METALLURGICAL CHARACTERISTICS OF THE MEFOS 3 MW DC ARC FURNACE

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ABSTRACT

Over the past twenty years the 3 MW DC arc furnace at MEFOS has been frequently used for development of new processes. These processes include recovery of valuable metals from slag, sludge and dust from steel and other metallurgical industry, treatment of ashes from power plant and incinerators, smelting reduction of minerals and zinc recovery from EAF dust.

The process characteristics of the DC arc furnace operation in terms of:
- *selective reduction,*
- *total reduction,*
- *process stability and flexibility,*
- *dust carry-over,*
- *thermodynamic conditions provided in the hot spot area,*
- *precision in composing slag products*

These are analysed and described in this paper based on technical results from selected test campaigns over the years and thermodynamic considerations.

The electromagnetic properties of DC arcs beneath the electrode have been studied by CFD simulation. The calculated result enables us to understand some interesting technical phenomena observed.

The heat balance has also been considered based on data obtained from test campaigns and heat balance calculation.

1. INTRODUCTION

DC arc furnace technology has been successfully used in many metallurgical applications for decades. The major applications include:
- melting of iron units such as DRI or scrap,
- smelting reduction of chrome fines for FeCr production,
- smelting reduction of ilmenite for titania slag production,
- smelting reduction of EAF dust for recovery of Cr, Ni, Mo and Zn,
- metal recovery from other metal-containing wastes.

The advantages of plasma arc process systems including DC arc furnaces and their potential applications have been extensively reviewed by MacRae[1] and will not be repeated here.

Since the 1980´s MEFOS has been engaged in the development of the DC arc furnace technology including the critical part of the conductive bottom refractory.

A number of applications of the DC arc furnace with hollow electrode, besides those mentioned above, have been tested at MEFOS during the last two decades:

- smelting reduction of pre-reduced iron ore for pig-iron production (the ELRED process),
- smelting reduction of steelmaking slags, dust, sludge and millscale for recovery of valuable metals such as V, Cr, Ni and Mo, and at the same time producing a slag product with targeted composition (the IPBM process),
- treatment of combustion ashes (the ABB AshArc process).

The characteristics of the DC furnace operation are analysed from the process point of view and from the electromagnetic property point of view.

The important process parameters and aspects to be considered in this paper include:

- selective reduction,
- total reduction,
- process stability,
- dust carry-over,
- process flexibility,
- the thermal condition around the DC arcs,
- thermodynamic conditions provided in the hot spot area,
- precision in composing slag products.

These are analysed using data from selected pilot trials and described by CFD simulations and thermodynamic considerations.

2. ELECTROMAGNETIC CHARACTERISTICS OF A DC ARC FURNACE

For an evaluation of the DC arc furnace's advantages in smelting reduction, a mathematical model, developed at MEFOS, of the arc region of a DC electric arc has been utilised. The model calculates temperatures and gas velocities in the arc region and can be used to predict conditions in the reaction zone in smelting reduction.

2.1 Mathematical model of a DC electric arc

In the model used for the calculations the arc is treated as a fluid [2, 5] with temperature-dependent thermodynamic properties [6, 7] The coupled conservation equations of energy, mass and momentum, which define plasma temperature, pressure and velocity, are solved together with Maxwell's equations. In Figure 1 a schematic presentation of the region of integration of the DC arc model is given. The system consists of the cathode (graphite electrode), the arc column, and the anode (steel bath). The calculation domain is defined so as to allow for entrainment and general interaction with the surrounding gases. When current is passing from the anode to the cathode, the resultant heating of the gas together with the generated Lorentz forces leads to the formation of a plasma column.

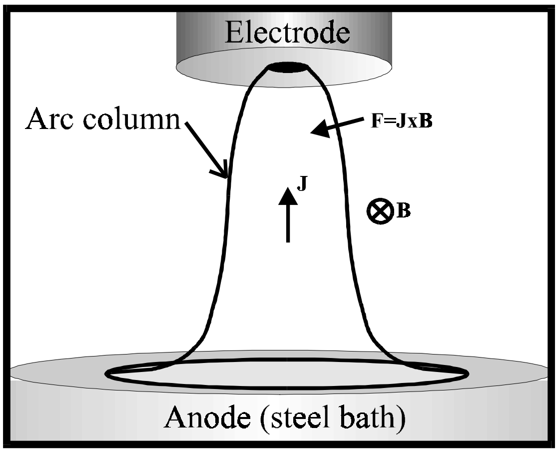

Figure 1. Calculation domain.

The following assumptions are made in the statement of the mathematical model of a DC arc:

- The arc is axis symmetric.
- The operation of the arc is independent of time, i.e. steady state.
- The arc is in local thermal equilibrium (LTE) [8], i.e. the electron and heavy-particle temperatures are very similar. This assumption has been shown to be valid throughout most of a gas tungsten arc, except for in the fringes of the arc and near the anode and cathode surfaces.[9, 10]
- The anode (border to the steel bath) is assumed to be flat and the bath itself is neglected.
- The MHD approximation [11] is applicable, implying that a simplified form of Maxwell's equations can be used to describe current and magnetic fields.

2.2 Simulation results

Predicted temperature contours for a DC arc are plotted in Figure 2. The highest arc temperatures are found at a central location close to the cathode. The temperature distribution in the arc is affected by the plasma flow for a given arc length and current distribution, see Figure 3**.** Hot gas from the cathode region is transported to the bath surface and thereafter spread parallel to the surface, forming an impinging region and a growing boundary layer along the surface of the steel bath. Simultaneously, cold gas is being entrained into the turbulent plasma jet. Steep temperature gradients are observed across the fringes of the jet.

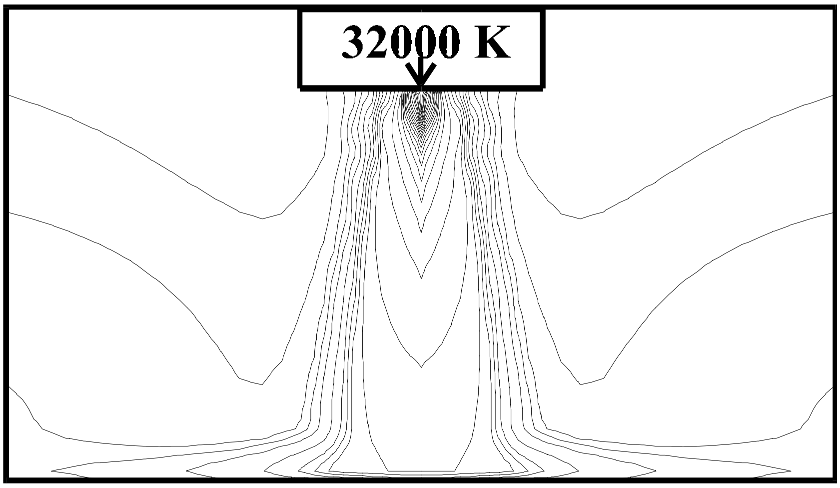

Figure 2. Temperature contours in the arc. The arc current is 36kA and the arc length 25 cm. Each line represents 1500 K.

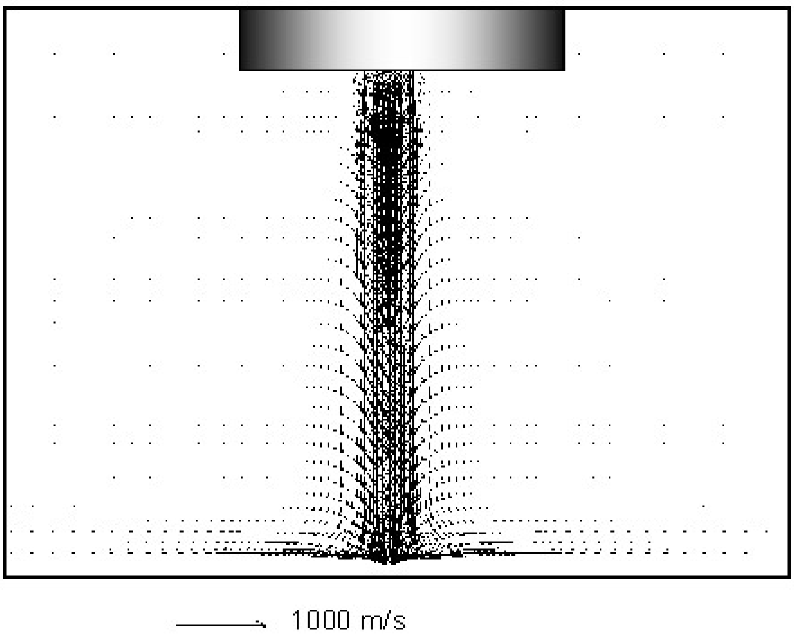

Figure 3. Gas velocities in the arc region.

The DC arcs resemblance of gaseous jets was shown by Chang and Szekely [12]. According to the work of Cheslak et al [13] impinging gaseous jets create parabolic deformations in liquids. A critical parameter in determining the depression made by an arc is the arc stability. The arc stability is likely to be affected by the shape of the formed depression. In the model a randomly moving arc is assumed to result in a spherical depression, because for a spherical depression with the centre positioned in the cathode spot the distance from the arc to the steel surface is equal at all points of the depression. The depth of the spherical depression is given by the assumption that the volume of the parabolic depression, V_P, equals the volume of the spherical depression V_S, see Figure 4**.**

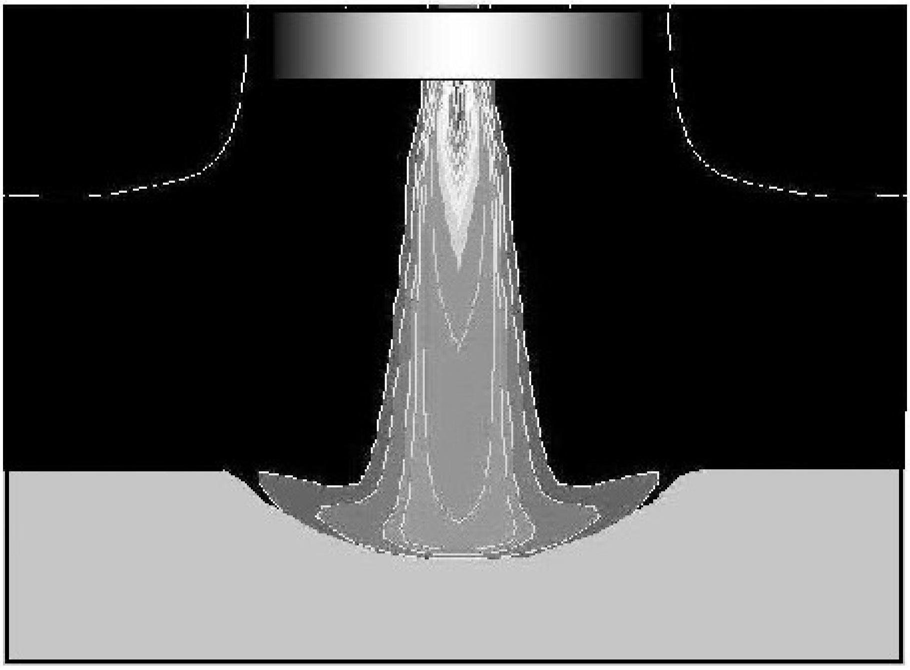

Figure 4. Assumed spherical depression created by a moving arc.

2.3 Some predictions from the CFD simulation

The model predictions show that the DC arc acts as a gas pump which is pumping and at the same time heating gas from around the electrode creating a hot gas jet directed down onto the metal bath. The impinging gas jet will push the slag away creating an open eye of metal and also a depression of the hot metal surface directly beneath the electrode.

When materials are fed through the hollow electrode into the arc zone they will be dragged into the hot gas jet and transported down to the molten metal. The fed materials are simultaneously heated, melted and chemically treated. This will lead to efficient reactions and reduced dust carry-over.

Furthermore, the depression in the metal bath together with the surrounding slag will act as a reaction chamber, which will contain the injected material enhancing the reduction thanks to the high temperature inside this “container”.

The depression and the shielding slag layer containing the heat will also lead to lower temperatures further away from the arc. This will create a frozen slag protecting lining refractory.

3. CHARACTERISTICS OF DC ARC FURNACE FROM A PROCESS POINT OF VIEW

The technical characteristics of a DC arc furnace based on experiences at MEFOS can be summarised as follows:

- high selectivity in reduction degree and in the “to be treated” materials
- low dust carry-over for treatment of fine grained materials
- high accuracy in control of the final slag composition
- ability in treating high aggressive slag

- rapid response time of important process parameters such as energy consumption rate and reduction efficiency
- high energy efficiency.

3.1 DC furnace operation at MEFOS

The normal DC arc furnace set-up at MEFOS is illustrated in Figure 5. The raw materials are fed through the hollow electrode, passing the hot plasma, melted and reduced before they drop into the slag/metal bath. The control system makes it possible to visualise the reduction efficiency since the input and output of carbon is continuously analysed and balanced. The specific energy consumption and feed rate are also recorded second by second. This together with good control of reduction efficiency makes it easier to run a stable process.

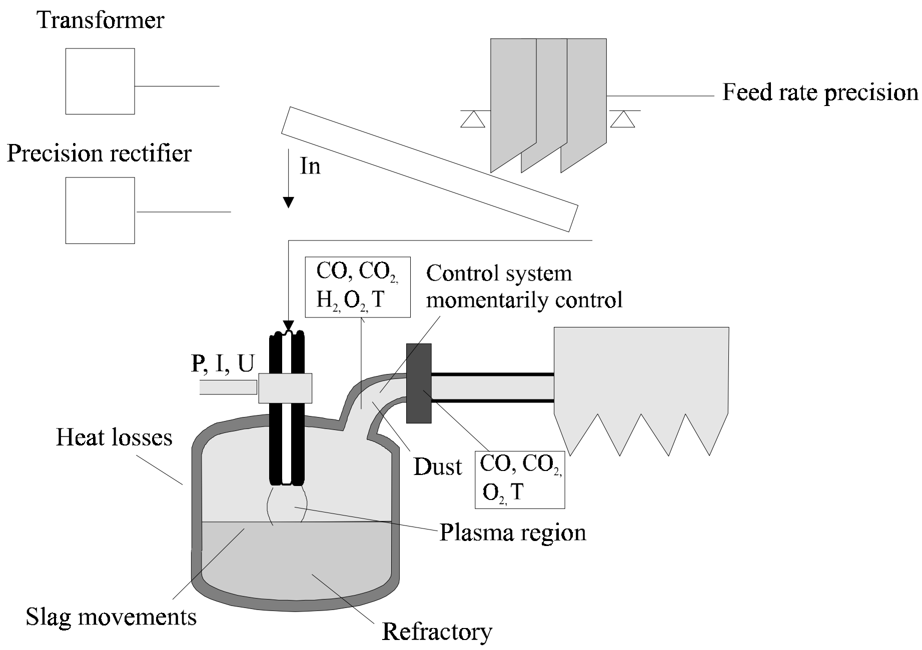

Figure 5. Set-up of the MEFOS 3 MW DC arc furnace.

Some typic tehnical data provided for the pilot tests at MEFOS are summarized in the following:

- power density: 0.5-0.8 MW/m^2
- length of the experiment: 1-2 weeks
- current: ~10KA
- voltage: ~200V
- fed through hollow electrode.

3.2 Low dust carry-over

Dust formation generally consists of two fractions:

- fume due to chemical evaporations
- carry-over dust due to mechanic handlings.

Carry-over dust is the dust originated from the raw materials being blown directly to the dust collection system without going through the intended treatment.

Table 1 shows a summary of dust carry-over results obtained from a pilot campaign where a fine-grained steel slag was reduced in the MEFOS 3 MW DC arc furnace for metal recovery. The calculation of the amount of the dust carry-over is based on an Al-balance since Al_2O_3 is a stable oxide and will not be reduced under the provided conditions.

Table 1. Dust carry-over results from a pilot campaign for slag reduction[14]

Test no.	Temperature, °C	Feed rate, tonnes/h	Dust carry-over, %
1:4	1700	1.5	0.4
1:5	1750	1.35	0.3
1:8	1750	1.7	2.0
1:9	1750	2.5	0.4
1:10	1750	2.7	0.3
1:11	1780	2.6	0.4
1:12	1710	2.3	2.0
1:14	1730	3.0	1.0
2:2	1650	0.8	1.0
2:3	1650	0.8	0.3
2:4	1617	1.55	0.35
2:5	1650	1.55	0.2
2:6	1640	2.0	0.7
2:7	1680	2.4	0.3
2:8	1585	2.8	0.35
2:9	1549	2.8	0.05
3:1	1735	1.5	0.4
3:2	1680	1.5	0.15
3:3	1640	1.5	0.15
3:4	1665	1.5	0.6
3:5	1620	1.5	0.4
		Average	**0.53**

The particle size of the treated steel slag is 0-5 mm.

Low dust carry-over is essential for EAF-dust based production of high quality secondary dust with high zinc oxide for further electrowinning of zinc. High dust carry-over will result in high content of iron in the zinc oxide product since EAF dust contains up to 35-45 % Fe_2O_3. High Fe-content will result in a large amount of leaching residue. During a test campaign at MEFOS over 50 dust samples have been taken and analysed. Generally the Fe-content was 1-3 % which indicated a dust carry-over of about 1-2 %. The treated EAF dust has a particle size of around 1 µm. The same figure has been observed in an industrial DC furnace for HCFeCr production in South Africa.

The low dust carry-over was explained by three mechanisms:

- Fed materials always pass through the hot plasma, they will be melted and treated directly and the risk to be “blown-away” is thus minimised,
- Low specific gas-flow in a DC furnace (100-200 m^3n/tonne treated materials depending on the reduction needed),
- The electromagnetic force around the electrode provides a tremendous downward force so that the fed materials will be forced to penetrate the slag/metal bath.

These are strongly supported by the CFD predictions shown in Figures 2-4.

Figure 6 shows the obvious co-relation between the amount of the carry-over dust, in terms of Fe-content in the EAF-dust based ZnO-fume product obtained in the baghouse filter, and the specific gas amount in the furnace. This explained well the high dust carry-over of the Waelz-kiln process and plasma-based shaft furnace process for treatment of EAF dust. Both processes have a specific gas amount that is about five times that of a DC furnace. The iron content in Waelz oxide is normally up to 5-10%.

3.3 Aggressive slag

High FeO-containing slag is normally an aggressive slag due to its melting point lowering effect. A typical slag for EAF-dust treatment obtained during test campaigns consists of 50 % FeO, 13 % CaO, 17 % SiO_2, 9 % MgO, 7 % MnO and 4 % Al_2O_3. This slag will have a melting point around 1300°C. Even though the operation temperature has been up to 1600°C, no indication on the lining has been observed. Since the lining material was chrome spinelle, $MgO*Cr_2O_3$, the Cr_2O_3-content in the slag has been used as an indicator on lining attack as shown in Table 2.

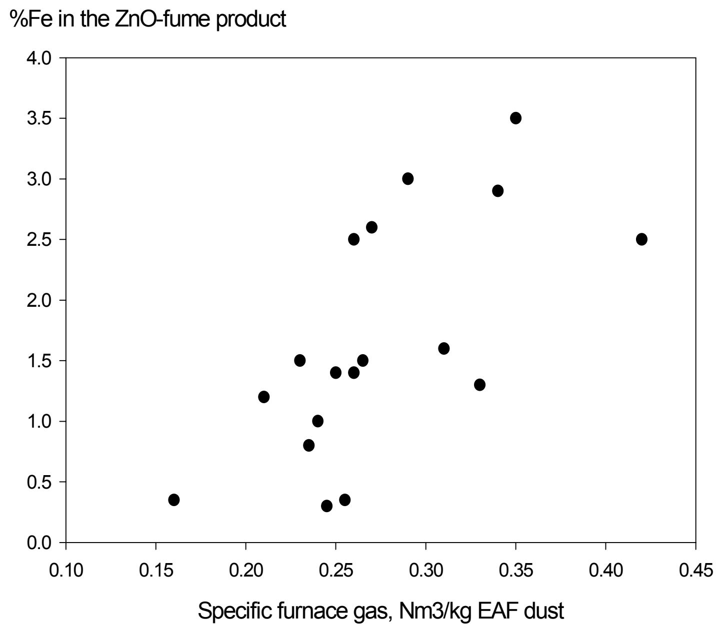

Figure 6. Effect of specific gas amount on dust carry-over.

Table 2. Cr_2O_3-content in the slag. Results from a test campaign for zinc recovery of EAF dust in MEFOS's 3 MW DC arc furnace.

Sample no.	**% Cr_2O_3 in EAF dust**	**Expected % Cr_2O_3 in the slag****	**% Cr_2O_3 in the slag**
Charge 1:1	0.3	0.6	0.57
Charge 2:1	0.3	0.6	0.64
Charge 3:1	0.3	0.6	0.79
Charge 3:2	0.3	0.6	0.76
Charge 3:3	0.3	0.6	0.75
Charge 4:1*	0.6	1.2	1.23
Charge 4:2	0.6	1.2	1.29
Charge 5:1*	0.6	1.2	1.03
Charge 5:2	0.6	1.2	1.10

* Charge 4-5: using another type of EAF dust

** Since both of the treated EAF dusts contain about 40-50 % (ZnO+PbO+halides+alkalis) and some FeO will also be reduced in the slag. It is simplified that the amount of slag after reduction will be about half of the input of EAF dust. The Cr_2O_3-content in the slag was thus expected to increase by 100 %.

These results show that the Cr_2O_3 in the final slag mainly originates from the EAF dust and the attack of the slag on the refractory is negligible. A frozen slag on the refractory provides good protection from the slag attack. Good process control such as energy rate is essential for creation of such a protecting layer. Too high energy rate will minimise the thickness of the layer of the frozen slag and too low energy rate will create build-up of unreacted materials in the furnace, which will result in unstable operation condition and hence poor reduction.

Compared to an AC-arc furnace it is much easier to create a protecting frozen slag and control its thickness in a DC arc furnace due to the symmetric nature of temperature contours around and beneath the electrode in the centre as shown in the CFD predicted diagram in Figure 4. The temperature distribution curves suggest a lower temperature on the furnace wall.

3.4 Precision in control of reduction degree and slag compositions

Due to the fact that all materials passing through the hot plasma region all possible reactions occur immediately and the reaction selectivity is simply determined by the carbon rate. The final slag product is easily composed by addition of slag modifiers. These characteristics of the DC furnace make it perfect for treatment of many metallurgical wastes. Most of the metallurgical wastes consist of four major fractions as shown in Table 3.

Table 3. Major fractions of metallurgical wastes.

	Main components
Fraction A: stable oxides	CaO, Al_2O_3, MgO and SiO_2
Fraction B: reducible oxides	FeO, Fe_2O_3, Cr_2O_3, NiO, MoO_3, MnO
Fraction C: easy to evaporate	ZnO, PbO, CdO, alkalis and halogens
Fraction D: organic waste	C-H compounds such as plastics or paints

The DC furnace has shown to be an excellent tool for simultaneous recovery of all those fractions from complex wastes as illustrated in Figure 7.

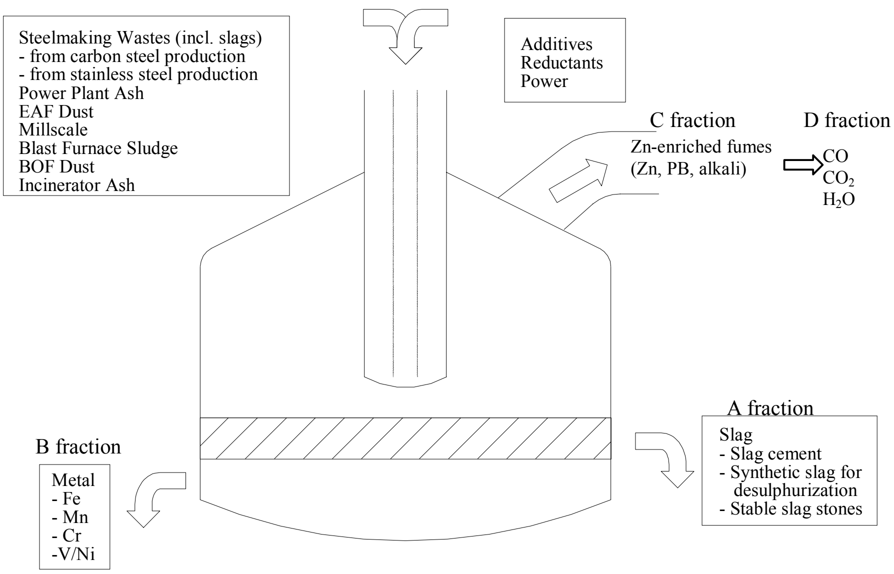

Figure 7. Recovery of materials from a complex waste using DC furnace.

The precision in control of the reduction degree and the final composition of the slag products are demonstrated in a pilot test campaign where BOF-slag has been reduced for metal recovery. Oxides in the reduced BOF slag were modified into several slag products by addition of Al_2O_3 or SiO_2 as shown in Table 4. As shown in the table, the slag composition is close to the target composition. The low Cr- and MgO-content in the slag products indicates once again that the slag lining of chrome-spinelle has been protected by a layer of frozen slag.

Table 4. Precision in reduction degree and slag composition control. Results from a pilot campaign on reduction of BOF slag for production of different slag products and metal recovery.

Slag product		% Fe	% CaO	% SiO_2	% Al_2O_3	% MgO	% Cr_2O_3
	BOF-slag	18.4	51	11.3	1.6	1.2	
1. Clinker raw material	***Target***	3-7	62-66	20-21	4-7	<5	
	From test	4.3	64.7	20.8	6.9	2.2	0.24
2. Metallurgical powder A	***Target***	<2	50-55	16	22	2-10	
	From test	0.35	56.6	19.6	21.9	2.85	0.03
3. Metallurgical powder B	***Target***	<2	50-55		25-30	2-10	
	From test	0.3	54.2	13.6	27.3	1.81	0.03
4. Hydraulic binder	***Target***	<2	45	33	14	2.5	
	From test	1.81	41.8	31.5	17.3	4.41	0.08
5. Hydraulic binder	***Target***	<2	45	33	14	2.5	
	From test	0.45	44.5	34.4	14.0	4.41	0.04

The DC furnace has also shown its great process flexibility. In the past ten years the following complex wastes have been treated in the MEFOS DC arc furnace:

- Dust, slag, millscale and pickling sludge from carbon and stainless steelmaking
- Organic material (solid and liquid)
- Catalyst
- Power plant ash
- Incinerator plant ashes
- Scrape residue

In many cases recovery of valuable metals is the main purpose and a total reduction for recovery of metals like V, Ni, Mo, Cr and Fe is desirable. Table 5 shows some indicative figures of metal recovery yield from MEFOS DC furnace trials.

Table 5. Yield of metal recovery from MEFOS DC furnace campaigns.

	Metal yield
V-recovery from low V-containing materials, 2-3 % V	>80%
V-recovery from high V-containing materials, > 5 % V	>90%
Cr-Fe recovery from steel industry wastes, 1-15 % metal	>95%
Ni-Mo recovery from complex wastes, 1-5 %	>99%

3.5 Thermodynamic condition in the hot spot area

The reduction selectivity of the DC furnace is also demonstrated in Figure 8. The equilibrium between ZnO in the slag and the C-content in the steel at different temperatures is shown in the figure. Analysis of samples is also plotted in the figure. The bath temperature in the molten slag and metal phase is about 1550°C. Figure 8 shows that the ZnO-content in the slag samples lies between the equilibrium lines of 1550 and 1800°C. This indicates that the EAF dust indeed has been treated at higher temperature than the average bath temperature measured. Again feeding through the hollow electrode could explain the observations shown in the figure. It is believed that a thermal steady state has been achieved around the area beneath the electrode. The thermal density is much higher there than in the bath, see Figures 4 and 8.

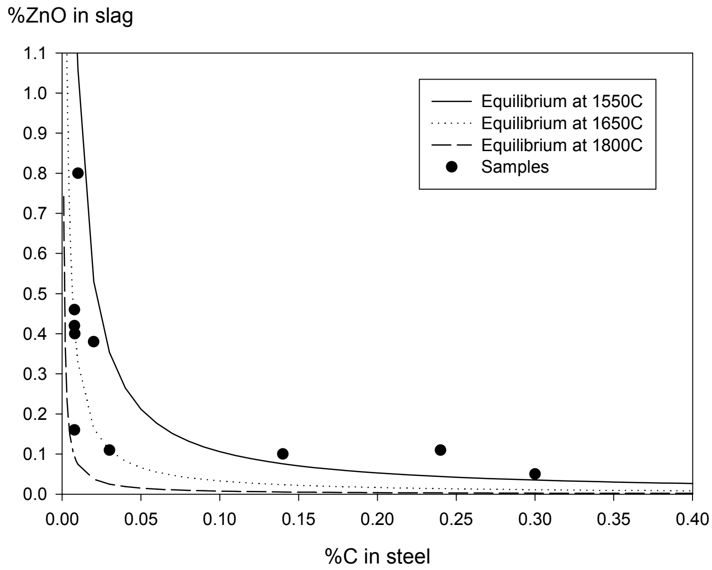

Figure 8. Equilibrium between ZnO-content in slag and C-content in steel.

3.6 Heat balance around the MEFOS 3 MW DC furnace

The heat balance data shows that the heat losses in the MEFOS 3 MW DC furnace mainly depend on the cooling water for the furnace shell and the roof. On the average the heat loss is about 250 kWh/h. For zinc recovery of EAF dust, or for total reduction of BOF slag, the theoretic energy consumption is about 1 MWh/tonne. For a treating rate of 1 tonne/h this means an energy yield of 80%. For a treating rate of 2 tonnes/h this means an energy yield of 90%. The low specific gas amount in a tight DC furnace is the main reason for the high-energy efficiency of the process. For a plasma-based shaft furnace the excess energy in the offgas is as high as 1000 kWh/tonne treated EAF dust. This means extra electric energy consumption.

4. CONCLUSIONS

It has been demonstrated by analysis of the results from selected pilot tests and CFD simulations that the MEFOS 3 MW DC furnace with hollow electrode has the following important characteristics:

- The DC current leads to a stable pumping of heated gas directly onto the metal bath.
- The hollow electrode enables injection of material directly into the arc region taking advantage of the hot gas pumped down onto the metal bath increasing melting of the material compared to a system where the material is injected besides the electrode.
- Good process control in terms of selective reduction, total reduction and precise composing of slag products makes it an excellent tool for treatment of complex material, such as wastes from metallurgical industry, catalysts etc.
- Low dust carry-over makes it suitable for treatment of fine-grained materials and for production of pure fume fraction.
- It is possible to treat a highly aggressive slag with up to 60 % FeO in MEFOS's 3 MW DC furnace. The furnace has also been used for selective oxidation purposes using Fe-oxide fines.
- Specific energy consumption close to the theoretically calculated value due to tight furnace and the "easy to control" rate of energy/feed (kWh/tonne), heat losses are mainly due to cooling of the furnace.

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