Electro-magnetic and Thermal Fluid Dynamics Analysis of NKK Electric Resistance Ash Melting Furnace

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To clarify the temperature distribution and slag flow in the NKK electric resistance ash melting furnace, experiments were carried out using a small-scale furnace as well as computational analysis of the electromagnetic field and thermal fluid dynamics of the slag. The results obtained by the experiment and computational analysis were in good agreement. Ash charged into the furnace is heated by the Joule heat generated near the electrode, and heated slag rises along the electrode due to reduced density and resultant buoyancy. When the slag reaches the surface of the slag bath, it flows in the radial direction away from the electrode. The buoyancy was found to be the major driving force of the slag flow in the bath.

1. Introduction

Melting treatment of bottom ash and fly ash generated from waste incinerators has good potential for rendering them harmless and recyclable[1]. NKK commercialized the electric resistance furnace that melts incinerator bottom ash and fly ash using the Joule heat generated by applying an alternating electric field to slag (**Fig.1**)[2].

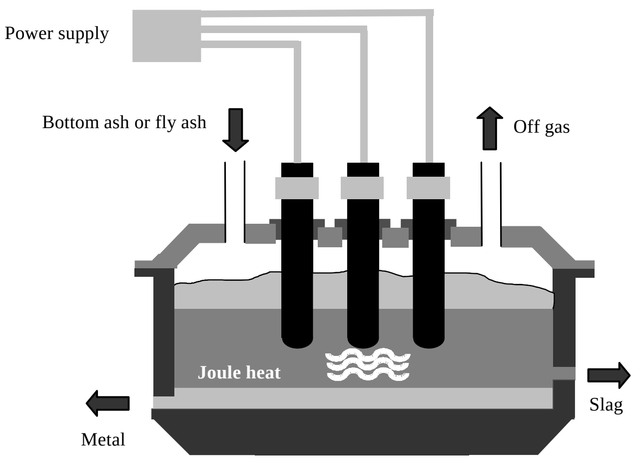

Fig.1 NKK electric resistance ash melting furnace

The features of the NKK electric resistance ash melting furnace are as follows.

(1) As ash is melted under a reducing atmosphere, virtually no HCl is emitted.

(2) As slag and metal are completely separated by the difference in their specific gravity, high-quality slag is obtained and can be used as roadbed material and other construction material[3].

(3) As ash is melted by electric resistance heat under a reducing atmosphere, very little off gas is generated compared with other ash treatment methods.

(4) Fly ash from the ash melting furnace has high concentration of zinc and it can be recovered and recycled as a resource for the non-ferrous industry.

These features of this furnace mostly derive from its gas-tight sealed structure that enables the reducing atmosphere inside the furnace to be maintained. However, because of this sealed structure, the inside of the furnace cannot directly be observed. To clarify the melting process of the ash charged into the furnace and the behavior of slag flow, simulated ash was experimentally melted by a small-scale furnace. Also, electromagnetic and thermal fluid dynamics analysis of the phenomena taking place inside the furnace was carried out.

2. Experiment by small-scale ash melting furnace

2.1 Outline of small-scale ash melting furnace

In this experiment, graphite crucibles of 100 to 250 mm diameters were used as the furnace body. The electrodes were graphite rods of 18 mm diameter. The graphite crucible was placed inside the cylindrical refractory to keep its temperature (**Fig.2**). The electrodes are electrically manipulated in the vertical direction. Two or three electrodes were used for applying 3-phase alternating current of up to 100 kW. For treating off gas, a post combustion chamber and spray chamber were equipped. Two types of bottom ash having the basicity (CaO/SiO_2) of 0.3 and 0.6 respectively were mainly used. Blast furnace slag was used for changing the basicity. A certain amount of ash was charged from the top of the furnace continuously. In order to allow the flow pattern of molten slag to be observed, the experiment was carried out in ambient atmosphere while purging the inside of the furnace by N_2 gas to suppress oxidation corrosion of the furnace body and electrodes. The slag temperature measured by a thermocouple was typically around 1400℃.

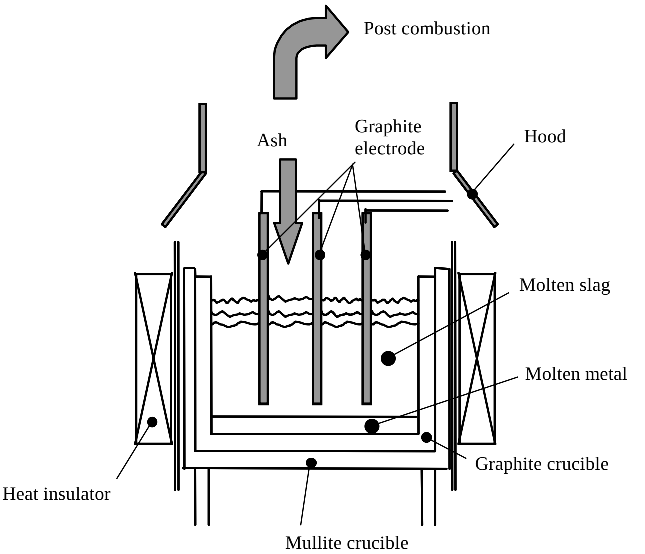

Fig.2 Experimental apparatus

2.2 Experimental results and discussions

Bottom ash with the basicity of 0.6 was charged into the furnace and melted by electric resistance heat. **Fig.3** shows the flow pattern observed on the surface of the slag bath when the charged ash was completely melted. It was observed that the slag flows in the radial direction from where each electrode contacted the surface of the molten slag bath, and collides with each other as counter flows in the middle of the two electrodes. When blast furnace slag that had a high basicity of 1.2 was used, the molten slag formed a flow pattern where two circles generated by radial flows contacted each other because it was more fluid than the bottom ash slag. When the bottom ash that had a low basicity of 0.3 was used, the distance of the radial slag flow was short, and its velocity was low because the fluidity of the slag was low.

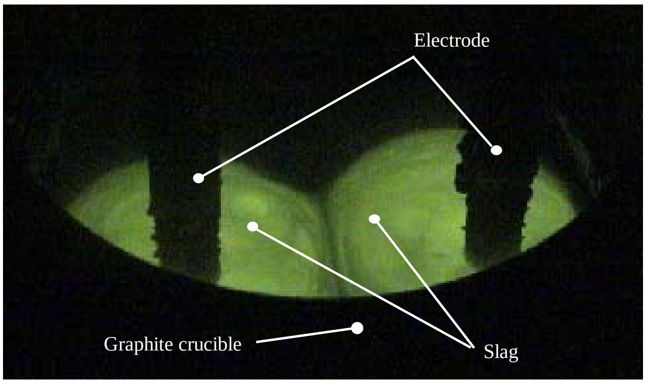

Fig.3 Flow pattern on the surface of the slag bath

This change of flow pattern is thought to occur because the viscosity of slag increases as the basicity decreases, and hence the average fluidity in the entire slag bath decreases. Another conceivable reason is that with decreasing basicity, the melting point of slag increases and the temperature of the slag near the surface decreases due to heat radiation at the surface, and so the viscosity tends to increase near the surface, which decreases fluidity near the surface.

Immediately after bottom ash was charged onto molten slag in the furnace, the interface section between the ash and slag was quickly cooled and its cross section was observed. **Fig.4** shows the vicinity of the ash-slag interface. Directly below the charged ash there is a sintered ash layer, then a half-melted ash layer, and then molten slag. Small bubbles are observed at the ash-slag interface, which are thought to have been produced by the pyrolysis of carbonate in the ash and the reaction between the slag and carbon in the ash.

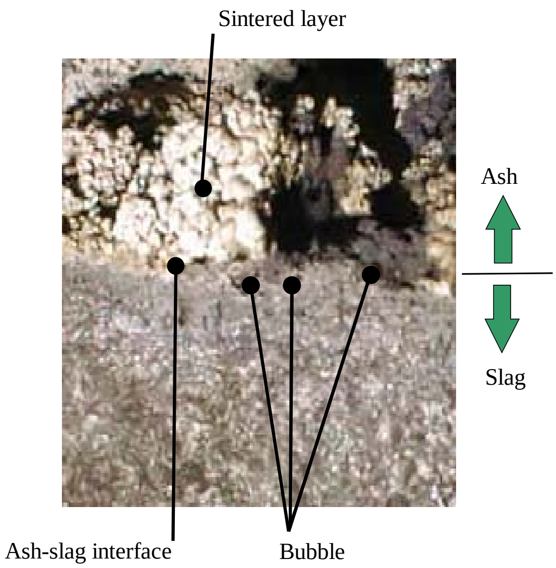

Fig.4 Observation of the ash-slag interface

3. Electro-magnetic and thermal fluid dynamics analysis

In the NKK electric resistance ash melting furnace, molten slag acts as an electrical conductor. Three electrodes supply the slag with three-phase alternating electric power and the slag is directly heated and melted by the Joule heat generated in the slag. The slag behavior in the furnace was investigated by applying electromagnetic and thermal fluid dynamics analysis with the procedure shown in **Fig.5**.

The procedure of the calculation algorithm was as follows.

(1) The electromagnetic field in the molten slag was analyzed by the A- ϕ (magnetic vector potential-electromagnetic potential) method using MAGNA-FIM (a general-purpose calculation code for electromagnetic analysis). As the induced electromotive force was found to be negligible as stated later, the generalized transport equation in FLUENT (a general-purpose calculation code for thermal fluid dynamics analysis) was used for calculating the distribution of electric potential for the sake of calculation efficiency.

(2) Next, the electric current density and the Joule heat were calculated from the distribution of electric potential. Using these values, thermal fluid dynamics in the molten slag were analyzed using FLUENT.

In this procedure, the values of electric conductivity and other temperature-dependent properties obtained by MAGNA/FIM or FLUENT were modified and converged based on the temperature distribution calculated by FLUENT.

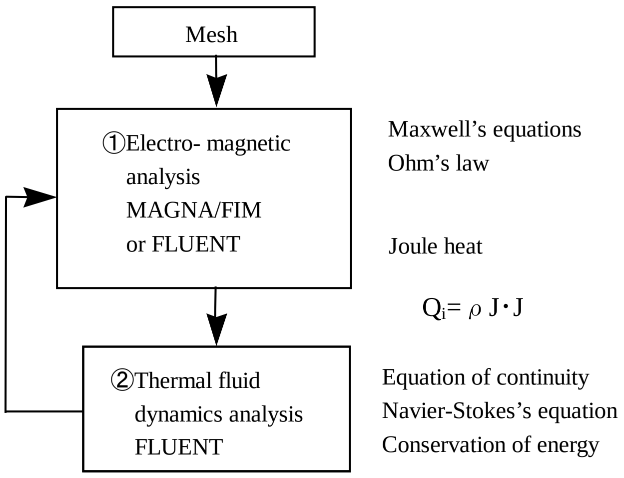

Fig.5 The procedure of electromagnetic and thermal fluid dynamics analysis

3.1 Electromagnetic analysis

The electromagnetic field in the molten slag in the ash melting furnace is expressed by Equations (1) to (4) based on the Maxwell's equations. Since the NKK ash melting furnace uses a low-frequency power source of 50 or 60 Hz, the term of displacement current in Equation (3) is negligible, and so the electric current was approximated to be quasi-steady.

Gauss' law: $\operatorname{div} E = \rho / \varepsilon$ ……(1)

Faraday's law of induction: $\operatorname{rot} E = -\partial B / \partial t$ ……(2)

Ampere's law: $\operatorname{rot} B / \mu = J$ ……(3)

Non-existence of magnetic monopole: $\operatorname{div} B = 0$ ……(4)

where,

E : Electric field vector
B : Magnetic field vector
J : Electric current density
ρ : Density of electric charge
ε : Dielectric constant
μ : Magnetic permeability

Ohm's law is expressed by Equation (5), since $v \times B$ is approximated to be zero as the magnetic field does not move.

$$J = \sigma E \quad \text{……(5)}$$

where,

σ : Electric conductivity

The magnetic vector potential (A) and electromagnetic potential (ϕ) are defined by the following equations.

$$B = \operatorname{rot} A \quad \text{……(6)}$$

$$E = -\partial A / \partial t - \operatorname{grad} \phi \quad \text{……(7)}$$

By using these A and ϕ, Equations (5) and (3) are modified as follows.

$$\operatorname{rot} (\operatorname{rot} A / \mu) = \sigma (-\partial A / \partial t - \operatorname{grad} \phi) \quad \text{……(8)}$$

By calculating the divergence of Equation (2) and substituting Equation (5), we obtain:

$$\operatorname{div} \operatorname{rot} B / \mu = 0 = \operatorname{div} J = \operatorname{div} \sigma E \quad \text{……(9)}$$

$$\operatorname{div} \sigma (-\partial A / \partial t - \operatorname{grad} \phi) = 0 \quad \text{……(10)}$$

The electromagnetic field was analyzed using MAGNA/FIM with Equations (8) and (10) as fundamental equations. From the result of calculation using MAGNA/FIM, the induced electromotive force was found to be negligibly small.

Hence, assuming $\partial A / \partial t = 0$, Equation (10) is modified to the following equation for σ and ϕ.

$$\mathrm{div}\,\sigma\ \ \mathrm{grad}\,\phi = 0 \qquad \cdots\cdots(11)$$

When the value of σ does not change in accordance with the position in the slag, this equation becomes the Laplace equation.

The electric potential ϕ is calculated by numerical analysis using the analytical function of the generalized transport equation in FLUENT applying Equation (11) as the fundamental equation for the sake of calculation efficiency.

Electric boundary conditions were set as follows. For the electric potential on the surface of electrodes, $\phi = \phi_0$ was given taking into account the phase voltage of each pole. Since molten metal exists at the bottom of the furnace, $\phi = 0$ was assumed at the bottom of the molten slag. Since no electric current flows out of the top surface of the molten slag and the surface of the wall, the differential coefficient in the direction normal to these surfaces was assumed to be $\partial\phi/\partial n = 0$ (**Fig.6**).

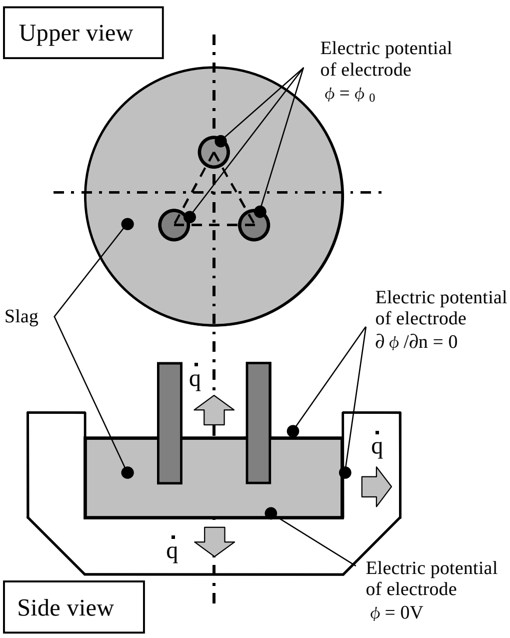

Fig.6 Numerical model of the ash melting furnace

The electric potential ϕ was obtained applying Equation (11) as the fundamental equation under these electric boundary conditions. From the electric potential ϕ, the electric current density vector at each mesh was obtained by the following equation.

$$J = \sigma E = -\sigma\,\mathrm{grad}\,\phi \qquad \cdots\cdots(12)$$

From the electric current density vector, the Joule heat Q_i at each mesh was obtained.

$$Q_i = \sigma^{-1} J \cdot J \qquad \cdots\cdots(13)$$

The Joule heat thus obtained was used as the term of generation in the energy equation in the thermal fluid dynamics analysis.

3.2 Thermal fluid dynamics analysis

In this analysis, the calculation code FLUENT was used, and the flow velocity vector and temperature distribution in the molten slag were obtained by the finite volume method. Equations (13) to (15) were used as controlling equations.

In the Navier-Stokes equation (15), the term of buoyancy ($-\rho\beta(T-T_o)g$) was added to the right side using the Boussinesq approximation.

Equation of continuity: $\mathrm{div}\, v = 0$ ……(14)

Navier-Stokes equation:

$$\rho\, Dv/Dt = -\mathrm{grad}\, p + \mu\,\Delta v - \rho\beta(T-T_o)g \qquad \cdots\cdots(15)$$

Law of conservation of energy:

$$\rho C_p DT/Dt = \lambda\,\Delta T + Q_i \qquad \cdots\cdots(16)$$

Symbols used here represent the following quantities.

- v : Flow velocity vector
- g : Gravitational acceleration
- J : Electric current density vector
- p : Hydrostatic pressure
- ρ : Density of molten slag
- μ : Viscosity of molten slag
- β : Coefficient of volumetric expansion of molten slag
- T : Temperature of molten slag
- Q_i : Joule heat

The Joule heat obtained in the previous section was used. The heat flux ($\dot{q}$) from the surfaces of the molten slag and wall was given as the boundary condition. The boundary conditions used for this thermal fluid dynamics analysis are summarized in **Fig.6**.

From the findings obtained by operating the small-scale furnace, the molten slag flow in the furnace was expected to be slow. Therefore, at first, the numerical analysis was performed applying the laminar flow model. As a result, comparatively large Rayleigh number Ra (the ratio between heat transfer by natural convection due to volume expansion and heat transfer by conduction) in the order of 10^8 was obtained. This is likely attributable to the fact that the slag flow in the vicinity of the electrodes behaves similar to the turbulent flow region. Hence, the k-ε model (two-equation turbulent flow model) was employed for the thermal fluid dynamics analysis.

4. Results of electromagnetic and thermal fluid dynamics analysis and discussion

The distribution of equipotential surfaces in the cross section of the slag bath obtained by electromagnetic analysis is shown in **Fig.7**. The electric potential is high in the vicinity of the electrode, and becomes lower with increasing distance from it. The equipotential surfaces show a shell-like distribution surrounding the electrode. The gradient of the electric potential is high near the electrode, particularly near the tip of the electrode.

Fig.7 Distribution of electric potential in the slag bath

The distribution of electric current density vectors in the slag bath is shown in **Fig.8**. The electric current density vectors run in the radial direction out of the electrode. The vectors are particularly large near the tip of the electrode. Since these vectors are normal to the equi-potential surfaces, the area where the equi-potential surfaces are densely located in **Fig.7** corresponds to the area where the electric current density vectors are large.

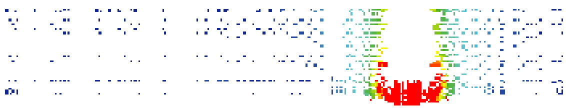

Fig.8 Distribution of electric current density vectors in the slag bath

Fig.9 shows the distribution of the Joule heat. The Joule heat is proportional to the square of the size of the electric current density vector. Therefore, a large amount of Joule heat is generated around the electrode, particularly near the tip of the electrode. Thus, it was found that the slag is heated around the electrode and near its tip, and large buoyancy is generated in these zones.

Fig.9 Distribution of Joule heat in the slag bath

Thermal fluid dynamics were analyzed using the Joule heat obtained by the electromagnetic analysis. **Fig.10** and **Fig.11** show the side view and top view respectively of the distribution of the velocity vectors in the slag bath. **Fig.10** shows that the molten slag forms large ascending flow toward the surface near the electrode, and forms descending flow toward the bottom near the furnace wall after it collides with the wall. Near the center of the furnace, the slag forms counter flows, which collide with each other and flow downward toward the bottom. The slag flows throughout the furnace, forming large circulating flows as a whole.

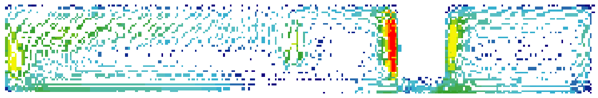

Fig.10 Side view distribution of the velocity vectors in the slag bath

The top view in **Fig.11** shows that the slag flows in the radial direction from around the electrodes. When the viscosity was changed simulating the change in basicity, the radial flow from around the electrodes became slower with increasing viscosity, indicating the same trend observed in the small-scale furnace experiment.

The distribution of the Joule heat obtained by the electromagnetic analysis showed a large heat generation near the tip of the electrode. The buoyancy of the molten slag heated by the Joule heat is considered to be the driving force that causes the ascending flow.

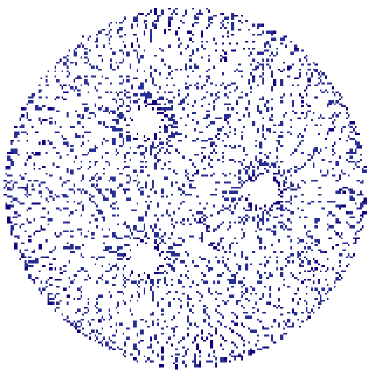

Fig.11 Top view distribution of the velocity vectors in the slag bath

Fig.12 shows the temperature distribution in the slag bath. The entire slag bath is heated almost evenly to about 1500℃ except near the surface around the electrode where the temperature is comparatively high. This homogeneous temperature distribution is likely to be attributable to the large circulating flows formed in the slag bath. It was also found that the temperature is high enough near the bottom of the furnace compared to the melting points of the slag and metal, so the entire zone inside the furnace was in the molten state.

The results of the thermal fluid dynamics analysis verified that in the operation of a real ash melting furnace, ash charged into the furnace is completely melted, and separated into a slag layer and metal layer, which are then discharged from the furnace. It was also found that the slag bath in the electric resistance ash melting furnace does not have any particularly high temperature zone, thus reducing oxidation corrosion of the refractories and electrodes.

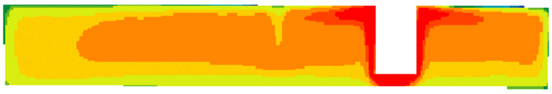

Fig.12 The temperature distribution in the slag bath

5. Conclusions

A small-scale electric resistance ash melting furnace was employed experimentally for melting incinerator ash, and computational analysis of the electromagnetic field and thermal fluid dynamics of the slag in the furnace was carried out.

From the experiment using the small-scale furnace, it was found that the slag flows in the radial direction from around the electrode, and that the ash charged into the furnace first forms a sintered ash layer, and then melts.

From the electromagnetic and thermal fluid dynamics analysis, it was found that buoyancy is generated in the slag heated near the electrodes, and large circulating flows are formed throughout the furnace, making the temperature in the entire slag bath almost homogeneous. The calculation indicated the radial slag flow from around the electrodes, which was in agreement with the behavior observed in the experiment using the small-scale furnace. The temperature inside the furnace was high enough due to the melting points of the slag and metal, so the entire zone inside the furnace was in the molten state.

Thus, the experiment and computational analysis verified that ash charged into the NKK electric resistance ash melting furnace is completely melted, forming a homogeneous slag bath, and high-quality slag and metal are obtained by gravitational separation.

References

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