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PARTICULARITIES OF MELTING DRI IN AC AND DC ARC FURNACES

ZASADY PROCESU TOPNIENIA DRI W PIECU ŁUKOWYM PRĄDU PRZEMIENNEGO I STAŁEGO

The energy demand of pre-reduced iron has been analyzed as a function of the amount of gangue, the SiO_2/CaO ratio in the gangue, the degree of metallization, the carbon content and the temperature. This energy demand, together with the thermal efficiency, therefore allows a theoretical estimate of the optimum feed rate necessary to balance the power input – MW plus chemical – at constant bath temperature.

In reality the steelmaker has great difficultly to monitor the analysis of the material being charged, which can vary from heat to heat or day to day, thus diminishing the maximum productivity. In an attempt to circumvent this problem we have investigated the use of electrical parameters, such as fluctuations and harmonics, to determine the optimum feed rate.

Another important subject we discuss refers to the different characteristics of the electrical system for continuously charged DRI (or HBI) compared to basket charged scrap melting. In particular we focus on the maximum level of arc voltage and its consequent effects on current, MW and electrode size and performance.

Keywords: DRI melting; Feed rate; Transformer parameters; Electrode consumption

Zapotrzebowanie na energię w procesie wstępnej redukcji żelaza zostało opisane funkcją sumy zawartości skały płonnej, stosunku SiO_2/CaO w skale płonnej, stopniem metalizacji, zawartością węgla oraz temperatury. Zapotrzebowanie na energię oraz sprawność cieplna pozwalają na teoretyczne oszacowanie optymalnej szybkości dozowania, potrzebnej do wyrównania dostarczonej energii – elektrycznej plus chemicznej – tak aby uzyskać stałą temperaturę kąpieli.

W rzeczywistości metalurgowi trudno jest kontrolować skład wszystkich materiałów używanych w procesie, który może się zmieniać z wytopu na wytop oraz z dnia na dzień. Powoduje to obniżenie wydajności procesu. Aby rozwiązać ten problem zbadano wpływ parametrów elektrycznych takich jak: zmienność i harmoniczne prądu, aby uzyskać optymalne wartości dla szybkości dozowania.

Kolejny ważny temat, który został przeanalizowany dotyczył różnych charakterystyk układu zasilania dla ciągłego ładowania DRI lub HBI w porównaniu do roztapiania złomu jako wsadu ładowanego koszami. Zwrócono szczególnie uwagę na maksymalną wartość napięcia łuku, który wpływa na inne parametry: natężenie prądu, moc, wydajność oraz średnicę i zużycie elektrod.

1. Introduction

Electric steelmaking with DRI is continually increasing in production; actually, it has doubled in the last 10 years. In 2007, 57 million tonne of electric steel were made from DRI out of a total arc furnace production of 400 million tonne, or some 14%. Approximately 100 arc furnaces are operating with significant amounts of DRI. Most of this steel is made in furnaces continuously charging DRI, together with the necessary slag fluxes, through an aperture in the roof. Almost the whole heat is made with a flat bath operation.

In this paper, we analyse the relation between DRI analysis and feed rate, and comment on the different requirements for the transformer parameters, power supply and electrodes.

2. Energy demand as a function of DRI analysis

Most steelmakers charging high percentages of DRI attempt to balance the feed rate to the available electrical power, the aim being to maintain a constant, and low, bath temperature (1530 to 1560°C) for most of the

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charging time. To achieve this balance it is desirable to know the energy demand of the DRI being charged but this is strongly dependent on the chemical analysis.

We have constructed a mathematical model of the energy required to convert cold or hot DRI into liquid steel taking into account the DRI analysis. The major parameters are – the content of gangue, its ratio of acid to basic oxides, degree of metallization and carbon content. The range of these parameters around the world is as follows:

Fe total: 89.2 to 94 %

Metallisation: 88 to 96 %

C : 0.3 to 4 % (Mainly as Fe3C gaseous reduction process)

SiO_2 : 1 to 5 %

Al_2O_3 : 0.5 to 3 %

CaO : 0.1 to 2 %

MgO : 0.1 to 1 %

The iron oxide exists mainly as FeO, as a result of the reduction of Fe_2O_3 of the ore entering the reduction unit. In general, the other acidic oxides make up more of the DRI than the basic oxides so CaO and MgO are also charged along with the DRI to generate a slag of the desired basicity.

The calculations are based on the enthalpies of the various constituents, the chemical reactions (principally the reduction of FeO, but also the exothermic reaction of Ca_2SiO_4 formation and the dissolution of Fe_3C). Values used and references from which they are taken are given in the appendix.

3. Thermal efficiency

In order to estimate the feed rate that is balanced to the input power it is necessary to have a figure for the thermal efficiency of the furnace. The thermal efficiency that is relevant here is the ratio of the energy contained in the melted contents – steel plus slag – to the total energy input to the system.

Even though DRI steelmaking involves a large fraction of time on flat bath, several factors favour a value not much different to scrap steelmaking:

- Arcs are almost always covered in foaming slag,
- Steel bath and slag temperatures are 'low' for most of the heat (1530 to 1560°C),
- Less air passes through the furnace because the slag door can stay closed most of the time and injected O_2 volumes are generally lower.

Based on typical scrap analysis we estimate an energy content of steel and slag at 1630°C to be 425 kWh/t Fe. Thus, a thermal efficiency of 73% is indicated (425/583), in which 583 kWh/t taken as an actual scrap melting average [1]. For DRI steelmaking, an analysis of our data shows a thermal efficiency of about 70%.

It is worth remarking that there is a significant difference in the energy obtained from O_2 injection between scrap melting and DRI practice. For scrap melting we concluded that 1 Nm^3 O_2 yielded 5.2 kWh [1] at 100% thermal efficiency, including energy from oxidation of metallics (Si, Mn, Fe,..), however in DRI practice 1 Nm^3 injected oxygen generates almost exclusively CO, yielding only about 2.6 kWh at 100% thermal efficiency.

The calculation algorithm for the DRI charging rate is shown in figure 1.

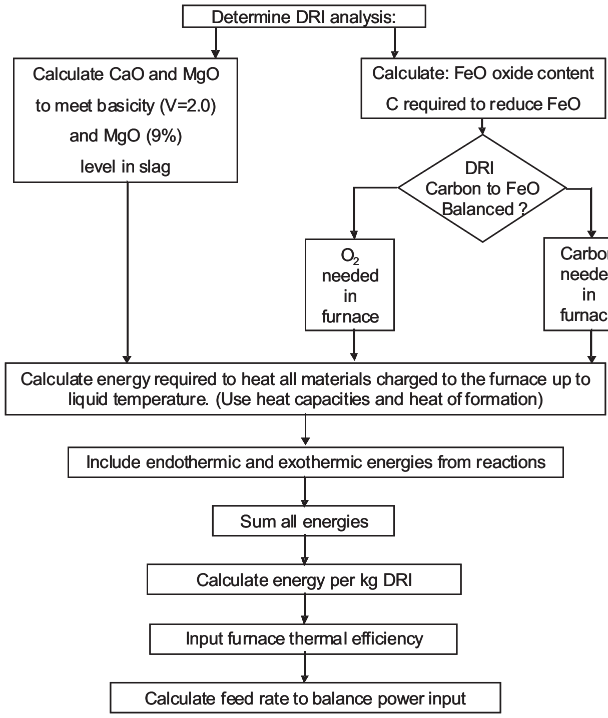

Fig. 1. Algorithm for calculating balanced DRI feed rate

Additionally we have assumed that 1% of the charged DRI is lost as fines from the furnace. All the Fe contained in the remaining 99% of DRI ends up as liquid steel or as FeO in the slag. We have assumed a typical slag FeO level of 25% during DRI feeding.

For eight different DRI applications the average total energy consumption of the arc furnaces is found to be 683 kWh/t liquid Fe with a standard deviation of 25 kWh/t. This is compared to scrap melting where the average and standard deviation are 583 and 49 kWh/t Fe [1].

4. Equivalent balanced feed rate (kg/MWmin)

The energy necessary to melt the DRI and the slag divided by the thermal efficiency allows the feed rate that balances the power input to be calculated. Figure 2

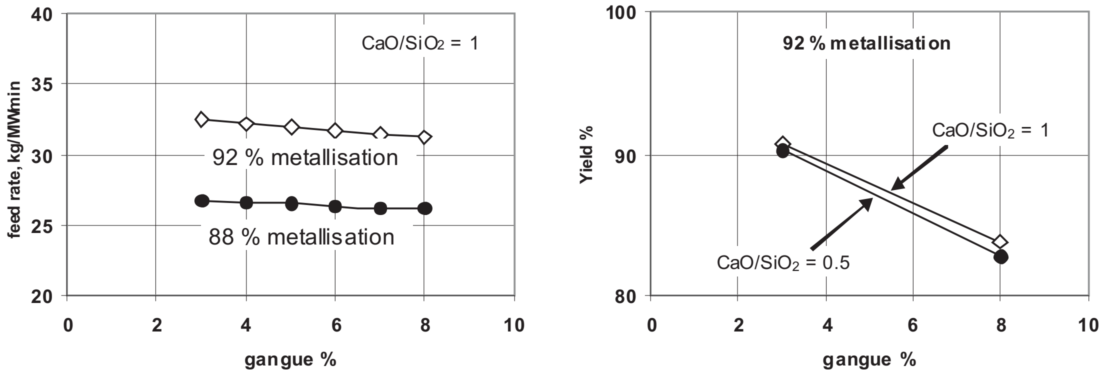

Fig. 2. Effect of % metallization and gangue on balanced feed rate and yield. C = 2.1%

shows the results for DRI containing 2.1% C (a typical figure). The major variable is the degree of metallization, with the gangue content showing a weak influence. For these calculations no extra oxygen was injected; any small amount of oxygen needed was assumed to come from air. In figure 2 the MW indicated are electrical.

The liquid steel yield is however strongly affected by the gangue content; it can drop by about 7% as the gangue increases from 3 to 8%. Surprisingly the actual level of the yield is only weakly dependent on the degree of metallization. If there is sufficient, carbon all the iron oxide is reduced in the bath and the loss is mainly determined by the slag FeO level (typically around 25%).

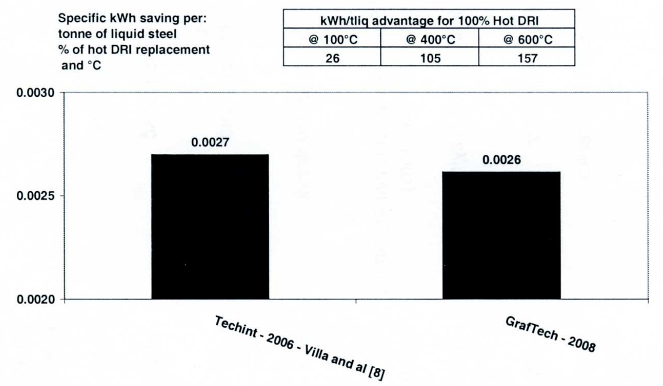

Fig. 3. Energy demand as a function of percentage of hot DRI and temperature

5. Feed rate charging hot DRI

Several steel shops are charging DRI hot to the arc furnace. Figure 3 shows results normalised to the % of DRI charged and its temperature. The reduction in energy is due to the enthalpy contained in the hot DRI. Figure 3 shows also our data from furnaces charging hot DRI along with similar published data. The table at the top of Figure 3 illustrates the effect on kWh/t liquid Fe using our specific conversion factor.

6. Temperature drift due to feed rate imbalance

As stated above, the steelmaker often does not have prior knowledge of the analysis of the DRI being charged to the furnace. In the absence of a continuous temperature measurement, the steelmaker can only take temperature dips at spaced intervals. If the DRI requires more or less energy than expected then the bath and slag will

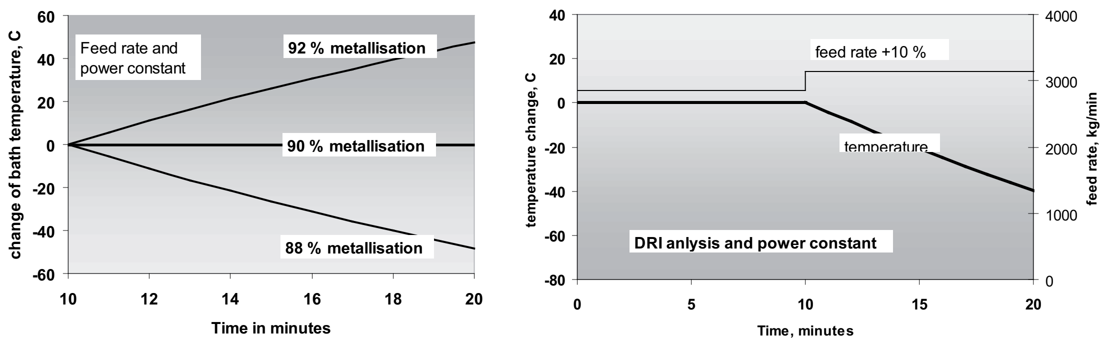

Fig. 4. Bath temperature drift due to DRI feed imbalance

drift in temperature away from the target value. Figure 4, on the left, shows a calculation of such a temperature drift due to a change of +/– 2% in metallization, other DRI parameters remaining constant. At 10 minutes into the heat, the furnace contains 50 t of liquid steel and 7.5 t (15%) slag. An electrical power of 100 MW is assumed and the DRI contains 5% gangue, 2.1% C, with a metallization of 90%. For this DRI without further chemical input the balanced feed rate is 28.6 kg/MWmin. As can be seen the temperature drift can exceed 50 deg C after 10 minutes.

On the right of figure 4 the feed rate is stepped up by 10% at t = 10 minutes, at which time the furnace is assumed to contain 100 t of steel and 15 t of slag. After a further 10 minutes, the temperature has dropped some 40 deg C. Of course, the inverse is also true – if feed rate is decreased by 10%, temperature will increase 40 deg C. (For these calculations the specific heat of liquid steel and slag is given in the appendix).

Today the highest cold DRI feed rate is about 45 kg/MWmin based on electrical power.

7. Can temperature drift be detected from electrical signals?

The danger with a negative temperature drift is that there is a risk of ferroberg formation. Ferrobergs form when a localised charging rate exceeds the ability of the slag to melt the pellets fast enough. A 'positive feedback' is created between the cooling slag and its ability to melt the pellets. These agglomerations quickly become coated with slag and are subsequently difficult to melt, prolonging heat time.

For positive temperature drift, the penalty is increased refractory and energy consumption, and a consequent reduction of productivity. With the aim of detecting over- or under-charging we have analysed current fluctuations and harmonics on several AC furnaces and voltage fluctuations on DC furnaces while DRI is being charged continuously. The aim was to detect changes in slag temperature via electrical signals, harmonics for AC and arc voltage fluctuations for DC.

7a. Current fluctuation and harmonics (AC)

Figure 5 shows the standard deviation of current fluctuations, averaged over 1 second intervals, as a percentage of the mean current for a furnace in which the feed rate was varied. 100% charge rate corresponds to the normal feed rate. In this example, feed rate was increased up to 180%. The graph shows an increase in current fluctuation with increased feed rate, implying an effect of the increased bath agitation on arc stability.

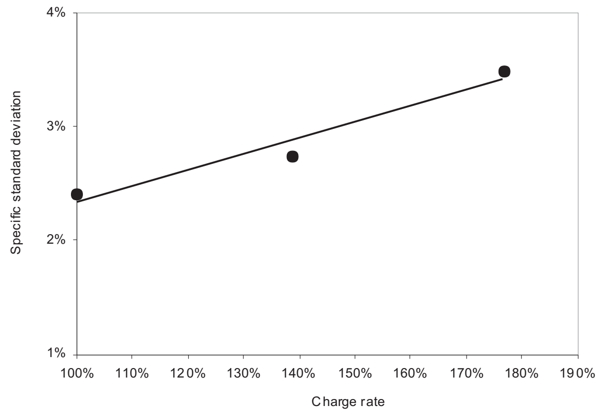

Fig. 5. Effect of charge rate on current fluctuations

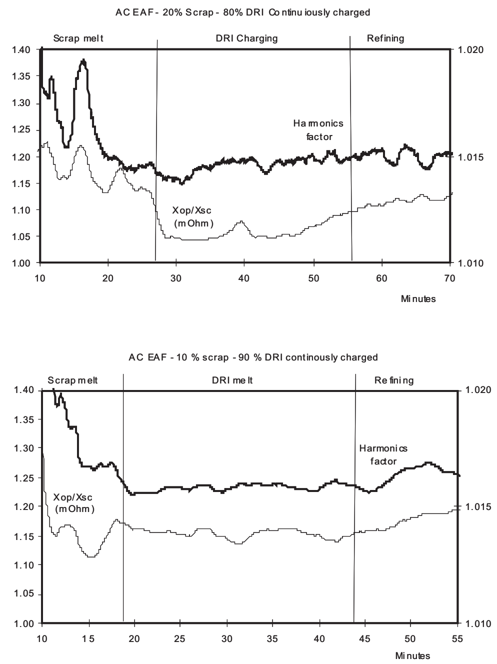

Fig. 6. Harmonic factors through a heat

Harmonic content can be indirectly measured in two ways, one by the ratio of operating to short circuit reactance, the other by the ratio of MVAs. The larger MVA is defined as $\sqrt{3}V_{rms}i_{rms}$ in which V_{rms} and i_{rms} are the average of the primary phase-to-phase voltages and the phase currents respectively. The smaller MVA is defined as $\sqrt{MW^2 + MVAR^2}$ in which the MVAR consider only the fundamental component (50 or 60 Hz) of the current wave.

Figure 6 shows measurements of these factors for heats on two separate furnaces, at 85 MW (upper) and 90 MW. Variations can be seen during DRI charging that we assume are related to changes in the slag.

Figure 7 shows further measurements on another furnace that used two levels of feed rate during the heat. At the normal feed rate the current fluctuations are lower in amplitude.

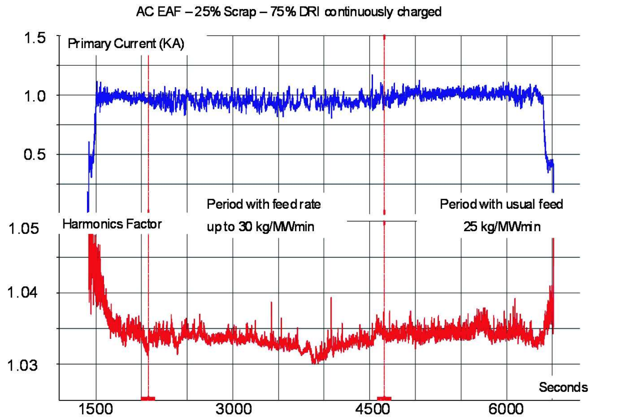

Fig. 7. Primary current and harmonic factor during a heat with 2 different feed rate

7b. Arc voltage fluctuations on DC furnaces during DRI feed

Because of the thyristor control of current, harmonics in the current are of little value for DC furnaces. In its stead we record arc voltage fluctuations, again in the hope that such fluctuations will indicate changes to the slag or steel bath. Figure 8 shows the standard deviation of arc voltage for different feed rates. The furnace operated at 100 MW with arc voltages of about 700 V. As can be seen higher feed rates result in a larger arc voltage fluctuation.

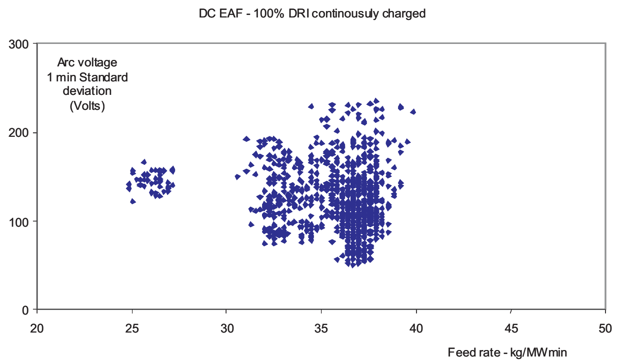

Fig. 8. Arc voltage standard deviation as a function of feed rate in a DC furnace

7c. Summary

Although there are indications that the feed rate influences both current fluctuations and harmonics in AC furnaces and arc voltage fluctuations in DC furnaces we have not found any simple link to either over- or under-charging. Nevertheless there is still the possibility that such a link can be found after sufficient detailed measurements have been performed on more furnaces.

8. Choosing transformer parameters (AC and DC) to match DRI operation

DRI steelmaking in general requires a somewhat different transformer to scrap based steelmaking. For DRI the furnace runs most of the time (in some cases 100%) on flat bath. It is essential that the arcs be covered by the slag to minimise energy losses to the panels. Compared to scrap melting the arc voltage on average is lower since in scrap melting much longer arcs can be used while the panels are shielded by scrap. For AC furnaces an arc voltage maximum around 450 V and 600 V working with 100 kA for DC seems to provide good thermal efficiency. It is normally also the desire of the steelmaker to run the furnace at maximum MW. Thus for DRI maximum MW and shorter arcs on average implies higher current than for scrap melting.

For example, an AC furnace designed to run at 100 MW with arcs limited to 450 V (+ 26 V resistive) would need to operate around 70 kA. The transformer voltage need not be as high as for a scrap melter. For example, if the furnace operated at a power factor of 0.8 a transformer tap of about 1000 V would provide the necessary MVA of 120. A scrap melter would use voltages significantly in excess of 1000 V at this power.

For a DC furnace designed for 150 kA, restricting the arc voltage to 600 V (90 MW) the AC transformer voltage required would be about 700 V (assuming a commutating impedance of 1 mΩ, and a power factor of 0.75). Two higher taps would be advisable.

It is of interest to note that some furnaces designed for DRI have transformer MVA larger than the tap tonne weight. (MVA/t > 1).

In summary the transformer for a DRI furnace requires a higher current capability and lower voltages than a scrap melter. This implies a more expensive transformer for the same MVA than for scrap melting, because of the requirement for more copper.

9. Dimensioning the Static VAR system, if needed

Like other furnace operations for which the arcs run for the majority of the time (sometimes 100%) on a slag covered liquid bath, furnaces operating with DRI generate much lower levels of flicker than scrap based furnaces. Figure 9 shows relative flicker levels for various types of *scrap* based furnaces. DRI operations would produce even lower values. In fact for DRI flicker is normally not a concern, nevertheless the use of a static VAR system can still be valuable mainly because it supports the power supply system. The result is a higher level of MW, especially for AC.

However, for DC furnaces a SVC system has less effect on the available arc voltage and the maximum controlled voltage [6], since most of the impedance drop occurs in the furnace transformer and not in the power supply system.

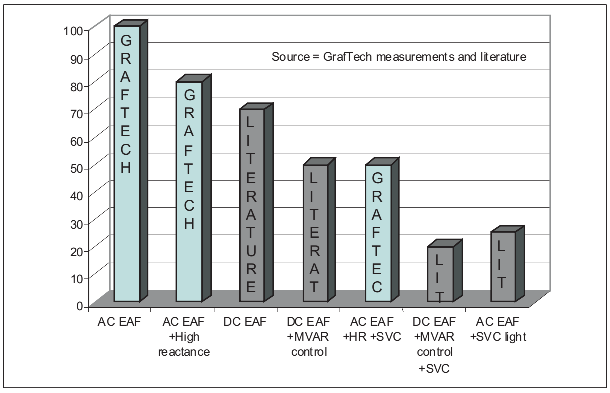

Fig. 9. Estimation of relative flicker generation for various arc furnaces using scrap

10. Electrode consumption and sizing

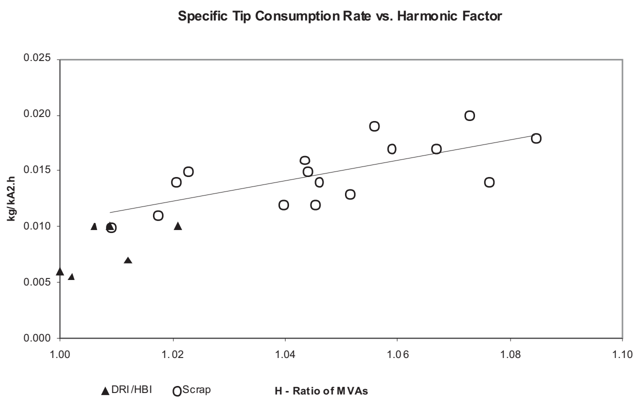

Fig. 10. Specific electrode tip consumption as a function of a harmonic factor

Here we repeat a surprising finding [9] about electrode consumption for DRI steelmaking; the specific tip consumption rate, in units of kg/kA^2h, is significantly lower than for scrap melting. Figure 10 shows our data as a plot of the specific tip consumption rate versus the average of a harmonic factor over the heat. Each point represents one furnace. The lowest heat-averaged harmonic factors occur on furnaces charging large percentages of DRI.

We first found this effect on AC furnaces charging large amounts of DRI, leading to a hypothesis involving reduced current derivatives, dI/dt, compared to scrap. However we have since then four examples of DC furnaces charging DRI and find a similar reduction in specific tip consumption rate compared to scrap melting in DC furnaces, Table 1.

TABLE 1

Specific tip consumption rate for DC furnaces charging DRI

Specific tip consumption rate (kg/kA^2h)			
A	B	C	D
0.0078	0.0064	0.0064	0.0061

As can be seen the values for DC are very similar to those for AC shown in figure 10. For this reason besides a hypothesis based on arc stability the explanation could be also chemically based: in DRI steelmaking the slag has a lower FeO oxide content for most of the heat. FeO slag levels in the range 20 to 30% are more common with DRI whereas levels over 30% are more common with scrap melting.

Finally, we like to comment on the choice of electrode diameter for DRI steelmaking. In general current loading is higher than for scrap. Figure 11 shows DRI loading as full circles compared to the curve for the mean scrap furnace loading. High current density is a component of electrode consumption [9].

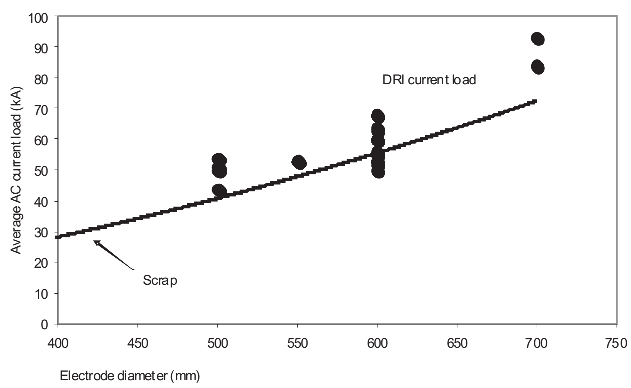

Fig. 11. Electrode current loading on DRI furnace compared to scrap

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Appendix: Heat capacities and heats of formation

	Heat capacity at 1800 K, kJ/mol	Heat of formation kJ/mol at 1800 K (exothermic)	Specific heat when liquid kWh/t	Reference
Fe	71.9			4
FeO	117.6			2
SiO_2	102.5			2
Al_2O_3	180.6			2
CaO	78.5			2
MgO	73.6			2
C	30.6			2
O_2	51.7			2
FeO + C = Fe + CO		142.8		7
Fe_3C = 3 Fe + C		9.98*		10
C + 0.5 O_2		117.4		2
2CaO+SiO_2 = Ca_2SiO_4		28.42		5
Fe			0.231	4
slag			0.31	3

* at 673 K

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