A New Drying Process of Dusts and Sludge by Employing Heat Storage Materials

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Industries consisted of high temperature processes discharge a certain amount of waste heat in a wide temperature range. In such industries, on the other hand, a large amount of primary energy is still used for drying processes of raw materials and wastes such as wet dust and sludge. In this study, a new drying process was proposed by employing metallic heat storage materials (HSMs) as drying media, which can store waste heat from low to mid temperatures (250–500°C) as both sensible and latent heat. The process possesses several advantages that the process size and exhaust gas volume are significantly small and heat recovery from a dusty gas is possible.

The cold model experiments understanding the motion of HSM balls and powder inside the rotary dryer and its numerical simulations were carried out. The behavior of HSM balls was simulated by using the friction coefficient as a fitting parameter. Further, assuming that a HSM ball forms a composite particle with a powder layer, the numerical simulations of its drying process were conducted. They confirmed that, drying time can be shortened significantly when the latent heat was considered. Design of the drying process of wet dust in a practical scale showed that the size of the dryer will be several times smaller than that of a conventional rotary dryer because of higher volumetric heat transfer coefficient between HSM and dusts. Since the heat exchange tower between waste gas and HSM balls is also compact, the proposed process shows a certain potential to be applicable as an actual drying process.

KEY WORDS: heat storage material; waste heat; drying process; wet dust; sludge; sensible heat; latent heat.

1. Introduction

Drying process is an essential pretreatment process to control moisture content in fine raw materials and products, and to enhance the volume reduction and facilitate their handling in many manufacturing industries. However, large energy is necessary for water evaporation (2260 kJ/kg at 100°C), drying process often uses a large amount of primary energy.

Industries consisted of high temperature processes, such as ferrous and nonferrous smelting and chemical engineering industries, still discharge a certain amount of waste heat in a wide temperature range. Figure 1 shows an example of the exhaust energy/exergy and their recovery in an integrated steel. A significant amount of unrecovered waste heats is still discharged to the environment without efficient recovery. Since the recovery ratios of the exhaust heat from the typical steel plant are only 25% and 17% in terms of exergy and enthalpy, respectively, it is still a large room to develop technologies to promote the heat recovery.

![Fig. 1. Exhaust energy/exergy and their recovery in an integrated steel plant.](image-url)
On the other hand, many drying processes of coal, iron ore pellet feed, wet dusts, slag, mill scale, sludge and so on are conducted in the steel plant. The reasons of difficulty to promote the recovery of waste heat are pointed out as follows:

1. Efficient heat exchange processes for dusty waste gas, high temperature melts such as molten steel and slag have not been established.

2. Proper media for the transportation and storage of recovered heat have not been developed.

In this study, a new drying process was proposed by employing metallic heat storage materials (HSMs) as drying media, which can store the waste heat of low to mid temperature range (250–500°C) as both sensible and latent heat. In this paper, the results of experimental analyses of the particles flow characteristics in a rotary dryer using a cold model and the numerical simulations using the discrete element method (DEM) are reported. In addition, the numerical simulations of heat transfer and drying of a composite particle as an existing state model of heat storage material and wet powder was conducted. Further, the process design with an actual scale was carried out by using the abovementioned results.

2. Outline of the Proposed Drying Process

A process image of the drying process proposed in this study is shown in Fig. 2. In this process, exhaust gas of low to mid temperature range (250–500°C) is flowed through the heat exchange tower with countercurrent, where HSM balls are packed. The heated HSM balls, e.g., up to 300°C, and wet powder to be dried are fed into a rotary dryer with specified feeding rates. The wet powder is dried with the heat supplied by the HSM balls. Further, if aggregated semi-dried powder is formed, they will be immediately broken by the impact of the balls. It will lead to an efficient drying process. The HSM balls are retrieved from dried powder by a simple separation process such as sieving or magnetic separation. Then, they are returned to the heat exchange tower and used repeatedly.

The advantages of the proposed drying process are pointed out as follows:

1. Drying process proceeds efficiently because the heat is supplied directly from hot HSM balls to wet powder and formation of aggregates is prevented.

2. The exhaust gas volume of the dryer will be extremely small compared to the conventional hot gas dryer. Therefore, a large gas treatment system will not be necessary and its heat loss will be reduced.

In this study, iron-based alloys, which are comparatively low price and have high strength, are chosen as HSMs. In addition, the use of latent heats with solid–solid phase transformation such as magnetic and eutectoid transformations occurred at relatively lower temperature was assumed to increase the process efficiency. In general, specific heat capacity of iron-based alloy is about 0.5 kJ/(kg · °C), and therefore, the latent heats of the solid–solid phase transformations are in the range of several tens of percentages of the sensible heat held by HSM of 500°C. For example, magnetic transformation of pure iron and a eutectoid transformation of an austenite steel will occur at around 770°C and 730°C, respectively, and the corresponding latent heats are approximately 20 kJ/kg and 83 kJ/kg respectively. Although, these temperatures are higher than those of the target exhaust gas, it will be lowered by the adjustment of composition of the alloys.

3. Cold Model Experiments and Simulations of the HSM Balls in the Rotary Dryer

In the rotary dryer, the behavior of HSM balls and powder, e.g. average residence time and residence time distribution, give a significant effect on the drying characteristics. Cold model experiments using stainless steel balls and iron powder were carried out. Then, the DEM simulations were carried out to replicate the behavior of steel balls obtained by the experiments.

3.1. Cold Model Experiment

An acrylic cylinder of 0.12 m in inside diameter and 0.24 m in length was used and it rotated on the inclined rotation machine under the conditions of the prescribed inclined angle and rotation speed. In order to avoid the effect of static electrical charge generated inside surface of the cylinder, the stainless steel sheet was pasted on the inner wall. There is a weir of 5 mm height at the exit of the cylinder to control the discharge speeds of balls and powder. Stainless steel balls (10 mmφ) and iron powder (∼50 μm) were fed into the rotating cylinder at the specified feeding rate.

The average residence times of the balls and powder were measured by the following method: Balls were fed into the rotating cylinder at the rate at between 5.97×10⁻³ and 1.43×10⁻³ kg/s. Powder was fed with the ratio of feeding rates of balls to powder from 5 : 1 to 20 : 1. The inclined angle of the cylinder was set to 1° or 3°. The rotation speed.
was set to 7.5 rpm, which was calculated in the case that Froude number shown in Eq. (1) was identical to an actual scale of a rotary dryer (diameter: 1.5 m, rotation speed: 2 rpm).3)

\[ Fr = \frac{N^2r}{g} \] ..............(1)

Here, \( N, r \) and \( g \) are rotation speed, cylinder radius and gravity acceleration, respectively.

The operation continued for approximately \( 1.8 \times 10^3 \) s to attain the steady state. Then, the rotation machine and feeder were stopped and the respective holdup amounts of balls and iron powder were measured. The average residence time, \( \tau \), was calculated by the following equation:

\[ \tau = \frac{H}{F} \] ..............(2)

here, \( H \) and \( F \) are the holdup in the cylinder and the feeding rate, respectively.

In order to obtain the residence time distribution, several grams of the colored stainless steel balls and stainless powder (\( -150 \mu m \)) were fed as tracers, and then, their discharged amounts were measured with time lapse. The amount of stainless steel powder in the mixture with iron powder was determined by the chemical analysis of the average concentrations of Cr and Ni.

3.2. Numerical Simulation of Particles Movement in the Rotating Cylinder

In DEM, the effect of contact between particles in vertical and tangential directions is modeled by using the Voigt model,21 in which the elastic spring and viscous dashpot are connected in parallel. In addition, the friction slider is introduced to estimate friction in the tangential direction. In principle, it is necessary to calculate both trajectories of comparatively big stainless steel balls and fine iron powder. However, since the computation load of a large number of particles is too big in DEM simulation, the simulation of comparatively big stainless steel balls only was conducted in this present study and the friction coefficient was parameter-fitted to reproduce the experimental results.

Table 1 shows the physical properties and calculation conditions for the DEM simulations. Young’s modulus, Poisson ratio, normal and shear stiffness coefficients of SUS304 were used. The reflection coefficients in vertical and tangential directions were obtained as 0.571 and 0.565 by the simple measurements.

In the simulations, the calculation for \( 1.0 \times 10^3 \) s to attain the steady state was first conducted in the same condition as the corresponding experiment. The average residence time was calculated using the holdup amount. In addition, residence times of 100 balls were calculated to obtain the residence time distribution.

4. Heat Transfer and Drying Simulations in the Dryer

4.1. Drying Conditions

A simple numerical simulation of the proposed drying process is conducted to obtain the drying characteristics of wet powder. In the simulation, feeding rate of wet powder into the dryer, \( F_p \), was assumed to be 8.3 kg/s (\( 3.0 \times 10^4 \) kg/h) and the initial moisture content, \( w_{p,1} \), was set at 10%. The value of \( F_p \) was assumed by considering that the amounts of generated dusts, sludge and so on in an integrated steel works with the annual production of 5 million tons of crude steel. The heat supplying rate, \( Q_a \), necessary to dry the wet powder with the feeding rate of \( F_p \) to the specified moisture content is calculated by the following equation:

\[ Q_a = F_p \left( 1 - w_{p,1} \right) \cdot C_{p,dp} + w_{p,1} \cdot C_{p,w} \left( T_{a1} - T_{p1} \right) \]

\[ + \left( F_p \left( 1 - w_{p,1} \right) - m_{w,2} \right) \cdot \left( \lambda_w + C_{p,v} \left( T_{v,2} - T_{a1} \right) \right) \] ....(3)

where, the first term represents the heat supplying rate to heat up to the drying temperature, \( T_a \). The second term shows both the heat supplying rate to heat up the generated vapor to the temperature at the dryer exit and the latent heat of vaporization. The initial temperature of wet powder, \( T_{p,1} \), was set to 20°C. Drying of the wet powder started at \( T_{a1}=100°C \), and the temperatures of HSM balls, dried product and outlet gas (water vapor), \( T_{v,2} \), were set at 120°C at the dryer exit. The specific heat capacity of dry powder, \( C_{p,dp} \), was set at 0.70 kJ/(kg · °C). \( m_{w,2} \) in Eq. (3) shows the amount of remained water in the powder (moisture content: \( w_{p,2} \)). Therefore, \( m_{w,2} \) can be calculated by solving the following equation:

\[ \frac{m_{w,2}}{F_p \left( 1 - w_{p,1} \right) + m_{w,2}} = w_{p,2} \] ..............(4)

When HSM is assumed as pure iron, the amount of heat supplied from the HSM balls is calculated to be 86 kJ/kg using the temperatures of HSM balls at the dryer entrance, \( T_{h,1}=300°C \), and at the dryer exit, \( T_{h,2}=120°C \). Dividing the heat supplying rate for drying, \( Q_a \), by 86 kJ/kg, the feeding rate of HSM particles, \( F_{hp} \), becomes 28 kg/s (\( 1.0 \times 10^5 \) kg/h). This means that the ratio of feeding rates between HSM balls and wet powder is approximately 3.4 : 1.

4.2. Simulation Model of Drying Process

In the simulation model, it is assumed that the powder layer forms on the surface of a HSM ball in the dryer, and the heat necessary to dry the layer is supplied from the surface of the ball (see Fig. 3). When the mass ratio between the HSM ball and the wet powder layer is corresponding to the ratios of their feeding rates, \( F_h : F_p = 3.4 : 1 \), the thickness of outer powder layer can be calculated as 1.1 mm.

In the simulation model, the following equations were derived by considering the energy and material balances in a HSM ball and powder layer.

Energy conservation equation in a HSM particle:
and gas flowed through the powder layer,

Energy conservation equation of the powder layer:

\[ \rho_e C_{e,p} \frac{\partial T_{e,\text{p}}}{\partial t} = \kappa_e \left( \frac{\partial^2 T_{e,\text{p}}}{\partial r^2} + \frac{2}{r} \frac{\partial T_{e,\text{p}}}{\partial r} \right) \] ..........................(5)

Equation of continuity in the gas phase in the powder layer:

\[ \dot{e}_p \frac{\partial \rho_{e,\text{g}}}{\partial t} + \dot{e}_p \rho_{e,\text{g}} \frac{\partial (\rho_{e,\text{g}} v_{e,\text{g}})}{\partial r} = R_w A_p \] ..........................(6)

Momentum conservation equation in gas phase in the powder layer:

\[ \dot{e}_p \frac{\partial (\rho_{e,\text{g}} v_{e,\text{g}})}{\partial t} + \dot{e}_p \rho_{e,\text{g}} v_{e,\text{g}} \frac{\partial (\rho_{e,\text{g}} v_{e,\text{g}})}{\partial r} = -\dot{e}_p \frac{\partial P_{e,\text{g}}}{\partial r} + \dot{e}_p \rho_{e,\text{g}} \left[ \frac{\partial^2 (\rho_{e,\text{g}} v_{e,\text{g}})}{\partial r^2} + \frac{2}{r} \frac{\partial (\rho_{e,\text{g}} v_{e,\text{g}})}{\partial r} \right] \] ..........................(7)

Energy conservation equation in gas phase in the powder layer:

\[ \dot{e}_p \frac{\partial (\rho_{e,\text{g}} C_{e,\text{g}} T_{e,\text{g}})}{\partial t} + \dot{e}_p \rho_{e,\text{g}} v_{e,\text{g}} \frac{\partial (\rho_{e,\text{g}} C_{e,\text{g}} T_{e,\text{g}})}{\partial r} = \dot{e}_p \kappa_e \left( \frac{\partial^2 T_{e,\text{g}}}{\partial r^2} + \frac{2}{r} \frac{\partial T_{e,\text{g}}}{\partial r} \right) - h_p A_p (T_{e,\text{g}} - T_p) \] ..........................(8)

Mass conservation equation of vapor in the gas phase of the powder layer:

\[ \dot{e}_p \frac{\partial (\rho_{e,\text{g}} Y_{e,\text{g}})}{\partial t} + \dot{e}_p \rho_{e,\text{g}} v_{e,\text{g}} \frac{\partial (\rho_{e,\text{g}} Y_{e,\text{g}})}{\partial r} = \dot{e}_p D_{e,\text{g}} \left[ \frac{\partial^2 (\rho_{e,\text{g}} Y_{e,\text{g}})}{\partial r^2} + \frac{2}{r} \frac{\partial (\rho_{e,\text{g}} Y_{e,\text{g}})}{\partial r} \right] + R_w A_p \] ..........................(9)

Energy conservation equation of the powder layer:

\[ (1 - \epsilon_g) \rho_{p,\text{p}} C_{p,\text{pp}} \frac{\partial T_{\text{p}}}{\partial t} = (1 - \epsilon_g) \kappa_p \left( \frac{\partial^2 T_{\text{p}}}{\partial r^2} + \frac{2}{r} \frac{\partial T_{\text{p}}}{\partial r} \right) \]
\[ + h_p A_p (T_{e,\text{g}} - T_p) - R_w A_p \lambda_w \] ..........................(10)

The heat transfer coefficient between the solid phases and gas flowed through the powder layer, \( h_p \), was calculated by the empirical equation about the convective heat transfer in packed bed obtained by Wakao and Kaguei.\(^8\)

\[ \frac{h_p d_p}{\kappa_g} = 2 + 1.1 \text{Re}^{0.6} \text{Pr}^{1/3} \] ..........................(11)

Where, \( \text{Re} = \frac{\rho_{e,\text{g}} d_p v_{e,\text{g}}}{\mu_{\text{g}}} \) and \( \text{Pr} \) (Prandtl number) is approximately 0.7. In addition, the pressure drop of gas passing through the powder layer was obtained by Eq. (12)\(^9\):

\[ \frac{\Delta P_{\text{g}}}{\Delta r} = -180 \left( \frac{1 - \epsilon_g}{\epsilon_g} \right)^2 \frac{\mu_{\text{g}} v_{e,\text{g}}^2}{d^2_{\text{p,pp}}} \] ..........................(12)

Regarding to the drying rate of wet powder, \( R_w \), it was derived considering the constant drying rate period, in which the moisture ratio (defined as the mass ratio of water to dry solid), \( W_w \), is higher than the critical moisture ratio, \( W_{w,c} \), and all supplied heat is consumed for water evaporation.

\[ R_w = \frac{h_p (T_{e,\text{g}} - T_d)}{\lambda_w} \] ..........................(13)

The drying rate was assumed to be in proportion to \( W_{e,\text{g}} \) when it is lower than \( W_{e,\text{p},c} \), which was set to 0.020.\(^10\)

\[ R_w = \frac{W_{e,\text{p}}}{W_{e,\text{p},c}} \frac{h_p (T_{e,\text{g}} - T_d)}{\lambda_w} \] ..........................(14)

In addition, the contact heat transfer coefficient between the surfaces of the HSM ball and the powder layer, \( h_c \), was calculated by Eq. (15) based on the assumption that heat transfer occurs dominantly through gas phase:

\[ h_c = \frac{k_e}{d_e} \] ..........................(15)

where, \( d_e \) is the average distance between the surfaces of the HSM ball and the powder layer and it can be obtained by the following equation:

\[ r_{\text{p},e} \times r_{\text{p},e} \times d_e = r_{\text{p},e}^3 - \frac{1}{8} \times \frac{4}{3} \pi r_{\text{p},e}^3, \quad d_e = \left( 1 - \frac{\pi}{6} \right) r_{\text{p},e} \] ..........................(16)

Multiplying \( h_c \) by the surface area in the unit volume of the powder layer, resulted in the rate of contact heat transfer.

### 4.3. Prediction of Drying Characteristics Using Simulations

In the numerical simulations, the time step and space grid were set to \( 1.0 \times 10^{-8} \) s and \( 2.0 \times 10^{-3} \) m, respectively, and the explicit difference method was applied to solve Eqs. (5)–(10). The physical properties of iron and the mixture of FeO and ZnO were assumed for the HSM ball and the powder layer, respectively, as listed in Tables 2 and 3. The initial moisture content of the wet powder, \( \epsilon_0 \), was set to 0.20.

A solid–solid phase transformation at around 250°C with latent heat of 20 kJ/kg was assumed as an example and it was added to sensible heat of HSM in the corresponding temperature range. In this case, the maximum specific heat capacity was set as not beyond 1.0 kJ/(kg · °C) as shown in Fig. 4. Total sensible heat of iron-base alloy between 120 and 300°C is 86.1 kJ/kg and therefore the above latent heat occupies more than 20% of this value.

### 5. Results and Discussion

#### 5.1. Cold Model Experiments

Figures 5–7 show the correlations between the average
residence times of stainless steel balls and iron powder under the different feeding rates. Feeding rate of stainless steel balls was changed among $5.97 \times 10^{-3}$ kg/s (100 balls per minutes), $1.02 \times 10^{-2}$ kg/s (170 balls per minutes) and $1.43 \times 10^{-2}$ kg/s (240 balls per minutes). The ratio of the feeding rates of stainless steel balls to iron powder was set at 20 : 1, 10 : 1 or 5 : 1. The inclined angle of the rotary cylinder was varied between 1° and 3°.

It is clear that the average residence time of stainless steel balls increases, and conversely, that of iron powder decreases with an increase in the feeding rate of iron powder. This implies that fine particles of iron powder make the movement of balls slower in the axial direction of the cylinder and flow faster through among balls. Under the present experimental conditions, the residence time of balls and powder show similar values when the feeding ratio of stainless steel balls to iron powder is smaller. The average residence time of both stainless steel balls and iron powder decrease and their difference also decreases with an increase in the feeding rate of the balls. Further, the larger inclined angle of the rotary cylinder tends to give shorter residence time.

The residence time distributions of stainless steel balls and iron powder are shown in Figs. 8 and 9, respectively, when the feeding rate of balls is $1.02 \times 10^{-2}$ kg/s and the feeding rate ratio of balls to powder was 10 : 1.

From these figures, it can be found that both of stainless steel balls and iron powder move in the cylinder with an intermediate state between a complete mixing flow and a plug flow. In addition, the peak residence times in the both figures are almost same as the average residence times of those in Fig. 6 under the same feeding rates, i.e., 10 : 1.

The residence times of stainless steel balls and iron powder under the different feeding rates. Feeding rate of stainless steel balls was changed among $5.97 \times 10^{-3}$ kg/s (100 balls per minutes), $1.02 \times 10^{-2}$ kg/s (170 balls per minutes) and $1.43 \times 10^{-2}$ kg/s (240 balls per minutes). The ratio of the feeding rates of stainless steel balls to iron powder was set at 20 : 1, 10 : 1 or 5 : 1. The inclined angle of the rotary cylinder was varied between 1° and 3°.

5.2. Cold Model Simulations

In the DEM simulations, the value of the friction coefficient was determined as a fitting parameter so as to obtain a good agreement with the results of the experiments. Tables 4–6 show the results when the ratio of feeding rates between stainless steel balls and iron powder was 10 : 1. Tables 4–6 show that the obtained friction coefficient de-
crease from 0.34 to 0.28 with the increase in feeding rates although their differences are not significant. The calculated and experimental results of the residence time distribution of stainless steel balls are shown in Fig. 10 under the conditions of the inclined angle 3°, the feeding rate of stainless steel balls: $1.43 \times 10^{-2}$ kg/s and the ratio of feeding rates of the balls to iron powder: 10 : 1. They reasonably agree to each other. The peaks of the distribution show the similar values to the average residence time around 90 s as shown in Table 6. These results support that it is possible to simulate the behavior of steel balls with the presence of powder in the rotary cylinder by fitting the friction coefficient as a parameter.

5.3. Heat Transfer and Drying Simulations of a Composite Particle

Figure 11 shows changes in the moisture content distribution of the powder layer of the composite particle. Drying starts at the interface due to the heat transfer from HSM ball and the formed dried zone moves toward the surface of the composite. During the drying process, the moisture content of the wet zone exceeded the initial value, 10%, because of the partial condense of the water vapor flowed outside of the composite. In this condition, the average moisture content in the powder layer becomes 1% after 175 s.

Figure 12 gives the temperature distribution of HSM ball and powder layer in the composite particle during drying. The powder layer shows a certain temperature curves at each time while the temperature within the HSM ball gives a flat profile. This is because the heat transfer rate of the steel is relatively faster than that of the powder layer.

| Table 4. Comparison of experimental and DEM simulation results (feeding rate of stainless steel balls: $5.97 \times 10^{-3}$ kg/s, ratio of feeding rates: 10 : 1). |
| --- |
| **Experiment** | **Simulation** |
| Hold up of stainless steel balls (kg) | 0.833 | 0.795 |
| Average residence time of stainless steel balls (s) | 140 | 133 |
| Friction coefficient (-) | - | 0.34 |

| Table 5. Comparison of experimental and DEM simulation results (feeding rate of stainless steel balls: $1.02 \times 10^{-2}$ kg/s, ratio of feeding rates: 10 : 1). |
| --- |
| **Experiment** | **Simulation** |
| Hold up of stainless steel balls (kg) | 1.03 | 1.03 |
| Average residence time of stainless steel balls (s) | 101 | 101 |
| Friction coefficient (-) | - | 0.32 |

| Table 6. Comparison of experimental and DEM simulation results (feeding rate of stainless steel balls: $1.43 \times 10^{-2}$ kg/s, ratio of feeding rates: 10 : 1). |
| --- |
| **Experiment** | **Simulation** |
| Hold up of stainless steel balls (kg) | 1.29 | 1.29 |
| Average residence time of stainless steel balls (s) | 90.3 | 89.8 |
| Friction coefficient (-) | - | 0.28 |

5.4. Consideration on the Practical Scale of the Process

Based on the above results, the behavior of the composite
particles in a rotary dryer was examined considering a practical scale of the process. Standard feeding rates of steel balls as HSM and wet dust (10% in the initial moisture) are set as 28 kg/s and 8.3 kg/s, respectively, i.e., ratio of their feeding rates is 3.4 : 1. Assuming that the volume fraction of steel balls occupied in the rotary dryer is about 5% and the average residence time of HSM ball and wet dust are as 175 s, the inside volume of the dryer is necessary to be 13 m³, e.g., 2 m in inside diameter and 4 m in length. In this case, the holdup of the steel balls is calculated as about 5 x 10³ kg.

Figure 13 shows the moisture content distributions in the rotary dryer with and without consideration of latent heat induced by the magnetic transformation of HSM. When the latent heat is taken into account, drying process proceeds quickly and the moisture content decreased to 1% at 2.7 m position, i.e., at 115 s after charging. This implies that the use of latent heat of solid–solid phase transformation is effective and may lead to reduction of the dryer volume to the two-thirds scale. Figure 14 shows the relation between the ratio of feeding rates and initial temperature of HSM necessary for drying the wet powder up to 1% of moisture. Naturally, higher the initial temperature of HSM, less amount of HSM. Increase in the HSM temperature also gives the reduction of dryer volume.

In order to evaluate the drying performance of the proposed drying process, the volumetric heat transfer coefficient, $U_a d$, was estimated, which is index defined as the effective heat transfer velocity per unit volume of the dryer. Using the heat supplying rate for drying up to the desired moisture content, $Q_d$, $U_a d$ can be expressed as the following equation:

$$U_a d = \frac{Q_d}{V_d \Delta T_{ln,d}} \quad \ldots \ldots \ldots \ldots (17)^{11}$$

where, $\Delta T_{ln,d}$ is shown as Eq. (18).

$$\Delta T_{ln,d} = \frac{(T_{h,1} - T_{p,1}) - (T_{h,2} - T_{p,2})}{\ln \frac{T_{h,1} - T_{p,1}}{T_{h,2} - T_{p,2}}} \ldots \ldots (18)$$

$T_h$ and $T_p$ show the temperature of HSM particle balls and wet powder, respectively, and the subscripts, 1 and 2 show the entrance and exit of the dryer, respectively. From the calculation as to heat supplying rate demand for drying in 4.1, $T_{h,1}$, $T_{p,1}$ and $Q_d$ were 300°C, 20°C and 2.4 x 10⁶ W, respectively. From Fig. 12, it was found that the average temperatures of HSM particles and powder at the entrance and exit of the dryer were 130°C and 110°C, respectively. By substituting these values into Eq. (18), $U_a d$ was calculated as 1.9 x 10⁵ W/(m³ °C). The calculated volumetric heat transfer coefficient is around several times higher than that of $U_a d$ of a conventional rotary dryer, in the range of 86–3.4 x 10⁴ W/(m³ °C).

The above results clearly give a certain potential of the proposed drying process. In the simulation model, it was assumed that HSM balls and wet powder form composite particles. It is necessary to further verify the validity of this assumption. However, it may not be far different from the actual mechanism of heat transfer in the proposed process, because HSM balls and wet powder will be well mixed and average thickness of the powder layer is comparatively thin.

Further, a heat storage process for the HSM balls was examined. The shape of the tower is assumed as a vertical cylinder and the waste gas of 500°C is blown up from the bottom of the packed bed of HSM balls. HSM balls of 80°C are continuously fed from the top of the tower at 28 kg/s and the void fraction of their bed is 50%. Then, they are heated up to 300°C and discharged from the bottom of the tower. A simple numerical model was prepared by dividing the tower whose volume into a number of cells and deriving energy conservation equations. In the model, each cell was composed of gas and HSM phases and their moving rates...
from cell to cell were identical to the feeding rates of gas, $F_g$, and HSM balls, $F_h$, respectively.

Gas phaseraphase:

$$\frac{d}{dt}(m_{g,i}C_{p,g}T_{g,i}) = F_gC_{p,g}(T_{g,i-1} - T_{g,i}) - h_{h,i}\left(A_{p,h}V_i\frac{T_h}{n_h}\right)(T_{g,i} - T_{h,i}) \ldots (19)$$

HSM balls:

$$\frac{d}{dt}(m_{h,i}C_{p,h}T_{h,i}) = F_hC_{p,h}(T_{h,i+1} - T_{h,i}) + h_{h,i}\left(A_{p,h}V_i\frac{T_h}{n_h}\right)(T_{g,i} - T_{h,i}) \ldots (20)$$

Both of the second terms of right sides of Eq. (19) and Eq. (20) show the convection heat transfer between the gas and HSM phases; where, $m$ shows the mass in each cell and subscripts $g$, $h$, and $i$ show the gas phase, HSM phase and the cell number. The heat transfer coefficient in the heat exchange tower can be defined by using Shirai’s equation (Eq. (21))

$$\varepsilon_h\left(\frac{h_{d,po}}{\kappa_g}\right) = 2 + 0.75Re^{0.5}Pr^{1/3} \ldots \ldots \ldots \ldots \ldots (21)$$

As for the superficial gas velocity in the heat exchange tower, $v_{g,i}$, which was used to calculate $h_{h,i}$, the following relationship was employed:

$$v_{g,i} = \frac{F_g}{V_i\rho_{g,i}} \ldots \ldots \ldots \ldots \ldots (22)$$

In the simulations, the explicit difference method was applied to solve Eqs. (19) and (20) numerically and the time step was set to $1.0 \times 10^{-4}$ s. Initially, the temperature of hot gas (assumed as air) and HSM particles (assumed as iron) was both 80°C. Then, blowing of air of 500°C was started at the flow rate of $F_g$. The temperatures of gas at the bottom of the heat exchange tower and HSM balls at the top were fixed to 500°C and 80°C, respectively. An example of the calculated temperature distribution in the vertical direction of the heat storage tower is shown in Fig. 15, assuming the diameter and height, gas flow rate are 1.5 m, 1.0 m (volume: 1.8 m$^3$) and 4.7 N m$^3$/s, respectively. The size of the tower is 1.5 m and 1.0 m).

Fig. 15. Temperature distributions of gas phase and HSM balls in the vertical direction of the heat exchange tower (gas flow rate: 4.7 N m$^3$/s, diameter and height of ME exchange tower: 1.5 m and 1.0 m).

Nomenclature

- $C_p$: Specific heat capacity (kJ/(kg · °C))
- $D$: Diffusion coefficient (m$^2$/s)
- $d_e$: Average distance between surfaces of a HSM particle and a wet powder layer (m)
- $d_p$: Particle diameter (m)
- $F$: Feeding rate (kg/s)
- Fr: Froude number (—)
- $g$: Gravity acceleration (m/s$^2$)
- $H$: Holdup (kg)
- $h$: Heat transfer coefficient (W/(m$^2$ · °C))
- $m$: Mass (kg)
- $N$: Rotation speed (rpm)
- $n$: Number of cells (—)
\( P \): Pressure (Pa)
\( \text{Pr} \): Prandtl number (—)
\( Q \): Heat supplying rate (kJ/s)
\( \text{Re} \): Reynolds number (—)
\( \dot{R}_w \): Drying rate (kg/(s · m²))
\( r \): Distance from center (m)
\( \rho_p \): Particle radius (m)
\( T \): Temperature (°C)
\( \Delta T_{\text{lm}} \): Logarithmic mean temperature difference (°C)
\( t \): Time (s)
\( Ua \): Volumetric heat transfer coefficient (W/(m³ · °C))
\( V \): Volume (m³)
\( v \): Velocity (m/s)
\( W \): Moisture ratio (—)
\( W_c \): Critical moisture ratio (—)
\( w \): Moisture content (—)
\( Y \): Mass ratio (—)
\( \varepsilon \): Void fraction (—)
\( \lambda \): Latent heat for evaporation (kJ/kg)
\( \mu \): Viscosity (Pa · s)
\( \rho \): Density (kg/m³)
\( \tau \): Average residence time (s)

Subscripts
- \( c \): Contact
- \( d \): Dryer, cylinder chamber
- \( dp \): Dry powder
- \( g \): Gas
- \( h \): Heat storage material, heat exchange tower
- \( i \): Cell number
- \( p \): Wet powder
- \( v \): Vapor
- \( w \): Water
- \( 1 \): Initial condition, dryer entrance
- \( 2 \): Dryer exit

REFERENCES
1) T. Akiyama: *J. Jpn. Inst. Energy*, 86 (2007), 161.
2) P. A. Cundall and O. D. L. Stack: *Geotechnique*, 29 (1979), 47.
3) M. Tajima, Y. Nisimoto, K. Shima and Y. Mantani: *Tetsu-to-Hanagé*, 90 (2004), 807.
4) S. Umekawa and H. Ino: *J. Jpn. Inst. Met.*, 70 (2006), 586.
5) M. Umemoto and K. Tsuchiya: *Tetsu-to-Hagané*, 88 (2002), 117.
6) Q. Chen and Z. P. Jin: *Metall. Mater. Trans. A-Phys. Metall. Mater. Sci.*, 26 (1995), 417.
7) The Association of Powder Process Industry and Engineering, Japan: Overview of Powder Engineering, The Association of Powder Process Industry and Engineering, Japan, Tokyo, (1995), 134.
8) N. Wakao and S. Kaguei: Heat and Mass Transfer in Packed Beds, Gordon and Breach Science Publishers, New York, (1982), 139.
9) J. Bear: Dynamics of Fluids in Porous Media, American Elsevier, New York, (1972), 764.
10) N. Hayashi and S. Shimada: *Dry. Technol.*, 25 (2007), 1935.
11) R. Toei: Dryer, Nikkan Kogyo Shimbun, Tokyo, (1980), 9.
12) The Society of Chemical Engineers, Japan: Handbook of Chemical Engineering, Maruzen, Tokyo, (1999), 171.