Heat balance analysis in electric arc furnace for process improvement

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Abstract. The current study deals with optimizing the melting process used in electric arc furnace by heat balance equations. Heat balance is a very important aspect in an arc furnace in which the energy input consists of electrical energy [65%], chemical energy [25%] and exothermic reaction heat [10%]. This energy is optimized with the charge mix, charge quantity, fluxes, fuel used, and O2 used in the burners. The present model considers all these aspects and gives heat distribution in the process. The model spreadsheet gives a reasonable prediction in terms of metal yield, composition, and energy consumption. The model also predicts the amount of iron oxidized in the process. The mass and heat balance model is a useful tool for process analysis and improves the process efficiency of electric arc furnace steelmaking.

Keywords Energy consumption analysis, Electric Arc Furnace, Steel scrap, Heat balance, Optimization

1 Introduction

The use of electric arc furnaces (EAF) for steelmaking has grown dramatically in the last few decades. Presently, around 36 % of the steel produced is made by the electric arc furnace route and this is expected to further increase to 50% in the next few years. Electric Arc Furnace (EAF) is the most common way to recycle steel from scrap. By melting the scrap in a furnace with the help of electrodes and an electric current, new, functional steel can be produced from old products. Once the scrap has been melted and refined to the desired composition and temperature, the molten steel is tapped into a ladle for secondary treatment and casting. The international iron and steel institute classifies EAFs based on power supply per ton of furnace capacity. Power classification ranges are shown in the following Table 1[1]

Vladimir Viktorovich Pavlov and Oxana Sergeevna Logunova conducted the study of charging material at large integrated steel factory. They found that by using alternative material charge, consumption of specific energy is changed[1] Jens Wendelstorf and Karl-Heinz Spitzer developed a process reactor model which will be helpful to predict tapping temperature and meltdown ststus[2]. Dr. Bernd Kleimt and et al. conducted the energy balance of electric arc furnace and developed one dynamic model which will be helpful for online observation and dynamic process control[3]. Dragoljub Gajic and et al. developed one model which predicts the value of electrical energy consumption as a function of the chemical composition the charging mix[5]. Jens Wendelstorf developed online model which demonstrate meltdown of solid material and temperature development in the furnace[6]. Marcus Kirschen et al. conducted mass and energy balance of EAF melting process which gives information about chemical energy input and total energy demand of particular EAF process[7]. Bake lee and Il Sohn reviewed the energy innovations for EAF steel making route and found that preheating of scrap will lower the energy consumption by 90 kWh/t. Bucket type and twin shell preheaters will also be effective in lowering overall power consumption by 60 kWh/t[8]. Biau lo et al. analysed flow characteristics of ferrite-flows and established an energy intensity production optimization model for production system in iron and steel industry. They suggested Unified resource deployment is the basic guarantee of the implementation of the optimization scheme. Therefore, resource sharing should be fully considered during the iron and steel company process design stage. The advanced energy saving technologies and measures, which favors production route re-optimizes, should be adopted in actual production process[9].

Using ultra-high power furnaces it is possible to increase productivity, reduce tap to tap time, and reduce electric energy consumption [1]

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Table 1 Electric power classification in the electric arc furnace

Range of power (KVA/t)	Furnace type
100-200	Low power
200-400	Medium power
400-700	High power
700-1000	Ultra-high power

2 Experimental work

2.1 Experimental set up

For this study, the electric arc furnace at Kalyani Carpenter Special Steels Limited, (KCSSL) Pune is used. The EAF at KCSSL has a capacity of 35 MT and it is equipped with a 22 MVA transformer. The details of the furnace used for the study is shown in following Electric Arc Furnace at KCSSL.

- Make: ABB
- Melting capacity: 35 MT
- Transformer Power: 22 MVA
- Tapping: Slide gate assembly
- Two virtual lance burners
- Bucket Charging: Minimum Two charges per heat
- Continuous DRI feeding Conveyor
- Charge Mix: In house scrap; forging flashes, HMS, Pig iron, DRI

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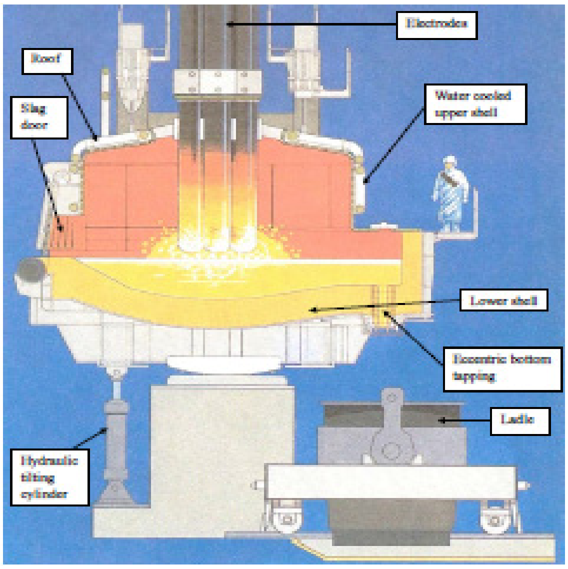

Fig. 1 Typical Electric Arc Furnace

There were one batch of experimentation that was carried out in the furnace

2.2 Melting Technique

Initially, the EAF roof is opened and about half of the total charge is charged into the furnace. After the initial charge, the roof is replaced on the furnace top and the furnace is powered on with a graphite electrode to generate electric arc. During the melting period, Virtual Lance Burners (VLB) run as per the computer preset program. The current and voltage selection is initially set and a profile for the melting set as per designed experimental requirements. After the initial lot is melted, the roof is opened and the second charge of another 30% of charge is added. After the second charge, the furnace is powered on and the VLB switched on. When all the 80% of charge is melted, a temperature reading is taken. When the temperature was greater than 1570°C The first metal sample for chemical analysis is taken. This is followed by the final 20% charge addition consisting mainly of DRI, using a conveyor belt feeder. At the various stages of the above operation, metal and slag samples were taken for chemical analysis. The process events were continuously recorded from start to end. On attainment of desired chemical composition, the heat is tapped into a ladle for secondary refining. The typical processing cycle carried out in the experimental batch is shown in Table 2 The heat input, in terms of electric arc, was gradual. The various processing times at various stages such as charging, melting, refining, sampling, foaming, and tapping are given.

Table No. 2 EAF process details for the experimental batches

Batch 1		Batch 2		Batch 3	
Time (Min.)	Process Details	Time (Min.)	Process Details	Time (Min.)	Process Details
0 – 3	The first charge added	0-3	First charge added	0-3	First charge added
3 – 23	First charge melting	3-52	Furnace melting	3-23	First charge melting
23 – 26	The second charge added	52-55	Second charge added	23-26	Second charge adeed
26 – 44	Second charge melting	55-74	Second charge melting	26-44	Second charge melting
44 – 45	First slag sample is taken	74-75	DRI feeding started	44-45	First slag sample taken
45 – 46	DRI feeding started	75-77	First slag sample taken	45-46	DRI feeding start
46 – 50	Temperature and the first metal sample is taken for analysis	77-79	Temperature and first metal sample taken for analysis	46-50	Temperature and first metal sample taken for analysis

50 – 55	Second slag sample is taken/Foaming and temperature raising	79-81	Second slag sample taken	50-54	Second slag sample taken. Foaming and temp. raising
55 – 56	Third slag sample is taken	81-86	Second and third slag sample taken	54-55	Third slag sample taken
56 – 58	Final coke injection	86-89	Foaming and temp. Raising	55-58	Final coke injection
58 – 59	DRI feeding ends	89-91	Forth slag sample taken	58-59	DRI feeding ends
59 – 62	Tapping temperature recorded	91-94	Final coke injection, DRI feeding ends	59-60	Tapping
62 – 65	Fourth slag sample is taken/ Tapping starts	94-96	Tapping	61-62	Fourth slag sample taken, Tapping start

The process schedule for Batch-1 and Batch-3 were almost same. In Batch 2 a prolonged processing was carried out, where the melting was carried out in a progressive manner. The arcing was very gradual for initial charge melting till 80% of the charge. Parameters such as power consumed during the process due to electric energy input, fuel combustion through lance burners and carbon injection is shown in Table 3

Table No. 3 EAF input data for three batches

Parameter	**Batch 1**	**Batch 2**	**Batch 3**
Charge mix, (MT)	39.50	36.00	37.50
Electric energy consumption, (kWh/MT)	384	424	428
VLB oxygen consumption (NM^3/MT)	33.19	45.04	44.08
VLB Fuel consumption, (Lit/MT)	0.0045	0.0057	0.0052
Carbon injection, (kg/MT)	0.017	0.009	0.011

The metallic and slag output from the furnace is shown in Table 4

Table No. 4 EAF output data for three batches

Parameter	Batch 1	Batch 2	Batch 3
Theoretical metallic output, MT	36.612	34.894	34.421
Actual metallic output, MT	37.420	32.900	33.820
Metallic loss, MT	-0.807	1.994	0.6
Theoretical slag output, MT	6.273	4.920	5.396
Actual slag output, MT	6.320	5.500	5.670
Slag loss, MT	-0.046	-0.579	-0.273
Yield %	94.73	91.38	90.18

The theoretical energy required to convert solid steel to molten condition is in the range of 350 kWh/ton. The EAF steelmaking is only 55 to 65 % efficient and as a result the total equivalent. energy input is usually in the range of 400 to 550 kWh/ton in modern operations. The energy input consists of more than half the energy input for the EAF is from electrical energy. Chemical energy from fuel contributes about 40% and 10% can come from the exothermic reaction heat. The chemical energy can be from the calorific value of the fuel the rate of heating is controlled by the fuel and oxygen burning rate. The output energy distribution shows that 60% of heat energy is contained in the superheated steel, slag carries about 10%; other heat losses are about 30%. Minimizing this can save process energy.

Table No. 5 Distribution of heat (in %) from input to output in a typical EAF

Heat Input		**Heat Output**	
Parameter	**%**	**Parameter**	**%**
Electric energy	56-60	Liquid Steel	55-60
Chemical energy	30-40	Cooling water	8-10
Burners	5-10	Miscellaneous	1-3
		Slag	8-10
Total	**100**	**Total**	**100**

Factors such as raw material composition, power input rates, and operating practices can alter the above balance. In operations utilizing a large amount of charge carbon or high carbon feed materials, up to 60 % of the energy contained in the off-gas may have high calorific due to large quantities of uncombusted carbon monoxide. The recovery of this energy in the EAF could increase energy input by 8 to 10 %. Thus, it is important to consider such factors when evaluating the energy balance for given furnace operation.

3 Governing equations

3.6 Governing equations for mass balance

1) Governing equation for this mass balance model is as

$\Sigma M_{input} = \Sigma M_{output} + \Sigma M_{ls}$ …………………(1)

where $\Sigma M_{input} = M_{Scr} + M_{flx} + M_{ck} + M_{dm} + M_{bd} + MO_2^{blown}$ ……………………………(2)

$\Sigma M_{output} = M_{st} + M_{sl} + M_{dust} + M_{gases}$ ....(3)

2) Iron balance

$W_{Fe}^{DRI}.M_{DRI} + W_{Fe}^{Scr}.M_{Scr} + W_{Fe}^{Flx}.M_{Flx} = W_{Fe}^{St}.M_{St} + W_{Fe}^{Sl}.M_{Sl} + W_{Fe}^{dust}.M_{dust}$ ……(4)

3) Silicon balance

$W_{Si}^{DRI}.M_{DRI} + W_{Si}^{Scr}.M_{Scr} + W_{Si}^{Flx}.M_{Flx} = W_{Si}^{St}.M_{St} + W_{Si}^{sl}.M_{sl}$……………………..(5)

Total

$M_{Scr} + M_{DRI} + M_{Flx} + M_{O2}^{blown} + M_{coke} = M_{st} + M_{sl} + M_{dust} + M_{gases}$…………………………(6)

Where

W_i^j = Weight percent of specie i in phase j M_{input} = Mass of all input scrap material.

M_{output} = Mass of all output material

M_{ls} = Mass of losses

M_{Scr} = Mass of scrap

M_{Flx} = Mass of fluxes

M_{ck} = Mass of coke

M_{dm} = Mass of deoxidizing material

M_{bd} = Mass of fuel

M_{O2}^{blown} = Mass of O_2 blown into the furnace

M_{st} = Mass of steel

M_{sl} = Mass of slag

M_{dust} = Mass of dust M_{DRI}

Mass balance analysis of steel production process has been carried out according to the input component, and using mass conservation law as mentioned in above equations.

4 Results and discussion

Heat balance is another important aspect of an electric arc furnace which enables optimization of process conditions to minimize the energy consumption. This enables energy management from the charge point of view. The broad energy parameters for three experimental batchs is shown in Table 6

Table No. 6 Heat balance for the experimental batches

Fuel used Kg	Fuel heat in kWh/MT	Electric heat in kWh/MT	Chemical heat kWh/MT	Total energy consumed kWh/MT
170	47.02	384.00	238.08	622.08
187	58.83	424.00	227.24	649.42
176	53.86	428.00	287.80	706.88

The Fig.2 shows that fuel used is moderately higher for Batch-2. The electrical heat input increases from Batch-1 to Batch-3. The heat input due to stoichiometric exothermic heat generated by various steel making reactions is moderately higher for Batch-3 compared to the other two batches. The overall heat used in the process increases from Batch 1 to Batch 3 progressively. It is seen that average 63% of heat comes from electrical energy and average 37 % of heat from fuel burnt in the furnace and the exothermic reaction heat varies from 7 to 9% due to exothermic reaction. This is important as minimising electrical energy saves energy cost, and this energy itself is produced with fuel combustion elsewhere. Hence, usage of fuel in furnace to generate heat is good. The present experiments shows 34 to 40% and possibility of enhancing this should be explored. However, this also increases emissions in the factory and the cost of this and impact on surrounding have to be assessed. The exothermic heat is <9%. To maximise this may be increasing carbon containing charge such as pig iron may be of helpful. The impact of this on the energy saving and productivity has to be assessed. Further pig iron is more expensive than scrap. The model developed can now be run to predict the theoretical power generation for a given charge mix.

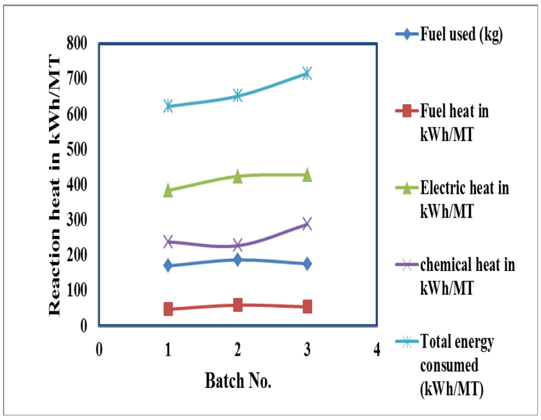

Fig. No. 2 Heat balance in the experimental batches

5. Summary and Conclusion

Three experimental trials were carried out in electric arc furnace at KCSSL to understand the process behaviour at various stage of processing. The elemental and slag constituents were tracked by studying the chemistry of the raw materials input and the output metal and slag obtained in the furnace. The model does the energy balance in the process and it is possible to optimise the electric energy consumption and fuel based energy and exothermic heat inputs. Using the model, it is now possible to reduce the process time, fuel, electric energy and oxygen consumption.

Acknowledgement

We thank the organisation KCSSL for providing the experimental facility.

References

1 Jeremy Jones, The EPRI centre for material production, C M R I, Pittsburgh, PP **1** (1997)
2 F. P. Edneral, vol. 1 Electric steelmaking, Mir publishers, Moscow, PP **17** (1979)
3 Richard J. Fruehan, AISI steel foundation, 11th edition, steelmaking and refining volume, chapter **10,** (1998)
4 Yuri N. Toulouevski and Iiyaz Y. Zinurov, Scientific basis for selection, Springer, pp **1**, (2010)
5 Ali Akbar Mottahedi et al, Int. J. of chemTech re, Vol.1,No1, pp **62** (2009)
6 F. Grobler and R.C.A. Minnitt, The Jr. of South-African inst. of mining and metallurgy, (1999)
7 R. J. fruehan, Y. Li, L. Brabie, Carnegie Mellon University, Pittsburgh.
8 Richard J. Fruehan, the AISI steel foundation, 11th edition, steelmaking and refining volume, chapter **2** (1998)
9 Jernkontoret, Sweden. [online]. Available: http://www.jernkontoret.se(2006, May 17).
10 Jacob paulraj, Steel world, pp **26** (2007)
11 Marcus Kirschen, Victor Risonarta, Herbert Pfeifer, Energy 34, pp **1065**, (2009)
12 Ismail Ekmekci, YasarYetisken, UnalCamdali, Int. Jr. of iron and steel re., 14(05) pp **01,** (2007)
13 Karl R. Haapala and John W. Sutherland(20), Annals of the CIRP vol. pp **1,** (2007)