

FUNDAMENTALS OF ZINC RECOVERY FROM METALLURGICAL WASTES IN THE ENVIROPLAS PROCESS

Masud A. Abdel-latif
Mintek, Randburg, Republic of South Africa
Masudal@mintek.co.za

KEY WORDS: Enviroplas, D.C. Arc Furnace, ISP Condenser, EAF Dust, LBF Slag, Dross, Premelting, Smelting, Zinc Fuming.

ABSTRACT

The Enviroplas process was developed at Mintek to treat certain metallurgical wastes, such as Lead Blast Furnace (LBF) slag, Electric Arc Furnace (EAF) dust, and Neutral Leach Residues (NLR) from the zinc industry. The process relies on a DC arc furnace and an ISP Lead Splash Condenser (LSC) for the direct recovery of the contained zinc as Prime Western grade (PWG) metal, with the simultaneous production of a disposable slag.

This paper outlines certain fundamental issues of the process, including feed preparation and specifications, operating temperatures, coke (coal) requirements, flux addition, and recycling of the fumes and the condenser dross. In addition, the chemical reactions involved and the associated kinetics are presented and discussed, as well as the major factors that influence the condensation process. Selected test results are also included to highlight the significance of the most important factors that affect the process.

INTRODUCTION

Over the past ten years, Mintek has been involved in an extensive R&D program in order to develop a viable and cost-effective method for the treatment of certain metallurgical wastes as a means of minimising, if not eliminating, the negative environmental impact of such materials. The success of the program has been demonstrated through the development of the Enviroplas process to a stage where it is ready for commercial implementation.

The Enviroplas process involves the smelting of Electric Arc Furnace (EAF) dust, Lead Blast Furnace (LBF) slag or Neutral Leach Residues (NLR) in a DC arc furnace and the subsequent recovery of the volatilised zinc in an ISP Lead Splash Condenser (LSC) as Prime Western grade metal. To date, more than 2000 tons of LBF slag and 300 tons of EAF dust has been processed, whereby high zinc extraction (of 85% from LBF slag and 98% from EAF dust) was consistently achieved, resulting in zinc fuming rate of more than 100kg Zn/hm² (LBF slag) and 130kg Zn/hm² (EAF dust). The zinc condensation efficiency at the pilot scale ranged from 65% to 75% and the produced slag consistently met the USA EPA TCLP test for safe disposal.

Recyclability of the generated fume and the condenser drosses was proven in a Top Blown Rotary Converter (TBRC), whereby more than 1000kg of typical dross was treated for lead metal recovery. Lead recovery was 90% and greater, giving a metal phase containing more than 99% Pb that is suitable for re-use in the condenser.

Throughout the developmental program, a great deal of experience and knowledge was gained with regard to the process fundamentals and their roles either in the smelting stage (fuming) or the condensation stage. In addition, the understanding of these fundamentals

clarified many aspects concerning raw materials specifications, and thus the requirements of any pre-treatment step that could be needed. This paper is intended to highlight certain fundamental issues that are believed to be important in zinc recovery in the Enviroplas process. Selected test results are also included to emphasise the significance of the most critical factors that affect the process.

DESCRIPTION OF THE ENVIROPLAS PROCESS

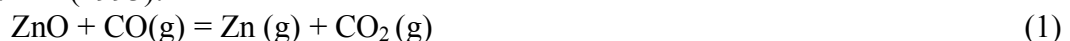
Depending on the material to be treated, the Enviroplas process can be described as follows: for LBF slag, feeding of liquid slag from a lead blast furnace through a holding furnace is an attractive energy-saving option, Schoukens et al (1995). However, dry and granulated slag (stockpiled in dumps) can be directly charged into the fuming furnace. Metallurgical coke is employed as the reducing agent and is delivered to the fuming furnace at a controlled rate. Coals, charcoal or other carbonaceous materials, low in moisture and volatile content can also be used as reducing agents.

In the case of EAF dust, Schoukens et al (1996), a pre-treatment stage is required, the aim of which is to remove most of the halogens and any other undesirable species present, and at the same time to transform the dust into a physically suitable form for smelting in the fuming furnace. The pre-treatment facility could be a rotary kiln, a DC arc furnace, or a water-washing facility followed by a pelletizing and induration stage. As before, dried metallurgical coke is introduced to the fuming furnace as a reductant. If required, fluxing agents can be delivered to the smelting furnace, also.

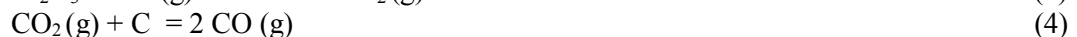
Zinc and lead oxides contained in the molten bath are reduced to their metals at temperatures of 1400^oC to 1500^oC, and thus report to the gas phase. The residual, or spent, slag as well as any iron alloy that is produced, is tapped from the furnace as required. The volatilised zinc and lead exit the furnace through a refractory-lined duct and enter the lead splash condenser (operated at 500^oC to 550^oC), where they are condensed. The lead-zinc solution is then cooled down to separate the zinc (at about 450^oC). The condenser off-gas passes through a combustion chamber, and any metal oxides are captured in a bag house. Condenser drosses and the fumes are then pre-treated before recycling to the fuming stage. Table 1 presents the chemical composition of EAF dust and LBF slag that have been processed in the pilot-plant facility shown in Figure 1.

CHEMISTRY OF ZINC FUMING

Due to the wide range of chemical species that are present, the reactions taking place in the fuming furnace are numerous and complex. However, the chemical reactions that lead to the extraction of zinc and its subsequent volatilisation can be described as follow, Dal and Rankin (1993):



It is widely believed that these reactions take place at the slag/gas interface in contact with the coke particles, Dal and rankin (1993). As a result, the local concentration, and thus the activity, of ferric ions in the slag and the partial pressure of carbon dioxide in the gas bubbles tend to increase with the progress of the reactions. However, the smelting conditions inside the furnace are normally very reducing such that the following reactions take place almost instantly:



Reaction 3 ensures that the activity of ferrous ion (wustite) in the slag is maintained at high level, relative to that of ferric ion, to cause reaction 2 to proceed to the right. In the meantime, reaction 4 keeps high carbon monoxide partial pressure in the gas bubble such that reaction 1 takes place as indicated. Obviously, the presence of sufficient carbon, coke reactivity and the operating temperature would have major influence on the extent of the reactions above.

The preceding paragraphs indicate that coke addition and the operation temperature are among the factors that determine zinc extraction and its fuming rate. Other parameters include: slag basicity, Fe^{3+}/Fe^{2+} ratio in the slag, the presence of a metallic phase in the hearth of the furnace, bath stirring, the arc attachment zone (AAZ) and its characteristics and the presence and level of certain impurity elements in the feed materials.

Reductant Addition: the amount of reductant (coke or coal) that is normally charged into the furnace depends on several considerations such as, Richardson et al (1985):

1. The level of zinc extraction to be achieved
2. CO/CO₂ partial pressure ratio in the off-gas that is necessary to prevent zinc vapour oxidation before it reaches the condenser. The ratio is dictated by the thermodynamics of zinc reversion reaction, and is usually controlled at a value of 10:1 and higher.
3. The relative amount of metallic iron production that can be tolerated.

Reductant addition can also be influenced by its chemical composition, i.e., fixed carbon, moisture, volatile matter, and ash components. The chemical analysis of the dust and LBF slag could also affect coke requirements, particularly, the analysis of zinc and lead oxides, Fe^{3+}/Fe^{2+} ratio in the feed, as well as the presence of other readily reducible metal oxides. Typically, EAF dust requires about 9% coke addition while LBS slag demands about 4% (see Figure 2 and Table 2).

Temperature: The kinetics of the fuming process are greatly influenced by the operating temperature, Rankin and Write (1990) and Quarm (1980). Elevated temperatures ensure that the diffusion rates of the reacting species (Zn^{2+} , Fe^{2+} , Fe^{3+}) are very fast and that the slag is very fluid and well mixed. In addition, high temperatures tend to suppress iron metal formation since zinc oxide reduction becomes more favourable, thermodynamically, than the reduction of FeO. This in turn leads to higher levels of zinc extraction if the reductant addition is kept constant, or to less coke requirements for the same level of zinc extraction. A high smelting temperature is also desirable so as to maintain the gas temperature to the condenser inlet at above 1000°C, below which zinc oxidation by carbon dioxide becomes excessive. This is important since oxidised zinc leads to operational difficulties as a result of more accretion build-ups, blockages, and by the production of higher amounts of drosses in the condenser. Needless to say that the condensation efficiency would be significantly affected.

However, increased operating temperatures may contribute to refractory erosion, by both thermal degradation and slag attack, if a frozen slag line can not be maintained. In addition, the overall energy requirements will increase with higher temperatures. Typically, EAF dust requires a smelting temperature of about 1500-1550°C in order to achieve a ZnO content in the final slag of 2% and lower. In comparison, LBF slag demands an operating temperature of 1400-1450°C to extract more than 85% of the contained zinc at good fuming rates (Figure 3).

Slag Basicity can influence zinc extraction as follows, Quarm (1965) and Kellogg (1967): higher basicity {defined as the $(CaO + MgO)/SiO_2$ mass ratio} tends to prevent the formation of zinc ferrite and zinc silicate that are more difficult to reduce than zinc oxide. In addition, basic slags have a stabilising effect on ferric ions, leading to lower

Fe^{3+} activity in the slag, and hence causing reaction 2 above to proceed to the right. These two effects contribute to better zinc extraction, thus lower ZnO in the final slag, and to enhanced zinc fuming rates. Changes to slag basicity can be accomplished by adding fluxing agents such as lime and calcined dolomite (to increase basicity), or silica (to lower it). However, flux addition might result in higher energy consumption, elevated slag liquidus temperatures with more basic slags, and obviously more slag to dispose of. Figure 4 presents the final ZnO analysis in the spent slag produced from LBF slag and EAF dust as a function of slag basicity. Obviously, a basicity of 1.0 and higher is required to limit the ZnO content to 2% and lower in the produced slag.

Ferric to Ferrous Ions Ratio: as pointed out earlier, ferrous ions play a direct and major role in zinc fuming from LBF slags and EAF dust. In fact, many believe that zinc fuming is mostly controlled by the diffusion rate of ferrous ion when zinc concentrations in the slag is above 2%, Kellogg (1967). Nevertheless, as a result of the reactions taking place, ferric ions are formed, and must be reduced to maintain high fuming rates, and to prevent magnetite precipitation which becomes likely to happen at $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios of about 5 and below. The negative impact of low $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio could be avoided by charging reactive coke into the furnace at the right amount and steady rate. In addition, when hot transfer of the slag is practised (discussed later), air ingress into the holding furnace should be prevented. It should be noted that the presence of liquid metal can also contribute to maintaining a high $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio in the slag where the reaction, Rankin (1990):



can take place at the slag-metal interface, provided that the bath is well-stirred and magnetite (ferric ion) is dissolved in the slag phase.

The Presence of a Metal Phase: The plasma furnace is usually operated with an iron heel so that anode contact is readily maintained. A metal phase can also be formed when extra reductant is added to the furnace to achieve higher zinc extraction. Although this is normally avoided or kept to a minimum, because of increased energy and reductant consumption, the production of iron could be a contributing factor to zinc fuming by lowering Fe^{3+} concentrations through reaction 5. This is likely to be the case when the diffusion rate of Fe^{3+} is fast (well mixed bath), and that the CO/CO₂ ratio in the gas bubble is low, which might lead to relatively high Fe^{3+} concentrations in the vicinity of the slag-gas interface.

When the reductant addition is high enough to cause the reduction of iron oxide, the produced iron may influence zinc extraction through the reaction, Rankin (1990) and Quarm (1980):



It is possible for this mechanism of zinc reduction to take place at the slag-gas interface, but less likely within the bulk of the slag or at the slag-metal interface. It should be noted that processing of EAF dust and LBF slag in the Enviroplas process normally results in the production of 30-40 kg iron metal per ton of feed.

Impurity Elements in the Feed: It is believed that zinc oxide reduction may be retarded by the presence of a relatively high sulphur content in the feed. This is believed to be due to a surface blockage at the slag-gas interface caused by the surface-active nature of sulphur in the slag, Dal and Rankin (1993). It is also possible that some zinc could be present as zinc sulphide, which is very difficult to fume as Zn(g), and could end up in a segregated matte (sulphide) phase that builds-up above the metal bath. In addition, sulphides of zinc and lead might be extracted into the gas phase, and collect in the condenser upon solidification. This would represent zinc and lead losses and adds to the dross generation.

The negative impact of high sulphur content in the feed could be minimised by increasing the slag basicity by the addition of lime. In this case, zinc sulphide reacts with lime as follows, Igiebob et al (1992):



The resulting oxysulphide can then be easily reduced by carbon monoxide forming zinc gas and calcium sulphide:



For reactions 7 and 8 to occur, zinc sulphide must remain dissolved in the slag, slag basicity is much higher than unity, and that the reactions are taking place at the slag-gas interface.

Other elements that could influence the overall zinc recovery include chlorine, fluorine, sodium, potassium, arsenic etc. Their impact is believed to be more pronounced on zinc condensation as compared to its extraction.

Arc Attachment Zone: The slag bath area where the plasma arc impinges is referred to as the arc attachment zone (AAZ). This zone is characterised by elevated temperatures, relative to the bulk of the slag, and by a higher degree of mixing, Szekely et al (1983). The reductant might also be driven away from this zone by the high gas velocities associated with the arc jet, particularly when the current flux is very high (short arc). In this case, the dominant mechanism of zinc oxide reduction in the AAZ is likely to be through Fe^{2+} route, although thermal dissociation could be a factor, but not to any significant degree.

Bath Stirring: Bath Stirring ensures that the slag is well mixed and thus the rates of mass and energy transfer are high. As a result, the chemical reactions occurring at the slag-gas interface are driven to near completion.

Bath stirring is caused by the following, Szekely et al (1983):

- 1) Transfer of jet momentum at the slag surface, namely at the AAZ.
- 2) Electromagnetic forces induced in the bath due to the passage of the electric current.
- 3) Natural convection caused by thermal gradients in the furnace.
- 4) Gas bubble-driven circulation

The degree of bath mixing will depend on slag fluidity and depth. In general, slag depth relative to furnace diameter, should be relatively low and has to be optimised for good zinc extraction (Figure 5). Gas injection (i.e. nitrogen) into the bath can be employed as a means of introducing vigorous stirring in the slag. Doing so resulted in more than a 25 % increase in the zinc fuming rate from LBF slag, producing slag containing about 1.2% ZnO, compared with more than 2 % ZnO without stirring.

FEED PREPARATION

The proceeding section highlighted certain requirements and specifications that the raw materials should meet. Other requirements include the following:

Reductant: The reducing agent, whether it is coke or coal, should be high in fixed carbon and low in ash and volatile matter contents. The moisture content should be as low as possible, since hydrogen in the furnace off-gas could have a detrimental effect on zinc condensation efficiency. The moisture can be driven off at moderate temperatures (150-200^oC). However, the volatile content, which contributes to the hydrogen level in the off-gas, requires higher temperatures in the range of 400-500^oC. This temperature range ensures that the volatile and water contents are less than 2.0 and 0.5% respectively, a range that has been seen to have little influence on zinc condensation.

The particle size and size distribution are factors to be optimised. The reactivity of the reductant can be improved by size reduction, however the fine fraction could lead to higher feed carry-over, which affects zinc condensation negatively.

EAF Dust and LBF Slag: the pre-treatment stage should aim at the following:

- 1) Reduce the moisture content to less than 0.1%. This is usually achieved at temperatures of 600^oC, where the combined moisture can also be driven off.
- 2) Removal of elements such as chlorine, fluorine, sulphur, potassium, sodium, arsenic, cadmium etc. Such components form volatile compounds in the fuming furnace and report to the condenser, adding to the dross formation problem and affecting the condensation efficiency.
- 3) Zinc losses should be kept to a minimum. This can be done by operating at relatively low temperatures, and adding fluxing agents that tend to stabilise zinc oxide.
- 4) The EAF dust, and to a lesser extent LBF slag, should be transformed to a physically suitable form that is easy to charge into the fuming furnace, such that dusting is minimised.
- 5) Air ingress to the pre-treatment stage should be prevented in order to avoid the formation of magnetite and its possible precipitation in the fuming furnace. This is mainly important in the case of LBF slag.
- 6) The pre-treatment operation should aim at low temperature as a means of reducing the overall energy consumption (in the order of 1250-1400^oC for the pre-melting option).
- 7) The requirement for flux addition should be low.
- 8) Pre-treatment of the feed should not adversely affect zinc extraction or its rate in the fuming furnace.

For LBF slags, the Enviroplas process allows for a holding (pre-melting) furnace operating at 1200-1250^oC (about 50-100 ^oC above the liquidus temperature). The holding furnace receives molten slag from the lead blast furnace, and possibly granulated slag from stockpile, and delivers it into the fuming furnace at a controlled rate. EAF dust, on the other hand, can be treated in a variety of ways, depending on both capital and operating costs. When a pre-melting option is chosen, the operating temperature would range from 1300 to 1400^oC, depending on the composition of the dust and the amount of silica (flux) required to transform it into a molten material easily transferable in the liquid state. Pre-melting trials of EAF dust at Mintek in a DC arc furnace required about 10% silica addition in order to obtain a free flowing slag at 1350^oC, with less than 10% Zn losses. Removal of impurity elements during the pre-melting was above the target, resulting in a very suitable feed to the fuming furnace.

CONDENSATION

The pilot-scale ISP condenser consists of a rectangular box that contains the molten lead and a rotor, a pump sump to allow circulation of Pb-Zn metal, a cooling launder, a flux bath and separation bath. The operating philosophy is as follows: the rotor speed is adjusted to attain a low condenser off-gas temperature (400-450^oC). Lead-zinc solution (about 3.5 – 4.5%Zn, balance Pb, at 550^oC) is continuously pumped from the condenser into the cooling launder, where it flows into the flux bath and finally into the separation bath, that is maintained at about 450-460^oC. As Pb-Zn solution cools down, zinc separates out and forms a layer, on top of the lead, and is tapped when required. The zinc-depleted lead flows back into the condenser at about 440-450^oC.

The rotor speed and its immersion depth influence the amount of lead being splashed and the droplet size and distribution of these droplets. These two factors determine, in part at

least, the rate of zinc condensation and absorption by the lead bath. Other factors include the concentration of zinc in the lead bath, pumping rate of the lead, and its temperature, relative to the gas inlet temperature to the condenser. Another important parameter that affects zinc condensation is the inlet gas composition, particularly, with regard to CO/CO₂ ratio, and hydrogen level. As mentioned before, the CO/CO₂ ratio should be 10:1 and higher as the gas enters the condenser in order to minimise zinc oxidation. Hydrogen level also influences zinc oxidation (specifically H₂ /H₂O ratio), but it also affects the formation of a so-called tooth-paste dross (a mixture of Pb-Zn oxides and metallic lead, the formation of which is promoted by hydrogen levels above 1 to 4% in the condenser off-gas). Chlorine in low concentrations is believed to enhance zinc condensation. However, when the zinc/chlorine ratio in the feed is lower than 70:1, zinc condensation efficiency starts to deteriorate. Another important factor that affects zinc condensation is the feed carry-over in the fuming furnace. A relatively high dusting rate (above 1% feed carry-over) leads to excessive zinc (and lead) oxidation, and thus lower zinc recovery. It is believed that entrained solid particles in the furnace off-gas act as reaction sites promoting the zinc reversion reaction. This is made even worse inside the condenser where the conditions are very turbulent. Another aspect of feed carry-over is related to side-reactions that take place in the AAZ. Due to the high temperatures in this zone, dissociation, reduction and subsequent volatilisation of components such as Fe, Mn, Si, and Cu could become severe, which has a negative impact on the condenser performance with regard to dross generation and to the quality of zinc metal produced. For instance, high iron content in zinc metal is not desirable because it leads to the formation of a metallic phase called hard zinc (zinc with 2-4% Fe), which is difficult to handle and at the same time represents a zinc loss that requires recycling after proper preparation. At the operating conditions employed at the pilot-scale, the target furnace off-gas composition, as predicted thermodynamically, is as follows, Jones (1987): CO = 50-55%, CO₂ = 4-5%, Zn(g) = 30-35%, H₂ = 1-2%, N₂ + others = balance. Under these conditions, the zinc condensation efficiency achieved ranged from 70 to 75%, where zinc metal conforming to PWG specifications was consistently produced from both LBF slag and EAF dust (Table 3).

In order to investigate the relationship between the furnace off-gas composition and dusting on zinc condensation, a test was conducted where ferrosilicon was used as a reductant, instead of coke. Fine EAF dust was fed to the fuming furnace at 1-2 tons/h. Doing so produced an off-gas containing more than 90% Zn and feed carry-over of less than 1%. The condensation efficiency during this test increased to more than 82%, as compared to 65-75% achieved when coarse EAF dust and coke were fed, and less than 60% with fine EAF dust and coke. This was a clear indication that the gas composition and feed carry-over played a major role in affecting the condensation efficiency.

Dross Generation: The ability to recycle the condenser dross is an important factor for the success of the Enviroplas process, where an industrial facility is projected to be able to condense 90% of the volatilised zinc. The rest is expected to report mostly to the dross phase as oxide, with an almost equal amount of oxidised lead. Generally, lead can be recovered from such material by reduction with coke or coal at 750-1000⁰C. The extracted lead should be of such quality that it can be recharged into the condenser. The remaining solid residue is mostly ZnO with relatively high levels of Cl, Na, K, and S, making it unsuitable for direct recycling. However, water-washing can be carried out to reduce the levels of these components to acceptable values. After drying, the final residue can be charged to the premelter or the fuming furnace.

In the pilot-scale tests, condenser dross generation was typically between 800 and 1000kg per ton of zinc produced. This is comparable with the industrial production rate of 300 to 400kg dross per ton of zinc. The produced dross contains about 35-45% ZnO, 30-40% PbO, with lesser amounts of other oxides such as FeO, SiO₂, CaO, MgO, and Al₂O₃. Other minor components present include Na₂O, K₂O, Cl, S etc.

Recyclability of the produced dross was investigated in a top blown rotary converter at temperatures between 750 and 1000^oC. Coke was used as reductant, and fluxing agents were added to investigate their influence on lead recovery to the metal phase. About 1000kg of typical dross was treated at 40 kg/h. The results indicate that lead recovery was in excess of 90%, producing a metal phase analysing more than 99% Pb that could easily be recycled to the condenser. The remaining ZnO-rich solid residue contained about 80% ZnO. A washing step eliminated more than 90% of the contained Cl, Na, K, and S, with less than 2% Zn losses into the wash water.

Fume Production: A zinc oxide rich fume is usually collected in the bag-house as a result of the combustion of the condenser off-gas which contains small amounts of Pb(g) and Zn(g). Typically, the fume contains 70-80%ZnO and 10-15%PbO. Depending on the levels of the impurity components (Cl, K, Na, S, Cd, etc), the fume can either be fed to the pre-melting furnace (low levels) or it can be combined with the lead-free dross for water-washing and drying.

CONCLUSIONS

Pilot-scale testwork has proven the technical feasibility of the Enviroplas process for the recovery of zinc from EAF dust and LBF slag. The produced slag consistently met the USA EPA TCLP test for safe disposal. Very good zinc extraction, fuming rates, and condensation efficiency were achieved during the testwork.

Chemical and physical factors that affect the fuming process include: temperature, reductant addition and reactivity, slag basicity, Fe³⁺/Fe²⁺ ratio, bath stirring, and arc attachment zone. The condensation step is affected greatly by gas composition (CO/CO₂ ratio, H₂ level, etc) and by the feed carry-over. Any pre-treatment step should aim at producing dust-free furnace off-gas with high CO/CO₂ ratio and low hydrogen levels.

REFERENCES

- Dal, I; and Rankin, WJ; 1993,. The Effect of Sulphur on the Rate of Reduction of Zinc Oxide from Slag. International Symposium – World Zinc '93, Hobart, 10-13 October 1993.
- Igiehon, UO; Terry, BS; and Grieveson, P, 1992. Formation of ZnCaOS During Heat Treatments in Zn-Ca-O-S System and its Role in Carbothermic Reduction of Zinc Sulphide in Presence of Lime. Trans. Inst. Min. Metall., 101, C155-C162, Sept. – Dec.
- Jones, RT. 1987. Computer Simulation of Pyrometallurgical Processes. Proceedings of the Twentieth International Symposium on the Application of Mathematics and Computers in the Minerals Industries, Vol. 2: Metallurgy, Johannesburg, SAIMM, 265.
- Kellogg, H, 1967. A Computer Model of the Slag Fuming Process for Recovery of Zinc Oxide. Trans. of the Metallurgical Society of AIM, 239, 1439, September.
- Quarm, TAA. 1980. Physical Chemistry and Pyrometallurgy. Trans. Inst. Min. Metall., C-139.
- Quarm, TAA, 1965. The Slag Fuming Process. Mining Magazine, 113 (2) 114.
- Rankin, WJ; and Wright, S, 1990. The Reduction of Zinc from Slag by an Iron-Carbon Melt. Metallurgical Transactions B, 211, 885, Oct..
- Richardson, GG; Brimacombe, JK; and Toop, GW, 1985. Kinetics of Zinc Slag-Fuming Process: Part I. Industrial Measurements. Metallurgical Transactions B, 1613, 513, Sept.
- Schoukens, AFS; Denton, GM; and Jones, RT, 1995. Pilot Plant Production of Prime Western Grade Zinc from Lead Blast Furnace Slags using the Enviroplas Process. Proceedings of the third International Symposium on Recycling of Metals and Engineered Materials; Point Clear, Alabama, Nov 1995, Minerals, Metals and Materials Society, 857.
- Schoukens, AFS; Abdel-latif, MA; Freeman, MJ; and Barcza, NA, 1996. The Enviroplas Process for the Recovery of Zinc, Chromium and Nickel from Steel-Plant Dust. Electric Furnace Conference Proceedings, 341.
- Szekely, J; McKelliget, J; and Choudhury, M. 1983. Heat Transfer, Fluid Flow and Bath Circulation in Electric Arc Furnaces and DC Plasma Furnaces. Ironmaking and Steelmaking, 10 (4), 169.

Table 1: Typical chemical analyses of LBF slag and EAF dust treated in the Enviropilas process, mass per cent

COMPONENT	LBF SLAG	EAF DUST
ZnO	15.3	24.5
PbO	2.7	2.4
CuO	0.6	0.2
FeO	30.6	0.0
Fe ₂ O ₃	0.0	41.3
Al ₂ O ₃	4.8	1.1
SiO ₂	22.8	4.8
CaO	11.0	7.9
MgO	4.6	3.9
Cr ₂ O ₃	0.1	0.8
MnO	-	3.3
S	2.4	1.8
C	0.03	3.3

Table 2: Experimental conditions and results pertaining to EAF dust and LBF slag processing in the Enviropilas process.

	EAF DUST	LBF SLAG
Feed rate, tons/h	1 – 2	1.0 – 1.5
Power, MW	1.2 – 2.3	0.8 – 1.1
Reductant type	Coke	Coke, Coal
Reductant feed rate, kg/h	80 - 180	40 – 70
Temperature, °C	1500-1550	1400-1450
ZnO in slag, mass per cent	1 – 2	2 – 4
Zinc extraction, %	96 - 98	80 – 90
Fuming rate kg/hm ²	>130	>100

Table 3. Typical zinc metal analyses produced in the Enviropilas process and PWG specifications, mass per cent.

	ZnO	Pb	Cu	Fe	Cd
Pilot-scale data	98.45	1.37	0.035	0.041	0.03
PWG specifications	98.5	0.5-1.40	0.20	0.05	0.20

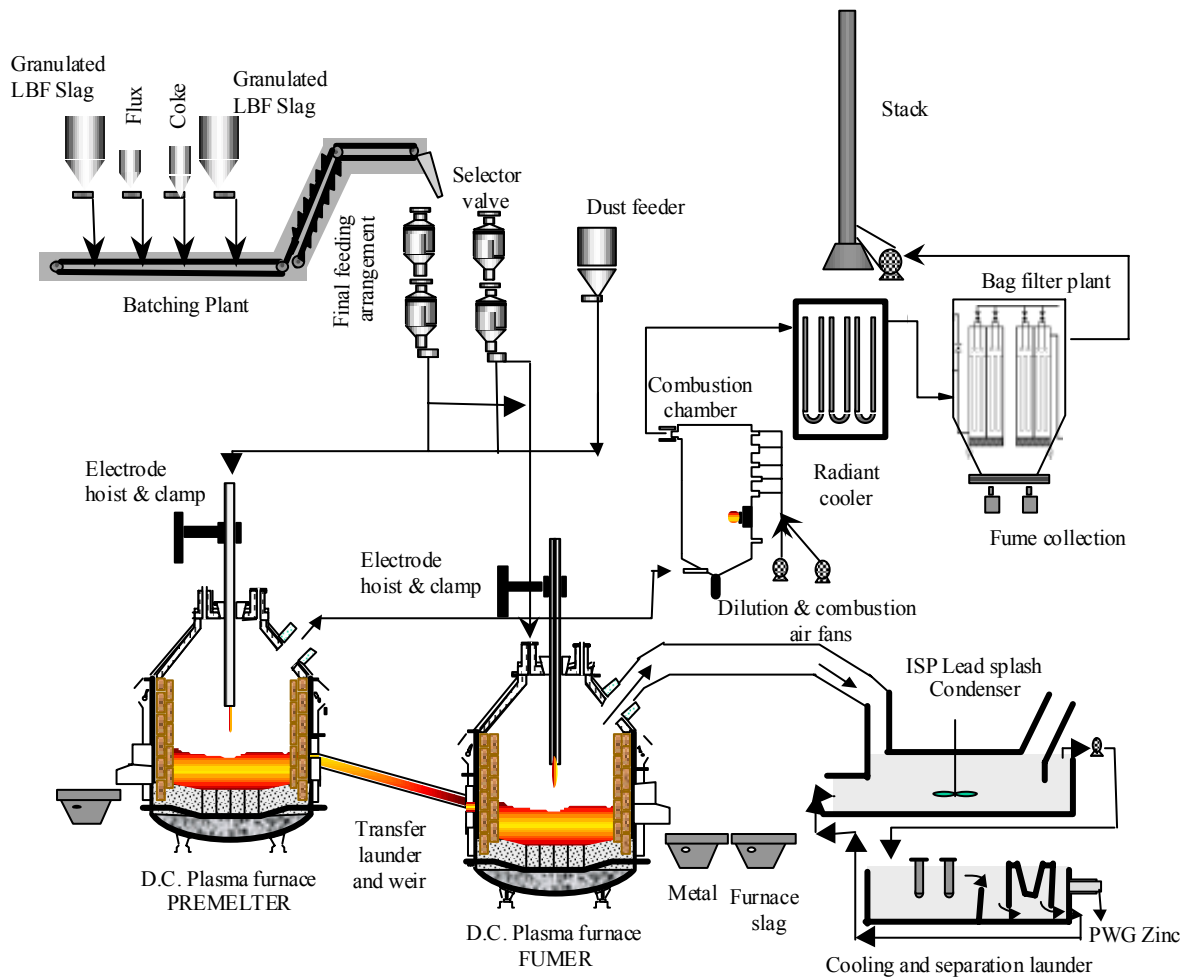


Figure 1. Schematic diagram of the Enviroplas pilot plant

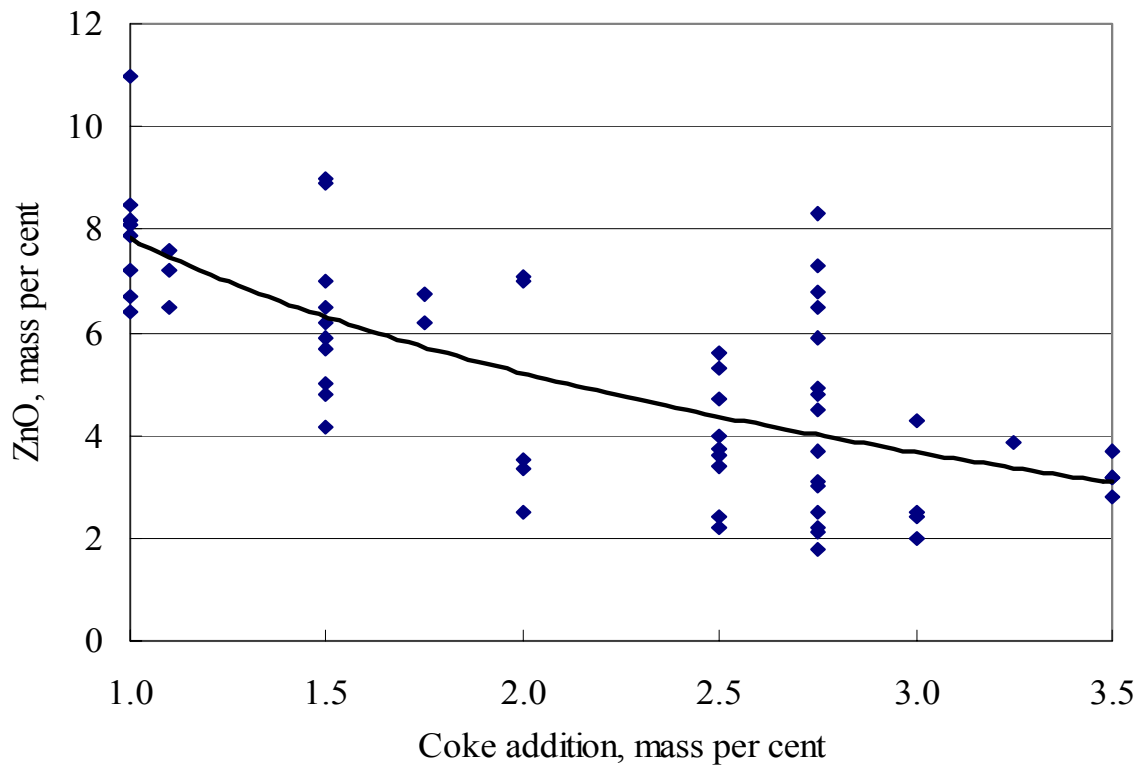


Figure 2. Influence of coke addition on ZnO content in the spent slag produced from LBF slag at 1 ton/h, temperature =1400-1450⁰C, slag basicity ratio = 0.8.

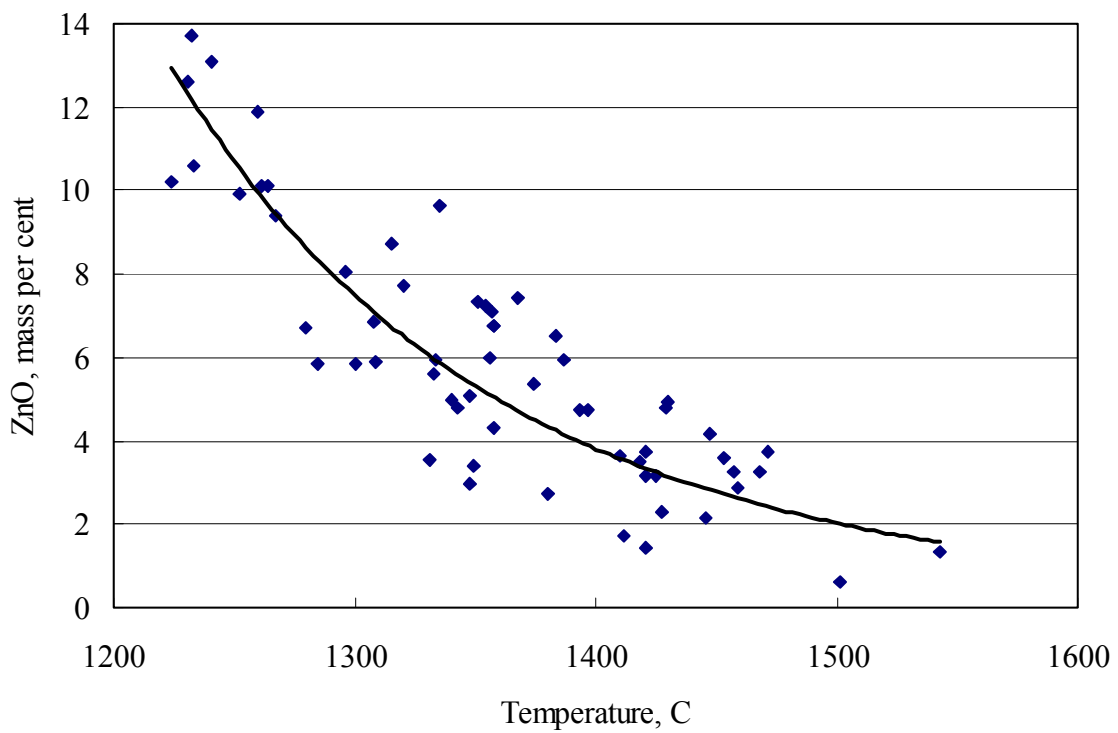


Figure 3. ZnO analysis in the spent slag versus tapping temperature. LBF slag at 1 t/h, Coke addition = 4%, slag basicity ratio = 0.8.

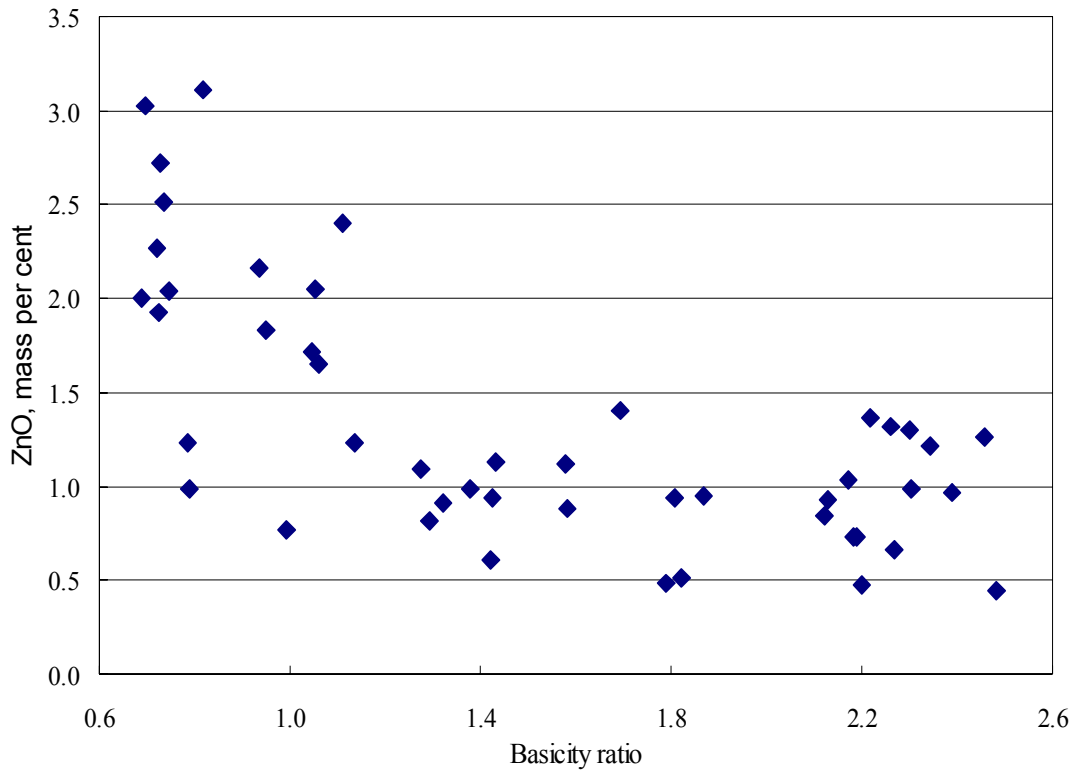


Figure 4. Influence of spent slag basicity on ZnO content. LBF slag and EAF dust at 1 ton/h and operating temperature of 1450-1500 °C

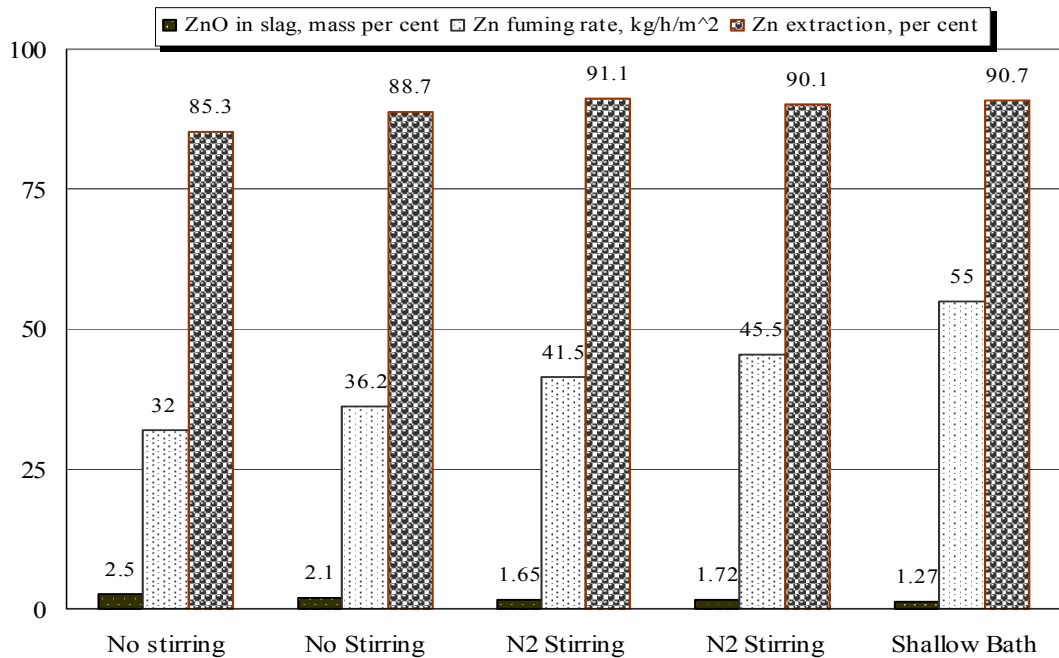


Figure 5. Effect of gas injection and slag depth on zinc fuming rate, its extraction, and ZnO content in spent slag. LBF slag at 550 kg/h, temperature = 1400°C, coke addition = 4%, slag basicity ratio = 1.0.

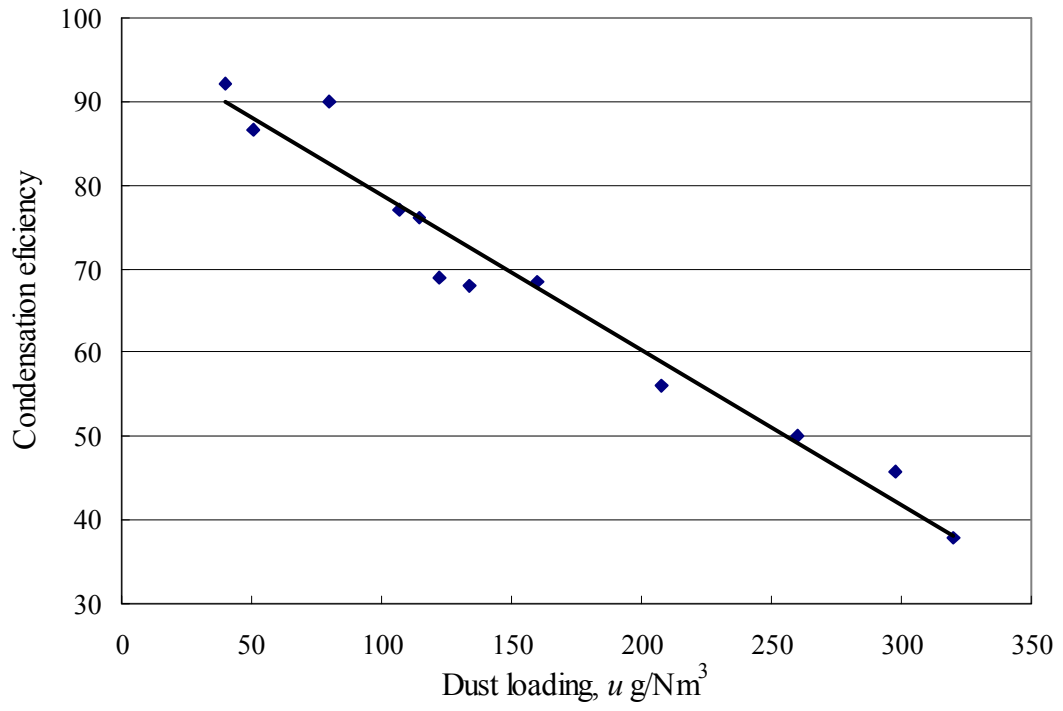


Figure 6. Zinc condensation efficiency versus dust loading