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# Iron oxide content in slag in a 100% DRI melting EAF: An economic approach

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*It was always the matter of question that how much is the optimal amount of Iron content in slag. Undoubtedly, decision of operation philosophy comes from profitability and especially in recent days, as the most important figure for operation to help plants to survive. Developing a proper model to investigate this issue, an energy model is prepared based on Fe total in slag in which sources and sinks of energy is calculated. Also the amount of slag not just for the iron as itself but also increasing fluxes to control refractory corrosion is considered. The cost model based on energy model is calculated in different cases of operation depending on the total iron of slag in different scenarios of DRI quality, cost of energy, profitability, and product cost. In the conclusion of this paper it is indicated that the optimal point of Fe total in slag is its minimum when we are talking about the countries with low energy cost and also the market is down. When the energy cost is higher, the profitability is up, billet cost is low, and there is an optimum point which is shown by calculation during different years. The main aim of writer is to declare this fact that each furnace should find its own optimal point of operation not just based on its figures and energy cost but also should adjust itself based on changes in market.*

**KEYWORDS**: EAF, ENERGY BALANCE, COST MODEL, SLAG, DRI

## INTRODUCTION

There was always a challenge between EAF operation philosophy to have higher yield or to choose lower energy consumption by generation of iron oxide against it. Economically speaking; is it wise to burn Iron or we shall reduce Iron in slag as much as possible by injecting carbon in proper conditions? In new world with very low steel prices as well as high level of production around the world, this questions is being important more and more for the steel producers worldwide.

The quantitative index of this issue is total Fe inside slag indicating how much energy is losing or gaining by chemical reactions while there is a certain range of iron oxide in slag to keep its foaminess. This balance is not anymore a metallurgical index, but now is an economical one too. For DRI melting plants, the mentioned issue faces the fact of outer source of Iron Oxide which goes to slag and energy shall consume to recover Iron back to molten steel.

In this paper, we are analyzing energy balance of DRI melting electric arc furnace according to thermodynamic relations and practical measurement in which chemical and electrical energy is considered as source and Slag, Steel, Fume, water as the sink of energy. This relation to Fe total in slag is investigating versus yield and energy sources according to Energy balance and calculations. Therefore in the first step we are making energy balance and afterwards a cost balance is calculating based on Fe total in slag in different cases.

## ENERGY BALANCE

Reaching to a clear picture of condition of furnace, an energy balance is presenting in the first step.

DRI as raw material is studied in two poor specification which is available in IRAN market and also standard DRI quality:

Local DRI: Fe Total: 88.5%; Metallization:90%; SiO2:3.8%; CaO:1.5%; MgO: 1.5%; Al2O3: 1%; C:1.5%

Standard DRI: Fe Total: 92.5%; Metallization:94%; SiO2:1.5%; CaO:1%; MgO:1%;Al2O3: 1%;C:1.5%

**Source of energy**

Electrical Power source: The total Arc power is calculating based on Measuring Power minus Calculating Lost:

$$P_A - R_A \times I_A^2 + P_B - R_B \times I_B^2 + P_C - R_C \times I_C^2 \quad (1)$$

In which $R_A$ , $R_B$ , and $R_C$ are measured by deep test.

Chemical Energy: The total chemical energy is calculating by summation of below sources:

a) Reaction of lancing oxygen to liquid iron [1]:

$$Fe + 0.5\, O_2 \rightarrow FeO + 6.58\, kwh/Nm^3 O_2 \quad (2)$$

As there is a hesitation that all lancing oxygen go to react with liquid iron, oxygen which are attending in reaction (2) calculates based on oxygen balance between its sources:

O2 in reaction with Fe = O2_Slag - O2_DRI + O2_C (3)

Where O2_Slag is the oxygen inside slag which is going out of the furnace, O2_DRI is the amount of Oxygen in DRI which is directly related to metallization and O2_C is the amount of oxygen which is refined by carbon generating CO.

b) Refining of Fe from Iron Oxide which takes energy [1]:

$$FeO + C \rightarrow Fe + CO - 3.83 kwh/Nm^3 O_2 \quad (4)$$

The exact amount of refined FeO is defined by calculating of total Carbon coming to reaction which is the summation of DRI carbon, charged, and injected carbon.

**Sink of Energy**

Steel: According to thermodynamic relation, the absorbed energy for steel tapping at 1620°C is 375kwh/T [2].

Slag: The amount of slag is directly adjusting based on basicity and acidic guange. Amount of Acidic Guange ($Al_2O_3$ and $SiO_2$) coming to bath from DRI and carbon sources. In the case of using low quality DRI as it is just available in IRAN market, the slag amount is changing from 237 to 320 Kg/TGB based on Fe of Slag and in the case of using standard quality DRI, this amount will be from 117 to 162 KG/TGB. Also it should be noted that if we increase FeO content of slag while Lime and Dolomitic lime consumption be same, the refractory corrosion will start as it is shown in black line in Fig.1. Therefore, the fluxes addition is adjusted in a way to control refractory corrosion which leads to sink more energy in slag as it is shown in yellow line in Fig.1. This fact is shown in below diagram in in isothermal solubility diagram [3] based on different FeO content of slag:

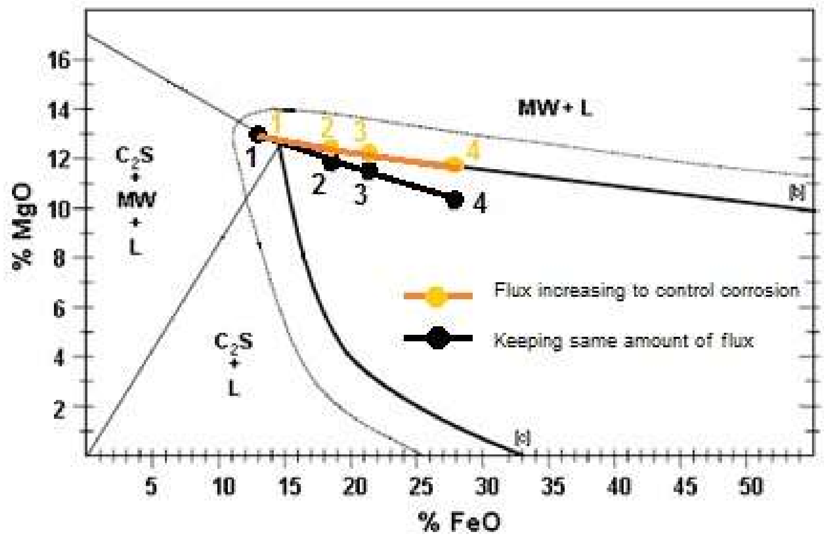


Fig.1 – INCREASING FLUX CONSUMPTION BY INCREASING FeO, Basicity (B3) 1.5

It is clear with unified basicity, the more FeO percentage, the more slag weight we have as shown in Table.1. The loss calculation is done based on 625 Kwh/ton for case I and the rest is calculating based on FeO and MgO heat capacity which is increased in other cases. This calculation is dependent on DRI quality which is done in both Local and Standard qualities DRI which are shown in tables 1 and 2.

Table.1 – SLAG ANALYSIS VERSUS Fe CONTENT INCREASING, LOCAL DRI

| | FeO | Fe total | SiO2 | CaO | MgO | Al2O3 | Slag amount (Kg/TGB) Local DRI |
|---|---|---|---|---|---|---|---|
| Case I | 13.5% | 15% | 23.7% | 37.8% | 13.0% | 4.1% | 241 |
| Case II | 17.9% | 20% | 21.6% | 34.5% | 12.2% | 3.8% | 264 |
| Case III | 22.4% | 25% | 19.3% | 30.9% | 12.0% | 3.4% | 295 |
| Case IV | 27.0% | 30% | 17.1% | 27.4% | 11.6% | 3% | 333 |

Table.2 – SLAG ANALYSIS VERSUS Fe CONTENT INCREASING, STANDARD DRI

| | FeO | Fe total | SiO2 | CaO | MgO | Al2O3 | Slag amount(Kg/TGB) Standard DRI |
|---|---|---|---|---|---|---|---|
| Case I | 13.5% | 15% | 21.3% | 34.0% | 13.0% | 8.5% | 117 |
| Case II | 17.9% | 20% | 19.4% | 31.0% | 12.2% | 7.8% | 129 |
| Case III | 22.4% | 25% | 17.4% | 27.8% | 12.0% | 6.9% | 144 |
| Case IV | 27.0% | 30% | 15.4% | 24.7% | 11.6% | 6.2% | 162 |

Fume: Because of always high temperature of free board in flat bath operation there is no generation of CO2 inside furnace, therefor the energy loss of fume is calculating based on below relation:

Fume Energy Lost= $Cp_{water} \times \Delta T_{wf} \times \frac{d}{dt} m_{wf} + Cp_{fume} \times T_{fume} \times \frac{d}{dt} m_{fume} - CO2\ generation\ energy$ (5)

In which CO2 generation energy is calculating based on amount of CO generated in furnace. The amount of CO is 1.375 times more than total oxygen refined in furnace (O2_C).

Cooling Water Panel: The total energy dissipating by water cooled panel is measured by below equation:

$$Cp_{water} \times (\Delta T_{w_r} \times \frac{d}{dt} m_{w_r} + \Delta T_{w_{us}} \times \frac{d}{dt} m_{w_{us}} + \Delta T_{w_{ebt}} \times \frac{d}{dt} m_{w_{ebt}}) \qquad (6)$$

In which $m$ is mass; $w_r$ is roof water; $w_{us}$ is upper shell water; $w_{ebt}$ is EBT water.

**Result of Energy Balance**

As a result of energy balance, you can find below diagram as a result of electrical and chemical energy balance in four cases of furnace operation based on Fe total in slag as below based on local DRI.

Table.3: ENERGY BALANCE IN DIFFERENT Fe CONTENT OF SLAG / LOCAL DRI

| Fe total | 15% | 20% | 25% | 30% | Unit |
|---|---|---|---|---|---|
| Source of energy | | | | | |
| Total chemical Energy | 13 | 36 | 65 | 101 | kwh/T |
| Total Electrical | 736 | 710 | 681 | 644 | kwh/T |
| Sink of energy | | | | | |
| Water | 103 | 99 | 95 | 90 | kwh/T |
| Fume | 110 | 106 | 101 | 96 | kwh/T |
| Slag | 151 | 156 | 165 | 175 | kwh/T |
| Steel | 385 | 385 | 385 | 385 | kwh/T |
| | | | | | |
| on time | 76 | 73 | 70 | 66 | Min |
| Yield loss in slag | 3.6% | 5.3% | 7.4% | 10.0% | |

It is clear that this balance is also dependent on DRI quality, therefore this calculation is also done based on standard DRI as shown in table.4.

Table.4: ENERGY BALANCE IN DIFFERENT Fe CONTENT OF SLAG / Standard DRI

| Fe total | 15% | 20% | 25% | 30% | Unit |
|---|---|---|---|---|---|
| Source of energy | | | | | |
| Total chemical Energy | 30 | 42 | 56 | 75 | kwh/T |
| Total Electrical | 603 | 589 | 573 | 552 | kwh/T |
| Sink of energy | | | | | |
| Water | 85 | 83 | 80 | 78 | kwh/T |
| Fume | 90 | 88 | 86 | 82 | kwh/T |
| Slag | 73 | 76 | 79 | 82 | kwh/T |
| Steel | 385 | 385 | 385 | 385 | kwh/T |
| | | | | | |
| on time | 62 | 61 | 59 | 57 | Min |
| Yield loss in slag | 1.8% | 2.6% | 3.6% | 4.9% | |

**COST BALANCE**

Making a cost balance, we shall define Gain and Losses of decreasing Fe inside slag.

**Gain**

The main gain of decreasing Fe inside slag is yield which is shown in tables 3 and 4. It is clear that when we use low quality DRI we are wasting lots of steel in slag rather than using standard DRI with the same percentage of Iron inside slag.

**Losses**

The main loss of decreasing Fe inside slag is losing energy which means we shall burn less Iron with oxygen or use less carbon not to refine Fe which both of them increase our electrical energy. Keeping the same amount of injecting oxygen we shall use more carbon, more energy and to use more electrode and EAF refractory consequently. On the other side our productivity will drop which means constant cost of plant will increase.

**Total Cost Balance study**

This is the question that whether the yield as the only gain can compensate the losses or not. It is clear that how much profitability of production and energy cost is higher; production cost is in the favor of higher total iron of slag while billet price has vice versa effect. It must be noted that this trade-off which indicates the optimal point of operation is not just depending on above mentioned items but also is dependent on DRI quality. Therefore in this research we are showing the optimal point of operation based on energy cost in Iran and Europe based on DRI quality in 2016 by change in the market time to time:

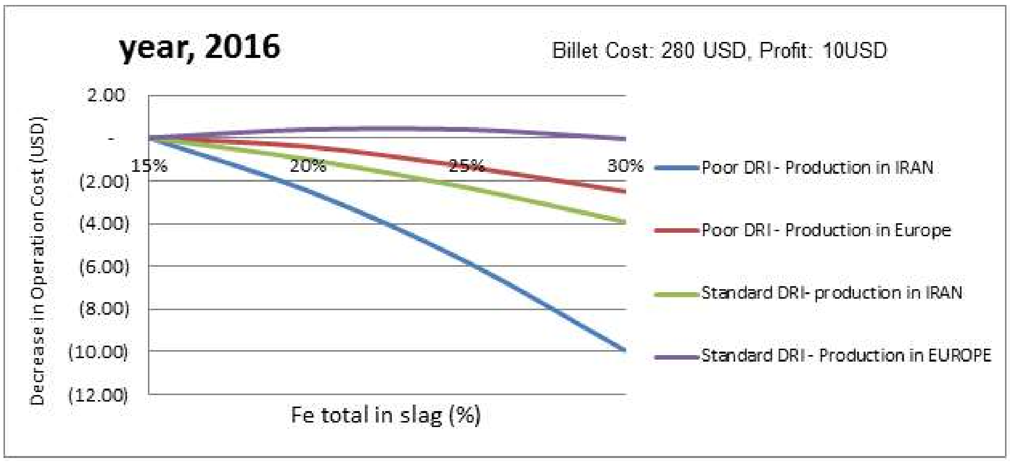


Fig.2: OPERATION COST S Fe TOTAL WHENBILLET PRICE AND PROFIT IS LOW

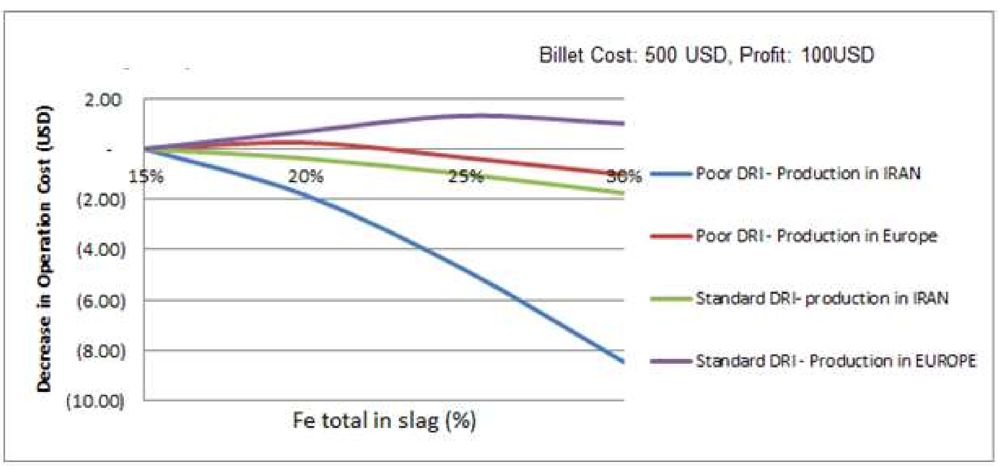


Fig.3: OPERATION COST S Fe TOTAL WHEN PROFIT IS IN ITS SUMMIT

As it could be seen, with consumption of better DRI we can operate with higher FeO inside slag which means not just from productivity point of view but also from economic pint of view, but this fact is weakening when we operate in countries with cheap price of electricity like IRAN in comparison to Europe.

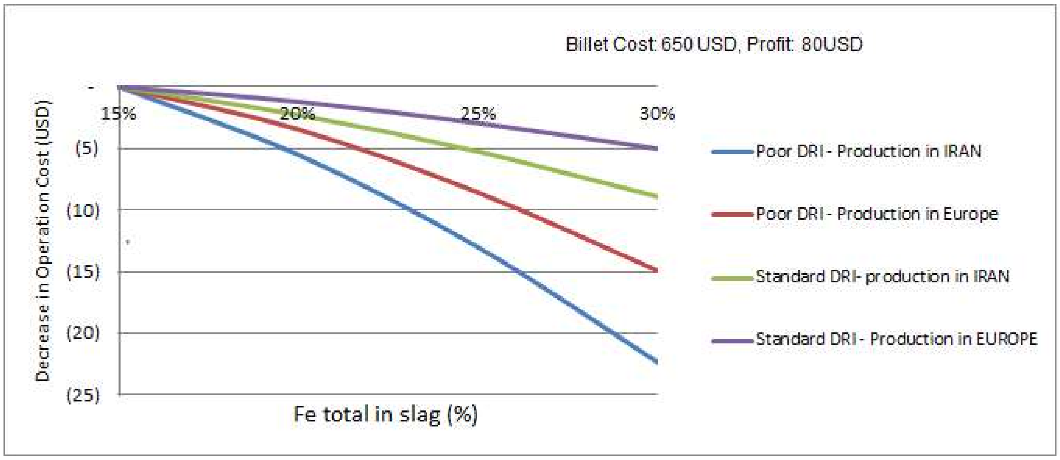


Fig.4: OPERATION COST S Fe TOTAL WHEN BILLET PRICE BUT PROFIT IS NOT SO MUCH HIGH

This investigation is changing even time by time, depending on billet price and profitability of production. As it is shown in above table, in when the price of billet is high and profitability is low (Fig.4) the less Fe content in slag the less production cost. But when profitability is high (Fig.3), optimal point for iron content of slag for standard DRI is around 25% while in IRAN or low quality DRI still the optimal point is minimal point for iron content. Although when the billet price is low, in 2016, due to low profitability operation for standard DRI in Europe is unified in the range of 20%~25% iron content of slag from operation cost of view.

## CONCLUSION

In this paper, an energy model was prepared based on measurement and calculations in one EAF DRI melting furnace during several cases of operation by changing FeO content of slag and also Dolomitic lime/lime consumption to prevent refractory corrosion coming up by generating FeO. Using energy model, a cost comparison was done based on changing Fe content of slag in different cases of operation and the consequence gains and losses are calculated accordingly. It shows that the optimal Iron content of slag is not just a fix number and is varying by changing of DRI quality, Billet Cost, Profitability, and energy cost. It means that each plant should find the optimal point based on its own raw material and cost condition of production and energy to its location and era. But it is a fact that the higher quality in DRI, energy cost, profitability, and the less billet price, the optimal point shifts to higher Fe content. Specifically as a practical result, it shows that in IRAN as a user of low quality DRI which brings too much slag and a country with a very low price of energy, and in this period of time which profitability is very low the minimal possible content of Fe is definitely the optimal point of operation.

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