Heat Transfer Simulation on Drying Processes of Nonfired Pellets Containing Combined Water in the Moving Bed Reactor

Tomohiro AKIYAMA, Reijiro TAKAHASHI and Jun-ichiro YAGI

Research Institute of Mineral Dressing and Metallurgy, Tohoku University, Katahira, Aoba-ku, Sendai, Miyagi-ken, 980 Japan.

(Received on May 17, 1990; accepted in the final form on September 14, 1990)

Attention has been focussed on nonfired pellets used in ironmaking industries from the point of view of energy saving. Heat transfer experiments for nonfired pellets were carried out for the better understanding of the fundamental process characteristics which would provide the basis for utilization technology of nonfired pellets. Heat transfer characteristics were investigated by both numerical simulation and experiments using moving beds. Decomposition rate of combined water contained in the nonfired pellets and temperature dependence of effective thermal conductivity were measured by means of TG-DTA and laser flash method, respectively. Heat transfer coefficient between gas and solid in the moving bed was determined by using fired pellets and a correlated equation was proposed. One dimensional mathematical model developed here provided excellent agreement between estimated temperature distribution in the moving beds and observed data.

KEY WORDS: ironmaking; direct reduction; nonfired pellet; drying; combined water; heat transfer coefficient; thermal conductivity; moving bed reactor.

1. Introduction

The technology to produce cement-bonded nonfired pellets was at first developed in Sweden for processing dust generated in ironmaking processes and the raw materials unsuitable to sintering. Currently, the nonfired pellets are often applied to ironmaking and ferro-alloy production processes from the viewpoint of energy saving. In addition to this, nonfired pellets have following advantages;

- 1) No generation of NO_x and SO_x in the production process thereby suppressing air contamination,
- 2) Acceleration of reduction of poorly reducible ores like iron sand and chromite with carbonaceous materials contained in the pellets,
- 3) High reducibility compared with fired pellets.

However, at present, some problems still remain unsolved, which concern fundamental properties of the nonfired pellets for improving utilization efficiencies. This paper deals with fundamental behaviors concerning heat transfer of nonfired pellets thereby contributing to the development of effective method for the utilization of the pellets.

Nonfired pellets usually contain moisture as free and combined water. Therefore, the investigation has to be done on the evaporation of free water and on the thermal decomposition of combined water which affects the temperature distribution in the reactors.¹⁾ Mathematical simulation was carried out for clarifying the thermal behaviors of a laboratory scale moving bed.

2. Heat Transfer Experiment

2.1. Sample

Chemical compositions of 3 kinds of nonfired pellets and a fired pellet are shown in Tables 1 and 2, respectively. Iron ore powder was agglomerated by addition of 7 mass% Portland cement and the prepared pellets attained enough crushing strength after 10 days curing. Mean crushing strength of the samples was 88 kg/pellet after 10 days curing. Three kinds of iron ores were used as raw materials. Each contained different amount of combined water. Combined water content of Australasian *R* and *H* ores were about 8 and 4 mass%, respectively. *M* ore produced in Brazil originally had no combined water, however, during agglomeration it absorbed 1.2 mass% water in the form of cement hydrate.

After drying the samples at 378 K, combined water contents (C.W.) were evaluated from the weight loss in wet basis. The samples were kept at 1 173 K over 24 h. The diameter range of the samples was from 13.4 to 13.6 mm and apparent densities of the samples *M*, *H* and *R* were 3.70, 3.50 and 3.13 g/cm³, respectively.

Heats of decomposition for the combined water of the samples *R*, *H* and *M* measured by differential scanning calorimeter (DSC) were respectively 143, 38.9 and 6.32 kJ/kg (wet solids). The result of thermogravimetry-differential thermal analysis (TG-DTA) is shown in Fig. 1. Sample powder used for TG-DTA measurements was from 10 to 100 mg in weight. By X-ray diffractometry shown in Fig. 2, goethite ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$) was identified in the sample *R*, whereas goethite and kaolinite ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$) were

Table 1. Chemical composition of the nonfired pellets.

(a) For thermal conductivity measurement								(b) For moving beds drying								
	T. Fe	FeO	CaO	SiO ₂	Al ₂ O ₃	MgO	C. W.		T. Fe	FeO	CaO	SiO ₂	Al ₂ O ₃	MgO	C. W.	F. W.
<i>M</i>	62.13	0.06	4.49	2.52	0.85	0.18	1.20	<i>H-A</i>	53.49	2.76	4.62	5.52	2.77	0.16	4.33	6.43
<i>H</i>	56.93	0.12	4.47	5.58	2.83	0.22	3.72	<i>H-B</i>	57.35	2.96	4.95	5.92	2.97	0.17	4.33	—
<i>R</i>	51.46	0.12	4.76	7.00	2.99	0.19	8.43	<i>H-C</i>	59.87	2.27	5.07	5.99	3.10	0.20	0.30	—

C. W.: Combined water, F. W.: Free water

H-A: No drying, *H-B*: Drying at 378 K, *H-C*: Drying at 973 K

Table 2. Chemical composition and apparent density of the fired pellet.

Chemical composition (mass %)						Apparent density (Mg/m ³)
T. Fe	FeO	CaO	SiO ₂	Al ₂ O ₃	MgO	
66.88	0.25	0.22	2.64	0.50	0.36	3.90

Fig. 1. Changes of weight loss (TG) and differential thermal analysis (DTA) patterns.

identified in the sample *H* as constituent minerals with combined water as well as hematite.

In the moving bed experiments, 3 kinds of non-fired pellets made from *H* ore were used as samples after different pretreatment. The sample *H-A* was only cured at room temperature for over 10 days, therefore, contained both free and combined water. The sample *H-B* contained only combined water because of pre-drying at 378 K over 24 h. The sample *H-C* had no water content because this sample was prepared by heating the sample *H-B* at 973 K over 5 h. Chemical composition of the samples is listed in Table 1. The sample pellets were 13 to 15 mm in diameter and were 13.5 mm in weight-mean diameter.

2.2. Thermal Conductivity²⁾

Theory of laser flash method for thermal diffusivity measurement was at first reported in 1961 and subsequent improvement on this method has been made by the application of corrections for the finite pulse-time effect and the radiation-loss effect. Fig. 3 shows experimental apparatus²⁾ used in this study. In this method, a flash of thermal energy by Ruby laser beam was supplied to the front face of a disk specimen which were 1 cm in diameter and 1 to 2 mm in thickness with a short interval and the temperature as a function of time at rear face was recorded by digital transient memory.

Fig. 2. X-ray diffraction patterns of 3 nonfired pellets using MoK α .

Thermal diffusivity D was given from correction factor A which was determined by the ratio of radiation-loss, the thickness of specimen l and a specific time $t_{1/2}$, at which the back face temperature reached half of its maximum value by the expression

$$D = A \cdot 0.1388 l^2 / t_{1/2} \quad \dots\dots\dots (1)$$

Thermal expansion of samples was measured by an apparatus for thermo-mechanical analysis and temperature dependence of sample thickness were shown in Fig. 4. It can be seen that sample *M* expanded slightly whereas samples *H* and *R* shrank significantly in the temperature range of decomposition of combined water. As content of combined water increased, shrinking ratio increased. However, once three samples were heated up to 1 273 K, they all showed similar tendency of thermal expansion like the fired pellet.

Obtained values of thermal diffusivity are shown in Fig. 5 in comparison with data reported. Thermal diffusivities of the nonfired pellets were considerably smaller than those of the fired pellets at any temperature. Using values of apparent density and specific

Fig. 3. Schematic diagram of experimental apparatus of the laser flash method.

Fig. 4. Relative change of specimen thickness for nonfired pellets as a function of temperature.

heat of the samples used, thermal conductivities were calculated and approximated by the following equations.

For the fired pellet

$$k_e(T_s) = 19.8 - 4.70 \cdot 10^{-2} T_s + 4.15 \cdot 10^{-5} T_s^2 - 1.23 \cdot 10^{-8} T_s^3$$

For the nonfired pellets

$$\left. \begin{array}{ll} \text{Sample M} & k_e = 0.279 k_e(T_s) \\ \text{Sample H} & k_e = 0.181 k_e(T_s) \\ \text{Sample R} & k_e = 0.087 k_e(T_s) \end{array} \right\} \dots\dots\dots(2)$$

2.3. Heat Exchange in the Moving Bed

A laboratory scale moving bed, which was constructed for a purpose of reduction of iron oxide to produce sponge iron, was used for heat transfer experiments of nonfired pellets. Fig. 6 illustrates a schematic diagram of the experimental apparatus. Details of the apparatus have been reported previous-

Fig. 5. Comparison of thermal diffusivities for nonfired and fired pellets obtained in this work with those of the previous.

Fig. 6. Schematic diagram of experimental apparatus.

ly,^{3,4)} therefore, the explanation given here is limited to the parts necessary for the heat transfer and drying studies.

Seven probes were equipped longitudinally to measure temperature, pressure and gas composition, at the levels of $L=0, 0.35, 0.70, 1.05, 1.40, 1.75$ and 2.00 m from gas inlet level. Temperature in the reactor was measured by CA thermocouples at positions of 5 mm inside from the wall. Gas concentrations of $N_2, H_2, H_2O, CO, CO_2, CH_4$ and O_2 were analyzed by using a mass spectrometer (MGA-1200), which can analyze $H_2O(g)$ up to 30 mol% by keeping capillary tube and gas sampling system warm for preventing condensa-

tion of moisture.

Heat loss through the wall was measured directly at each level by using a heat flow meter which was used in the previous paper⁴⁾ and radial heat flux was evaluated by averaging the heat flux measured in circumferential direction.

Under the fixed operating conditions listed in Table 3, temperature, concentration and pressure changes with time were measured until a steady state was obtained. Therefore, longitudinal distributions of temperature, pressure and concentration were determined from the measurements at the steady state. In the experiments, nitrogen gas was used and 6 experimental runs were conducted for 3 kinds of the sample pellets. Two different experimental conditions were set up for the same samples by changing flow rate of gas and/or charging rate of solids.

In selection of operating conditions, attention was focussed on re-condensation of moisture. In other words, rather low thermal flow ratio was selected in the case of high moisture pellets because of preventing moisture condensation at the top of the moving bed. In this case, outlet gas temperature was regulated not to be under 403 K.

3. Analysis of Experimental Results

3.1. Heat Transfer for a Single Pellet

A fundamental equation for heat transfer was derived within the framework of following assumptions:

(1) Heat transfer controls decomposition rate of combined water.

(2) Decomposition of the combined water proceeds topochemically.

On the basis of these assumptions the fundamental equation can be written as follows:

$$\rho_s C_s (\partial T_s / \partial t) = (1/r^2) \frac{\partial}{\partial r} \left(k_e r^2 \frac{\partial T_s}{\partial r} \right) - \rho_s \Delta H (df/dt) \quad \dots\dots\dots (3)$$

This equation was discretized⁵⁾ by using the fully implicit scheme and S.O.R. technique was used to converge numerical computation, where $r_0/20$ m and 1 s were selected as finite increments for radial distance and time.

Since fractional decomposition of combined water was assumed to depend only on temperature, decomposition rate can be represented as follows:

$$\partial f / \partial t = (df/dT_s) (\partial T_s / \partial t) \quad \dots\dots\dots (4)$$

Table 3. Experimental conditions.

Pellets	H-A		H-B		H-C	
Run No.	A-1	A-2	B-1	B-2	C-1	C-2
T_g (K)	1 173	1 173	1 176	1 172	1 183	1 178
P (MPa)	0.127	0.127	0.122	0.122	0.122	0.122
G_g (kg/m ² s)	0.700	0.596	0.576	0.453	0.574	0.432
G_s (kg/m ² s)	0.378	0.436	0.531	0.380	0.388	0.388
β^* (—)	0.463	0.627	0.791	0.718	0.578	0.769

* $\beta = C_s G_s / C_g G_g$ (at 973 K)

As a result, Eq. (3) can be rewritten as follows:

$$\{\rho_s C_s + \rho_s \Delta H (df/dT_s)\} (\partial T_s / \partial t) = (1/r^2) \frac{\partial}{\partial r} \{k_e r^2 (\partial T_s / \partial r)\} \quad \dots\dots\dots (5)$$

Therefore, numerical computation was necessary for df/dT_s in place of $\partial f / \partial t$. It was obtained by normalizing TG curves in Fig. 1 with final weight loss, and by differentiating them with respect to temperature. As shown in Fig. 7(b), endothermic curves have different shapes of peak. These curves measured were approximated simply as shown in Fig. 7(a) to be incorporated into the mathematical model.

Endothermic peaks for samples *R* and *H* were clearly understood to appear corresponding to the decomposition of goethite and kaolinite. On the other hand, heat absorption of the sample *M* was widely observed with many small peaks. Based on this observation, decomposition of combined water for the sample *M* was modeled to be constant rate from 423 to 723 K.

Fig. 1 also depicts the effect of heating rate on weight loss curves in TG measurement. From this result, so large difference was not found between data for the heating rates of 3 and 10 K/min. Even after keeping sample *R* at 413, 523 and 573 K, combined water of 8.43 mass%, which was originally contained, was not decomposed completely, and measured weight loss was actually only 2.23, 5.41 and 7.65 mass%. Since the heating experiments were carried out at the temperatures lower than or equal to a temperature at which the maximum heat absorption occurs, decomposition of the combined water was not found to proceed at the specified temperature but in some

Fig. 7. Decomposition rate of combined water measured for 3 kinds of pellets.

temperature range.

3.2. Heat Transfer in the Moving Bed

3.2.1. Fundamental Equation

Based on the kinetic analysis of single particles, a mathematical model was derived within the framework of following assumptions:

- (1) Gas was in plug flow; this does not apply when tube to pellet diameter ratio is small.¹³⁾
- (2) Pellets were in plug flow; this condition is valid when influence of a shear zone¹⁴⁾ is negligible.
- (3) Thermal radiation between pellets was negligible; this does not apply to high temperature processes when particle size is large.
- (4) Thermal conductivity between pellets was negligible; this assumes point contacts between pellets.
- (5) Temperature distribution in a pellet was concentric.
- (6) Heat loss stemmed only from sensible heat of gas.
- (7) Ergun equation⁶⁾ was applicable to pressure drop in the reactor.

Table 4 gives heat transfer model and fundamental equations derived on the basis of the model. Heat transfer coefficient h_p was assumed to be represented in the form of Eq. (6).

$$Nu = 2.0 + \alpha Pr^{1/3} Re_p^{1/2} \dots\dots\dots (6)$$

For obtaining the value of the parameter α , simulating computation was carried out from the top to the bottom (*i.e.*, from $z=2$ m to $z=0.35$ m) of the moving bed under 2 unknown parameters of h_p and outlet gas temperature at level of No. 7 because it was very difficult to measure the outlet gas temperature accurately. Then, optimal value of α was determined by minimizing the root-mean-square-errors between observed and computed value as defined below.

$$\varepsilon = [(1/N) \sum_{i=1}^N (1 - T_{calc}/T_{obs})^2]^{1/2} \dots\dots\dots (7)$$

3.2.2. Heat Transfer Coefficient between Gas and Solid⁷⁾

It was reported that heat transfer rate between gas and solid, calculated from previously reported empirical equations such as Ranz's equation,⁸⁾ was too large to simulate longitudinal temperature distribution in the industrial counter-current moving bed such as blast furnace.⁹⁾ In this study the heat transfer coef-

ficient between gas and solid measured by using the above-mentioned moving bed. Three modes of heat transfer experiments of which condition was listed in Table 5, have been carried out by using nitrogen stream and fired hematite pellets. Longitudinal distribution of both pellet and gas temperatures and heat loss from the furnace wall were measured after a steady-state was obtained.

Pellet temperature was measured by a sheathed CA thermocouple of 0.5 mm in diameter, which was inserted into the center of the pellet. Before each experiment, the pellet was placed at the top of the reaction tube. As the pellet went down, temperature rose slowly from the original room temperature to the inlet gas temperature. The longitudinal temperature distribution was estimated by the temperature change measured and descending velocity of the pellet which was calculated from starting and finishing position, as well as elapsed time under the assumption of constant descending rate.

In general, indication of a thermocouple installed in the reaction tube does not show true gas temperature due to various thermal effects. In our experiments, thermocouples were protruded at 5 mm inside from inner wall and were covered with sampling tube as shown in Fig. 8. During the temperature measurement, gas in the reaction tube was sucked to the gas analyzer at the rate of 200 cm³/min through it. The gas temperature thus measured was corrected by taking the heat balance for the thermocouple tip.⁷⁾ Thermal radiation from gas to the thermocouple tip and reaction heat can be neglected since pure nitrogen was used. Assuming that thermal conduction through the thermocouple was negligible except No. 7 level, heat balance equation around the thermocouple tip was derived as shown below.

Table 5. Sectional heat balances during the heat transfer experiments.

Experimental variables		Run 14	Run 18	Run 24	Units
Flow rate		420.1	304.29	507.13	Nl/min (STP)
Charging rate		0.4917	0.4829	0.5070	kg/min
Heat absorbed by solid (Q_s)	0 -0.35 m	1 772	3 240	702	W
	0.35-0.70 m	1 460	1 196	764	W
	0.70-1.05 m	828	686	790	W
	1.05-1.40 m	880	491	689	W
	1.40-1.75 m	927	446	976	W
Heat given up by gas (Q_g)	0 -0.35 m	1 967	3 331	933	W
	0.35-0.70 m	1 539	1 233	894	W
	0.70-1.05 m	906	717	880	W
	0.05-1.40 m	972	515	759	W
	1.40-1.75 m	971	457	1 011	W
Measured heat loss (Q_{Loss})	0 -0.35 m	195	91	231	W
	0.35-0.70 m	164	73	199	W
	0.70-1.05 m	133	56	167	W
	1.05-1.40 m	101	38	134	W
	1.40-1.75 m	70	20	102	W
Total heat loss		663	278	833	W
Percentage of heat loss		5.5	3.2	6.0	%

Table 4. Heat transfer model and fundamental equations.

	Gas in plug flow Solid temperature with radial symmetry
$\left(\rho_s C_s + \rho_s dH \frac{df}{dT_s} \right) \frac{\partial T_s}{\partial t} = \frac{1}{r^2} \cdot \frac{\partial}{\partial r} \left(k_e r \frac{\partial T_s}{\partial r} \right)$	
$\frac{\partial T_g}{\partial z} = - \frac{6(1-\varepsilon)h_p(T_g - T_s)/\phi d_p + 4U(T_g - T_w)/D}{G_g(C_g + T_g dC_g/dT_g) + \int_{T_s}^{T_g} C_g^{H_2O} dT_s \cdot G_{H_2O} df/dT_s}$

Fig. 8. Longitudinal distribution of wall heat transfer coefficient circumferentially averaged.

$$h_i(T_g - T_j) = \sigma \epsilon_i T_j^4 - T_{ss}^4 \quad \dots\dots\dots(8)$$

where the left-hand side expresses input heat from gas to the thermocouple tip by convection and the right-hand side is output heat from the tip to the surface of pellets by radiation, respectively. In general, heat transfer coefficient h_i from gas to a column perpendicular to gas flow was able to be obtained by the following Hilpert's equation.¹⁰⁾

$$Nu = 0.615 Re^{0.466} (4 \times 10 < Re < 4 \times 10^3) \quad \dots\dots\dots(9)$$

The thermocouples used were sheathed by SUS310S stainless steel and its emissivity ϵ_i was given by the following approximation based on the data of TPRC.¹¹⁾

$$\epsilon_i = 0.14 + 0.0001 T_j \quad \dots\dots\dots(10)$$

As a result, the corrected gas temperature at each level was obtained by adding 3 to 17 K to the thermocouple indication.

Heat loss from a wall was directly measured by using a heat flow meter after reaching steady state. The measurements were conducted at 6 points in circumferential direction and at 5 points in longitudinal direction from Nos. 2 to 5 levels on the wall for obtaining the distribution of heat loss. From the data of all experimental runs, overall wall heat transfer coefficient U defined at inside surface of the reactor wall was represented by the following equation which was obtained by least square method.

$$U = 2.03 - 0.472z \quad \dots\dots\dots(11)$$

Sectional heat balance based on the experimental data was listed in Table 5 showing total heat loss of only 3 to 6 %. This showed the good thermal insulation of our experimental apparatus. For calculating the data in Table 5, however, longitudinal thermal conduction through reaction tube was disregarded.

Root-mean-square-error ϵ was calculated by Eq. (7) for various α and gas temperature at outlet. Error maps were drawn from the calculated data for the 3 runs as shown in Fig. 9. From the figure, the value of 2 parameters was determined simultaneously by finding the least error position in the map. In Fig. 9, the position was shown by star mark. Optimum values of α were obtained by this procedure as 0.30, 0.42 and 0.44 for Runs 14, 18 and 24, respectively. Therefore, the corrected equation can be written as

Fig. 9. Error maps in the plot of α vs. outlet gas temperature.

Eq. (12) by averaging the measured value of α .

$$Nu = 2.0 + 0.39 Pr^{1/3} Re^{1/2} \quad \dots\dots\dots(12)$$

The value of α obtained here was significantly small in comparison with Ranz's equation⁸⁾ having 1.8 as the value of α as shown in Fig. 10. The disagreement between experimental data and this equation may be mainly caused by the difference of packing structure and gas flow change due to the difference.⁷⁾

Fig. 11 shows longitudinal distribution of h_p and Biot number Bi which was defined as (Internal resistance)/(Surface resistance) = $h_p d_p / k_s$. Since Bi value was less than 0.15 for every run, surface resistance controlled the overall heat transfer process and temperature difference between center and surface was negligibly small.¹²⁾ Eq. (12) was employed to simulate the drying process in the following section.

3.2.3. Simulation Results

Experimental results of Runs A-2, B-1 and C-1 are demonstrated in Figs. 12 to 14, respectively. Since pellets contained water in Runs A-2 and B-1, water vapor generated in the upper part. Especially, in Run A-2, pellets had both free and combined water therefore a large amount of water vapor appeared suddenly at the top. However, no water vapor generated in Run C-1 due to the use of the pellets fired at 973 K. Concentration of carbon dioxide measured by the gas analyzer was less than 0.20 %, therefore thermal effect

Fig. 10. Comparison between observed and calculated temperature distributions for Run 18.

Fig. 11. Longitudinal distribution of Bi and h_p .

Fig. 12. Comparison between observed and calculated distributions of process variables for Run A-2.

Fig. 13. Comparison between observed and calculated distributions of process variables for Run B-1.

Fig. 14. Comparison between observed and calculated distributions of process variables for Run C-1.

of decomposition of calcium carbonate was negligible.

Simulation was carried out from Nos. 2 to 6 levels because thermocouple indication at No. 7 level did not express gas temperature and the lower part under No. 2 level was heated subsidiary to prevent inlet gas temperature from decreasing. Calculated temperature, pressure drop and concentration of water vapor which were depicted in the same figures coincided very well with the experimental data. Focussing attention on water vapor content in Run B-1, calculated curve was able to explain characteristics of the experimental data. Pressure drop was able to be estimated by following Ergun's equation;

$$\Delta P/L = f_1 V + f_2 V^2 \quad \dots\dots\dots(13)$$

$$\text{where, } f_1 = 150\mu(1-\epsilon)^2/d_p^2\epsilon^2, \\ f_2 = 1.75\rho(1-\epsilon)/d_p\epsilon^3$$

4. Conclusion

In order to elucidate applicability of nonfired

pellets to blast furnace and direct reduction processes, heat transfer characteristics were investigated by measuring thermal conductivity, drying experiments and mathematical simulation.

From heat exchange experiments, heat transfer coefficient between gas and solid in the moving bed was evaluated by error map method. Obtained results were correlated in the terms of Nusselt, Prandtl and Reynolds numbers as follows;

$$Nu = 2.0 + 0.39 Pr^{1/3} Re_p^{1/2}$$

Rate of thermal decomposition of combined water was simulated well by a mathematical model derived on the assumption of heat transfer control using measured heat absorption function with temperature and measured temperature dependence of effective thermal conductivity.

Moving bed drying experiments provided the effects of free and combined water on the longitudinal temperature distribution. Simulation model developed here gave good agreement with measured temperature, pressure drop and concentration of water vapor.

Nomenclature

- a : Surface area per unit volume ($=6(1-e)/d_p\phi$) (1/m)
 Bi : Biot number (—)
 C_g, C_s, C_{H_2O} : Specific heat of gas, solid and water vapor, respectively (J/kgK)
 C_{H_2O} : Content of combined water (mass%)
 d_p : Diameter of a pellet (m)
 D : Thermal diffusivity (m²/s)
 e : Void fraction (—)
 f : Fractional decomposition of combined water (—)
 G_g, G_s, G_{H_2O} : Mass flow rates of gas, solid and water at inlet, respectively (kg/s)
 h_t : Heat transfer coefficient in Eq. (7) (W/m²K)
 h_p : Heat transfer coefficient between gas and solid (W/m²K)
 H : Heat of decomposition (J/kg)
 H_v : Latent heat of water (J/kg(H₂O))
 k_e : Effective thermal conductivity (W/mK)
 k_g, k_s : Thermal conductivity of gas and solid, respectively (W/m²K)
 N : Number of data (—)
 Nu : Nusselt number (—)
 Pr : Prandtl number (—)
 Q_{Loss} : Heat loss (W/m²)
 r_0 : Diameter of a pellet (m)
 r : Radial coordinate (m)
 Re_p : Reynolds number based on a particle

$$(\rho d_p u / \mu) \text{ (—)}$$

- t : Time (s)
 T_s, T_g, T_a : Solid, gas and ambient temperatures, respectively (K)
 T_s^0, T_g^0 : Initial temperatures of solid and gas, respectively (K)
 T_{obs}, T_{calc} : Observed and calculated temperature, respectively (K)
 T_j : Temperature at the junction of thermocouple (K)
 T_{ss} : Surface temperature of solid (K)
 U : Wall heat transfer coefficient (W/m²K)
 V : Gas flow rate (m/s)
 w, w_0 : Weight loss and final weight loss of sample (kg)
 z : Longitudinal coordinate from the bottom (m)
 α : Constant in Eq. (6) (—)
 β : Thermal flow ratio (—)
 ϵ : Root-mean-square-error defined in Eq. (7)
 ϵ_t : Emissivity of thermocouple (—)
 ρ : Density of bulk gas (g/cm³)
 ρ_s : Apparent density of solid (kg/m³ (solid))
 σ : Stefan-Boltzmann constant (W/m²K⁴)
 ϕ : Geometric coefficient (—)

REFERENCES

- 1) T. Akiyama, Y. Ashizawa, R. Takahashi and J. Yagi: *Bull. Res. Inst. Miner. Dressin. Metall., Tohoku Univ.*, **44** (1988), 191.
- 2) H. Ohta, T. Akiyama, I. Suh, R. Takahashi, J. Yagi and Y. Waseda: *Tetsu-to-Hagané*, **75** (1989), 1877.
- 3) Y. Takahashi and R. Takahashi: *Bull. Res. Inst. Miner. Dressin. Metall., Tohoku Univ.*, **35** (1979), 147.
- 4) J. Yagi, R. Takahashi and T. Akiyama: *Bull. Res. Inst. Miner. Dressin. Metall., Tohoku Univ.*, **42** (1986), 91.
- 5) S. V. Patankar: *Numerical Heat Transfer and Fluid Flow*, McGraw-Hill, New York, (1980), 41.
- 6) S. Ergun: *Chem. Eng. Progr.*, **48** (1952), 89.
- 7) T. Akiyama, R. Takahashi and J. Yagi: *Tetsu-to-Hagané*, **76** (1990), 848.
- 8) W. E. Ranz: *Chem. Eng. Progr.*, **48** (1952), 247.
- 9) M. Hatano and K. Kurita: *Tetsu-to-Hagané*, **66** (1980), 1898.
- 10) R. Hilpert: *Forsch. Gebiete Ingenieurw.*, **4** (1933), 215.
- 11) Thermophysical Properties of High Temperature Solid Materials, Y. S. Touloukian, ed., Thermophysical Res. Cent., Purdue Univ., New York, (1972), 233.
- 12) J. Szekely, J. W. Evance and H. Y. Sohn: *Gas-Solid Reactions*, Academic Press, New York, (1976), 51.
- 13) T. Akiyama and J. Yagi: *Bull. Res. Inst. Miner. Dressin. Metall., Tohoku Univ.*, **46** (1990), 32.
- 14) J. C. He, M. Kuwabara and I. Muchi: *Tetsu-to-Hagané*, **72** (1986), 2048.