Numerical Analysis of Multi-Smelter for Melting Metal Waste

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In view of the limited natural resources and the protection of the global environment, a process for treating the waste materials discharged from industrial production and human life is strongly requested to be developed. A multi smelter was proposed, which consists of coke packed bed in the lower part and free board where fine materials are fluidized during operation in the upper part. It can reduce significantly the volume, eliminate toxicity and recover some materials such as metals, because it has high temperature that can melt waste and reducing atmosphere. Many melting tests were done successfully from February 1999 using the multi-smelter constructed at Osaka Prefecture University. Reactor can treat the waste materials of 1 ton/day. In this operation test, industrial waste materials like used TV sets, air conditioners and refrigerators was melted without secondary emission of dangerous materials like dioxin. In this multi-smelter, the packed bed part seems to play an important role for melting metallic wastes effectively and for achieving a stable operation. On the basis of this foresight, a two-dimensional mathematical model has been proposed, which considered transport phenomena of heat, mass and momentum together with melting and chemical reactions in the high temperature packed bed for processing waste materials. Numerical simulation was conducted to investigate in-furnace phenomena and effects of operating conditions on the process stability. As the results, the process characteristics such as distributions of gas concentration, temperature and velocity have been obtained; they are useful to evaluate the performance of the multi-smelter and to improve the operations leading to less energy consumption and more waste materials treatment. The results showed the multi-smelter is a useful process for melting some kind of waste materials like used refrigerators, air-conditioners, the major part of which were originally made from iron and plastics.

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1. Introduction

Much attention is focused on the waste materials processing. Recently, 50 million tons of municipal waste materials and 400 million tons of industrial waste materials have been generated every year in Japan. Among them, metallic wastes from the industries are estimated as 30 million tons per year.\(^1\) It is strongly required that the amount of waste materials must be reduced as low as possible and remaining wastes should be effectively used as resources for the other purposes for protecting environments and also for saving fossil energy and the other natural resources.

Many processes for incinerating or melting the waste materials have been attempted to be developed in Japan. Amongst these processes,\(^2\) a packed bed melting furnace has recently received high evaluations because the process can eliminate toxicity and reduce significantly the volume. Specifically, a multi-smelter\(^3\) is expected to be a promising process for melting metallic wastes, which are changed to reusable materials without generating dioxin.

Figure 1 illustrates a schematic representation of a multi-smelter, which consists of coke packed bed in the lower part, and free board where fine materials are fluidized during operation. This furnace is furnished with some tuyeres at the different levels: two levels in the packed bed and one level in the free board. Oil burners are equipped at the slag outlet and at the free board respectively for auxiliary heating when low thermal level is observed at the lower part of the packed bed.

Waste materials and coke are charged at the top of the packed bed. Light materials like plastics are mainly burned or gasified in a fluidized bed condition in the free board and heavy materials like metals dropped to the top of the packed bed and are heated with gas flow then reduction reaction and/or melting proceed. Molten slag and metals are discharged from the tapping hole.

In this multi-smelter, the packed bed part seems to play an important role for melting metallic wastes effectively and for achieving a stable operation. On the basis of this foresight, a mathematical model has been proposed, which considered transport phenomena of heat, mass and momentum together with melting and chemical reactions for melting waste materials. Numerical simulation was conducted to investigate in-furnace phenomena and effects of operating conditions on the process stability. As a result, the multi-smelter was found to be a useful process for melting some kind of waste materials like used refrigerators, air-conditioners, the major part of which were originally made from iron and plastics.
2. Mathematical Model

Figure 2 illustrates the packed bed part of the multi-smelter. It consists of a cylindrical coke packed bed of 0.5 m in diameter and 0.58 m in height with two stage tuyeres tilted 15 degrees to a horizontal plane. In the packed bed, three phases of gas, liquid and packed particles coexist. Among these three phases, momentum, heat and mass exchanges take place together with melting of the metallic, chemical reactions and combustion of coke in the vicinity of tuyeres.

2.1 Fundamental equation

A general expression for momentum, heat and mass transfer with sink and source terms is described as eq. (1) for three phases in the two-dimensional cylindrical coordinate system.

\[ \frac{\partial \left( \epsilon_i \rho_i u_i \phi_i \right)}{\partial x} + \frac{1}{r} \frac{\partial \left( \epsilon_i \rho_i v_i \phi_i \right)}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \epsilon_i \Gamma \frac{\partial \phi_i}{\partial r} \right) + S_{\phi_i} \]  

Where, subscript \( i \) in eq. (1) expresses gas, liquid and solid (g, s, l) of three phases, \( r \) and \( x \) are independent variables expressing radial and axial coordinates, \( \epsilon_i \) is volume fraction of \( i \)-th phase, \( \phi \) designates process variables of vertical velocity (\( u \)), horizontal velocity (\( v \)), mass (\( 1 \)), enthalpy (\( h \)) and mass fraction (\( m \)). \( \Gamma \) is transport coefficient and \( S \) is source term. The transfer coefficients and source terms for each variable are summarized in Table 1.

However, for packed particles, kinematic model\(^3\) is applied because this model is simple and has enough simulation precision for a simple cylindrical reactor.

2.2 Evaluation of effective contact area

In the multi-smelter, three phases of gas, liquid and packed particles occupy packed bed region and the liquid hold up is assumed to be dynamic hold up only. Equation (2) can be written for the volume occupation fraction in a packed bed.

\[ \epsilon_g + \epsilon_l + \epsilon_i = 1 \]  

Effective contact area between gas and liquid, \( a_{gl} \) is estimated by eq. (3)\(^5\) and that between liquid and solid, \( a_{ls} \) is calculated from eq. (4).\(^5\) Then, effective contact area between gas and solid can be calculated by subtracting \( a_{ls} \) from particles surface area as described in eq. (5).

\[ a_{gl} = 0.34 F_r^{1/2} W_{el}^{2/3} / d_s \]  

\[ a_{ls} = \frac{6 \epsilon_{ls}}{d_s} \left[ 0.4 R e_{ls}^{0.218} W_{el}^{0.0428} F_r^{0.0238} N C^{0.0235} \right] \]  

\[ a_{gs} = \frac{6 \epsilon_{gs}}{d_s} - a_{ls} \]  

2.3 Interaction parameters

The interaction parameter between gas and solid phases is given by modified Ergun’s relation\(^6\) for considering liquid coexistence, which is expressed by eq. (6).

\[ F_{gs} = \left[ \frac{15 \mu_{gs} a_{gs}}{36(1 - \epsilon_s)} + \frac{1.75 \rho_{gs} a_{gs}}{6} |\vec{v}_g - \vec{v}_s| \right] (\vec{v}_g - \vec{v}_s) \]

The interaction parameter between gas and liquid is calculated by eq. (7), which is derived by modifying Fanning equation\(^7\) for effective contact area between gas and liquid.

\[ F_{gl} = \frac{a_{gl}}{a_{gl} + a_{ls}} \frac{3 C_{p} p_{g} e_{gl}}{4 d_i} |\vec{v}_g - \vec{v}_s| (\vec{v}_g - \vec{v}_s) \]  

The size of a liquid droplet is estimated from eq. (8).\(^8\) This equation is derived as the maximum size of the droplet passing through the densest packing of packed bed.

\[ d_i = \frac{2 \sqrt{3} - 3}{3} d_s \]
Table 2 Reactions and phase transformation considered in the mathematical model.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>No.</th>
<th>Reaction rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>C + 1/2O₂ = CO</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>C + O₂ = CO₂</td>
<td>2</td>
<td>Meng et al. (1966)</td>
</tr>
<tr>
<td>C + CO₂ = 2CO</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>C + H₂O = CO + H₂</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CO + H₂O = CO₂</td>
<td>5</td>
<td>Howard et al. (1973)</td>
</tr>
<tr>
<td>CO + H₂O = CO₂ + H₂</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>H₂ + 1/2O₂ = H₂O</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Gaseous</td>
<td>8</td>
<td>Zhang et al. (1997)</td>
</tr>
<tr>
<td>Carburization</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Melting</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

tive contact area as described by eq. (9).

\[
\tilde{R}_b = \frac{180\mu_l(a_{sl})}{36(1 - \varepsilon_{sl})} (\tilde{\eta}_l - \tilde{\psi}_s)
\]  

(9)

2.4 Heat transfer coefficient

Convective heat transfer coefficients between gas and solid and between gas and liquid are obtained from Ranz and Marshall’s equation modified by Akiyama et al. (1980) for packed bed processes as expressed by eq. (10).

\[
h_{sl} = (2.0 + 0.39 Re_{sl}^{1/2} Pr_{s}^{1/3}) \lambda_{s}/d_i \quad (i : s, l)
\]  

(10)

The solid-liquid convective heat transfer coefficient can be obtained from eq. (11) given by Pohlhausen (1917) for forced convection.

\[
h_{sl} = (0.664 Re_{sl}^{1/2} Pr_{l}^{1/3}) \lambda_{l}/d_i
\]  

(11)

2.5 Chemical reactions

Chemical reactions considered in the mathematical model are listed in Table 2 together with melting of iron, which is a phase change. Rates of chemical reactions are derived as follows.

An expression of overall reaction rate considering chemical reaction and diffusion through gaseous film, which was derived by Muchi et al., (1966) is used for combustion and gasification of coke. Howard’s rate equation (1973) is applied to combustion of CO and equilibrium is assumed for combustion of H₂ and water gas shift reaction.

Carburization rate of iron was obtained experimentally in a previous study (1971) where carburization reaction at solid iron surface from CO gas and diffusion of carbon in solid iron were considered. The carburization rate is applied to the mathematical model.

Melting rate of iron is calculated from eq. (12), which is derived by assuming heat transfer rate as the rate-limiting step.

\[
R_m = a_{sl} h_{sl}(T_g - T_m)/\Delta H_m
\]  

(12)

2.6 Computational method

Equation (1) was discretized according to the control volume method and numerical analysis was conducted by using TDMA method. The equation of continuity for gas phase was solved as a pressure equation derived by connecting with the equation of motion according to SIMPLE method. (15) While liquid pressure was not defined due to discontinuous characteristics of liquid phase therefore volume fraction of liquid was obtained from the equation of continuity.

Flow chart of numerical computation is shown in Fig. 3. Computation proceeds in the order of mesh configuration, reaction rate, gas phase: velocity, pressure, temperature and composition, solid phase: velocity, temperature and composition and liquid phase: velocity, volume fraction and temperature. Then iteration was conducted until convergence was obtained.

3. Numerical Simulation

3.1 Operating conditions

Table 3 lists main operating conditions. Blast temperature is selected as 298 K for the case where coke is only charged, while selected as 873 K for melting wasted refrigerators. Theoretical air volume for complete combustion of the supplied oil is introduced to a burner. The amount of coke charged is obtained as simulation results.
3.2 Computing domain and mesh constitution

Figure 4 illustrates the domain and mesh constitution of the multi-smelter for numerical analysis. The domain is a half of the packed bed part of the multi-smelter which has a cylindrical shape in axis symmetry and the size of 0.5 m in diameter and 0.58 m in height as shown in Fig. 2. Tuyeres are located at the two levels of 0.12 m and 0.40 m up from the bottom and are inclined by 15° with a horizontal line. The gas inlets in two-dimensional numerical analysis are assumed to be two slits of the same sectional area as that of the practical tuyeres. As the results, the width of the both slits is obtained as 0.001 m.

The domain of 0.25 m × 0.58 m is divided into 30 × 150 meshes. In axial direction, the finest mesh located at the gas inlet level has the length of the gas inlet width and the regions around the gas inlets are divided finer than the other area.

3.3 Temperature distribution for charging coke only

Figure 5 represents temperature distributions of gas and coke particles in the multi-smelter for charging only coke. Air is supplied at 298 K through two slits. The air combusts with coke increasing temperature rapidly up to around 2000 K in the vicinity of the slits. High temperature region around the lower slit extends wider than that of the upper slit. This is because the auxiliary fuel supply from the burner was considered as equivalent energy and material supply from the tuyere in this computation. In the peripheral region, lower temperature about 1400 K appears between upper and lower slit and under the lower slit. This is due to high heat loss through the wall.

On the other hand, coke charged at the top of the packed bed is heated rapidly by the heat exchange with ascending high temperature gas. The coke packed bed shows very high temperature around the upper and lower slits similar to gas temperature. The highest temperature of the coke around the lower slit is higher than that around the upper slit by about 100 K. This difference is mainly caused by the oil burner. To compare coke temperature with gas temperature, the former shows more gentle distribution.
3.4 Temperature distribution for refrigerators melting

In this simulation, the averaged values of physical properties were used for the solid phase. For melting, refrigerators were melted at the specified melting point while coke was kept as solid. The ration of refrigerators and coke was given at top of the bed and was changed during melting.

Figure 6 shows Computed isotherms of gas, solid and liquid in the multi-smelter for the case of refrigerators melting. In this Case, the temperature distributions of the gas and solid showed the tendency similar to the case of charging coke only. However, since the waste refrigerators were charged, the temperature level in the region over the upper tuyere dropped a little, though with blowing of preheated air at 873 K. But, in the region under the upper tuyere, the low-temperature region near the wall and near the central axis became small.

The melting zone is shown by the dotted lines in the same figure. The refrigerators melted around the upper tuyere level. The refrigerators melting is earlier in the near wall than in the central axis region. Under the melting zone, molten iron was heated by gas stream and packed coke while dropping, and the temperature distribution in radial direction was not so non-uniform.

3.5 Gas composition distribution for refrigerators melting

Figure 7 illustrates distributions of O₂, CO₂ and CO concentrations in the packed bed of the multi-smelter for the case of refrigerators melting. Oxygen in the blast is consumed sharply by the combustion with coke in the vicinity of the inlets. Correspondingly, CO₂ is formed in the same area and the highest concentration reaches 16%. The CO₂ concentration is decreased by gasification reaction with coke as the gas ascends. The CO₂ concentration is less than 2% inside the central half part of the packed bed. On the other hand, CO gas is formed rapidly by the reactions of both O₂ and CO₂ with coke. In the central part of the packed bed, formation rate of CO is reduced by the decrease of O₂ and CO₂ concentrations and around the central axis, CO concentration is increased up to 30%.

3.6 Flow characteristics of the solid for refrigerators melting

Figure 8 illustrates distributions of reaction rate, timeline and descent velocity in the packed bed for the case of refrigerators melting. The descent velocity is slightly higher in the peripheral region than in the central region by about 0.1 mm/s. As a whole, coke flows down almost vertically. However, around the upper slit level, coke flow changes the direction slightly to the slit due to the consumption of coke in the vicinity of the gas inlet. Around the lower slit, the coke flow changes the direction to the lower gas inlet and under the lower slit a conical shaped dead zone is formed.

The coke charged at the top of the packed bed reaches to the upper gas inlet level at 2500 s, and it is quicker in the peripheral region than in the central region. After the upper gas inlet level, the descent velocity decreases and the coke reaches to the lower gas inlet level at 8000 s. The reaction of coke proceeds significantly around the gas inlets and the highest rate is 1 kg/m³.

4. Conclusion

A two dimensional mathematical model has been developed for analyzing a multi-smelter which was constructed for processing industrial waste materials. Numerical analysis has been conducted for some operations of the multi-smelter. As the results, process characteristics such as distributions of concentration, temperature and velocity have been obtained,
which are useful to evaluate the performance of the multi-smelter and to improve the operations.

**Nomenclature**

- $a$: Specific surface area [m$^2$/m$^3$-bed]
- $C_D$: Drag coefficient [-]
- $C_p$: Specific heat [J/kg·K]
- $d$: Mean particle diameter [m]
- $d_c$: Mean particle diameter of coke [m]
- $F$: Volumetric momentum flux [N/m$^3$]
- $Fr$: Froude number \(= a_c G^2/\rho g \) [-]
- $F_{r,ij}$: Radial interaction force between $i$ and $j$ phases [N/m$^3$]
- $F_{x,ij}$: Vertical interaction force between $i$ and $j$ phases [N/m$^3$]
- $G$: Mass flow rate [kg/m$^2$s]
- $g$: Gravitational force [m/s$^2$]
\Delta H^c$: Enthalpy source [W/m^3-bed]  
\( h \): Enthalpy [J/kg]  
\( h_{ij} \): Heat transfer coefficient between i and j phases [W/m^3-K]  
\( m \): Fractional mass [-]  
\( N_e \): Dimensionless surface tension \( N_e = (1 + \cos \theta) [-] \)  
\( P \): Pressure [Pa]  
\( Pr \): Prandtl number \( (= \mu C_p/\lambda) [-] \)  
\( r \): Radial distance [m]  
\( Re \): Reynolds number \( (= G_i d_j/\mu_i) [-] \)  
\( R_k \): Reaction rate of k-th reaction [kg/s-m^3-bed]  
\( R_m \): Melting rate [kg/s-m^3-bed]  
\( S \): Source term [(kg-m/s, J, kg)/s-m^3-bed]  
\( S_{tg} \): Mass transfer rate from solid to gas [kg/s-m^3-bed]  
\( T \): Temperature [K]  
\( T_m \): Melting point [K]  
\( u \): Vertical velocity [m/s]  
\( v \): Radial velocity [m/s]  
\( \vec{v} \): Velocity vector [m/s]  
\( We \): Weber number \( (= G_i^2/L_a J_0^2) [-] \)  
\( x \): Vertical distance [m]  

Greek  
\( \Gamma \): Diffusive transport coefficient [kg/m-s]  
\( \epsilon \): Volumetric fraction [m^3/m^3-bed]  
\( \eta \): Distribution ratio of reaction heat [-]  
\( \theta \): Contacting angle [degree]  
\( \lambda \): Thermal conductivity [W/m-K]  
\( \mu \): Viscosity [Pa s]  
\( \eta \): Stoichiometric coefficient [-]  
\( \rho \): Density [kg/m^3]  
\( \sigma \): Surface tension [N/m]  
\( \phi \): Dependent variable [(kg-m/s, J, kg/kg)]  
\( \Psi \): Shape fraction of particle [-]  

Subscript  
\( a \): Average

References