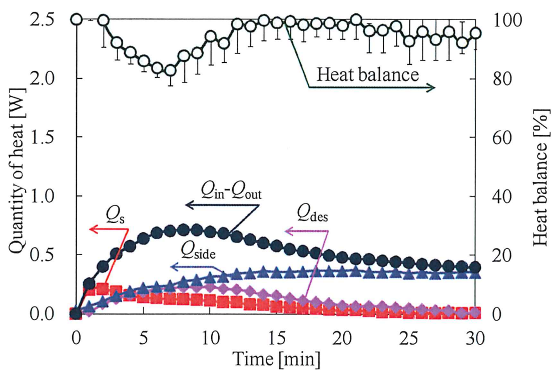

Fig. 8 Calculation results of each heat consumption and heat balance for the hot air experiment (inlet hot air temperature 55 °C)

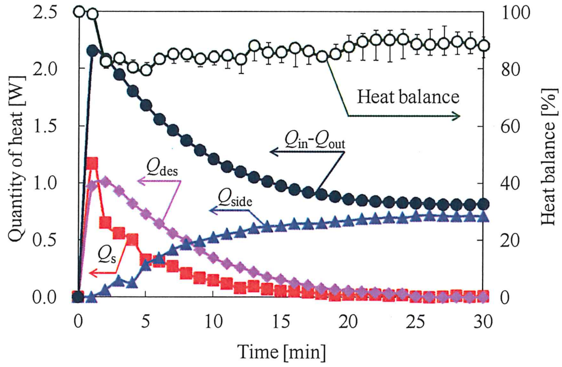

Fig. 9 Calculation results of each heat consumption and heat balance for the microwave experiment (inlet hot air temperature 55 °C and microwave output of 50 W)

indicate that, excluding desorption, the ratio of heat loss becomes large for indirect heating.

Figure 9 shows the calculation results of each heat consumption and the heat balance for the combined hot air and microwave experiment with an inlet temperature of 55°C and microwave output of 50 W. Q_s reached its maximum about 1 min after the start of the microwave experiment and decreased thereafter. Q_{des} reached its maximum about 2 min after the start and decreased thereafter. Q_{side} increased after the start of the experiment and became dominant in the latter half of the experiment. The heat balance for the 30 min experiment was about 85–90 %. Compared to hot air heating, microwave heating showed a small time difference for the maximum value arrivals of the sensible heat and desorption heat consumption. Therefore, microwave heating can lower the ratio of heat losses other than desorption by direct heating.

Even if the hot air temperature and microwave output were changed, the results showed similar tendencies as those detailed above. The repeatability of the heat balance in this experiment apparatus was less than ±6 %.

Next, the ratio of the desorption heat to all heat consumption in the packed bed was calculated as an index to indicate the microwave effect. The ratio of desorption heat to all

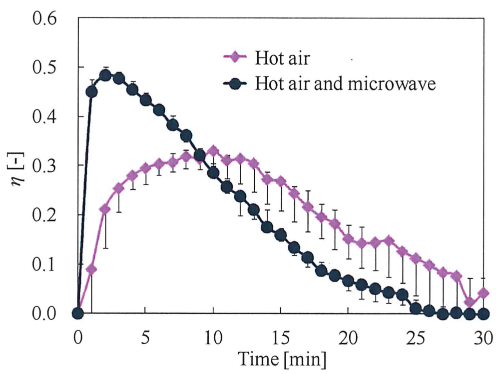

Fig. 10 η versus time

Table 3 Calculation results of η_{max} and t_{max}

		η_{max} [-]	t_{max} [min]
Hot air	55 °C	0.333	10
	75 °C	0.384	7
	100 °C	0.343	8
Hot air and microwave	55 °C + 30 W	0.388	3
	55 °C + 50 W	0.484	2
	55 °C + 100 W	0.410	3
	75 °C + 50 W	0.413	3

heat consumption in the packed bed is defined as follows:

$$\eta = \frac{Q_{des}}{Q_{in} - Q_{out}} \tag{11}$$

Figure 10 shows the calculated result for a hot air temperature of 55 °C and microwave output of 50 W. Table 3 shows the calculation results of η_{max} and arrival time of η_{max} (t_{max}) for each experiment.

The following results are shown in Fig. 10 and Table 3. η_{max} was larger with microwave irradiation than with hot air only. The maximum of η_{max} was 0.484 for the experiment combining hot air at 55 °C and a microwave output of 50 W. The t_{max} was faster with microwave irradiation than hot air only. The η of the microwave experiment was larger than the η of the hot air experiment up to 8 min from the start of the experiment but became smaller thereafter. These results suggest that microwave heating is effective for desorption at the beginning.

4. Conclusions

The purpose of this study was to quantify the microwave heating effect. The heat transfer during microwave-assisted desorption of water vapor from a zeolite packed bed was evaluated, and the following results were obtained.

1. The temperature rise in the zeolite packed bed and desorption rate were faster with microwave combination heating than with hot air heating only.
2. The calculated heat balance suggests that microwave heating is effective for desorption from the start.

In the future, further studies on other adsorbents will be carried out to compare with the effect of microwave irradiation. Examinations including the cost of microwave irradiation will also be performed.

Nomenclature

A_{lm}	Logarithmic mean heat transfer area	m^2
C_p	Specific heat at constant pressure	$Jkg^{-1}K^{-1}$
E	Field intensity	Vm^{-1}
f	Frequency	Hz
ΔH_{ads}	Adsorption heat	Jkg^{-1}
ΔH_{des}	Desorption heat	Jkg^{-1}
h	Specific enthalpy	Jkg^{-1}
M	Mass	kg
	Mass flow rate	kgs^{-1}
P	Heat loss of microwave	Wm^3
p	Steam pressure	pa
p_0	Saturated steam pressure	pa
p/p_0	Relative pressure	
Q_{des}	Quantity of desorption heat	W
Q_{gas}	Quantity of hot air heat	W
Q_{in}	Quantity of inlet heat	W
Q_{MW}	Quantity of microwave heat	W
Q_{out}	Quantity of overflow heat	W
Q_s	Quantity of sensible heat	W
Q_{side}	Quantity of heat dissipation	W
q_{ads}	Adsorption amount	kg/kg
q_{des}	Desorption amount	kg/kg
R	Gas constant	
r	Radial range	m
T	Temperature	°C
$\tan\delta$	Dielectric loss angle	
t_{max}	Arrival time of η_{max}	min

Greek letters

ε_r	Relative permittivity	
η	Ratio of desorption heat to all heat consumption in the packed bed	
θ	Time	s
λ	Effective thermal conductivity	$Wm^{-1}K^{-1}$
ρ	Density	kgm^{-3}

Subscripts

c	Center of zeolite packed bed
max	Maximum value
p	Packed bed
w	Adsorbed water
wall	Wall surface of zeolite packed bed
z	Zeolite

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