

Performance of a Novel Steam Generation System Using a Water-zeolite Pair for Effective Use of Waste Heat From the Iron and Steel Making Process

Koichi NAKASO, Yuuki TANAKA, Shotaro ESHIMA, Shunsuke KOBAYASHI and Jun FUKAI*

Department of Chemical Engineering, Graduate School of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395 Japan.

(Received on August 6, 2014; accepted on September 25, 2014)

To reduce CO₂ emission from the iron and steel making process, a novel steam generation system using waste hot water is proposed to use waste heat effectively from the process. This system adopts a direct heat exchange method for the adsorption heat pump to increase the heat transfer rate between the adsorbent and heat transfer fluid. In this study, the performance of the system is evaluated according to the mass of steam generated during the cyclic operation. The regeneration process is first studied taking the transport phenomena in the generator into account. The mass of steam generated is then estimated based on the distributions of water content and temperature in the generator. The results from the model exhibit good agreement with the experimental results. The effect of the operating conditions on the performance of the steam generation process is studied. It was found that there was an appropriate regeneration time to maximize the mass of steam generated during the cycle. For the effective use of adsorption heat, reuse of the water drained from the steam generation process (Drainage Recycling) is proposed. As a result, recycling the drainage water is a practical and helpful method to improve the performance of the system.

KEY WORDS: effective use of waste heat; steam generation; adsorption heat pump; numerical.

1. Introduction

Efforts in energy conservation research are pursued because of the limitation of fossil fuel and the environmental issues of global warming. The steel industry is one of the largest energy-consuming manufacturing industries. Large amount of waste water at less than 100°C and exhaust gas at less than 200°C, in particular, are released from the iron and steel making processes. The reduction of CO₂ emission from the process is also an important issue for the steel industry. Although some strategies for the separation and reduction of CO₂ in the exhaust gas from the process have been proposed recently as shown in Fig. 1,^{1,2)} another energy source for the separation and reduction of CO₂ is required. For stable and economic operation, effective use of waste heat from the iron and steel making process, in particular thermal energy storage, is necessary. Because heat transfer phenomena are governed by the temperature difference between the heat source and heat sink, a method to upgrade the temperature level of waste heat is a key technology for the effective use of waste energy. The heat pump system is one of the promising methods for upgrading the temperature level. There are several types of heat pump systems. The mechanical heat pump is generally used for air

conditioning and refrigeration. To raise the temperature level, the mechanical heat pump is not always suitable because of the lack of durability of the system components. A chemical heat pump uses the reaction heat from reversible reactions. Because its working temperature depends on the chemical reaction, a chemical heat pump can be used from low to high temperatures.

The authors focused on the adsorption heat pump using a

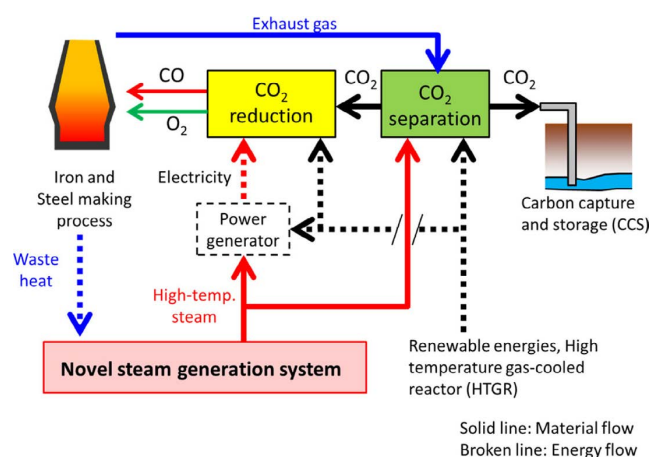


Fig. 1. Concept of the reduction in CO₂ emission from the iron and steel making process using the novel steam generation system. (Online version in color.)

* Corresponding author: E-mail: jfukai@chem-eng.kyushu-u.ac.jp
DOI: <http://dx.doi.org/10.2355/isijinternational.55.448>

zeolite-water pair, which is classified as a chemical heat pump, to upgrade the temperature level of the waste hot water. In particular, the authors adopted a direct heat exchange method for the adsorption heat pump system to overcome the low heat transfer rate between the packed bed and heat transfer fluid.^{3–6)} **Figure 2** shows the schematic of the cycle for the novel adsorption heat pump. At the start of the process, the steam generator with a dry adsorbent is evacuated using a vacuum pump to avoid air-entrained steam. Saturated water vapor at low pressure is then introduced as the preheating process. By adsorbing water vapor, the temperature of the adsorbent is increased. Subsequently, hot water is introduced to the dry adsorbent as an adsorbate and a heat transfer fluid. The direct contact of water and zeolite results in the evaporation of excess water by releasing adsorption heat from the zeolite. When the steam generator is full of water, the steam generation process is terminated. After draining the residual water between the adsorbent particles, regeneration of the adsorbent is started. Drying and desorption of the adsorbent occur continuously by introducing dry gas. After the regeneration process, the adsorbent returns to its initial state. Waste heat can be used in the novel steam generation system for generating the saturated water vapor in the preheating processes, for heating feed water in the steam generation processes, and for heating dry gas in the regeneration processes. In the direct heat exchange method, the large surface area of adsorbent particles can be used for the convection heat transfer as well as the reaction. In our previous studies, superheated steam at 0.1–0.4 MPa was generated using water at 80°C and dry gas at 130°C with

laboratory-scale apparatus using zeolite as the adsorbent.^{3–5)} In addition, the generation of steam under the cyclic operation of steam generation and regeneration processes was demonstrated experimentally.⁶⁾

In this study, the performance of the system using a water-zeolite pair was numerically investigated in terms of the mass of steam generated during the cyclic operation. To predict the progress of the regeneration process, a mathematical model for each process was developed and compared with the experimental results. The mass of the steam generated in the cyclic steam generation and regeneration processes was studied. As shown in Fig. 2, the steam generation process strongly depends on the progress of the regeneration process. The regeneration process was first numerically studied under various conditions. The result of each calculation of the regeneration process was used as the initial condition of the steam generation process. Accordingly, the mass of steam generated was calculated under various regeneration conditions. The effect of the operating conditions on the mass of steam generated was investigated.

2. Experiment

Figure 3 shows a schematic of the experimental apparatus, which consists of a cylindrical generator, water reservoir, feeding pump, compressor, drier, gas heater, condenser, an electronic balance, and a humidity meter. The generator was made of stainless steel 100 mm high and 78 mm in inner diameter. K-type thermocouples were inserted into the generator to monitor the transient temperatures. Cylindrical particles of Zeolite 13X of about 0.27 kg were used as

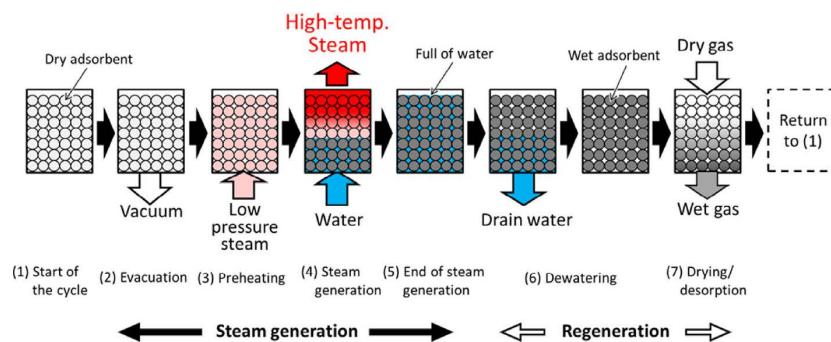


Fig. 2. Schematic of the cycle for the novel steam generation system. (Online version in color.)

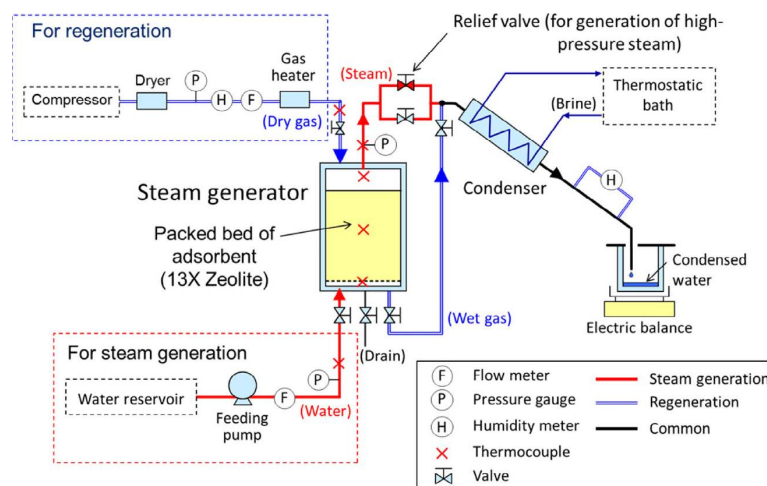


Fig. 3. Schematic of the experimental apparatus. (Online version in color.)

adsorbent. In the steam generation process, the generated steam was condensed by the condenser to obtain the mass of steam generated. The stainless steel pipe line was heated using electric heating cables to prevent condensation of the steam generated. In the regeneration process, dry air from the compressor was heated to a preset temperature and then introduced through the generator for pushing the wet gas out. The temperature, dew point and superficial velocity of dry air were 140°C, -50°C DP (3.94 Pa), and 0.57 Nm/s, respectively. To observe the effect of the regeneration time on the mass of steam in the cycle operation, the regeneration time was changed from 600 to 3 600 s.

To validate the numerical model for the regeneration described in the following section, another experiment on regeneration was carried out using another generator for which the inner diameter was 21 mm because of the limitation of the flow rate of the compressor. The temperature, dew point and superficial velocity of dry air were 80–130°C, -50°C DP, and 1–1.6 m/s, respectively. To reduce the effect of the remaining water in the gap between the particles on the regeneration, the wet particles were wiped before packing into the generator. This is because any remaining water sometimes results in non-uniform distribution of voids in a packed bed. To measure the water content of the adsorbent during the regeneration, the humidity of the outlet gas was measured using the humidity meter. The relative humidity of the outlet air was almost 100% at the beginning of the process because evaporation of free water took place all over the packed bed. Therefore, the humidity meter was used instead of the condenser. To prevent condensation in the humidity meter, the outlet gas was heated before introduction to the meter.

3. Mathematical Model

3.1. Calculation of the Regeneration Process

A mathematical model considering transport phenomena during the regeneration process was developed. As seen in Fig. 2, the regeneration process mainly takes place along the flow direction, that is, the axial direction of the cylindrical generator. Therefore the regeneration process was studied using a one-dimensional mathematical model. **Figure 4** shows the computational domain. For the governing equations, the following conservation equations of mass and energy for solid and gas were considered. The mass conservation of water vapor was especially solved to consider the rate of regeneration in the calculations. Ergun's

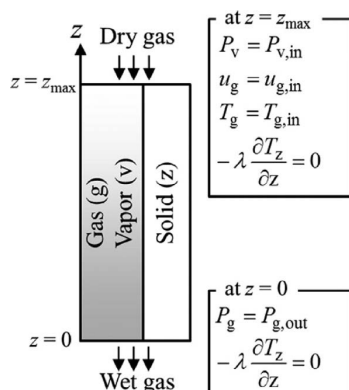


Fig. 4. Computational domain and boundary conditions.

equation was used instead of the momentum conservation equation for gas.

The mass conservation of gas phase ($i = g$) and water vapor ($i = v$, $v \subset g$) are given by the following equation:

$$\varepsilon_b \frac{\partial \rho_i}{\partial t} = -\frac{\partial(\rho_i u)}{\partial z} + \delta_{iv} \varepsilon_b \frac{\partial}{\partial z} \left(D_v \frac{\partial \rho_v}{\partial z} \right) - (1 - \varepsilon_b) \rho_z S_{reg}, \quad (i = v, g) \quad (1)$$

where ε_b , ρ , t , u , D , and S_{reg} is the porosity of the packed bed, density, time, superficial velocity, diffusivity, and rate of regeneration, respectively. δ_{iv} indicates Kronecker's delta because the second term on the right hand side of Eq. (1) is the diffusion of water vapor in the gas phase. It should be noted that gas consists of air and water vapor (g [gas] = a [air] + v [water vapor]). Assuming an ideal gas, the gas state equation was used to convert the density to the pressure:

$$\rho_i = \frac{M_{wi}}{R} \frac{P_i}{T_g}, \quad (2)$$

where M_w , R and T are the molecular weight, gas constant and temperature, respectively. Accordingly, Eq. (1) is expressed by the following equation:

$$\begin{aligned} \frac{\varepsilon_b M_{wi}}{R} \frac{\partial}{\partial t} \left(\frac{P_i}{T_g} \right) = & -\frac{M_{wi}}{R} \frac{\partial}{\partial z} \left\{ \left(\frac{P_i}{T_g} \right) \cdot u \right\} \\ & + \delta_{iv} \frac{\varepsilon_b M_{wi}}{R} \frac{\partial}{\partial z} \left\{ D_v \frac{\partial}{\partial z} \left(\frac{P_v}{T_g} \right) \right\} - (1 - \varepsilon_b) \rho_z S_{reg}, \quad (i = v, g) \quad (3) \end{aligned}$$

The energy conservation of the gas phase ($i = g$), and solid (zeolite, $i = z$) were given by the following equation:

$$\begin{aligned} \varphi_i \rho_i c_{pi} \frac{\partial T_i}{\partial t} = & -\delta_{ig} \frac{\partial(c_{pi} \rho_i u T_i)}{\partial z} + \varphi_i \frac{\partial}{\partial z} \left(\lambda_i \frac{\partial T_i}{\partial z} \right) \\ & + (-1)^{\delta_{iz}} (1 - \varepsilon_b) h a_p (T_z - T_g) \\ & + \delta_{iz} \Delta H_{reg} (1 - \varepsilon_b) \rho_z S_{reg}, \quad (i = g, z) \quad (4) \end{aligned}$$

where, φ , c_p , λ , a_p , h , and ΔH_{reg} indicate the volume fraction, heat capacity, thermal conductivity, specific surface area, heat transfer coefficient, and enthalpy of regeneration, respectively. The fourth term on the right hand side of Eq. (4) is energy consumption resulting from the regeneration.

For the momentum conservation of gas, Ergun's equation⁷⁾ was used:

$$\frac{\partial P_g}{\partial z} = - \left\{ 150 \frac{(1 - \varepsilon_b)^2}{\varepsilon_b^3} \left(\frac{\mu_g}{d_p^2} \right) + 1.75 \frac{1 - \varepsilon_b}{\varepsilon_b^3} \left(\frac{\rho_g |u|}{d_p} \right) \right\} u \quad (5)$$

where, μ and d_p are the viscosity and particle diameter, respectively.

The regeneration consists of drying and desorption. It depends on the water content of zeolite. It was assumed that the drying takes place at higher than the saturated amount of water adsorbed on zeolite ($x > x_{sat}$). It is defined by assuming that boundary layer around a zeolite particle is dominant, and given by the following equation:

$$S_{reg} = - \left(\frac{\varepsilon_b}{1 - \varepsilon_b} \right) \frac{M_{w,v}}{RT_g} \frac{a_p k_{gz}}{\rho_z} (P_{v,sat}(T_z) - P_v) \quad (6)$$

where k_{gz} is mass transfer coefficient.

The rate of desorption at lower than x_{sat} is based on the

Table 1. Physical properties and parameters in the calculations.

ρ_z [kg/m ³]	1047 ^{*1}
ϵ_b [-]	0.46
λ_z [W/(m·K)]	0.15 ^{*1}
c_{pz} [J/(kg·K)]	823
λ_w [W/(m·K)]	0.67
c_{pw} [J/(kg·K)]	4200
ρ_w [kg/m ³]	971
λ_v [W/(m·K)]	$(8.74 \times 10^{-5})T - (8.34 \times 10^{-3})$
c_{pv} [J/(kg·K)]	$(-5.3047 \times 10^{-1})T + (2.245 \times 10^{-3})$
μ_v [Pa s]	$(3.97 \times 10^{-8})T - (2.4374 \times 10^{-6})$
λ_a [W/(m·K)]	$(7.15 \times 10^{-5})T + (5.0667 \times 10^{-3})$
c_{pa} [J/(kg·K)]	$(4.6609 \times 10^{-4})T^2 - (2.5413 \times 10^{-1})T + 1040$
μ_a [Pa s]	$(3.9683 \times 10^{-8})T + (6.7698 \times 10^{-6})$
L [kJ/kg-water]	$(-1.443 \times 10^{-3})(T-273.15)^2 - 2.292(T-273.15) + 2501$
Q [kJ/kg-water]	1350
ΔH_{reg} [kJ/kg-water]	$\begin{cases} L & \text{(for drying)} \\ L + Q & \text{(for desorption)} \end{cases}$
ΔH_{ads} [kJ/kg-water]	Q
A [1/s]	4.0×10^5
E [J/mol]	3.5×10^4
N [-]	3

^{*1} Density and thermal conductivity of zeolite are the effective values for a zeolite pellet, which are considered pore inside the particle.

measurement data from thermal analysis:

$$S_{reg} = -A \exp\left(\frac{-E}{RT_z}\right)(x - x_{eq})^N \dots\dots\dots (7)$$

x_{eq} indicates the equilibrium water content of zeolite, which is expressed by the function of the partial pressure of water vapor and temperature $x_{eq} = f(P_v, T_z)$.

For the initial conditions, uniform distributions of pressure P_{ini} , temperature T_{ini} and water content x_{ini} were assumed. Boundary conditions are also shown in Fig. 4. The physical properties are summarized in **Table 1**. The discretization of all governing equations in space was based on a finite volume method. The time deviation terms were discretized using an implicit scheme. Considering the effects of the grid number and time step on the calculation, the typical grid number and time step were 200 for $z_{max} = 0.1$ m and 1×10^{-3} s, respectively.

3.2. Estimating the Mass of Steam Generated

To understand the performance of the system, the mass of the steam generated in the cyclic steam generation and regeneration processes was studied. According to a previous study, a system satisfied the energy balance in the steam generation process.⁶⁾ This implies that the mass of steam generated can be estimated based on the energy balance between the initial and the final states of the steam generation process. While the initial state of the steam generation process strongly depends on the local distributions of temperature and water content in the zeolite after the regeneration process, the final state of the steam generation process is independent of the regeneration process. In this study, the mass steam generated was therefore estimated using the

energy balance based on the local temperature and water content profiles at the final state of the regeneration process.

For the preheating process shown in Fig. 2(3), the temperature of the adsorbent is increased by the adsorption of water vapor. The energy balance for a unit mass of zeolite during the preheating process is given by the following equation:

$$(c_{pz} + c_{pw}\bar{x}_2)(\bar{T}_{z2} - T_{ref}) - (c_{pz} + c_{pw}\bar{x}_1)(\bar{T}_{z1} - T_{ref}) = (\bar{x}_2 - \bar{x}_1)\{c_{pw}(T_{ph} - T_{ref}) + L_{ph}\} + \Delta H_{ads}(\bar{x}_2 - \bar{x}_1) \dots (8)$$

where subscript 1 and 2 indicate the initial and final states of the preheating process, respectively. The first and second terms on the left hand side of Eq. (8) are the enthalpy of the packed bed after and that before the preheating process, respectively. The first term on the right hand side of Eq. (8) is the input energy from saturated vapor introduced into the adsorbent for preheating. The second term is the adsorption heat. T_{ref} , L , and ΔH_{ads} are the reference temperature, latent heat and enthalpy of adsorption, respectively. It should be noted that the sensible heat of water vapor in the void of the packed bed is ignored in this study because its enthalpy is less than 0.3% of total enthalpy supplied. $\bar{x}$ and $\bar{T}$ are the averaged local water content and temperature, respectively. For example, $\bar{x}_1$ and $\bar{T}_{z2}$ are given by:

$$\bar{x}_1 = \frac{\int_{V_R} x_1 dv}{\int_{V_R} dv} \text{ and } \bar{T}_{z2} = \frac{\int_{V_R} T_{z2} dv}{\int_{V_R} dv} \dots\dots\dots (9)$$

where, V_R is the volume of the steam generator. Based on the adsorption equilibrium for a water-zeolite pair, x_2 after preheating is given by $x_2 = f(P_{ph}, T_{z2})$. When the local $(x_2 - x_1)$ value is negative, adsorption would not take place in this region. That is, $T_{z2} = T_{z1}$ and $x_2 = x_1$ are given, respectively. From Eq. (8), the averaged adsorbent temperature after the preheating process $\bar{T}_{z2}$ is given by

$$\bar{T}_{z2} = \frac{(c_{pz} + c_{pw}\bar{x}_1)\bar{T}_{z1} + (\bar{x}_2 - \bar{x}_1)(c_{pw}T_{ph} + \Delta H_{ads} + L_{ph})}{c_{pz} + c_{pw}\bar{x}_2} \dots (10)$$

Equations (9) and (10) and the equation of adsorption equilibrium are solved simultaneously.

After the preheating process, water is introduced into the packed bed (see Fig. 2(4)). The energy balance during the steam generation process is given by

$$\begin{aligned} & [c_{pz} + c_{pw}\{x_f + (m_d/m_z)\}](T_{z3} - T_{ref}) - (c_{pz} + c_{pw}\bar{x}_2)(\bar{T}_{z2} - T_{ref}) \\ & = c_{pw}\{(x_f - \bar{x}_2) + (m_d/m_z) + (m_v/m_z)\}(T_{w,in} - T_{ref}) \\ & \quad - (m_v/m_z)\{c_{pw}(T_v - T_{ref}) + L_v\} + \Delta H_{ads}(x_3 - \bar{x}_2) \end{aligned} \dots\dots\dots (11)$$

where the first term on the left hand side of Eq. (11) indicates the final state of the steam generation process. As seen in Fig. 2(5), the steam generator is full of water at the end of the steam generation process. Therefore, x_f indicates the "full" water content, which means the adsorbed water and free water in the particle. (m_d/m_z) is the mass of water between the particles per unit mass of zeolite. Subscript 3 indicates the final state of the steam generation process. The first term on the right hand side of Eq. (11) is the enthalpy of the input water. $\{(x_f - x_2) + (m_d/m_z) + (m_v/m_z)\}$ indicates

the mass of input water per unit mass of zeolite. (m_v/m_z) is the mass of steam generated per unit mass of zeolite. The second term on the right hand side of Eq. (11) is the enthalpy of the steam, which is assumed to be saturated steam at temperature T_v . The third term on the right hand side of Eq. (11) is the adsorption enthalpy. Here, $x_3 = x_{\text{sat}}$. Based on the experiment, the average temperature at the end of the steam generation process T_{z3} is given by the following equation assuming a linear temperature profile in the generator.

$$T_{z3} = \frac{T_v + T_{w,\text{in}}}{2} \dots\dots\dots (12)$$

The mass of water between the particles per unit mass of zeolite (m_d/m_z) is given by $\{\varepsilon_b/(1-\varepsilon_b)\}(\rho_w/\rho_z)$, and is the same as the mass of drainage water after the steam generation process. Accordingly, the mass of steam generated per unit mass of zeolite is given by:

$$\left(\frac{m_v}{m_z}\right) = \frac{1}{c_{pw}(T_v - T_{w,\text{in}}) + L_v} \left[\Delta H_{\text{ads}}(x_3 - \bar{x}_2) - (c_{pz} + c_{pw}\bar{x}_2)(T_{z3} - \bar{T}_{z2}) - c_{pw} \left\{ (x_f - \bar{x}_2) + \left(\frac{\varepsilon_b}{1-\varepsilon_b} \right) \left(\frac{\rho_w}{\rho_z} \right) \right\} (T_{z3} - T_{w,\text{in}}) \right] \dots (13)$$

3.3. Calculation of Reuse of the Drainage Water (Drainage Recycling, DR)

After the steam generation process, water at higher than input temperature remains in the void of the packed bed. It is then released from the generator as drainage water (see Fig. 2(6)). This is helpful when this drainage water is used as the input water in the next cycle. In this study, the reuse of the drainage water, called Drainage Recycling (DR) is studied. In the n^{th} steam generation process, the drainage water of the previous $((n-1)^{\text{th}})$ cycle is first introduced and then the normal input water (which is the same as the first cycle) is fed to fill the packed bed of adsorbent. Therefore, the enthalpy of the n^{th} input water per unit mass of zeolite is expressed by:

$$c_{pw} \{ (x_f - \bar{x}_2) + (m_d/m_z) + (m_v^{(n)}/m_z) \} (T_{w,\text{in}}^{(n)} - T_{\text{ref}}) = c_{pw} (m_d/m_z) (T_{z3}^{(n-1)} - T_{\text{ref}}) + c_{pw} \{ (x_f - \bar{x}_2) + (m_v^{(n)}/m_z) \} (T_{w,\text{in}}^{(1)} - T_{\text{ref}}) \dots (14)$$

where $T_{z3}^{(n-1)}$ is the temperature of drainage water at $(n-1)^{\text{th}}$ cycle. ($m_v^{(n)}/m_z$) is the mass of steam generated at the n^{th} cycle per unit mass of zeolite. The temperature of the n^{th} input water $T_{w,\text{in}}^{(n)}$ is therefore expressed by

$$T_{w,\text{in}}^{(n)} = \gamma T_{z3}^{(n-1)} + (1-\gamma) T_{w,\text{in}}^{(1)} \dots\dots\dots (15)$$

where:

$$\gamma = \frac{(m_d/m_z)}{(x_f - \bar{x}_2) + (m_d/m_z) + (m_v^{(n)}/m_z)} = \frac{\left(\frac{\varepsilon_b}{1-\varepsilon_b} \right) \left(\frac{\rho_w}{\rho_z} \right)}{\left\{ (x_f - \bar{x}_2) + \left(\frac{\varepsilon_b}{1-\varepsilon_b} \right) \left(\frac{\rho_w}{\rho_z} \right) \right\} + \left(\frac{m_v^{(n)}}{m_z} \right)} \dots\dots (16)$$

According to Eq. (13), mass of steam generated per unit

mass of zeolite at n^{th} cycle is given by:

$$\left(\frac{m_v^{(n)}}{m_z}\right) = \frac{1}{c_{pw}(T_v - T_{w,\text{in}}^{(n)}) + L_v} \left[\Delta H_{\text{ads}}(x_3 - \bar{x}_2) - (c_{pz} + c_{pw}\bar{x}_2)(T_{z3}^{(n)} - \bar{T}_{z2}) - c_{pw} \left\{ (x_f - \bar{x}_2) + \left(\frac{\varepsilon_b}{1-\varepsilon_b} \right) \left(\frac{\rho_w}{\rho_z} \right) \right\} (T_{z3}^{(n)} - T_{w,\text{in}}^{(n)}) \right] \dots (17)$$

In the same way, a linear temperature profile is assumed at the end of the steam generation process. T_{z3} for the n^{th} cycle is therefore given by using the temperature of the saturated steam T_v and the temperature of the input water for the n -th cycle $T_{w,\text{in}}^{(n)}$,

$$T_{z3}^{(n)} = \frac{T_v + T_{w,\text{in}}^{(n)}}{2} \dots\dots\dots (18)$$

In the calculation of DR, Eqs. (15)–(18) are solved simultaneously. When the averaged water content is higher than its saturated value, steam cannot be generated. In this case, the temperature of water after the n^{th} cycle $T_{z3}^{(n)}$ is calculated using Eq. (17) considering $(m_v^{(n)}/m_z) = 0$. The temperature of the input water in the $((n+1)^{\text{th}})$ cycle $T_{w,\text{in}}^{(n+1)}$ is then calculated using the Eqs. (15) and (16).

The temperature of the drainage water depends on the temperature of the steam generated. Before the drainage water is released from the generator, the temperature of the remaining water ranges from $T_{w,\text{in}}$ to T_v . When the drainage water is released from the generator under atmospheric pressure, its maximum temperature is limited to 100°C. Such a limited case is called the “Limited DR”. On the other hand, the ideal no-limitation case is called the “Full DR”.

4. Results

4.1. Comparison between the Model and Experiment for the Regeneration Process

The numerical results from the model were compared with the experimental results for validation. **Figure 5** shows the comparison between the calculation and experiment for the regeneration process. The initial temperature and water content were 25°C and 0.6 kg-water/kg-zeolite, respectively. Three gas inlet conditions were studied. As seen in the figure, there is a little difference between calculated water content and experimental one at the initial stage of the regeneration process especially for the higher flow rates. To study the reason of the difference, the effect of the heat loss on the calculated results was studied considering the heat transfer between adsorbent and ambient air. However, there was little difference between the calculation results. The difference between calculation and experiment is probably due to the distribution of the flow velocity of the regeneration gas. However the calculation could reasonably predict the temperature at the center of the generator as well as the water content of zeolite.

4.2. Effect of Regeneration Time on the Mass of Steam Generated in the Cyclic Operations

Performance of the system is discussed in terms of the mass of steam generated in the cyclic operation under

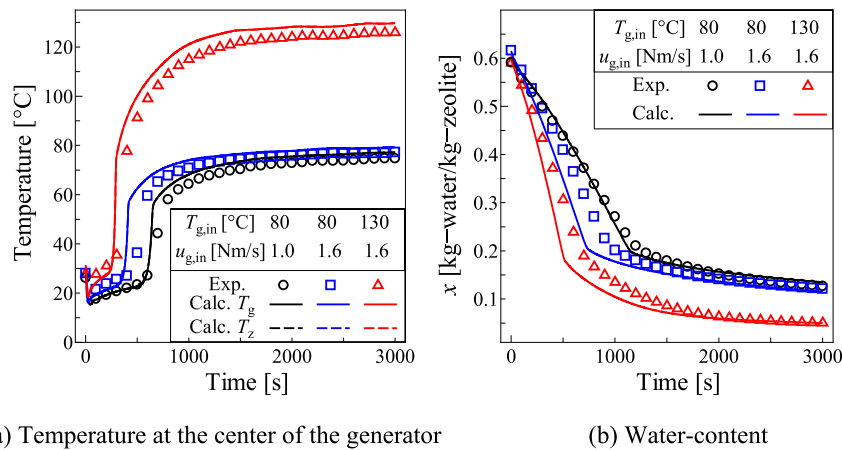


Fig. 5. Comparison between experiments and calculations for the regeneration process. (Online version in color.)

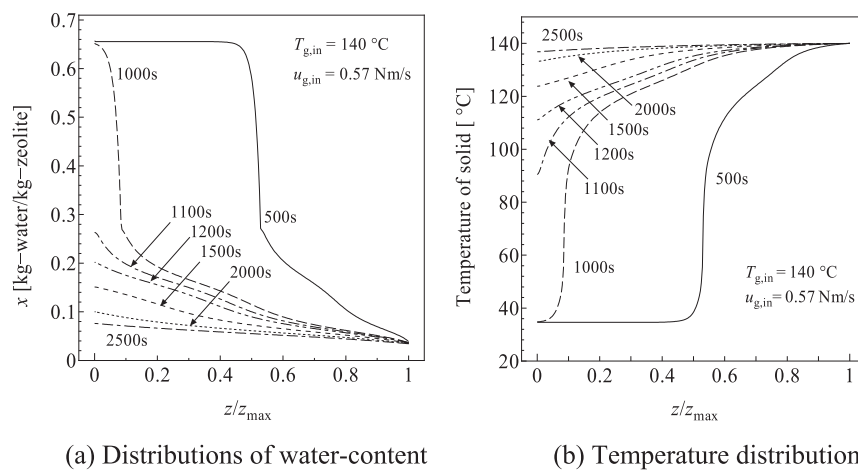


Fig. 6. Calculated distributions of the water content of zeolite and temperature at various regeneration times ($T_{g,in} = 140$ °C, $u_{g,in} = 0.57$ Nm/s, $x_{ini} = 0.7$ kg-water/kg-z, $T_{z,ini} = 80$ °C, $z_{max} = 0.1$ m).

various regeneration conditions. When the time for the regeneration was inadequate, the mass of steam generated in the following steam generation process would decrease. As a first step, the effect of the regeneration time on the mass of steam generated in the cyclic operations was studied. As an example, Fig. 6 shows the distributions of solid temperature and water content at various regeneration times. The operating condition was set based on the cycle experiment. An increase in temperature and decrease in water content occurred simultaneously from the gas inlet ($z = z_{max} = 0.1$ m) with time. Accordingly, the regeneration of zeolite proceeded from the gas inlet. For example, from the result of $t_{reg} = 1000$ s, while desorption took place in most parts of the generator, drying still took place near the gas outlet. From the results, drying finished at about 1200 s.

Figure 7 shows the relationship between the mass of steam generated and the regeneration time t_{reg} . To calculate the mass of steam generated, the distributions of temperature and water content at each t_{reg} , shown in Fig. 6, were used. Steam generation under atmospheric pressure with no-preheating case was assumed based on the experimental conditions. As seen in Fig. 7(a), the calculated mass of steam increased with the regeneration time and reached the saturated value of about 0.12 kg-steam/kg-zeolite. This implied that there was an appropriate regeneration time to maximize the mass of steam generated during the cycle. To

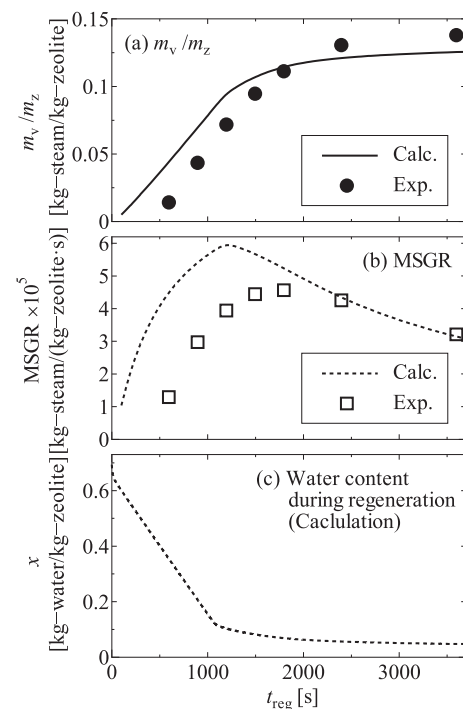


Fig. 7. Effect of the regeneration time on the mass of steam generated and the mean steam generation rate ($T_{g,in} = 140$ °C, $u_{g,in} = 0.57$ Nm/s, $x_{ini} = 0.7$ kg-water/kg-z, $T_{z,ini} = 80$ °C, $z_{max} = 0.1$ m, $T_{w,in} = 80$ °C, $T_v = 100$ °C, No-preheating case).

assess the appropriate regeneration time clearly, the mean steam generation rate (MSGR) was introduced. This is defined as the mass of steam generated during the cycle period, that is, the sum of the regeneration time t_{reg} and the time for the steam generation t_{sg} . In fact, t_{sg} changed with the mass of steam generated because the water was fed at the constant feeding rate. In this calculation, the average time for the steam generation was set to 389 s based on the experiment. The results are shown in Fig. 7(b). The mean steam generation rate exhibited a maximum value of 6.0×10^{-5} kg-steam/(kg-zeolite-s) at the regeneration time of 1 200 s. It should be noted that when the mean steam generation rate was maximum, all the drying of the adsorbent was complete as shown in Figs. 6 and 7(c). After this moment, the rate of regeneration slowed because the rate of desorption depending on $(x_{\text{eq}} - x)$ was much lower than that of drying. Therefore the increasing rate of (m_v/m_z) changed at this moment. That was why there was the maximum value of the MSGR.

The experimental data are also plotted in Fig. 7. When the regeneration time is short, calculated mass of steam and MSGR are higher than the experiment. This difference could be attributed to the estimation of the progress of the regeneration process. As discussed in the previous section, the present calculation for the regeneration process tends to estimate slightly lower water content. This could affect the estimation of mass of steam generated during the cyclic operation. Although the heat loss and sensible heat of the generator were considered in the other calculations, these effects were little according to the calculated results. However the calculated data exhibited similar tendencies to the experiment. From the results, the maximum mean steam generation rate was important information for deciding the appropriate regeneration condition.

4.3. Effect of Drainage Recycling on the Mass of Steam Generated

Figure 8(a) shows the effect of the number of DR cycles on the mass of steam generated. The dashed and solid lines indicate the Limited DR and Full DR, respectively. The first cycle (cycle number = 1) implied the No-DR case. The mass

of steam generated increased as the number of DR cycle increased. It should be noted that the effect of the number of DR cycle was significant for the first four cycles. This was because the temperature of water in the generator at the end of steam generation was fully developed for the first four cycles, as shown in Fig. 8(b). The temperature of the inlet water increased from 80°C to 110°C with the Full DR cycle. In the following results for the DR case, the cycle number was set to 10 to remove the effect of the cycle number of DR on the mass of steam generated.

Figure 9 shows the effect of DR on the mass of steam generated and the MSGR under various regeneration times. The calculation was done for $T_{\text{g,in}} = 120^\circ\text{C}$, $u_{\text{g,in}} = 0.7$ Nm/s, $T_v = 160^\circ\text{C}$ and $z_{\text{max}} = 0.1$ m. The time for steam generation was assumed 600 s for calculating the MSGR. As seen in the figure, an increase in the maximum value of the MSGR and a decrease in the appropriate regeneration time at which the maximum MSGR was reached, occurred simultaneously when applying DR. The maximum MSGR was 1.7 times higher than for the No-DR case.

Figure 10 shows the relationship between the preset steam temperature and the maximum mean steam generation rate. Each set of data shown in the graph indicates the maximum value of MSGR obtained for each operating condition and for $t_{\text{reg}} < 3\,000$ s. The effect of DR on the maximum mean steam generation rate was significant for the higher steam temperature. In particular, the Full DR was clearly effective than the Limited DR. According to the results, it can be said that the effect of the temperature of the feed water on the mass of steam generated was significant. When water at higher temperatures is not available in the practical process, DR is the more effective and helpful method.

The effect of the fraction of voids on the mass of steam generated with/without DR was studied. Generally the fraction of void in the packed bed ranges from 0.4 to 0.8. Moreover, in a practical application, an increase in the voids of the packed bed might be necessary because the pressure drop of dry gas for the regeneration process should be reduced. The effect of fraction of voids on the mass of steam generated is shown in Fig. 11. For the initial conditions of

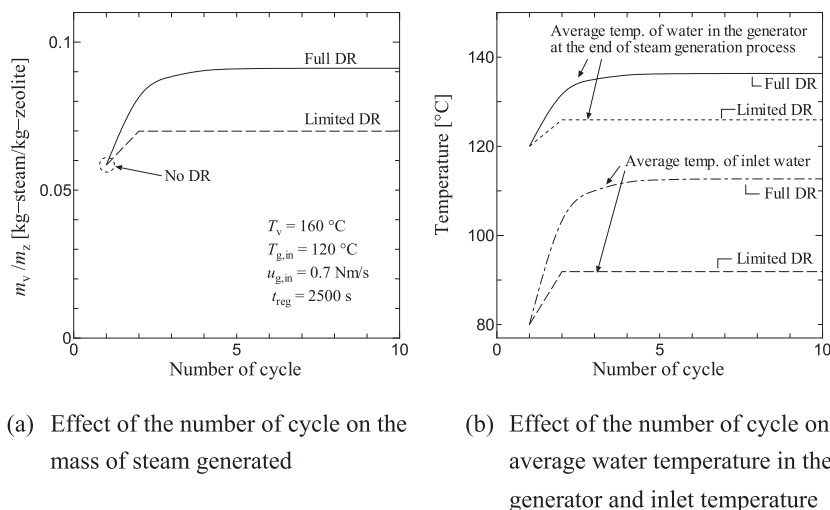


Fig. 8. Effect of recycling of the drainage water on the steam generation process ($T_{\text{g,in}} = 120^\circ\text{C}$, $u_{\text{g,in}} = 0.7$ Nm/s, $x_{\text{ini}} = 0.7$ kg-water/kg-z, $t_{\text{reg}} = 2500$ s, $z_{\text{max}} = 0.1$ m, $T_v = 160^\circ\text{C}$, $T_{\text{w,in}} = 80^\circ\text{C}$).

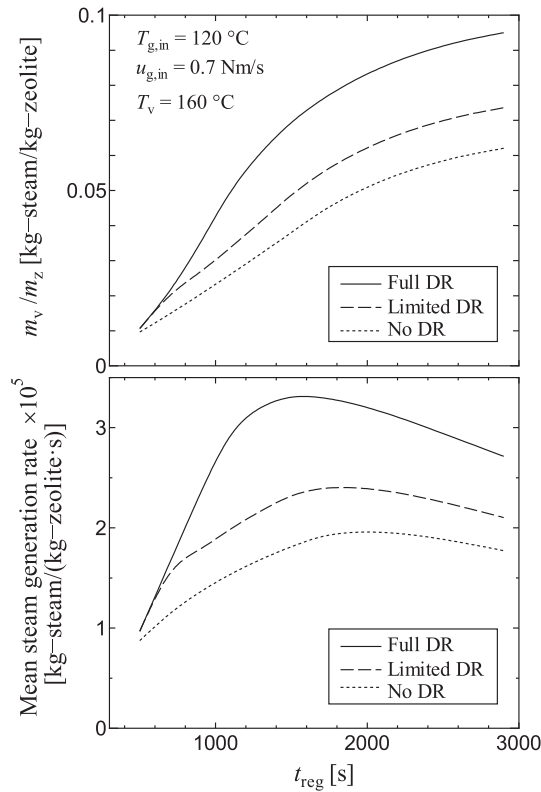


Fig. 9. Effect of the regeneration time on the mass of steam generated and the mean steam generation rate ($T_{g,in} = 120^\circ\text{C}$, $u_{g,in} = 0.7 \text{ Nm/s}$, $x_{ini} = 0.1 \text{ kg-water/kg-z}$, $z_{max} = 0.1 \text{ m}$, $T_v = 160^\circ\text{C}$, $T_{w,in} = 80^\circ\text{C}$).

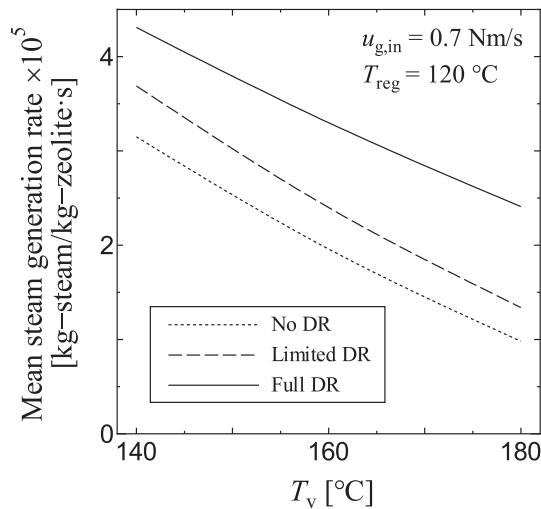


Fig. 10. Maximum steam generation rate at various steam temperatures ($T_{g,in} = 120^\circ\text{C}$, $u_{g,in} = 0.7 \text{ Nm/s}$, $x_{ini} = 0.1 \text{ kg-water/kg-z}$, $z_{max} = 0.1 \text{ m}$, $T_v = 160^\circ\text{C}$, $T_{w,in} = 80^\circ\text{C}$).

the calculation, uniform distributions of temperature and water content were assumed and shown in the figure. From the results, the effect of fraction of voids on the mass of steam can be reduced by applying the DR. While steam cannot be generated for the fraction of voids of more than 0.6 in the No DR case, considerable steam can be expected for the Full DR case. It should be noted that the difference between the Limited DR and Full DR cases was significant especially for higher volume fractions. Thus the Full DR and not the Limited DR was required for the severe conditions of steam generation.

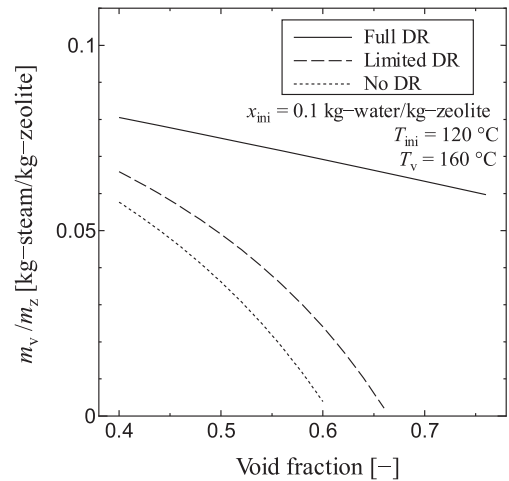


Fig. 11. Effect of the fraction of voids on the mass of steam generated with drainage recycling ($T_{z,ini} = 120^\circ\text{C}$, $x_{ini} = 0.1 \text{ kg-water/kg-zeolite}$, $T_v = 160^\circ\text{C}$, $T_{w,in} = 80^\circ\text{C}$).

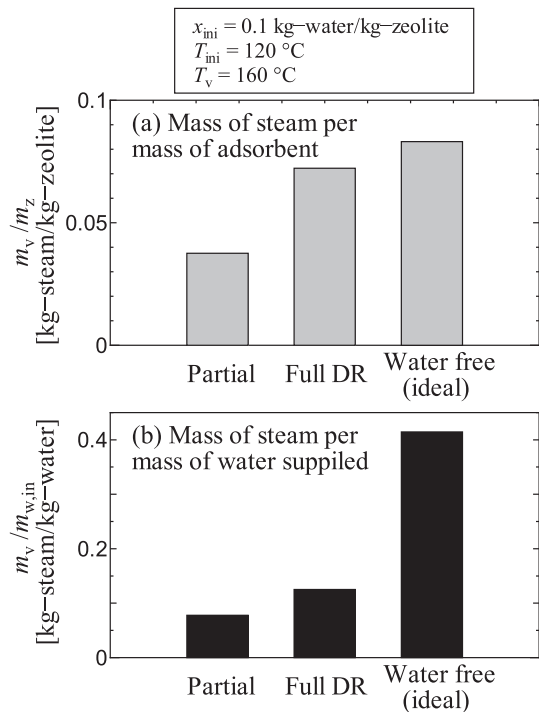


Fig. 12. Comparison of methods of water feeding in terms of the mass of adsorbent and the mass of water supplied during the steam generation process ($T_{z,ini} = 120^\circ\text{C}$, $x_{ini} = 0.1 \text{ kg-water/kg-zeolite}$, $T_v = 160^\circ\text{C}$, $T_{w,in} = 80^\circ\text{C}$).

Consequently, the novel steam generation system can generate not only high-temperature steam but also water at a higher temperature. The DR proposed in this study is the method to convert the sensible heat of drainage water to high-temperature steam. It would be ideal if as small volume as possible of the feed water could be supplied to cover the adsorbent. One method to realize the ideal case is to feed water from the top of packed bed of the adsorbent. However, this is generally difficult, as demonstrated in our previous study.⁴⁾ **Figure 12** shows the mass of steam generated using various feeding methods. Figure 12(a) shows the mass of steam generated per unit mass of zeolite. Figure 12(b) shows the mass of steam generated per unit mass of feed water. $m_{w,in}$ is the averaged mass of water supplied to the generator

during ten cycles. “Partial” indicates there is no drainage water at the end of the steam generation process. “Water free” is the ideal case, that is, there is no residual water including free water in the particle at the end of the steam generation process. As seen, DR exhibits better performance than “Partial”. This is because the reuse of drainage water can substantially reduce the mass of feed water. Therefore, DR is a powerful and practical method of approaching the ideal operation of the novel steam generation system.

5. Summary

The performance of the novel steam generation system has been studied for the application of effective use of waste heat from the iron and steel making process. Because the performance strongly depends on the regeneration process, a numerical model for the regeneration process has been developed taking transport phenomena in the zeolite packed bed into account. The model is found to be satisfactory in predicting the temperature and water content in the packed bed during the regeneration process. Based on the results of the regeneration process, the mass of steam generated during cyclic operation is estimated. As a result, the appropriate regeneration time to maximize the mean steam generation rate during the cycle is identified. Furthermore, reuse of the drainage water of the steam generation process, that is, Drainage Recycling has been proposed to effectively use the waste heat of the process. Because this method can be followed without any special modifications in the packed bed, it is more practical than existing methods of performance improvement. The effect of Drainage Recycling on steam generation is more pronounced especially for severe conditions such as a higher fraction of voids in the packed bed.

Acknowledgements

This work was partially supported by the NEDO project under the Research and Development Program for Innovative Energy Efficiency Technology, and by the Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (C) 25420923.

Nomenclature

A	= Frequency factor	[1/s]
a_p	= Specific surface area	[m ² /m ³]
c_p	= Specific heat	[J/kgK]
D	= Diffusion coefficient	[m ² /s]
d_p	= Particle diameter	[m]
E	= Activation energy	[J/mol]
h	= Heat transfer coefficient	[W/m ² K]
k_{gz}	= Mass transfer coefficient	[m/s]
L	= Latent heat	[J/kg-water]
M_w	= Molecular weight	[kg/mol]
m	= Mass	[kg]
N	= Order of the reaction	[-]
P	= Pressure	[Pa]
Q	= Enthalpy of adsorption/desorption	[kJ/kg-water]
R	= Gas constant	[J/mol K]

S_{reg}	= Rate of regeneration	[kg-water/kg-zeolite·s]
t	= Time	[s]
T	= Temperature	[K]
u	= Superficial velocity	[m/s]
V_R	= Volume of the steam generator	[m ³]
v	= Volume	[m ³]
x	= Water content	[kg-water/kg-zeolite]
z	= Coordinate	[m]
γ	= mass ratio of drainage to water supplied	[-]
δ_{ij}	= Kronecker's delta	[-]
ε	= Porosity	[-]
ΔH	= Reaction enthalpy	[J/kg-water]
λ	= Thermal conductivity	[W/mK]
μ	= Viscosity	[Pa·s]
ρ	= Density	[kg/m ³]
ϕ	= Volume fraction	[-]

Superscript

(n) = Cycle number

Subscripts

a	= Air
ads	= Adsorption
b	= Packed bed
d	= Drainage
eq	= Equilibrium
f	= Full
g	= Gas phase
i	= Index
j	= Index
in	= Inlet
ini	= Initial
max	= Maximum
out	= Outlet
p	= Particle
ph	= Preheating
R	= Reactor
ref	= Reference
reg	= Regeneration
sat	= Saturated
sg	= Steam generation
v	= Water vapor
w	= Water
z	= Zeolite

REFERENCES

- 1) Y. Kato: *ISIJ Int.*, **50** (2010), 181.
- 2) T. Miwa and H. Okuda: *J. Jpn. Inst. Energy*, **89** (2010), 28 (in Japanese).
- 3) E. Oktariani, A. Noda, K. Nakashima, K. Tahara, B. Xue, K. Nakaso and J. Fukai: *Int. J. Energ. Res.*, **36** (2012), 1077.
- 4) E. Oktariani, K. Tahara, K. Nakashima, A. Noda, B. Xue, A. T. Wijayanta, K. Nakaso and J. Fukai: *J. Chem. Eng. Jpn.*, **45** (2012), 355.
- 5) B. Xue, K. Tahara, K. Nakashima, A. Noda, E. Oktariani, A. T. Wijayanta, K. Nakaso and J. Fukai: *J. Chem. Eng. Jpn.*, **45** (2012), 408.
- 6) B. Xue, Y. Iwama, Y. Tanaka, K. Nakashima, A. T. Wijayanta, K. Nakaso and J. Fukai: *Exp. Therm. Fluid Sci.*, **46** (2013), 54.
- 7) S. Ergun: *Chem. Eng. Prog.*, **48** (1952), 89.
- 8) A. Gorbach, M. Stegmaier and G. Eigenberger: *Adsorption*, **10** (2004), 29.