ZnO AND PbO REDUCTION FROM SLAG PARTICLES IN ICP FUMING PROCESS

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Introduction

Inductively-coupled plasma (ICP) is one of the most promising methods for the treatment of lead and zinc blast furnace slags. Because of the unique plasma torch design, the ICP technology allows the axial injection of raw materials in the highest temperature zone of the plasma.[1] In addition, the absence of electrodes allows plasma generation not only under inert environment, but also under reducing or oxidising atmospheres. The plasma is characterised by high energy densities and temperatures, which allows to achieve high heat and reactant transfer rates, so fuming rates are high even at low Zn/Pb content of the slag. However, the process involves a series of complicated phenomena, such as plasma generation, oxide reduction, multiphase (*i.e.* gas-particle) flow and heat transfer, *etc.*, and there is a very limited understanding of the process kinetics. The latter becomes a bottleneck to further optimise the plasma fuming process. In general, the reaction kinetics is believed to be closely related to the plasma behaviour, slag composition, gas reductant nature, energy input, heat transfer of the system among others. This paper aims to a quantitative understanding of the zinc and lead fuming behaviour under the ICP driven process, which can provide a significant insight into the influence of process parameters on the ICP fuming behaviour, allowing for a further optimisation of process parameters.

Model development

A model for the reduction of zinc oxide and lead oxide by hydrogen under ICP fuming process was developed. This model incorporates the complex process phenomena such as gas-particle flow, heat transfer, slag melting, mass transfer and chemical reactions.[2] The numerical simulations of the ICP process show that a high temperature zone is located in the plasma torch. When the slag particle was injected into the high temperature region, most of the particles with original shapes were completely or partially melted, forming spheres as shown in Figure 1a. This particle reduction model is, therefore, based on the assumption that particles are spheres.

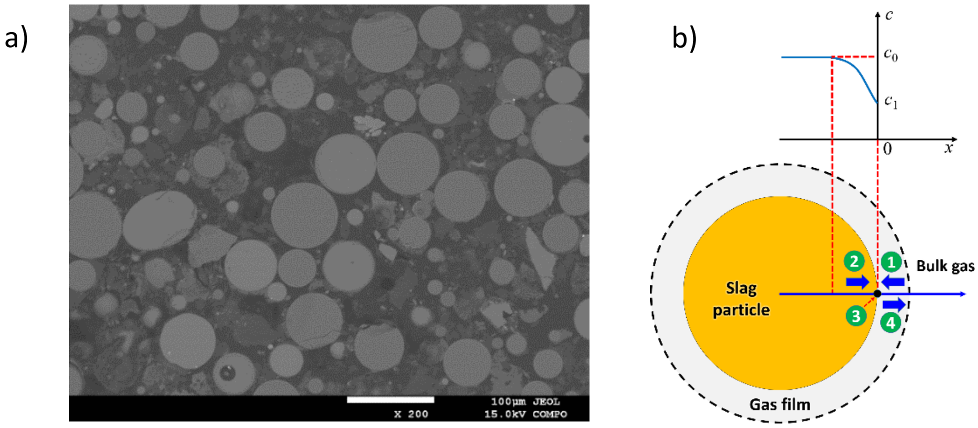

Figure 1: (a) typical SEM image showing the spherical shape of the slag particles sampled after the ICP fuming experiment, (b) Schematic illustration of the unreacted shrinking core model for gas-slag particle reduction

It is assumed that the sphere particles are single phase (*e.g.* solid or liquid) and their initial compositions are homogenised. The gas-particle reaction can be divided into the following steps as shown in Figure 1b, namely:

1. Mass transfer of hydrogen from the bulk gas to the particle surface;
2. Diffusion of metallic oxides in the slag to the reaction interface;
3. Interface chemical reactions;
4. Transfer of H_2O and volatile metals through the gas film to the bulk gas.

Since the high temperature and turbulent gas surrounds the slag particle during the ICP fuming process, hydrogen transfer and interface chemical reactions should not be the rate-limiting step. Therefore, it is reasonable to assume that the diffusion of metallic oxides to the reaction interface is the rate-limiting step. Fick's second law (assuming a constant diffusion coefficient) was employed to describe the diffusion of metallic oxides in the slag particles. By fitting with experimental data, the apparent diffusion coefficients were obtained.

Modelling case

Table 1: Compositions of the as-prepared CaO-'FeO'-SiO_2-based slags (in wt%)

Slag	Fe_2O_3	SiO_2	CaO	Al_2O_3	PbO	ZnO	SO_3
S-free slag	32.8	35.7	20.0	5.2	1.7-3.03	4.8-5.3	--

Table 2: Operation conditions for the ICP fuming treatment

Slag type	H_2 flow-rate (L/min)	H_2 to Ar ratio in the plasma (%)	Power input (kW)	Slag feeding rate (g/h)	Total gas flow (L/min)
S-free	3	1.6	30	753	~ 310

The model was applied to simulate the ICP fuming behaviour of the CaO-'FeO'-SiO_2-based slag. Table 1 shows the compositions of the as-prepared slags. The ground particles were continuously injected into the reactor through the ICP torch. The input conditions used in the present simulation are listed in Table 2.

Results and discussion

Figure 2 presents the comparison between the simulation results and the experimental data as well as the concentration distributions of ZnO and PbO in the slag particle with a diameter of 68 µm. The concentrations of ZnO and PbO outside the particles are significantly lower than those inside the particles, forming a typical diffusion layer of ZnO and PbO. The concentration profiles of zinc and lead predicted by the present model agree very well with the measurements.

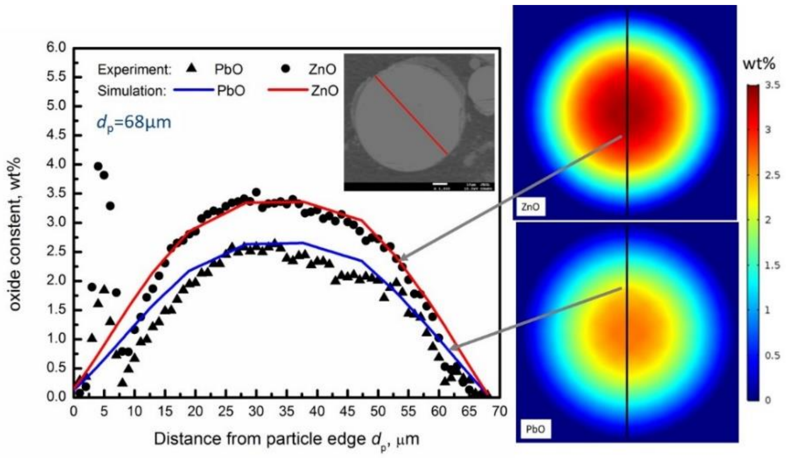

Figure 2: Comparison between the simulation results and the experimental data for the concentration profiles of ZnO and PbO, particle diameter equal to 68 µm

The concentration distributions of H_2, H_2O, Pb and ZnO in the particle and the surrounding gas phase are shown in Figure 3. There is a high concentration zone of gaseous species behind the particles where the content of gaseous products is higher.

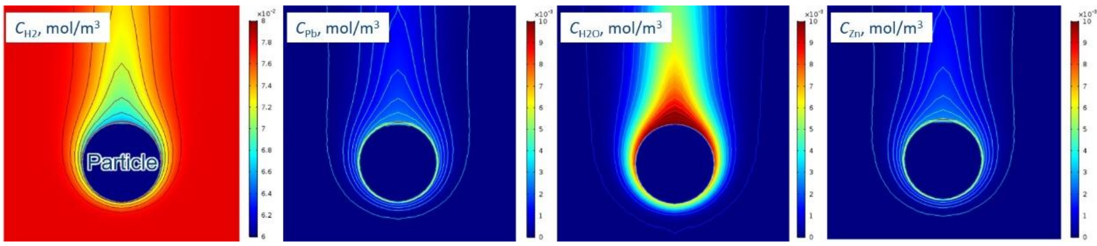

Figure 3: Concentration contours of gaseous products (H_2, Pb, H_2O and Zn) in the gas domains for the slag particle with a diameter of 68 µm

Figure 4 presents the change in residence time as a function of particle size and the melting degree of the sampled particles. Obviously, the particle residence time decreases with the increase of particle diameter. In practice, a long residence time is favourable for the Zn and Pb fuming. The simulation also shows the melting details of the particles with different diameters. For example, the particle of 68 µm will be completely melted during the ICP fuming, because its residence time (0.15 s) is longer than the melting time (0.04 s). However, a large particle of 150 µm is only partially melted due to the short residence time.

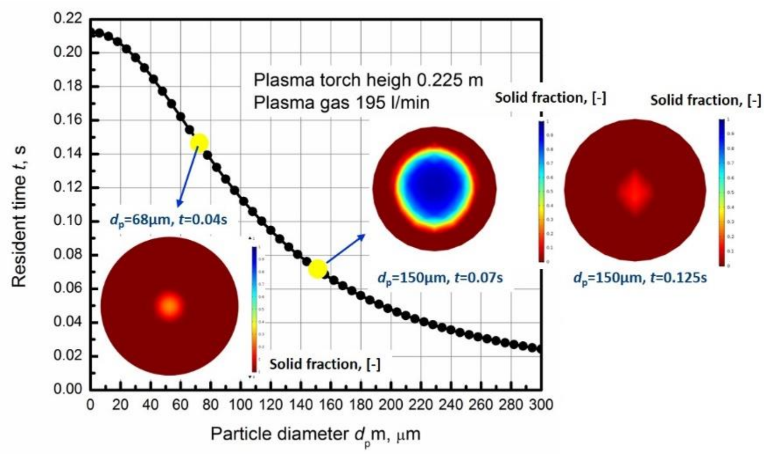

Figure 4: The relationship between residence time and particle diameter, and the melting degree of particles with different diameters when passing through the plasma torch

Conclusion

A mathematical model has been developed to describe the Zn and Pb fuming from slag particles under the ICP plasma treatment. Fick's second law was used to describe the diffusion of metallic oxides, and the diffusion coefficients were determined by experimental data fitting. The predicted concentration profiles of zinc oxide and lead oxide are in good agreement with the measurements. The simulation indicates a diffusion layer of ZnO and PbO outside the particle under the ICP fuming process, and the lead fuming is faster than the zinc fuming. The small particles are favourable for melting, and they have a higher fuming rate than the large particles.

References

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2. M. Kazemi, M.S. Pour, D. Sichen, "Experimental and modeling study on reduction of hematite pellets by hydrogen gas", *Metall Trans B*, **48** (2) 1114-1122 (2017).