Material Balance of an Electric Arc Furnace at the Libyan Iron and Steel Company

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Abstract—**Material balance has been applied for existing Electric Arc Furnace(EAF) at the Libyan Iron and Steel Company(LISCO) in Misurata city. First the required data were collected from the plant, then the material balance has been applied totally and on an elemental basis and led to a system of independent material balances which has been solved numerically. The obtained results includes the composition of used scrap, the quantity of infiltrated air, steel in slag , off-gas, and the electrode and refractory consumption. Also the results have been compared with the actual plant data and similar studies.**

Index Terms: **material balance, Electric Arc Furnace (EAF), air infiltration, steel, slag, electrodes consumption, refractories consumption.**

I. INTRODUCTION

A. Iron and Steel

Iron is found in nature as an oxides, like hematite(Fe_2O_3) and Magnetite (Fe_3O_4) and in order to get the elemental iron, oxygen and other impurities must be removed by a reduction process at a temperature below the melting point of the iron. The direct reduction process is a widely used method to reduce the iron ore. This process utilize the coal or natural gas as a reduction agent. The reduction process occur directly in solid state and the product iron called the sponge iron or the direct reduced iron(DRI) [1]. The properties of the iron can be modified by adding various other metals like Aluminum, Nickel, Manganese, and some non-metals, notably carbon and silicon to form steel[2].

There are three methods for making steel, Basic Open Heart Method, Basic Oxygen Convertor Method, and Electric Arc Furnace(EAF) Method[3]. There are two important advantages of the EAF method: using of the scrap as a raw material instead of iron ore and the required specific investment per ton of steel is much lower than the other production methods[4].

In 2017, approximately, 472 million metric tons of liquid steel (28 % of the world's total) were produced by using the EAF method in the world. While 422 thousand metric tons were produced in Libya in the same year[5].

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B. Electric Arc Furnace

EAF is a steel making furnace in which iron material Like Scrap, DRI is heated and melted by a heat of electric arcs striking between the furnace electrodes and the charged material. Graphite electrodes are typically used in a triangular arrangement to create a three-phase arc. The electrical energy is the primarily energy input and the chemical energy from exothermic reactions form the secondary energy input.

Figure.1 shows a sectional view of EAF. The furnace consists of spherical heart (bottom), cylindrical shell and a swinging roof.

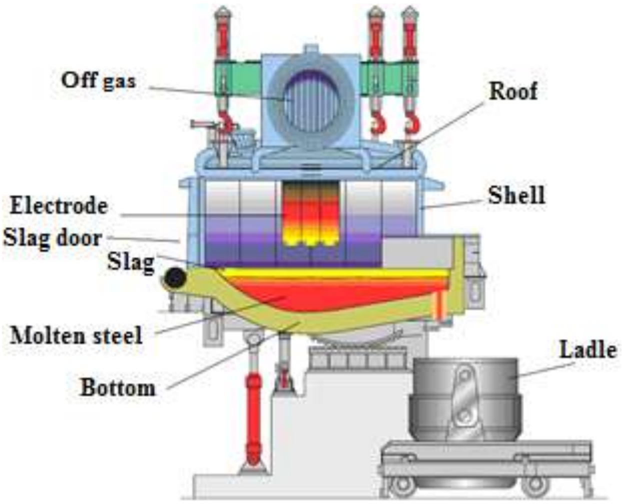

Figure 1.Cross-Sectional View of an EAF

The roof has four holes, three for consumable graphite electrodes held by a clamping mechanism, and the fourth hole is for exiting the off gas. An elbow duct relates to the fourth hole to exhaust the fume produced by the melting process; the fume elbow can be disconnected from the fume exhaust line to allow the roof to swing. The DRI can be provided through the roof. The furnace is mounted on a tilting mechanism for tapping the molten steel through a tap hole[6].

C. Typical Electric Arc Furnace Time Cycle

The EAF operating cycle is called tap-to-tap time. First, Scrap iron is carried by a traveling overhead crane along the steel shop bay in a loading basket up to above the furnace and then unloaded into the furnace, which is open at this stage[6].

Once the scrap iron has been loaded, the furnace roof closes and the material inside is melted by an electric arc created by three electrodes. Once the liquid steel bath is accomplished, further row material can be added to the furnace. This could be scrap iron, again loaded with the scrap basket, or DRI, loaded into the furnace by material handling system. The material handling system consists in a transportation system that brings the DRI to the EAF. A conveyor belt brings the material to a hopper placed above the roof of the furnace; the material goes into the furnace through the duct placed at the bottom of the hopper.

At the melting phase, oxygen and carbon powder are injected in the steel bath by means of consumable lances. The oxygen is injected into the EAF to increase the efficiency. Lime and dolomite can be loaded through the slag door to form the slag.

Once the melting phase is over, the next phase starts to transfer the liquid steel into a ladle prepared in a suitable position in the furnace lower part. This is obtained by tilting the whole furnace forward from its horizontal position. Backward tilting of the furnace during the melting process is used to eliminate slag on the surface of the molten steel. Slag is poured out to the ground through a slagging door. The pouring phase is achieved through a hole in the lower part of the furnace, through which the liquid steel is poured into the ladle. The hole opens by tapping plug. The ladle sites on a car that travels on rails to be carried to an area away from the furnace[6].

D. Aim of the Study

This study aims to apply the material balance principles for an EAF using actual data and calculating the unknown amounts and compositions, then comparing it with similar studies and statistical data in steel melt shop 1 at LISCO.

II. MATERIAL BALANCE

In the industrial process, the material balance is important in the planning for the process design, in the economic evaluation, in process control, and in process optimization. The material balance is nothing than an accounting for material flows and changes in inventory of material for a system [7]. According to the conservation law of matter, the sum of the weights of the substances entering the system is equal to the sum of the substances going out the system, or briefly" what comes in must go out"[7]. The general material balance equation is

$$\left\{\begin{array}{l}\text{accumulation}\\ \text{within}\\ \text{the}\\ \text{system}\end{array}\right\} = \left\{\begin{array}{l}\text{input}\\ \text{through}\\ \text{the}\\ \text{system}\\ \text{boundaries}\end{array}\right\} - \left\{\begin{array}{l}\text{output}\\ \text{through}\\ \text{the}\\ \text{system}\\ \text{boundaries}\end{array}\right\}$$
$$+ \left\{\begin{array}{l}\text{generation}\\ \text{within}\\ \text{the}\\ \text{system}\end{array}\right\} - \left\{\begin{array}{l}\text{consumption}\\ \text{within}\\ \text{the}\\ \text{system}\end{array}\right\} \qquad (1)$$

With respect to a total mass balance, and the elemental mass balance, the generation and consumption terms are zero(by neglecting the transfer between the mass and energy in the ordinary chemical reactions. The accumulation term is related to the change in total or elemental mass within the system with respect to time[7]. So, by taking a basis of the time, the accumulation term in eq. 1 Can be omitted, and the general material balance equation becomes

$$\left\{\begin{array}{l}\text{mass}\\ \text{input}\\ \text{through}\\ \text{the}\\ \text{system}\\ \text{boundaries}\end{array}\right\} = \left\{\begin{array}{l}\text{mass}\\ \text{output}\\ \text{through}\\ \text{the}\\ \text{system}\\ \text{boundaries}\end{array}\right\} \qquad (2)$$

Figure. 2 shows the typical amounts of inlet and outlet streams in steel melt shop 1 at the plant per ton of liquid steel.

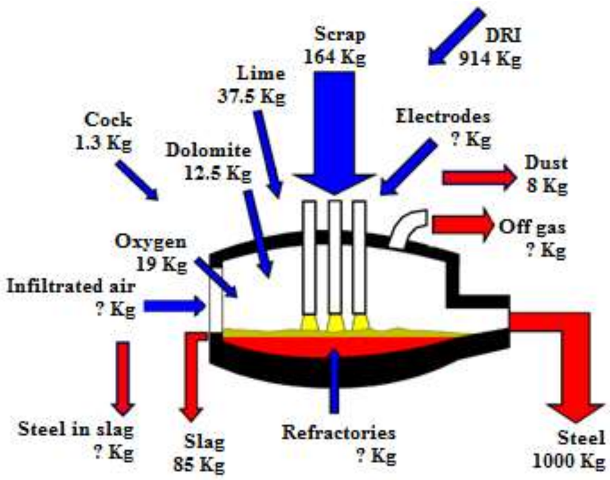

Figure 2. Inlet and outlet materials for EAF per ton of steel

All the known chemical compositions of inlet and outlet streams of the EAF are shown in table 1 and 2 respectively. There is no information about chemical analysis for the used scrap, the amount of the off gas and its composition, and the amount of infiltrated air. Statistically, the electrodes consumption (Kg per ton of liquid steel) is in the range of (2.9-3.5)Kg/t, the refractories consumption is in the range of (2.4-7) Kg/t, and the loss in steel(i.e. steel in slag) is about 15 Kg/t. These statistical values will be considered as unknowns and will be calculated by the material balance. In most studies, the infiltrated air has not been taken into account, while few has like M. Kirschen and H. Pfeifer [8]; E. Hajidavalloo et al.[9]; and H. Wang. Et al.[10] , and they have found that it has a significant amount, so it should to be considered. The composition of infiltrated air can be assumed as: 23.3 % Oxygen and 76.71 % Nitrogen. In this paper, all the compositions are given in weight percent.

Table 1. Chemical Composition of Inlet Materials (%) [6]

Material or element	DRI	Lime	Dolomite	Electrodes	Refractories	Cock	Infiltrated Air
Fe	92.85	-	-	0.15	-	-	-
Ca	-	-	-	0.15	-	-	-
C	2.35	-	-	99.3	15	88.5	-
Al	-	-	-	0.05	-	-	-
P	0.032	-	-	-	-	-	-
Si	-	-	-	0.15	-	-	-
S	0.008	-	-	-	-	0.5	-
SiO_2	1.6	-	-	0.05	-	4	-
Al_2O_3	2.4	-	-	0.05	-	5	-
Fe_2O_3	-	-	-	0.05	-	1	-
CaO	0.01	95	65	-	-	1	-
MgO	0.56	5	35	0.05	85	-	-
MnO	0.19	-	-	-	-	-	-
O_2	-	-	-	-	-	-	23.3
N_2	-	-	-	-	-	-	76.71
sum	100	100	100	100	100	100	100

Table 2. Chemical Composition of Outlet Materials (%) [6]

Material or element	Steel	Steel in slag	Slag	Dust
Fe	98.7048	98.7048	-	-
Ca	0.1196	0.1196	-	-
C	0.196	0.196	-	-
Cr	0.033	0.033	-	-
Cu	0.043	0.043	-	-
Al	0.779	0.779	-	-
Mg	0.0006	0.0006	-	-
Ni	0.0149	0.0149	-	-
Mn	0.085	0.085	-	-
P	0.013	0.013	-	-
Si	0.0001	0.0001	-	-
S	0.011	0.011	0.004	-
SiO_2	-	-	17.3	1.7
Al_2O_3	-	-	7.9	4.4
Fe_2O_3	-	-	6.05	79
Cr_2O_3	-	-	0.38	1.1
P_2O_5	-	-	0.59	-
CaO	-	-	49	6.5
MgO	-	-	18.2	-
MnO	-	-	0.576	7.3
CO	-	-	-	-
CO_2	-	-	-	-
N_2	-	-	-	-
sum	100	100	100	100

There are a total of 14 element balances (Fe, Ca, C, Cr, Cu, Al, Mg, Ni, O, P, Si, S, Mn, N) can be written, plus an overall mass balance. Therefore the number of unknowns cannot exceed 14, the number of independent relationships between variables.

The total unknowns are 17 including the composition of off gas, and in order to solve the system, the analysis of off gas can be taken from similar studies like(Pfeifer H, Kirschen M [8]) as initial approximation which is: 25 % CO_2 , 25 % CO , 50 % N_2. By trial and error , the following analysis fit with an acceptable solution for the system : 17 % CO_2 , 29 % CO , 54 % N_2 .

Total balance

$$\begin{aligned}&W_{DRI} + W_{Scrap} + W_{Dolomite} + W_{Lime} + W_{Air}\\&+ W_{Oxygen} + W_{Refractories} + W_{Cock} + W_{Electrodes}\\&= W_{Steel} + W_{StSl} + W_{Slag} + W_{Offgas} + W_{Dust}\end{aligned} \tag{3}$$

Where:
W_X refers to the weight (mass) of X
StSl refers to the steel in slag
Air refers to the infiltrated air

Iron balance

$$\begin{aligned}&F_{Fe_{DRI}} W_{DRI} + F_{Fe_{Scrap}} W_{Scrap} + \left[\frac{112}{160} F_{Fe_2O_3}\right]_{Cock} W_{Cock}\\&+ \left[\frac{112}{160}(F_{Fe_2O_3}) + F_{Fe}\right]_{Electrodes} W_{Electrodes}\\&= \frac{112}{160}\left(F_{Fe_2O_3}\right)_{Slag} W_{Slag} + \frac{112}{160}\left(F_{Fe_2O_3}\right)_{Dust} W_{Dust}\\&+ F_{Fe_{Steel}} W_{Steel} + F_{Fe_{StSl}} W_{StSl}\end{aligned} \tag{4}$$

Where:
F_x refers to the weight(mass) fraction of X

The material balance equations for the other elements can be written in a similar way to get a system of linear algebraic equations which can be expressed in terms of matrices as follow:

$$\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix} \tag{5}$$

Eq. (5) can be expressed in a simple matrices form as

$$[A]\,[X] = [B] \tag{6}$$

Where: A matrix of Coefficients , B matrix of constants, X matrix of unknowns.

And the solution for this system is

$$[X] = [A]^{-1}\,[B] \tag{7}$$

Where $[A]^{-1}$ is inverse matrix[11].

The solution has been accomplished by Excel using matrix inversion and multiplication built-in functions.

III. RESULTS AND DISCUSSION

The estimated scrap composition shown in table 3 agree with the typical analysis in similar studies like E. Hajidavalloo, et. Al [9].

Table 3.The Estimated Composition of Used Scrap

Element	Cr	Fe	C	Cu	Ni	P	Si	S	Mn
%	0.37	98.4	1.7	0.26	0.09	0.03	0.04	0.02	0.21

The estimated values of the infiltrated air and the off gas are 127.9 Kg/t and 181.8 Kg/t respectively, and these results are agree with H.Pfeifer and M. Kirschen [8].

Table 4 show a comparison between the estimated and statistical values of electrodes consumption, refractories consumption, and the steel in slag.

Table 4. A Comparison Between the Estimated and Statistical Values

Quantity	$W_{Electrodes}$	$W_{Refractories}$	W_{StSl}
Estimated value(Kg/t)	3.6	2.4	15.2
Statistical value(Kg/t)	2.9-3.5	2.4-7	15

In order to check whether the results are accurate or not, the differences between the quantities of the inlet and the outlet individually (for each element) and totally have been estimated and shown in Table 5 and 6 respectively.

Table 5. Inlet and Outlet Quantities for Elements

element	in(Kg/t)	out(Kg/t)	in-out(Kg/t)
Fe	1008.6954	1009.871	-1.175574462
Ca	31.347731	31.352879	-0.005147733
C	28.7264	31.657548	-2.931147576
Cr	0.5904	0.616157	-0.025757025
Cu	0.4264	0.43645	-0.01005
Al	11.64656	11.647062	-0.000502125
Mg	8.0876659	9.3361217	-1.248455792
Ni	0.1476	0.151235	-0.003635
O	84.995562	83.475544	1.520018189
P	0.34168	0.3508151	-0.009135116
Si	6.8822612	6.9382824	-0.056021218
S	0.11242	0.11505	-0.00263
Mn	1.5909229	1.6942075	-0.103284691
N	97.4217	93.357677	4.064022551
Total	1281.013	1281	-

Table 6. Inlet and Outlet Quantities for Streams

In(Kg/t)		Out(Kg/t)	
DRI	914	Steel	1000
Scrap	164	Slag	85
Dolomite	12.5	Steel in Slag	15.2
Lime	37.5	Off gas	181.8
Electrodes	3.6	Dust	8
Refractories	2.4	-	-
Infiltrated air	127.9	-	-
Oxygen	19	-	-
Cock	1.3	-	-
Total	1282.2	Total	1290

The differences between the inlets and outlets are small; so the results are acceptable.

IV.CONCLUSION

In the present study, by applying the material balance, the unknown amounts and compositions of some steams for the EAF have been estimated in a good agreement with the plant data and similar studies.

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BIOGRAPHIES

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