Energy Optimization of Steel in Electric Arc Furnace

Dora E Ledesma-Carrión*

Av. Patriotismo 711, Col., San Juan Mixcoac, Del. Benito Juárez , Mexico

Abstract

The aim of this work is to create a representative mathematical model of the process of steelmaking for the quantities of raw materials and energy consumption optimal for producing a ton of steel of the specific composition. The specific steel is grade 1010. The reaction enthalpies are critical in the conceptualization and the percentages of carbon and iron in the steelmaking process. There should be a maximum of FeO in slag and a bounded particle C. chemical reactions electric arc furnace enthalpies linear programming steel-making.

Keywords: Chemical reactions; Electric arc furnace; Enthalpies; Linear programming; Steel-making

Introduction

Longtime has been passed to optimize the energy of the electric arc furnace (EAF), as Gordon H. Geiger [1] and Rodolfo D. Morales [2] authors have focused their efforts on this type of furnace using linear programming techniques. Steel production in EAF is adapted as an optimization problem, equations of mass and energy balance with the profit function are coupled to see if the metal load can optimally produce the desired steel (Figure 1).

Therefore, it is crucial to establish the chemical reactions that take place in the process of steelmaking to obtain reaction enthalpies. It is necessary to know where are carried out such reactions, that part of the metallic charge involves and how each contributes.

Homologation of units must be maintained because although the method allows to mix variables of different nature, the made must be coherent and consistent interpretation.

It was assumed that the reactions were not focused on the direct reduced iron. But also involved other iron present in the metallic charge, as well as ferro-alloying, slag formers, injected oxygen and carbon particles. All as a single system, a large pot subject to the physico-chemical processes.

The technical parameters of electrical and thermal efficiency are mainly due to factors such as the lining of the container, refractory or pan, tilt of the injectors, the input speed of the coal particles, the pre-heated oven and preferential area inside retaining furnace high temperature.

Figure 1: Schematization the steel-making process.

Mass balance

To set the mass balance must first determine what goes into the system and what comes out. Incoming masses are those from Direct Reduced Iron (DRI), the scraps, injected oxygen, injected carbon particles, coke, alloying elements and additives. The masses that come out are those formed in the slag from the trainers and additives, CO, O_2, steel. The power here does not apply.

Energy balance

Closely related to the previous balance is energy balance. It is here that becomes relevant the determination of the chemical reactions involved in the process of steelmaking into EAF. Calculating enthalpies at $1600°C$ and the reaction enthalpies were calculated from the heat capacities taken from tables of Barin and standard enthalpies of transformation. They were compared with BASEDAT and REACTION [3] programs to corroborate the calculations made in Excel at the stage of pretreatment of input data.

As input energies are enthalpies of the components of the DRI, scrap, O_2 (including the injected), C (coke + injected particles), reaction enthalpies (endogenous and exogenous) and electricity. Output energies are steel (including gaseous residues), slag and thermal losses. It should take into account the thermal and electrical efficiencies in the process. These are considered as input data.

Chemical composition

It is of paramount importance to establish the chemical composition because it affects all calculations. For this reason, it was thought that the user of this model were an expert, which establish data preparation phase. Therefore, the manufacturing process is independent, which are only interested in determining the reactions are carried out. Fees inputs, the desired product, energy consumption and prices will be established.
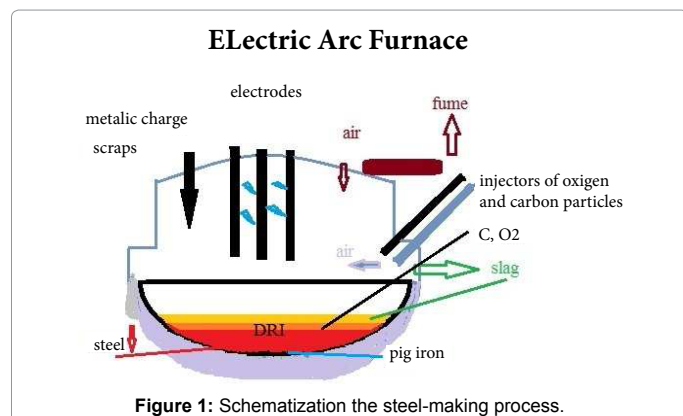
*Corresponding author: Ledesma-Carrion DE, Av. Patriotismo 711, Col. San Juan Mixcoac, Del. Benito Juárez , Mexico, Tel: +52-55-52781000; E-mail: dora.ledesma@inegi.org.mx

Energy sources

Mainly are three: oxygen injection, injection of carbon particles and electricity. Thermal and electrical efficiencies are considered.

Function of energy consumption

Some authors prefer to adjust the energy consumption empirically, as Köhle [4]. In this model it is not necessary and yet, they can enter through the data preparation phase and be incorporated into the mechanics of the model.

Profit function

It is defined as the difference between revenues and expenditures. It is assumed that the cost function of raw materials include transportation and different inputs come with well-defined costs to be prorated respect to the chemical compositions. The simplex method allows slack in the extreme exactitude in the coefficients. That is why as modeling tool has proven to be highly efficient with respect to their predictions.

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Thermodynamics of the process

It is based on the enthalpies calculation, because it is believed that at 1600°C radiation losses are greater than dissipation. Since this model is closely related to the chemical composition, it is not considered the radiation loss, only by thermal and electrical losses. Radiation bounces off the walls of the furnace by the action of the slag and coatings (Figure 2).

Input data: percentages of the compositions of DRI, scraps, the desired slag from additives, ferro-alloying elements, load and desired steel coke and gaseous Iron gangue. The data to be determined, or output, are the amounts of input variables to produce a ton of steel, the amount of spent fuel (electricity, particles C and oxygen). So that energy consumption and the amounts of each component to maximize the benefits of the company. Labor appears as fixed and constant cost, so it does not affect the function to maximize.

Brief state of the art

Information on energy levels, particle injection, oxygen and supplies are taken from the references [4,5].

Considerations are made to linearize own conceptualization to reach the structural form of a linear programming.
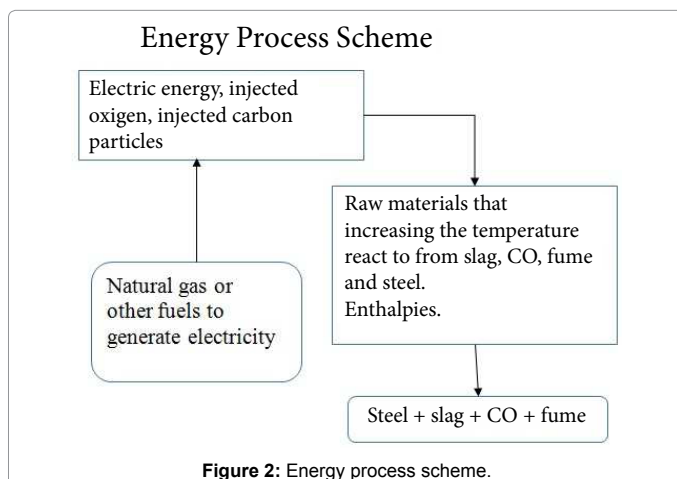

Figure 2: Energy process scheme.

Ionas, et al. [6] by considering the preheated process takes into consideration two aspects: the heat transfer between fluid and particles and heat transfer between the gas layer and an exchange surface, thermal gradients quantizing. The objective function used is a Cobb-Douglas quality/price. It takes into account technical parameters such as the lining of the container, the optimum angle of inclination of the injectors, the inlet velocity of the coal particles, etc. Economic parameters such as exchange rates, inflation, market prices, among others. And weights that reflect the relative importance or contribution of each parameter.

This model shows that preheating has a homogeneous increase existing preferential area retains the high temperature, so that the reactions be differentiated or staggered with respect to time and temperature.

This work bases its hypotheses on which the furnace is efficient (the furnace passed the pre-heated).

Build a model that takes into account the maximum possible variables that adequately describe the physical and chemical phenomena occurring within an electric arc furnace taking into account energy and economic restrictions have been under investigation for some time.

For a detailed description of the process of steelmaking see the final report of the European Commission [5].

Geiger model considers that the reactions are performed zonally, this is, is the sponge iron in the scrap or slag, it does not consider it as a single system where the subsystems interact by exchanging energy.

In addition, energy balance considers the sum of different sources equaling the thermochemical energy and then equating to an estimate of the amount of energy for steel. The latter bound is underestimated by Geiger to considerer only Fe in sponge iron.

A model based on balances for areas was developed by Wendelstorf and Spitzer [7] which optimizes mass balance, momentum, energy and species establishing the differential equation

$$\frac{d\psi_i}{dt} = \sum_{\forall j \neq i} F_{\psi,i,j} + S_{\psi,i}$$

For a conserved quantity Ψ_i in the balance volume i, S_{ψ_i} is the sum over all source terms of balanced quantity Ψ_i in the balance volume i and $F_{\psi,I,j}$ is the interaction term for Ψ_i between the balance volumes i and j. For the simple case of heat transport without mass or species transport between two balance volumes, the interaction term for the enthalpy content H is

$$F_{H,i,j} = A_{i,j}\alpha_{i,j}(T_{i,j}^{boundary} + T_i)$$

The interaction area $A_{i,j}$, and the heat transfer coefficient $\alpha_{i,j}$ must be provided, while the actual boundary temperature boundary $T_{i,j}^{boundary}$, can be calculated from the symmetry/conservation relations.

Whereas a new method by Duan, et al. [8] focus on improving preheating using oxygen injectors and improving slagging. Hot metal is charged into EAF in two portions or steps: firstly, 35 wt% to 40 wt% hot metal is pretreated by blowing oxygen in a specially designed reactor for decarburization, improving temperature, and melting pre-melted slag; secondly, another 35 wt% hot metal is charged into EAF with high basicity refining slags.

Li and Hong [9] used nonlinear differential equations for a dynamic model of EAF steelmaking process and assumed that the simulation

was conducted during the later stage of scarp melting process when the heat transfer from arc is supposed directly to the liquid and gaseous phases and, then from the liquid phases to the solid phases. Also, the formulation of scrap melting process was merely based on heat transfer. The heat absorbed by the solid may be utilized to heat or melt itself. The quantity of each one depended on a temperature ratio between the solid and the liquid. And, the scrap lump was dealt with as roundness approximately and assumed to be melt symmetrically.

All models are based on balances of volume, mass, energy, etc. The optimization is over balances not costs or profit.

Conceptualization of Model

The mass and energy balances are established using a set of linear equations. The inputs to solve the system of equations take into account:

1. Chemical processes of raw materials such as scrap, direct reduced iron (DRI), coke, ferro-alloys, the desired composition of steel and slag;

2. Physical processes: required energy levels, reduced energy losses, phase transformations. The outputs are, per ton of steel, the specific energy consumption (electricity, gas, rubber, coke, etc.), optimum amount of raw materials, oxygen and chemical composition.

The model and its application to steel grade 1010 appear together. It should be noted that there may be more equations and they must be added if it can be determined, and there is information about them.

The steelmaking process analysis identifies three main phenomena: The management of carbon and oxygen levels throughout the process and the presence of Fe in raw materials. This leads to establish the first four restrictions:

Set

f_r^s fraction of component s present in r,

X_r^s quantity in Kg of the component s present in r,

E_e quantity of electric energy to produce one ton of steel,

E_{O_2} quantity of oxygen to produce one ton of steel,

E_{part}^C quantity of injected carbon particles to produce one ton of steel,

ΔH_r Enthalpy per unit mass produced by r,

$f_{X_j,r}^s$ fraction of component X_j of s present in r,

$X_{X_j,r}^s$ quantity in Kg of the component X_j of s present in r.

To calculate the enthalpies are considered the following reactions at 1600°C:

Restriction for coal (carbon). It includes coke:

$$\sum_{X_j} f_{X_j,DRI}^C X_{X_j,DRI}^C + \sum_{X_j} f_{X_j,scr1}^C X_{X_j,scr1}^C + f_{FeMn}^C X_{FeMn}^C +$$

$$f_{CO}^C X_{CO}^C + f_{coke}^C X_{coke}^C + E_{part}^C - f_{steel}^C X_{steel}^C \geq 0 \tag{1}$$

$$\sum_{X_j} f_{X_j,DRI}^C X_{X_j,DRI}^C + \sum_{X_j} f_{X_j,scr1}^C X_{X_j,scr1}^C + f_{FeMn}^C X_{FeMn}^C +$$

$$f_{CO}^C X_{CO}^C + f_{coke}^C X_{coke}^C + E_{part}^C - f_{steel}^C X_{steel}^C \leq 3 \tag{2}$$

$$0.02505X_9 + 0.0033X_{10} + 0.0040X_{18} + 0.0010X_{24} + 0.9940X_{36} + 0.0040X_{38} + 0X_{42} + 1X_{45} - 1X_2 \geq 0 \tag{3}$$

$$0.02505X_9 + 0.0033X_{10} + 0.0040X_{18} + 0.0010X_{24} + 0.9940X_{36} +$$

$$0.0040X_{38} + 0X_{42} + 1X_{45} - 1X_2 \leq 3 \tag{4}$$

Restriction for coke:

$$0.006X_{35} + 0.994X_{36} \leq 20 \tag{5}$$

Restriction for Fe (balance of Fe):

$$f_{steel}^{Fe} X_{steel}^{Fe} + f_{slag}^{Fe} X_{slag}^{Fe} + f_{fume}^{Fe} X_{fume}^{Fe} - \sum_{X_j} f_{X_j,DRI}^{Fe} X_{X_j,DRI}^{Fe} -$$

$$f_{scr1}^{Fe} X_{scr1}^{Fe} - f_{scr2}^{Fe} X_{scr2}^{Fe} - f_{FeSi}^{Fe} X_{FeSi}^{Fe} - f_{FeMn}^{Fe} X_{FeMn}^{Fe} = 0 \tag{6}$$

$$1X_6 + 0.1166X_{29} + 0.7773X_1 - 0.1166X_9 - 0.0467X_{10} - 0.7089X_{13} -$$

$$0.9858X_{22} - 0.9872X_{28} - 0.6654X_{37} - 0.4761X_{39} = 0 \tag{7}$$

Restriction for O_2 (balance of O_2

$$\sum_{X_j} f_{X_j,slag}^{O_2} X_{X_j,slag}^{O_2} + f_{fume}^{O_2} X_{fume}^{O_2} -$$

$$\sum_{X_j} f_{X_j,DRI}^{O_2} X_{X_j,DRI}^{O_2})^{O_2} - f_{CO}^{O_2} X_{CO}^{O_2} - E_{inj}^{O_2} = 0 \tag{8}$$

$$0.2227X_1 + 0.0334X_{29} + 0.1491X_{30} + 0.0094X_{34} -$$

$$0.0334X_9 + 0.02663X_{14} - 0.01412X_{15} = 0 \tag{9}$$

There must be balance between additives

Restriction for CaO (balance of CaO):

$$f_{slag}^{CaO} X_{slag}^{CaO} - f_{DRI}^{CaO} X_{DRI}^{CaO} - f_{CaO} X_{CaO} = 0 \tag{10}$$

$$0.5484X_{31} - 0.01X_{11} = 0 \tag{11}$$

Restriction for MgO (balance of MgO):

$$f_{slag}^{MgO} X_{slag}^{MgO} - f_{DRI}^{MgO} X_{DRI}^{MgO} - f_{MgO} X_{MgO} = 0 \tag{12}$$

$$0X_{32} - 0X_{12} = 0 \tag{13}$$

Restriction for S:

$$f_{steel}^S X_{steel}^S + f_{slag}^S X_{slag}^S - f_{DRI}^S X_{DRI}^S -$$

$$f_{scr1}^S X_{scr1}^S - f_{scr2}^S X_{scr2}^S - f_{coke}^S X_{coke}^S \leq 0 \tag{14}$$

$$1X_5 + 0.0016X_{33} - 0.0001X_{16} - 0.0002X_{21} -$$

$$0.0003X_{27} - 0.006X_{35} \geq 0 \tag{15}$$

Also for Fe-alloying

Restriction for Al + Si (balance of Al+Si):

$$f_{steel}^{Si} X_{steel}^{Si} + f_{steel}^{Al} X_{steel}^{Al} + f_{slag}^{Si} X_{slag}^{Si} + f_{slag}^{Al} X_{slag}^{Al} -$$

$$\sum_{X_j} f_{X_j,DRI}^{Si,Al} X_{X_j,DRI}^{Si,Al} - \sum_{X_j} f_{X_j,scr1}^{Si,Al} X_{X_j,scr1}^{Si,Al} -$$

$$\sum_{X_j} f_{X_j,scr2}^{Si,Al} X_{X_j,scr2}^{Si,Al} - f_{FeSi}^{Si} X_{FeSi}^{Si} = 0 \tag{16}$$

$$1X_3 + 0.1309X_{30} + 0.0106X_{34} - 0.0234X_{14} - 0.0159X_{15} -$$

$$0.002X_{19} - 0.0025X_{25} - 0.3346X_{37} = 0 \tag{17}$$

Restriction for FeSi and FeMn (Balance of FeSi and FeMn):

$$f_{steel}^{Fe} X_{steel}^{Fe} + f_{steel}^{Si} X_{steel}^{Si} + f_{steel}^{Mn} X_{steel}^{Mn} -$$

$$f_{FeMn} X_{FeMn} - f_{FeSi} X_{FeSi} \geq 0 \tag{18}$$

$$1X_3 + 1X_4 + 1X_6 - 1X_{37} - 1X_{39} \geq 0 \tag{19}$$

The composition of raw materials is critical in the production of steel.

Restriction on the mass of DRI:

$$\sum_{X_j} f_{X_j,DRI} X_{X_j,DRI} \leq cot \quad a$$

$0.0010X_8 + 0.15X_9 + 0.05X_{10} + 0.01X_{11} + 0X_{12} + 0.7089X_{13} +$

$0.05X_{14} + 0.03X_{15} + 0.0001X_{16} \leq cot \quad a = 0.5$ (21)

$X_8, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16} \geq 0$ (22)

Restriction on the mass of scrap 1:

$$\sum_{X_j} f_{X_j,scr1} X_{X_j,scr1} \leq cot \quad a \qquad (23)$$

$0.0030X_{17} + 0.0040X_{18} + 0.0020X_{19} + 0.0050X_{20} +$

$0.0002X_{21} + 0.9858X_{22} \leq cot \quad a = 0.5$ (24)

$X_{17}, X_{18}, X_{19}, X_{20}, X_{21}, X_{22} \geq 0$ (25)

Restriction on the mass of scrap 2:

$$\sum_{X_j} f_{X_j,scr2} X_{X_j,scr2} \leq cot \quad a \qquad (26)$$

$0.0040X_{23} + 0.0010X_{24} + 0.0025X_{25} + 0.0050X_{26} +$

$0.0003X_{27} + 0.9872X_{28} \leq cot \quad a = 0.5$ (27)

$X_{23}, X_{24}, X_{25}, X_{26}, X_{27}, X_{28} \geq 0$ (28)

Restrictions on impurities:

$f_{steel}^{imp} X_{steel}^{imp} - f_{DRI}^{imp} X_{DRI}^{imp} - f_{scr1}^{imp} X_{scr1}^{imp} - f_{scr2}^{imp} X_{scr2}^{imp} = 0$ (29)

$1X_7 - 0.0010X_8 - 0.0030X_{17} - 0.0040X_{23} = 0$ (30)

Bounds on energy:

$cot \quad a \quad inf \leq E_e \leq cot \quad a \quad sup$ (31)

$cot \quad a \quad inf \leq E_{O_2} \leq cot \quad a \quad sup$ (32)

$cot \quad a \quad inf \leq E_{part}^C \leq cot \quad a \quad sup$ (33)

$X_{43} \leq cot \quad a \quad sup = 600$ (34)

$X_{43} \geq cot \quad a \quad inf = 466.667$ (35)

$X_{44} \leq cot \quad a \quad sup = 10.4632$ (36)

$X_{44} \geq cot \quad a \quad inf = 4.3161$ (37)

$X_{45} \leq cot \quad a \quad sup = 500$ (38)

$X_{45} \geq cot \quad a \quad inf = 440$ (39)

Restriction mass balance:

$$\sum_{X_j} f_{DRI}^{X_j} X_{DRI}^{X_j} + \sum_{X_j} f_{scr1}^{X_j} X_{scr1}^{X_j} + \sum_{X_j} f_{scr2}^{X_j} X_{scr2}^{X_j} +$$

$$\sum_{X_j} f_{slag}^{X_j} X_{slag}^{X_j} + f_{FeSi} X_{FeSi} + f_{FeMn}^C X_{FeMn}^C +$$

$$f_{CO} X_{CO} + f_{coke}^C X_{coke}^C + f_{coke}^S X_{coke}^S + f_{CaO} X_{CaO} +$$

$$f_{MgO} X_{MgO} + E_{O_2} + E_{part}^C = \sum_{X_j} f_{steel}^{X_j} X_{steel}^{X_j} \qquad (40)$$

$1X_1 + 1X_2 + 1X_3 + 1X_4 + 1X_5 + 1X_6 + 1X_7 - 0.0010X_8 - 0.15X_9 -$

$0.05X_{10} - 0.01X_{11} - 0X_{12} - 0.7089X_{13} - 0.05X_{14} - 0.03X_{15} -$

$0.0001X_{16} - 0.003X_{17} - 0.004X_{18} - 0.002X_{19} - 0.005X_{20} -$

$0.0002X_{21} - 0.9858X_{22} - 0.004X_{23} - 0.0001X_{24} - 0.0025X_{25} -$

$0.005X_{26} - 0.0003X_{27} - 0.9872X_{28} + 0.15X_{29} + 0.28X_{30} +$

$0.5484X_{31} + 0X_{32} + 0.0016X_{33} + 0.02X_{34} - 0.006X_{35} -$

$0.994X_{36} - 1X_{37} - 0.04X_{38} - 0.96X_{39} - 1X_{40} - 0X_{41} +$

$1X_{42} - 0X_{43} - 1X_{44} - 1X_{45} = 0$ (41)

$\Delta H_{reaction} = \Delta H_{endothermal} - \Delta H_{exothermal}$ (42)

$\Delta H_{endothermal} \geq 0$ (43)

$\Delta H_{exothermal} \leq 0$ (44)

$\Delta H_{losses} = (1 - \varepsilon_T)(\varepsilon_e Ee - \Delta H_{exothermal})$ (45)

$E_e \rightarrow \varepsilon_T E_e = \varepsilon_T X_{47}$ (46)

$\Delta H_{O_2} + \Delta H_C + \Delta H_{DRI} + \Delta H_{scr1} + \Delta H_{scr2} + \Delta H_{coque} +$

$\Delta H_{CaO+MgO} + \Delta H_{FeSi+FeMn} + \Delta H_{endothermal} +$

$(-2 + \varepsilon_T)\Delta H_{exothermal} - \varepsilon_T \varepsilon_e E_e = 0$ (47)

$\Delta H_{steel} + \Delta H_{fume} + \Delta H_{CO} + \Delta H_{slag} - \varepsilon_T \varepsilon_e E_e = 0$ (48)

Then

$\Delta H_{steel} = \Delta H_{Fe,DRI,scr1,scr2} + \Delta H_{C,DRI,scr1,scr2} +$

$\Delta H_{S,DRI,scr1,scr2} + \Delta H_{Si,DRI,scr1,scr2} + \Delta H_{Mn,DRI,scr1,scr2} + \Delta H_{imp}$ (49)

$\Delta H_{O_2} + \Delta H_C + \Delta H_{DRI} + \Delta H_{scr1} + \Delta H_{scr2} + \Delta H_{coke} +$

$\Delta H_{CaO+MgO} + \Delta H_{FeSi+FeMn} + \Delta H_{reactions} +$

$\Delta H_{losses} + E_e = \Delta H_{steel}$ (50)

$-5.963X_8 - 74859.3X_9 + 17558.4X_{10} - 13605.6X_{11} + 0X_{12} +$

$228169.5X_{13} - 157944.89X_{14} - 93870.7X_{15} + 649.7X_{16} + 289.9X_{17} +$

$5420.9X_{18} + 5115.7X_{19} + 1705.8X_{20} + 1299.4X_{21} + 313804.0X_{22} +$

$289.9X_{23} + 3498.7X_{24} + 5504.1X_{25} + 1705.8X_{26} + 1949.2X_{27} +$

$314248.3X_{28} + 992.9X_{29} + 2565.5X_{30} + 3164.1X_{31} + 0X_{32} +$

$333.3X_{33} + 4838.2136X_{34} + 38983.1X_{35} + 639688.0X_{36} + 203.2X_{37} +$

$2817.1X_{38} + 6.1X_{39} - 2343969.2X_{40} + 0X_{41} + 2924.7X_{42} -$

$642.7X_{43} + 419368.7X_{44} + 643532.3X_{45} = 0$ (51)

$992.9X_1 + 7695.6X_2 + 21821.63X_3 + 18708.9X_4 + 208338.7X_5 +$

$17721.21X_6 + 17312.63X_7 + 992.9X_{29} + 2565.5X_{30} + 3164.1X_{31} +$

$0X_{32} + 333.3X_{33} + 4838.2136X_{34} + 2924.7X_{12} - 642.7X_{43} \leq 0$ (52)

Restriction for desired steel:

$X_1 = 10, X_2 = 1, X_3 = 0, X_4 = 1.5, X_5 = 0.2, X_6 = 993.3, X_7 = 4$ (53)

Equation (49) is used instead of the (50) proposed by Gordon H. Geiger [1] since his scheme breaks the balance in assuming that the sum of the thermal and electrical energies are those that produce steel in the DRI. The logic in this work is that the incoming power to the system (electrical) is transformed into thermal energy, do not overlap, this is transformed, so the total energy is not the sum but an equality of power with thermal more losses. Also to estimate it and not take into account the contributions of the other components would be a lower bound not equality. The electrical energy would not adding, but subtracting, and consequently would have to adjust the dimension for the difference.

These equations must be coupled to an objective function. This function is the link between the steelmaking process physical-chemical variables and economic world as it usually evaluates financial or accounting issues (Tables 1 and 2).

The proper function, since the input data is the desired chemical composition of steel, is the benefits and not the cost. The cost function explicitly considers only variables associated with the process and raw materials. This is the price that has been paid by forcing optimization to obtain, from the chemical composition, the desired steel under the constraint of energy consumption.

Objetive fuction:

$$Max \sum_j c_j X_{steel}^{X_j} - \sum_j c_j X_{DRI}^{X_j} - \sum_j c_j X_{scr1}^{X_j} - \sum_j c_j X_{scr2}^{X_j} -$$

$$\sum_j c_j X_{add}^{X_j} - \sum_j c_j X_{fe-all}^{X_j} - \sum_j c_j X_{coke}^{X_j} - E_e - E_{O_2} - E_{part}^C \qquad (54)$$

$$Max \quad 200X_2 + 300X_4 + 40X_5 + 198660X_6 + 800X_7 - 0.0029172X_8 -$$

$$0.43758X_9 - 0.14586X_{10} - 0.02912X_{11} - 2.06800308X_{13} -$$

$$0.14586X_{14} - 0.087516X_{15} - 0.0002917X_{16} - 0.0099X_{17} -$$

$$0.0132X_{18} - 0.0066X_{19} - 0.0165X_{20} - 0.00066X_{21} - 3.25314X_{22} -$$

$$0.013213X_{23} - 0.003303X_{24} - 0.0082582X_{25} - 0.016516X_{26} -$$

$$0.0009909X_{27} - 3.26101776X_{28} - 0.0198X_{35} - 3.2802X_{36} -$$

$$12.540X_{37} - 1.32X_{40} - 2.67X_{43} - 0.33X_{44} - 3.3X_{45} \qquad (55)$$

Table 3 shows enter data for steel grade 1010. The system was solved using the simplex method. For this, the LP GAMS solver was applied.

Results

Tables 4 and 5 show summary of runs for steel grade 1010. The

Code	Variable	Code	Variable	Code	Variable
X_1	Fume, FeO gas final product	X_{16}	S in the DRI	X_{31}	CaO in the slag
X_2	C in the steel	X_{17}	Impurities in the scrap1	X_{32}	MgO in the slag
X_3	Si in the steel	X_{18}	C in the scrap1	X_{33}	S in the slag
X_4	Mn in the steel	X_{19}	Si in the scrap1	X_{34}	Al_2O_3 in the slag
X_5	S in the steel	X_{20}	Mn in the scrap1	X_{35}	S in the coke
X_6	Fe in the steel	X_{21}	S in the scrap1	X_{36}	C in the coke
X_7	Impurities in the steel	X_{22}	Fe in the scrap1	X_{37}	FeSi
X_8	Impurities in the DRI	X_{23}	Impurities in the scrap2	X_{38}	C in FeMn
X_9	FeO in the DRI	X_{24}	C in the scrap2	X_{39}	FeMn
X_{10}	Fe3C in the DRI	X_{25}	Si in the scrap2	X_{40}	CaO added
X_{11}	CaO in the DRI	X_{26}	Mn in the scrap2	X_{41}	MgO added
X_{12}	MgO in DRI	X_{27}	S in the scrap2	X_{42}	CO process residue
X_{13}	Fe in the DRI	X_{28}	Fe in the scrap2	X_{43}	EE electric energy [KWh]
X_{14}	SiO_2 in the DRI	X_{29}	FeO in the slag	X_{44}	EO_2 net injected O_2
X_{15}	Al_2O_3 in the DRI	X_{30}	SiO_2 in the slag	X_{45}	EC part injected C particle

Table 1: Variables and codes.

Reaction	Enthalpy [cal]	Complete] molecule [cal]	$(-2 + \varepsilon_T) * \Delta H_{exothermal}$ [Kcal]
$\Delta H(FeO_{DRI} \rightarrow Fe + 1/2O_2)$	60,971.51	121,943.02	121.9430
$\Delta H(Fe_3C_{DRI} \rightarrow 3Fe + C)$	-1,951.55	-1,951.55	2.2833
$\Delta H(CaO + SiO_2 + Al_2O_3 \rightarrow Ca + 2Al + Si + 3O_2)$	780,538.01	780,538.01	780.5380
$\Delta H(Si + O_2 \rightarrow SiO_2)$	-226,818.46	-226,818.46	265.3775
$\Delta H(C + 1/2O_2 \rightarrow CO)$	-28,301.30	-56,602.59	66.2250
$\Delta H(Fe + 1/2O_2 \rightarrow FeO)$	-60,971.50	-121,963.02	142.6733
$\Delta H(C_{graphite} \rightarrow C)$	906.804	906.804	0.9068
$\Delta H(FeSi \rightarrow Fe + Si)$	34,109.08	34,109.08	34.1090
$\Delta H(FeMn \rightarrow Fe + Mn)$	1,358.44	1,358.44	1.3584
$\Delta H(MgO + SiO_2 + Al_2O_3 \rightarrow Mg + 2Al + Si + 3O_2)$	0.00	0.00	0.00
$\Delta H(2Al + 3/2O_2 \rightarrow Al_2O_3)$	-421,636	-843,271.92	986.6281

$\Delta H\left(Ca+1/2O_2 \rightarrow CaO\right)$	-151,652	-303,306.99	354.8691
$\Delta H\left(Mg+1/2O_2 \rightarrow MgO\right)$	0.00	0.00	0.00
$\Delta H\left(Fe_3C+FeO \rightarrow 4Fe+CO\right)$	30,718.66	30,718.66	30.7187
$\Delta H\left(CaO+MgO+SiO_2+Al_2O_3 \rightarrow Ca+Mg+2Al+Si+7/2O_2\right)$	0.00	0.00	0.00
$\Delta H\left(FeO+C \rightarrow Fe+CO\right)$	32,670.21	32,670.21	32.6702
$\Delta H\left(Si+2FeO \rightarrow SiO_2+2Fe\right)$	-104,875.44	-104,875.44	122.7042

Table 2: Reaction enthalpies for steel grade 1010 (MgO is not present).

Enter data	[%/Ton steel]	Enter data	[%/Ton steel]	Enter data	[%/Ton steel]
DRI	-	**Scrap 1**	-	**Scrap 2**	-
Impurities	0.1	Impurities	0.3	Impurities	0.4
FeO	15	C	0.4	C	0.1
Fe$_3$C	5	Si	0.2	Si	0.25
	-	Mn	0.5	Mn	0.5
Iron gangue	-	S	0.02	S	0.03
CaO	1	Fe	98.58	Fe	98.72
MgO	0	-	-	-	-
SiO$_2$	5	**Total**	100	**Total**	100
Al$_2$O$_3$	3	-	10 [Kg/	-	-
S	0.01	Fume	ton steel]	**FeSi**	-
Others, Fe	70.89	FeO	100	FeSi	100
-	-	FeO, O	22.27	-	-
Total	100	FeO, Fe	77.73	**Total**	100
Coke charge		FeMn	-	**CaO, MgO**	-
S	0.6	C	4	MgO	0
C	99.4	FeMn	96	CaO	100
Total	100	**Total**	100	**Total**	100
CO	100	Slag	100	Efficiency	-
C	42.88	FeO	15	Thermal	83
O	57.12	SiO$_2$	28	electrical	90
	-	Al$_2$O$_3$	2	-	-
CO$_2$	100	CaO	54.84	-	-
C	27.29	MgO	0	-	-
O	72.71	S	0.16	-	-
Steel	-	-	-	-	-
C	0.1	Traces	-	Impurities + traces	-
Si	0	P	0	S	0.4
Mn	0.15	Ni	0	-	-
S	0.02	Sn	0	**Total**	100
Fe	99.33	Cr	0	-	-
Impurities	0.4	Mo	0	-	-
Traces	0	V	0	-	-

Table 3: Desired steel, thermal and electrical efficiency, DRI, slag, scrap ferro-alloys, Iron gangue composites.

Total C	**11.18%**	**11.18**	**11.18%**	**15%**	**20%**
C particles	11.18%	6.18%	1.18%	0%	0%
Coke	0%	5%	10%	15%	20%
X_1	10	10	10	10	10
X_2	1	1	1	1	1
X_3	0	0	0	0	0
X_4	1.5	1.5	1.5	1.5	1.5
X_5	0.2	0.2	0.2	0.2	0.2
X_6	993.3	993.3	993.3	993.3	993.3
X_7	4	4	4	4	4
X_8	799.4754793	799.4754793	799.4754793	799.4754793	799.4754815
X_9	25.29610735	25.29610735	25.29610735	25.29754712	25.31754953

X_{10}	248.0940113	248.0940113	248.0940113	248.0938191	248.0911037
X_{11}	0	0	0	0	0
X_{12}	0	0	0	0	0
X_{13}	180.4358237	180.4358237	180.4358237	180.4355326	180.4300038
X_{14}	92.31646143	92.31646143	92.31646143	92.31646143	92.33250805
X_{15}	15.82097997	15.82097997	15.82097997	15.82097997	15.82939477
X_{16}	0	0	0	0	0
X_{17}	801.0783089	801.0783089	801.0783089	801.0783089	801.0783354
X_{18}	37.29752181	37.29752181	37.29752181	37.29729194	37.29407898
X_{19}	482.1995219	482.1995219	482.1995219	482.1995219	482.1995151
X_{20}	0	0	0	0	0
X_{21}	0	0	0	0	0
X_{22}	185.0447753	185.0447839	185.0447907	185.2401678	185.455371
X_{23}	199.3223985	199.3223985	199.3223985	199.3223985	199.3223781
X_{24}	206.7628415	206.7628415	206.7628415	206.762784	206.7619726
X_{25}	371.7391762	371.7391762	371.7391762	371.7391762	371.7391882
X_{26}	0	0	0	0	0
X_{27}	1.312338347	1.312338347	1.312338347	1.312338347	1.312338344
X_{28}	504.5241146	504.5241146	504.5241146	504.5241146	504.5241155
X_{29}	0	0	0	0	0
X_{30}	699.7135455	699.7135417	699.7135417	699.4306861	699.3406552
X_{31}	236725218.7	236725218.7	236725218.7	236725218.7	236725218.7
X_{32}	0	0	0	0	0
X_{33}	0	0	0	0	0
X_{34}	169.0606159	169.0606159	169.0606159	169.0606159	169.0549374
X_{35}	0	0.001214486	0.002428979	0.003061	0.007854536
X_{36}	-0.000001	0.201199913	0.402400831	0.603603254	0.804782568
X_{37}	266.1726684	266.1726669	266.1726669	266.062032	266.025118
X_{38}	0.017891297	0.017891297	0.017891297	0.015592584	0.015592584
X_{39}	2.202453522	2.202437936	2.202423781	1.952579696	1.562141753
X_{40}	129820109.9	129820109.9	129820109.9	129820109.9	129820109.9
X_{41}	0	0	0	0	0
X_{42}	-0.000001	0	0	0.07392749	0.099650731
X_{43}	43.06312964	43.06312964	43.06312964	43.06312964	43.06312964
X_{44}	104.632	104.632	104.632	104.632	104.632
X_{45}	0.447282432	0.247290011	0.047296298	0	0
%Fe n DRI	60	70	70.89	80	90
X_{1}	10	10	10	10	10
X_{2}	1	1	1	1	1
X_{3}	0	0	0	0	0
X_{4}	1.5	1.5	1.5	1.5	1.5
X_{5}	0.2	0.2	0.2	0.2	0.2
X_{6}	993.3	993.3	993.3	993.3	993.3
X_{7}	4	4	4	4	4
X_{8}	799.5	799.5	799.5	799.4	799.4
X_{9}	21.3	19.5	19.3	19.2	19.2
X_{10}	247.4	246.9	246.9	246.9	246.9
X_{11}	0	0	0	2369.8	2369.8
X_{12}	0	0	0	0	0
X_{13}	151.9	144.9	144.4	142	142
X_{14}	93.6	93.7	93.7	93.9	93.9
X_{15}	16.6	16.7	16.7	16.8	16.8
X_{16}	0	0	0	0	0
X_{17}	801	801	801	801	801
X_{18}	37.2	37.2	37.2	37.2	37.2
X_{19}	482.3	482.3	482.3	482.3	482.3
X_{20}	0	0	0	0	0
X_{21}	0	0	0	0	0
X_{22}	227.9	218.1	217.3	213.6	213.6
X_{23}	199.4	199.4	199.4	199.4	199.4
X_{24}	206.8	206.8	206.8	206.8	206.8

X_{25}	371.8	371.9	371.9	371.9	371.9
X_{26}	0	0	0	0	0
X_{27}	1.3	1.3	1.3	1.3	1.3
X_{28}	504.5	504.5	504.5	504.5	504.5
X_{29}	13.1	14.7	14.9	15.1	15.1
X_{30}	691	690.1	690	689	689
X_{31}	236725218.7	236725218.7	236725218.7	236725218.7	236725218.7
X_{32}	0	0	0	0	0
X_{33}	0	0	0	0	0
X_{34}	168.5	168.5	168.4	168.4	168.4
X_{35}	0.1	0.1	0.1	0.1	0.1
X_{36}	1.9	1.9	1.9	2	2
X_{37}	262.6	262.2	262.2	261.8	261.8
X_{38}	4.8	4.9	4.9	4.9	4.9
X_{39}	0	0	0	0	0
X_{40}	129820109.9	129820109.9	129820109.9	129820086.2	129820086.2
X_{41}	0	0	0	0	0
X_{42}	1.4	1.4	1.4	1.2	1.2
X_{43}	43.1	43.1	43.1	43.1	43.1
X_{44}	104.6	104.6	104.6	104.6	104.6
X_{45}	0	0	0	0	0

Table 4: Summary of runs for steel grade 1010.

Coke, C [Kg]	Ecpart [Kg]	C in the Scrap1 [Kg]	C in the Scrap2 [Kg]	C in FeMn [Kg]	Total C [Kg]	[%]All C sources to sources to [0%] the load coke	Profit [%/Ton]
0.0000001	0.4472824	37.297522	206.76284	0.0178913	244.52554	0.00%	0.00%
0.2011999	0.24729	37.297522	206.76284	0.0178913	244.52674	0.00%	0.00%
0.4024008	0.0472963	37.297522	206.76284	0.0178913	244.52795	0.00%	0.00%
0.6036033	0	37.297292	206.76278	0.0155926	244.67927	0.06%	5.77%
0.8047826	0	37.294079	206.76197	0.0155926	244.87643	0.14%	10.55%
0.0059602	0	37.290877	206.76116	0.0155926	245.07359	0.22%	15.32%
0.2071386	0	37.287695	206.76036	0.0155926	245.27079	0.31%	20.09%
0.4083182	0	37.284552	206.75957	0.0155926	245.46803	0.39%	24.85%
0.6094958	0	37.281284	206.75874	0.0155926	245.66511	0.47%	29.64%
0.8101779	0	37.223131	206.74406	0.0155926	245.79296	0.52%	49.92%
0.0108609	0	37.164929	206.72939	0.0155926	245.92077	0.57%	70.18%

Table 5: Amount of carbon from all sources respect to load variation the coke.

main results for the percentages of carbon and iron are shown. Well as profits about them.

Analysis and Discussion

From Tables 4 and 5, the Figures 3-6 were built. As seen from Figure 3, the behavior of the components of DRI for percent carbon is similar to impurities, FeO, Al_2O_3 and SiO_2. The same applies for Fe and Fe_3C. The optimum is between 14-15% of C in coke.

Also, the behavior between the two groups is reversed, that is, for example, while the impurities are increased Fe decreases after 15% C.

From Figure 4, the benefits are increased as the % Fe in the DRI is increased to 70.89% in the optimal. After drastically decrease the benefits. The price of the gangue or metallic charge is substantially increased compared to its quality.

For a poor gangue in Fe, profits are negative or very low. For higher amounts of 2%C steel becomes brittle.

From Figure 5 and Table 5, profits will be obtained 70.18% at full load of 0.571% C respect to 0%C in coke (2.01086085 Kg C).

From Figure 6, a quick slagging occurs between 60 and 70% Fe in the DRI (0.16 kg / ton steel /%Fe in DRI). The maximum slagging is
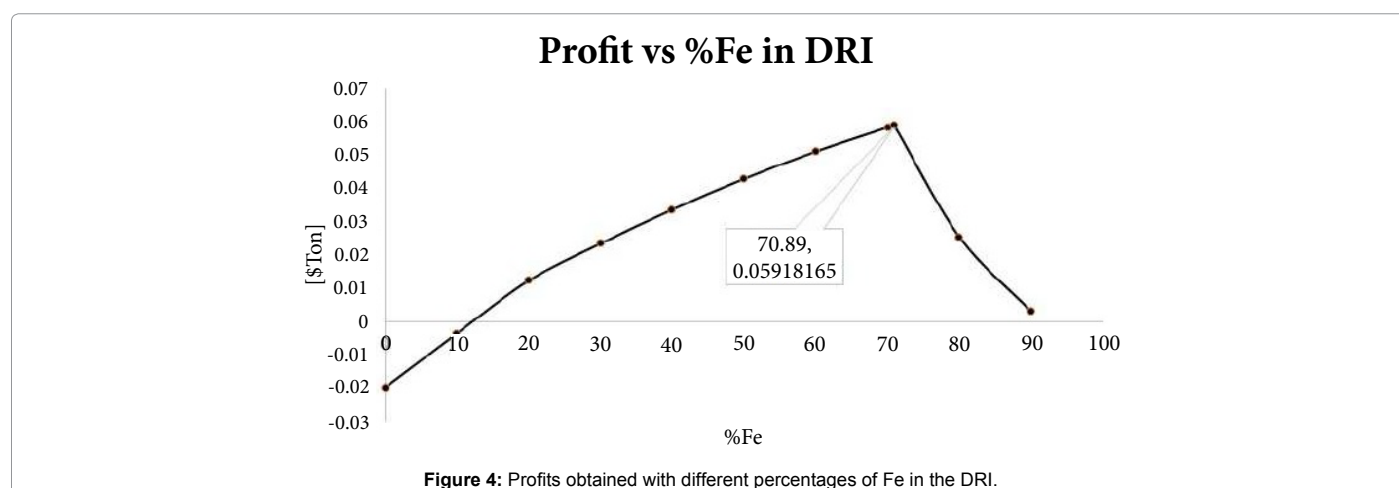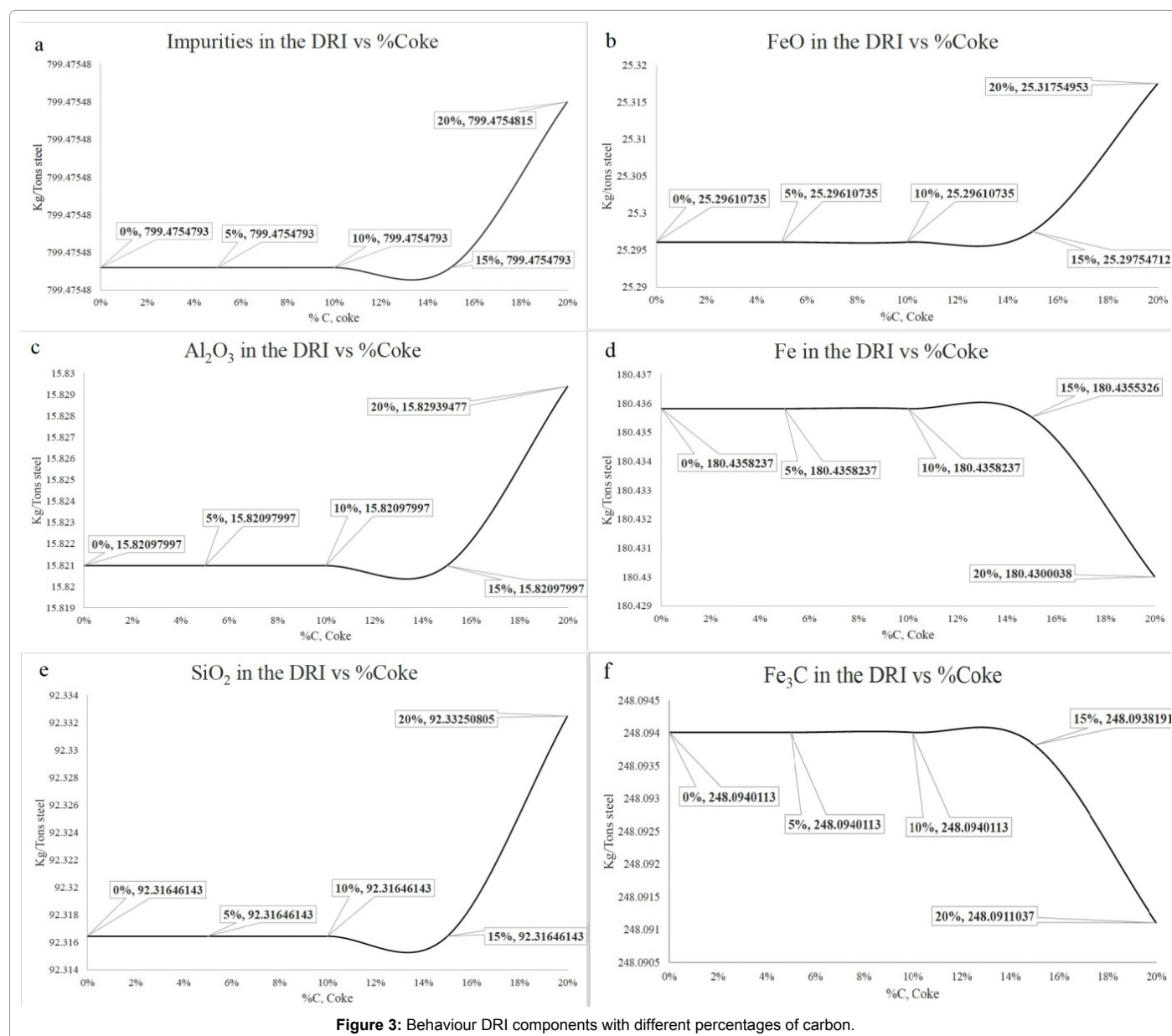
carried out between 70 and 70.89% at a rate of 0.2247 [kg / ton steel /% Fe in DRI]. After between 80 and 90% is stabilized.
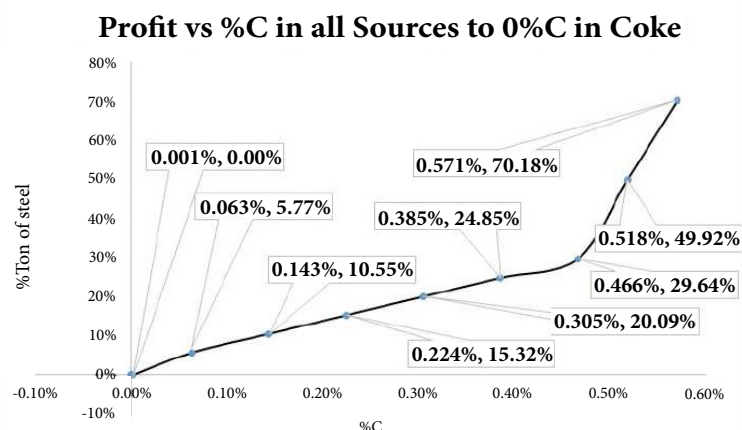
From Table 4, the remaining compounds of the slag Al_2O_3, SiO_2 decrease as the %Fe in the DRI is increased while that calcium oxide remains constant.

Conclusions

1. Reducing energy costs in the steel-making process can only be significant in managing the composition of the slag and the cost of getting rid of it ecologically. The same applies to the fume.

2. Costs are sensitive to the composition of the DRI and the metal charge.

3. From feasibility analysis, a minimum percentage of injected particles C to be carry out reactions and this is 0.8 kg / ton of steel.

4. The model is sensitive to the definition of chemical reactions that take place in the steelmaking process more than just the energy electrical bounds, particles C and, electrical and thermal efficiencies.

5. Maximum profit is 0.059$/Ton of steel respect to 70.89%Fe in the DRI. In this optimum the production of slag (FeO) is stabilized.

Figure 3: Behaviour DRI components with different percentages of carbon.

Figure 4: Profits obtained with different percentages of Fe in the DRI.

Figure 5: Profits obtained with different percentages of % C in all sources.
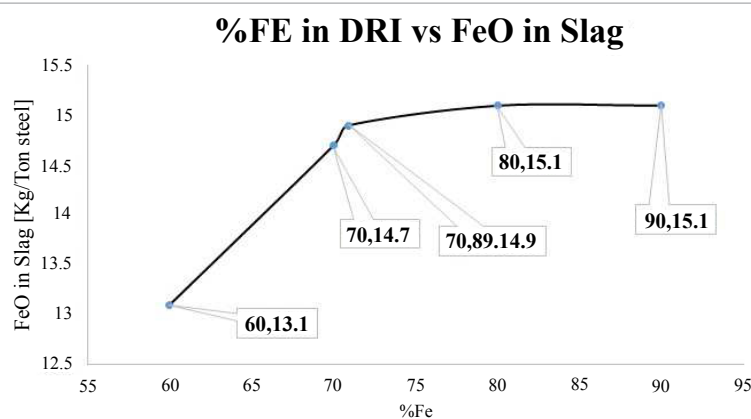
Figure 6: Slag compound formed from Fe in DRI.

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