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Discovering Hidden Parameters' Estimates in Operation of an Innovative Electric Arc Furnace by applying Optimization Techniques

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Abstract

Energy-Efficient electric arc furnace (EAF) operations require careful monitoring and skillful manipulation of different parameters. With high-precision sensors, the instantaneous values of different parameters are available throughout operation of EAF but there are parameters that cannot be measured due to different constraints. These hidden parameters can be helpful in better understanding and future improvement of EAF operations. The focus of this work is to find best possible estimates of two of those parameters at different stages of a heat for an innovative EAF with specially designed shaft to save energy. A stage-based spatial-temporal energy balance model was constructed with few quantities expressed in term of the hidden parameters. The estimates of hidden parameters, discovered after application of optimization on the constructed model, reveal their cyclic behavior throughout the heat.

Keywords: *EAF, Energy, Energy balance model, Optimization*

1. Introduction

Electric arc furnace (EAF) makes use of electric arc to heat charged material. The obvious outcome of energy-efficient electric arc furnaces is comparatively cost-effective steel production that implies rising profits for steel industry [1] [2]. The steelmaking operation in EAF is a complex process with involvement of many parameters. Usage of shaft is one of the innovations intended to preheat the scrap, resulting in saving of energy [3]. ECOARCTM (ECOlogically friendly and ECOnomical ARC furnace) is a Japanese-developed modern EAF with specially designed shaft [4] with continuous operation [5]. We used operational data from one of ECOARCTM for our work.

The data logged in historical/operational database is a precious resource that can be used to analyze heats. The number of variables stored can vary for different electric arc furnaces [6]. The operational database that we used contains values of numerous parameters collected by different sensors for every second throughout the hundreds of heats of ECOARCTM . However, there are parameters that can only be estimated and values of them cannot be obtained by sensors or other devices due to certain constraints. The correct estimation of these unknown parameters can lead to better understanding and improvement of EAF operations. This work focuses on

a. Formulation of spatial-temporal energy balance model for ECOARC TM by equating the heat balances for different stages of a heat in the two zones of EAF.

b. Estimation of two of unknown parameters for each stage of POT of a heat. The balance equations with the hidden parameters as member of their summands lead to formulation of objective function that is to be minimized.

The word "Heat" will be used in this paper in different contexts with different meanings and in order to avoid confusion, we feel it appropriate to present brief explanation in this section. Heat is form of energy and when we will discuss about heat balances, we will be referring to balances of heat that is form of energy. However the word heat is also used to represent an individual batch of molten steel [7]. In this paper, whenever we will use the word in later sense, heat will be written in italic typeface. We will also use italicized heat to represent entire operation of EAF with shaft (a delicate extension to the scope of the word).

We will begin, in Section 2, with introduction of some basic terminologies and description of part of EAF operation that is relevant to our work. In Section 3 we will explain concepts of heat balances with respect to ECOARC TM furnace. The contents of Section 4 carry description of formulation of heat balances in terms of unknown parameters, and in this context, we demonstrate how different input and output items can be calculated at stage level. This section is followed by Section 5 in which optimization process to estimate unknown parameters, is mentioned. Section 6 illustrates the nature of results achieved. In Section 7, the conclusion is made in which description of possible future investigation is also included.

2. Brief description of EAF with shaft

Electric arc is the major source of energy, used to heat charged material in an electric arc furnace (EAF). The scrap is the main component of the charged material that is described by weight in tons. The operating cycle of an EAF is called tap-to-tap cycle. The time duration for this whole cycle is called tap-to-tap time and is usually denoted in minutes. The different operations performed in this cycle can be placed in either of following two categories.

1. Power-on furnace operation time (POT)
2. Power-off furnace operation time

POT includes the operations that are performed when the electric arcs are on. The following two main operations are carried out at EAF during the POT:

1. Melting of solid charge materials performed in melting period of POT
2. Heating of liquid bath to refine impurities from molten steel, performed in the superheating period of POT

Both of these operations require heat that is provided by electrical and chemical energy. The most of the time of POT comprises of scrap melting operation. When the superheating operation finishes, the electric arcs become off. Tapping and preparation for next heat are the main components of Power-off furnace operation time that is much smaller than POT.

2.1. Details of the operation

In this subsection, we describe only that part of operation that is relevant to our study and the data of which was used for our work. Fig.1 illustrates a typical "ECOARCTM ", an electric arc furnace with shaft.

The Scrap metal is the input to the operation of steel making and this input is to be melted for subsequent process. The scrap passes through operation of preheating in shaft before it charges the furnace. Scrap preheating is carried out by thermal energy of off-gases [8]. In order to maintain certain scrap height in the shaft, scrap is charged by shaft-charging car called “skip”, approximately 10-13 times a heat.

The batches of scrap loaded on skip car are off-loaded into shaft and after preheating they are charged into furnace one by one. Getting inspiration from the skip car, we will use the word “SCIP”(SCrap In Preheating) in this paper to describe the stage of melting period of POT during which a batch of scrap, charged by skip car, remains in lowest region of shaft before charging into furnace. The slight change of spelling from skip to scip should be noticed.

Melting of scrap in liquid bath is most time-consuming period of POT and scrap preheating makes it possible to reduce the time of this period. Hence before the immersion of scrap in liquid bath, scrap is already preheated to degree that it takes much lesser time to melt completely in liquid bath as compared to the condition when scrap is not preheated.

In order to provide required heat to melt the scrap, the electrodes are lowered onto the scrap and the scrap is subjected to high electric arc. For rapid formation of molten pool, proper adjustments of voltages and arc length throughout the melting process are required. To further accelerate the melting process, the chemical heat from combustion of oxygen plays important role but it also results in the oxidization of iron. Carbon powder injected into the bath reduces this oxidized iron and hence unacceptable drop of yield is avoided. Moreover the Carbon injection has another advantage; the foaming of slag (generated by small bubbles of CO floating in upward direction) that is another important technique to increase the efficiency of Electrical Energy usage.

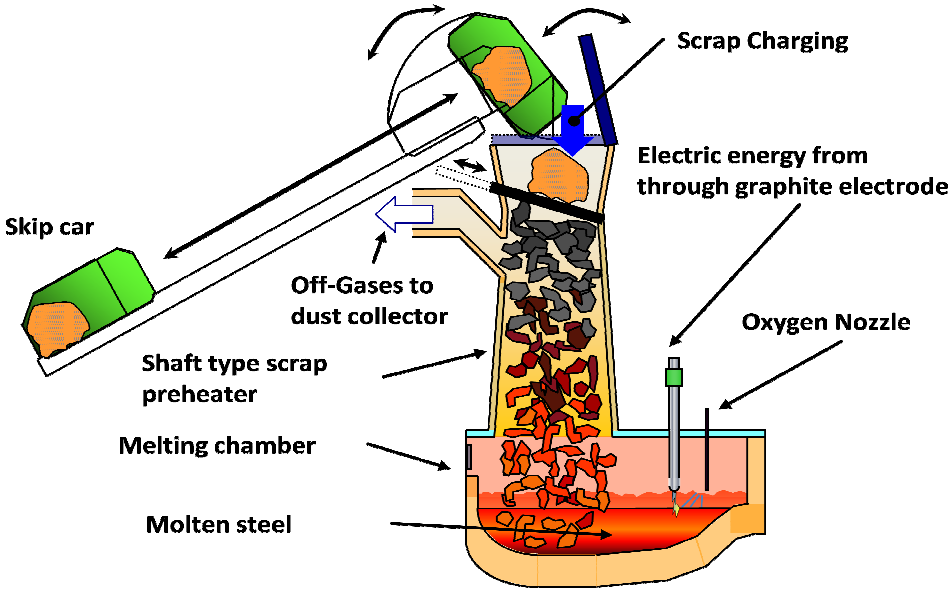

Figure1. The sketch of ECOARC TM

The foaming of slag also results in enhanced thermal efficiency and better arc stability. Several batches of preheated scrap are brought from shaft into the furnace for melting in every heat. Before the molten steel goes through the process of tapping, it is superheated for further refinement. The Hot Heel [9] comprising some molten steel and slag is not tapped so that this untapped material helps to preheat and to accelerate the meltdown of the next charge of scrap.

3. Understanding heat balances of ECOARC ™

Heat is the form of energy that melts the scrap in the furnace. The law of conservation of energy explains that it is the transformation of energy from one form to other that makes some particular type of energy appear or disappear in the system. Thermal energy appears in EAF due to transformation of electrical or chemical Energy supplied by different sources.

3.1. Sources of energy

The energy supplied to EAF comes from two groups of sources that are:

1. External Sources
2. Internal Sources

Electric arcs and burners come into group of external sources whereas oxidation reactions of carbon and other elements contained in the melt are the internal sources of energy. The heat generated by external sources is not completely transferred to the solid charging material or to liquid bath and some part is loss during heat transfer process [10]. The portion of heat that is not loss and is used in transferring of heat to melt the scrap is useful heat. If this heat transfer process can be improved then energy-efficiency of EAF operations can get better. The heat released due to the exothermic oxidation reactions occurring in the bath is almost completely utilized and its absorption results in temperature of liquid bath to increase. We will try to use implications of law of conservation of energy at two levels described as follows:

1. Zonal Level (we will consider heat balances at two zones of ECOARC ™ namely shaft and furnace)
2. Stages Level(we will equate heat balances for stages of POT of a *heat*)

In ECOARC ™, POT of a *heat* usually comprises of 10-13 scips of melting period followed by superheating. POT of a *heat* that consists of 12 scips, has 13 stages (12 stages of melting period and one stage of superheating) that means we will come out with 26 heat balance equations (13 stages x 2 zones). These equations have input and output items. Before describing these input and output items, we will explain the zones and stages for a *heat* of ECOARC ™.

3.2. Zones and Stages of ECOARC ™

Figure 2 illustrates the typical movement of scrap from shaft to melting chamber of the furnace.

It can be seen that the shaft consists of three parts or regions through which the scrap flows before entering into melting chamber of the furnace. Off-Gases pass upward through all the three regions charged with scrap. When a new heat starts, portion of the scrap heated during the previous heat is already in the shaft. The scrap in the upper region has lowest temperature. The heat starts with scrap moving from lowest region into the furnace. Consequently the scrap is transferred from each region into the next region below and the emptied upper region is further charged with cold scrap.

Even though, the shaft of ECOARC TM comprises of three regions through which the scrap passes but since it is not possible to get data at this sub-shaft level, we will consider entire shaft as one zone. Although this inevitable decision leads to a simpler formulation of problem, we will have to assume error-prone approximations.

The time when portion of scrap enters into the melting chamber is ending time of the scip. In Fig.2, ti (i ranges from 1 to 12) denotes the timing of ending of 12 scips. Time instance t13 marks the beginning of superheating and t14 shows the time when most of molten steel is tapped and portion of molten steel is left as hot heel for the next heat. For this work, values of t12 and t13 are equal. In other words, as soon as last scip ends, the superheating period starts.

In the next subsections, first, we will describe input and output items briefly followed by formulation of heat balance equations based on these items. We will then present an example to illustrate heat balance in the two zones for a POT of entire heat (rather than for each stage). After this, we will demonstrate how we can calculate different input and output items at stage level.

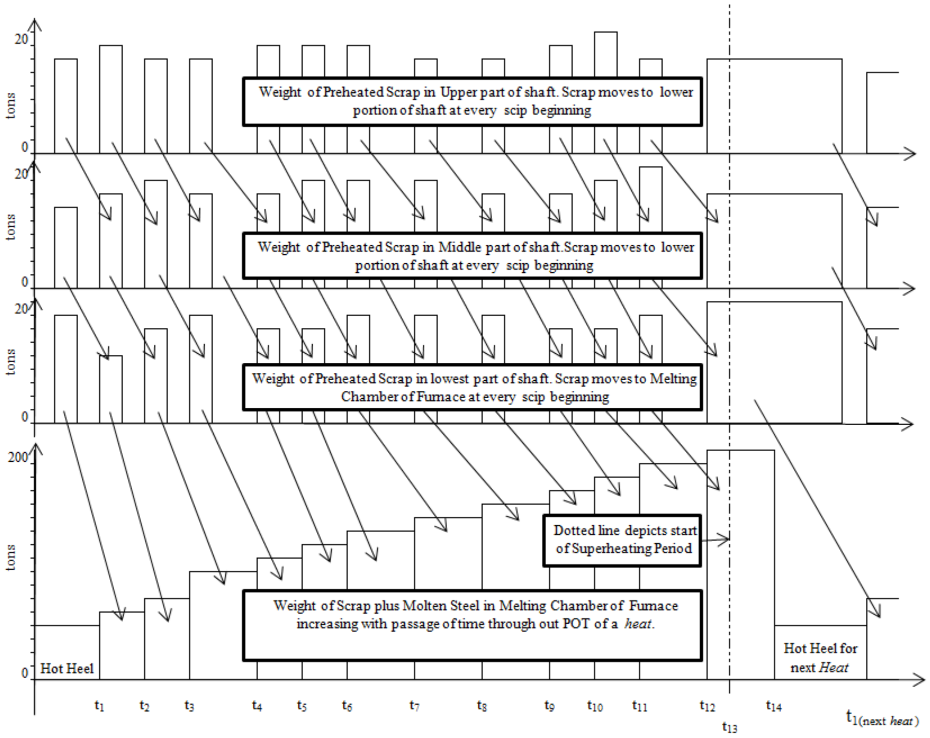

Figure2. The sketch of ECOARCTM illustrating movement of scrap from shaft to melting chamber of the furnace exemplified by the POT of heat comprising of 13 Stages

3.3. Input and output items for heat balance equations

Since this section and the coming sections will contain model description in form of mathematical notations, we think it appropriate to begin this section with the brief explanation of the notational conventions, we used in this work.

3.3.1. Notational conventions

The following notational conventions are used throughout this document.

a. If a notation contains subscript with only one item, then this item is just a text representing single value.

   For example, different types of sources and destinations of energy are described by "Q" followed by letter(s) in subscript form. The subscript explains the nature of energy in condensed form. In notation $\mathbf{Q}_{g\_f\_to\_s}$, **"g_f_to_s"** is just a text, used to describe the nature of "Q". **In this paper, we will use this type of notation to describe the items of super heating period of POT of a *heat* by appending "SH" at the end of subscript.**

b. If a notation contains subscript with two items with **comma** as separator, then the first item is just a text but the second item is a numerical variable representing the scip number of a melting period of POT of the *heat*. For example $\mathbf{Q}_{g\_f\_to\_s,i}$ means $\mathbf{Q}_{g\_f\_to\_s}$ of i^th^ scip. Hence $\mathbf{Q}_{g\_f\_to\_s,i}$ will grow only in one dimension. **In this paper, we will use this type of notation to describe the scips of melting period of POT of a *heat*.**

1) Input and output items for heat balance equations of furnace

Input heat [kilowatt hour or kWh]

Q_e : Electrical energy consumption
Q_c : Chemical Energy from carbon oxidation
Q_m : Chemical Energy from metal oxidation
Q_{p_f} : Sensible heat of preheated scrap entering into the furnace

Output heat [kWh]

Q_{st} : Sensible heat of molten steel
Q_{sl} : Sensible heat of slag
Q_{g_f} : Sensible and latent heat of off-gases in furnace
Q_{el} : Electrical power loss
Q_{wl_f} : Heat losses through water cooling wall in furnace

2) Input and output items for heat balance equations of shaft

Input heat [kWh]

$\mathbf{Q}_{g\_f\_to\_s}$: Heat carried by off-gases from furnace into the shaft

Output heat [kWh]

Q_{p_s} : Sensible heat of preheated scrap
Q_{g_s} : Sensible and latent heat of off-gases in shaft part
Q_{wl_s}: Heat losses through water cooling panels in shaft part

3.4. Heat balance equations

1) Heat balance equations for furnace

The input and output energy (heat) for furnace for melting and superheating period is described as follows:

Melting Period of POT	*Superheating Period of POT*
$Q_{in\_f,i} = Q_{e,i} + Q_{c,i} + Q_{m,i} + Q_{p\_f,i}$	$Q_{in\_f\_SH} = Q_{e\_SH} + Q_{c\_SH} + Q_{m\_SH} + Q_{p\_f\_SH}$
$Q_{out\_f,i} = Q_{st,i} + Q_{sl,i} + Q_{g\_f,i} + Q_{el,i} + Q_{wl\_f,i}$	$Q_{out\_f\_SH} = Q_{st\_SH} + Q_{sl\_SH} + Q_{g\_f\_SH} + Q_{el\_SH} + Q_{wl\_f\_SH}$

$Q_{\mathbf{in\_f,i}}$ and $Q_{\mathbf{out\_f,i}}$ denote the input and output heat of furnace zone for ith scip of melting period of POT respectively. Since $Q_{\mathbf{in\_f,i}}$ and $Q_{\mathbf{out\_f,i}}$ must be equal according to law of conservation of energy, we have :

$$Q_{e,i} + Q_{c,i} + Q_{m,i} + Q_{p\_f,i} = Q_{st,i} + Q_{sl,i} + Q_{g\_f,i} + Q_{el,i} + Q_{wl\_f,i}$$

Similarly $Q_{\mathbf{in\_f\_SH}}$ and $Q_{\mathbf{out\_f\_SH}}$ denote the input and output heat of furnace zone for super heating period of POT respectively. Since $Q_{\mathbf{in\_f\_SH}}$ and $Q_{\mathbf{out\_f\_SH}}$ must be equal according to law of conservation of energy, we have :

$$Q_{e\_SH} + Q_{c\_SH} + Q_{m\_SH} + Q_{p\_f\_SH} = Q_{st\_SH} + Q_{sl\_SH} + Q_{g\_f\_SH} + Q_{el\_SH} + Q_{wl\_f\_SH}$$

2) Heat balance equations for shaft

The input and output energy (heat) for shaft for melting and superheating period is described as follows:

Melting Period of POT	*Superheating Period of POT*
$Q_{in\_s,i} = Q_{g\_f\_to\_s,i}$	$Q_{in\_s\_SH} = Q_{g\_f\_to\_s\_SH}$
$Q_{out\_s,i} = Q_{p\_s,i} + Q_{g\_s,i} + Q_{wl\_s,i}$	$Q_{out\_s\_SH} = Q_{p\_s\_SH} + Q_{g\_s\_SH} + Q_{wl\_s\_SH}$

$Q_{\mathbf{in\_s,i}}$ and $Q_{\mathbf{out\_s,i}}$ denote the input and output heat of shaft zone for ith stage respectively. As $Q_{\mathbf{in\_s,i}}$ and $Q_{\mathbf{out\_s,i}}$ must be equal according to law of conservation of energy, we have :

$$Q_{g\_f\_to\_s,i} = Q_{p\_s,i} + Q_{g\_s,i} + Q_{wl\_s,i}$$

Similarly $Q_{\mathbf{in\_s\_SH}}$ and $Q_{\mathbf{out\_s\_SH}}$ denote the input and output heat of furnace zone for super heating period of POT respectively. Again $Q_{\mathbf{in\_s\_SH}}$ and $Q_{\mathbf{out\_s\_SH}}$ must be equal according to law of conservation of energy, we have :

$$Q_{g\_f\_to\_s\_SH} = Q_{p\_s\_SH} + Q_{g\_s\_SH} + Q_{wl\_s\_SH}$$

3.5. Example of heat balance

For the sake of simplicity, we will describe the working of ECOARC TM furnace by showing heat balances at shaft and furnace for entire heat (rather than for each stage).

Fig.3 illustrates heat balance of the two zones for a heat by using some hypothetical values for different sources and destinations of energy. We have used kWh/ton as a unit of measurement of energy. Table-1 describes different sources and destinations of energy that play their roles in any or both of the two zones as illustrated in Fig.3. It can be seen that total input and total output of energy is equal in both zones.

It can be observed that there are two rows in Table-1, (shown by dotted squares in Figure.3) that play their roles in both zones of shaft and furnace.

1. The off-gases take heat from furnace to shaft where part of heat preheats the scrap and rest is unutilized and exits from shaft along with flowing off-gases. $\mathbf{Q}_{g\_f\_to\_s}$ and Q_{g_f} denote the gain of shaft and loss of furnace respectively for this type of heat transfer.
2. The preheated scrap when inserted into furnace from shaft, bring the heat as input to furnace. Q_{p_s} and Q_{p_f} denote the loss of shaft and gain of furnace respectively for this type of heat transfer and are equal.

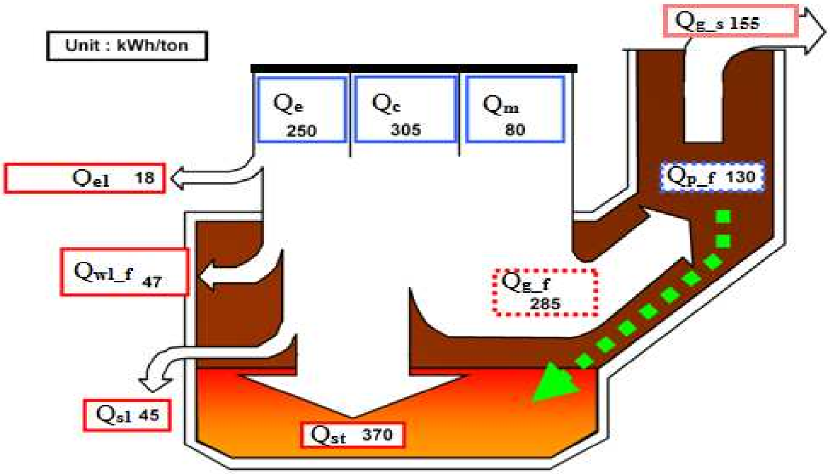

Figure3. The hypothetical values of different energy sources and destinations for a heat of ECOARC TM [11]

Table 1. Tabular representation of data from Fig.3 to illustrate energy (heat) balances of shaft and furnace

Energy Sources / Destination	Shaft		Furnace	
	Input	Output	Input	Output
Electrical energy			250	
Chemical energy from Carbon oxidation			305	
Chemical energy from metal oxidation			80	
Electrical energy loss				18
Heat losses with water cooling wall				47
Heat losses due to slag				45
Heat transferred to Steel				370
Heat taken by off-gases from exit of furnace	285			285
Heat into furnace from preheated scrap		130	130	
Heat taken by off-gases from exit of shaft		155		
Total	285	285	765	765

We have already mentioned that in ECOARC ^{TM} furnace, scrap is supplied approximately 10-13 times a *heat* from shaft to furnace in discrete stages called scips. In the next section, we will describe ECOARC ^{TM} operation at stage level thus we will need 13 heat balance equations for Shaft and 13 heat balance equations for furnace with the **supposition** that there are 12 scips in melting period followed by superheating stage in the POT of each *heat*.

4. Problem formulation

The purpose of our work is to estimate the "hidden" parameter(s) that play their role and have considerable impact on the outcome of a heat. We plan to discover the values of two of these unknown or hidden parameters by optimization. These unknown parameters are involved in some of input or output items of heat balances of shaft and/or furnace. We will begin with description of the procedure to calculate the values of different input and output items. Since few items' values are immeasurable due to presence of unknown parameters, this will lead to usage of optimization technique that would be the subject of the next section.

4.1. Calculation/Estimation of items of heat balance equations at stage level

We begin this subsection by reiterating that every heat can be subdivided into discrete stages. A stage either represents scip of melting period of POT or superheating period. Before stating, how we calculated or estimated different input and output items of heat balance equations for each stage, we will briefly describe some parameters related to a scip for ECOARC TM furnace. If the parameter has some applicable calculation for superheating stage, then the relevant terminology is also mentioned.

Beginning time of i^{th} *Scip*: The time instance when the i^{th} batch of scrap moves from middle region of shaft to lowest region of the shaft.

Ending time of the i^{th} *Scip*: The time instance when the i^{th} batch of scrap moves from lowest region of shaft to melting chamber of the furnace.

Duration of the Scip ($D_{Scip,i}$): Obviously the difference of ending and beginning time of the i^{th} scip is its duration denoted by $D_{Scip,i}$. We can also describe $D_{Scip,i}$ as the time interval between ending time of $(i-1)^{th}$ and i^{th} scip. The duration of the first scip is the time interval between the beginning of *heat* and the time instance when first batch of scrap was introduced into furnace. The duration of a scip tells us that how long, portion of scrap remains in lowest part of shaft for preheating purpose. D_{SH} represents the duration of superheating period. The quantities will be expressed in terms of second.

The *weight of scrap of* i^{th} *Scip* ($W_{Scip,i}$): The parameter signifies the weight of portion of scrap that is added from shaft to furnace at the end of i^{th} scip. The unit of the quantity is ton. We used term "weight" [units: N, kgf, etc.] here but mean "mass" [units: kg, ton, etc] analogous to usage of term "tapping weight" in steel community that is actually "tapping mass".

The Electrical Energy utilization in i^{th} *Scip*($EEU_{Scip,i}$): If $EE_{Scip,i-1}$ and $EE_{Scip,i}$ are the values of electrical energy at the ending time of $(i-1)^{th}$ and i^{th} scip respectively then the electrical power utilization ($EEU_{Scip,i}$) *is the difference between* $EE_{Scip,i}$ and $EE_{Scip,i-1}$. EEU_{SH} represents electrical energy utilization during superheating period. The quantity will be expressed in unit of MegaWatt hour(MWh).

The *Injected Carbon utilization in* i^{th} *Scip* ($IC_{Scip,i}$): The parameter describes the weight of carbon that is injected throughout the duration of i^{th} Scip. IC_{SH} represents the weight of carbon that is injected during superheating period. The unit of the quantity is kilogram.

With the introduction of these terminologies, we are now in position to describe the items of heat balance equations for every stage. It should be noted that unit of all input and output items will be Kilowatt hour (kWh).

4.1.1. Calculation of items of heat balance equations of furnace at stage level

4.1.1.1. Input items

1) *Electrical energy consumption* (Q_e)

The amount of electrical energy delivered from external high voltage grids is monitored throughout the *heat*. $\mathbf{Q_e}$ for i^{th} scip can be calculated by simply multiplying $EEU_{Scip,i}$ *(Electrical Energy utilization in* i^{th} *Scip)* by 1000 to transform the unit of MWh into kWh. For superheating stage, the same procedure will be adopted. Thus the electrical energy consumption for each stage can be calculated as follows:

Melting Period of POT	Superheating Period of POT
$Q_{e,i} = EEU_{Scip,i}$ x 1000	$Q_{e\ SH} = EEU_{SH}$ x 1000

2) *Chemical Energy from Carbon oxidation* (Q_c)

The main sources of carbon are as follows:

a. Coke that is continuously injected throughout the POT in form of powder
b. Coke that is charged together with scrap once in each *heat*

Besides these sources, carbon also comes along with raw material, has its presence in dust and also is constituent of hot heel. We have to calculate energy generated from oxidation of carbon from these sources also.

We can approximate how much energy is released as the result of oxidation of carbon present in the injected coke for different stages of POT along following lines:

We have already described $IC_{Scip,i}$ *and* IC_{SH} (quantities related to *injected Carbon utilization in* i^{th} *scip of melting period and of superheating period respectively*). We will represent quantities concerning **energy released from oxidation of carbon present in injected coke for i^{th} scip and superheating stage** by $Q_{IC,i}$ *and* Q_{IC_SH} respectively and can calculate them as follows:

$Q_{IC,i} = IC_{Scip,i}$ x Heat of Combustion of Carbon in kWh/kg
$Q_{IC\_SH} = IC_{SH}$ x Heat of Combustion of Carbon in kWh/kg

To estimate energy generated from oxidation of carbon found in charged coke, dust, hot heel and raw material for each stage, we made an assumption that energy released from oxidation of carbon present in above-mentioned sources is uniform throughout the duration of POT. Based on this assumption, first of all we approximated how much carbon is utilized from different sources throughout the POT. After estimating the weight of the carbon, we divided this weight with POT duration. This gave us weight of Carbon released per minute throughout the POT. Then, we multiplied the resultant with $D_{Scip,i}$ (Duration of each scip) and D_{SH}. In this way we approximated the carbon from other sources besides injected coke, that is utilized during different scips ($C_{other\_sources,i}$)and superheating period($C_{other\_sources\_SH}$).

Afterwards we calculated energy released due to oxidation for every stage. We will denote quantity describing **energy released from oxidation of Carbon present in different sources except injected coke** in ith scip and superheating period by by $Q_{OtherSourcesofCarbon,i}$ and $Q_{OtherSourcesofCarbon\_SH}$ respectively and can calculate these quantities as follows:

$$Q_{OtherSourcesofCarbon,i} = C_{other\_sources,I} \text{ x Heat of Combustion of Carbon in kWh/kg}$$
$$Q_{OtherSourcesofCarbon\_SH} = C_{other\_sources\_SH} \text{ x Heat of Combustion of Carbon in kWh/kg}$$

Thus the energy for each stage can be calculated as follows:

Melting Period of POT	Superheating Period of POT
$Q_{c,i} = Q_{IC,i} + Q_{OtherSourcesofCarbon,i}$	$Q_{c,SH} = Q_{IC\_SH} + Q_{OtherSourcesofCarbon\_SH}$

3) *Chemical Energy from Metal oxidation(Q_m)*

During melting stage of POT, Iron and its alloys (Silicon, Magnesium, Phosphorus, etc) are oxidized and release different amount of energy. Ideally this calculation requires extensive use of material balance data for each *heat*. However due to unavailability of material balance data for each *heat*, we approximated average of energy released due to metal oxidation per minute applicable to melting period of the POT of every *heat*. We will denote this quantity by M. To get energy from Metal oxidation for each scip, we just have to multiply the quantity "M" by duration of the scip. Metal oxidation does not occur during superheating period and hence is equivalent to zero. Thus Q_m for each stage can be calculated as follows:

Melting Period of POT	Superheating Period of POT
$Q_{m,i} = M \text{ x } D_{Scip,i}/60$	$Q_{e\_SH} = 0$

4) *Sensible heat of preheated scrap(Q_{p_f})*

We have already mentioned that due to unavailability of data at sub-shaft level, we will consider entire shaft as one unit or zone. When the off-gases move from furnace into the shaft, scrap is heated in three regions of shaft to different extents. The lowest region of shaft that is closest to furnace exit is the most heated one. The extent to which the scrap is heated in the lowest region of shaft is immeasurable quantity so we again had to make another approximation. We approximated average temperature (T_{ls}) of the lowest region of shaft at the beginning of every stage. If W_{ls} and C_{ls} indicate the weight and specific heat of preheated scrap in the lowest region of shaft respectively then the *sensible heat* or thermal energy stored in the scrap can be calculated by:

$$Q_{p\_f,i+1} = W_{ls,i} \text{ x } T_{ls,i} \text{ x } C_{ls,i} \text{ x } 1000 / 860$$

Where $W_{ls,i} = W_{Scip,i}/\textbf{yield}$. *Yield* corresponds to ratio of steel achieved through scrap in EAF. We divide numerator by 860 to convert unit of Kcal into kWh.

In our model depicting *heat*, when the duration of first scip is over, then preheated scrap is entered into the furnace for the first time therefore $Q_{p\_f,1}=0$. For superheating period, $Q_{p\_f\_SH}$

depends on the attribute values of last scip of melting period before superheating. Thus the energy or heat brought into the furnace by preheated scrap can be calculated as follows:

Melting Period of POT	Superheating Period of POT
$Qp_{f,i} = 0 \; \{ i = 1 \}$ $Qp_{f,i} = W_{ls,i-1} \text{ x } 1000 \text{ x } C_{ls,i-1} \text{ x } T_{ls,i-1} / 860 \; \{ i > 1 \}$	$Qp_{f\_SH} = W_{ls,max\_i} \text{ x } 1000 \text{ x } C_{ls,max\_i} \text{ x } T_{ls,\, max\_i} / 860$ *Where max_i is the last scip of melting period.*

4.1.1.2. Output items

1) ***Sensible heat of molten steel***(Q_{st})

In order to find, how much heat is actually utilized in melting the preheated scrap we should know two things:

1. How much scrap is already preheated is shaft?
2. How much heat is required to melt the scrap of same weight completely?

The difference between above two quantities is the required amount of heat to melt the preheated scrap in the furnace. For the first scip, Q_{st} will be 0 since already melted hot heel is present in furnace.

For the second scip (when preheated scrap enters into furnace for the first time), we can calculate Q_{st} as follows:

$$Q_{st,i} = [W_{ls,i-1} \text{ x } H_{req\text{-}melt\text{-}ton} - (W_{Scip,i-1} \text{ x } H_{pre\text{-}scrap,i-1})] \text{ x } Ratio_{Melting,i}$$

Where we have already described $W_{Scip,i}$ and $W_{ls,i}$. $H_{req\text{-}melt\text{-}ton}$ corresponds to heat required to melt one ton of scrap and is constant quantity. $H_{pre\text{-}scrap,i}$ corresponds to heat of preheated scrap per ton of i^{th} scip and is calculated as follows:

$$H_{pre\text{-}scrap,i} = T_{ls,i-1} \text{ x } C_{ls,i-1} \text{ x } 1000 / 860.$$

$Ratio_{Melting,i}$ corresponds to the ratio of weight of melted scrap in i^{th} scip to weight of total scrap in furnace during same stage and is another approximated quantity.

During Scips after the second scip, the furnace contains

1. Unmelted Scrap from previous scips that is already present in furnace
2. Incoming preheated scraps from shaft

We can calculate sensible heat for post-second-scip stages using following recursive equation:

$$Q_{st,i} = [\{W_{ls,i-1} \text{ x } H_{req\text{-}melt\text{-}ton} - (W_{Scip,i-1} \text{ x } H_{pre\text{-}scrap,i-1})\} + \{W_{ls,i-2} \text{ x } H_{req\text{-}melt\text{-}ton} - (W_{Scip,i-2} \text{ x } H_{pre\text{-}scrap,i-2})\} \text{ x } (1 - Ratio_{Melting,i-1})] \text{ x } Ratio_{Melting,i}$$

For superheating period, since all scrap is to be melted, we have $Ratio_{Melting\_SH} = 1$.
If max_i is the last scip of melting period, We can calculate sensible heat to melt all scrap in super heating stage as follows:

$$Q_{st\_SH} = [\{W_{ls,\, max\_i} \text{ x } H_{req\text{-}melt\text{-}ton} - (W_{Scip,\, max\_i} \text{ x } H_{pre\text{-}scrap,\, max\_i})\} + \{W_{ls,\, max\_i-1} \text{ x } H_{req\text{-}melt\text{-}ton} - (W_{Scip,\, max\_i-1} \text{ x } H_{pre\text{-}scrap,\, max\_i-1})\} \text{ x } (1 - Ratio_{Melting,\, max\_i})]$$

The *sensible heat* or thermal energy stored in the molten steel in furnace is fundamentally equivalent to the sum of heats used to melt the scrap in different stages of POT. In summary, the quantity can be calculated as follows:

Melting Period of POT	Superheating Period of POT
$Q_{st,i} = 0$ $\{i = 1\}$ $Q_{st,i} = [W_{ls,i-1} \times H_{req\text{-}melt\text{-}ton} - (W_{Scip,i-1} \times H_{pre\text{-}scrap,i-1})] \times Ratio_{Melting,i}$ $\{i = 2\}$ $Q_{st,i} = [\{W_{ls,i-1} \times H_{req\text{-}melt\text{-}ton} - (W_{Scip,i-1} \times H_{pre\text{-}scrap,i-1})\} + \{W_{ls,i-2} \times H_{req\text{-}melt\text{-}ton} - (W_{Scip,i-2} \times H_{pre\text{-}scrap,i-2})\} \times (1- Ratio_{Melting,i-1})] \times Ratio_{Melting,i}$ $\{i > 2\}$	$Q_{st\ SH} = [\{W_{ls,\ max\_i} \times H_{req\text{-}melt\text{-}ton} - (W_{Scip,\ max\_i} \times H_{pre\text{-}scrap,\ max\_i})\} + \{W_{ls,\ max\_i-1} \times H_{req\text{-}melt\text{-}ton} - (W_{Scip,\ max\_i-1} \times H_{pre\text{-}scrap,\ max\ i-1})\} \times (1- Ratio_{Melting,\ max\_i})]$

2) Sensible heat of slag(Q_{sl})

Part of heat is utilized in raising the temperature of slag. To estimate this sensible heat, we made approximations for following two parameters:

1. Weight of Slag(W_{slag}) that is consumed for entire *heat* (described in kilograms)
2. Slag temperature(T_{slag})

Using W_{slag}, first we calculated the weight of slag consumed per tapping ton ($W_{slag/t\text{-}tap}$) described in kg/ton. Afterwards we calculated heat loss due to slag for one ton of molten steel($Q_{sl/ton}$) described by kWh/ton as follows:

$Q_{sl/ton} = C_{slag}/860 \times W_{slag/t\text{-}tap} \times T_{slag}$
Where C_{slag} is the specific heat of slag.

In order to find heat loss per minute due to slag($Q_{sl/m}$), following calculation was made:
$Q_{sl/m} = Q_{sl/ton}$ x Tapping Weight of *heat* / POT

We estimated Q_{sl} for all stages of POT as follows:

Melting Period of POT	Superheating Period of POT
$Q_{sl,i} = D_{Scip,i}/60 \times Q_{sl/m}$	$Q_{sl\_SH} = D_{SH}/60 \times Q_{sl/m}$

3) Sensible and latent heat of off-gas in furnace part(Q_{g_f})

Heat loss in furnace due to off-gases (denoted by Q_{g_f}) has two constituents as follows:

1. Latent heat of off-gases (heat absorbed causing change in state) denoted by $Q_{g\_f\_latent}$
2. Sensible heat (heat absorbed causing raise in temperature) denoted by $Q_{g\_f\_sensible}$

In order to calculate $Q_{g\_f\_sensible,i}$ we used following formula:
$Q_{g\_f\_sensible,i} = C_g/860 \times F_{g,i} \times T_{g\_F,i} \times D_{Scip,i}/60$

Where
C_g corresponds to specific heat of off-gases

$F_{g,i}$ corresponds to average volume of off-gases flowing through furnace exit per minute during ith scip described by Nm^3/min
$T_{g\_F,i}$ corresponds to average temperature of off-gases in furnace in ith scip described by °C

Since our operational data lacked $F_{g,i}$ and $T_{g\_F,i}$, we again had to make assumptions. We treated $F_{g,i}$ as parameter that is to be estimated using optimization technique. Regarding $T_{g,i,}$, for the sake of simplicity, we assumed temperature of off-gases to be same for all scips.

Basically Carbon monoxide released in furnace, accounts for latent heat of off-gases. In order to calculate $Q_{g\_f\_latent,i}$, we used following formula:
$Q_{g\_f\_latent,i} = F_{g,i} \text{ x } \mathit{Percentage\ of\ CO} / 100 \text{ x } \mathit{Heat\ of\ combustion\ of\ CO} / 860 \text{ x } D_{Scip,i} /60$
Where Heat of combustion of CO = 3020 kcal / Nm^3

In the similar manner, we can calculate $\boldsymbol{Q_{g\_f}}$ for superheating period.
$Q_{g\_f\_sensible\_SH} = C_g / 860 \text{ x } F_{g\_SH} \text{ x } T_{g\_F} \text{ x } D_{SH} /60$
$Q_{g\_f\_latent,SH} = F_{g\_SH} \text{ x } \mathit{Percentage\ of\ CO} / 100 \text{ x } \mathit{Heat\ of\ combustion\ of\ CO} / 860 \text{ x } D_{SH} /60$

Hence we estimated $\boldsymbol{Q_{g\_f}}$ for all stages of POT as follows:

Melting Period of POT	Superheating Period of POT
$Q_{g\_f,i} = Q_{g\_f\_sensible,i} + Q_{g\_f\_latent,i}$	$Q_{g\_f\_SH} = Q_{g\_f\_sensible\_SH} + Q_{g\_f\_latent\_SH}$

4) Electrical power loss(Q_{el})

To estimate loss of electrical power for each scip, we assume that for every stage of POT, particular percentage of electrical energy is wasted. Thus we can calculate $\boldsymbol{Q_{el}}$ for all stages of POT as follows:

Melting Period of POT	Superheating Period of POT
$Q_{el,i} = Q_{e,i} \text{ x } \mathit{AssumedLossPercentage}/100$	$Q_{el\ SH} = Q_{e\ SH} \text{ x } \mathit{AssumedLossPercentage}/100$

5) Heat losses through water cooling wall in furnace part(Q_{wl_f})

Part of Energy (Heat) in Furnace is wasted through water cooling wall. To calculate Q_{wl_f} for all stages of POT, we assumed wasted heat per ton due to water cooling wall, based on domain expert opinion. Using this assumed value, we calculated wasted heat per minute denoted by **“$Q_{wl\_f/m}$”.** Using this quantity, we find Q_{wl_f} *for all stages of POT as follows:*

Melting Period of POT	Superheating Period of POT
$Q_{wl\_f,i} = Q_{wl\_f/m} \text{ x } D_{Scip,i} /60$	$Q_{wl\_f\_SH} = Q_{wl\_f/m} \text{ x } D_{SH} /60$

4.1.2. Calculation/Estimation of items of heat balance equations of shaft at scip level

4.1.2.1. Input items

1) Heat carried by off-gases into the shaft($Q_{g\_f\_to\_s}$)

The main source of energy (heat) into the shaft is the heat carried by off-gases entering into the shaft from exit of the furnace. The estimation of this sole input item is already discussed when we demonstrated calculation of Q_{g_f} . In other words, the output item $Q_{g\_f,i}$ for furnace becomes input item for shaft and hence following relation holds between the two parameters:

Melting Period of POT	Superheating Period of POT
$Q_{g\_f\_to\_s,i} = Q_{g\_f,i}$	$Q_{g\_f\_to\_s\_SH} = Q_{g\_f\_SH}$

4.1.2.2. Output items

1) Sensible heat of preheated scrap(Q_{p_s})

The preheating of scrap depends on the efficiency of heat exchange that takes place in the shaft. Part of heat of off-gases is transferred to scrap depending on heat exchange efficiency. However the efficiency of heat exchange in the shaft, denoted by η_{scrap}, is immeasurable quantity. We will use optimization technique to estimate this value. We can estimate Q_{p_s} for different stages of POT as follows:

Melting Period of POT	Superheating Period of POT
$Q_{p\_s,i} = \eta_{scrap,i} \times (Q_{g\_f\_to\_s,i} - Q_{wl\_s,i})$	$Q_{p\_s,i} = \eta_{scrap\_SH} \times (Q_{g\_f\_to\_s\_SH} - Q_{wl\_s\_SH})$

2) Sensible and latent heat of off-gas in shaft part(Q_{g_s})

Similar to Q_{g_f}, heat loss in shaft due to off-gases (denoted by Q_{g_s}) has also two constituents as follows:

1. Latent heat of off-gases denoted by $Q_{g\_s\_latent}$
2. Sensible heat denoted by $Q_{g\_s\_sensible}$

In order to calculate $Q_{g\_s\_sensible}$ for different stages of POT, we used similar strategy used in calculation of $Q_{g\_f\_sensible}$
To calculate $Q_{g\_s\_sensible}$ for different scips, following formula was used.

$Q_{g\_s\_sensible,i} = C_g / 860 \times F_{g,i} \times T_{g\_S,i} \times D_{Scip,i} /60$,
where C_g and $F_{g,i}$ are already described.
$T_{g\_S,i}$ corresponds to average temperature of off-gases in shaft described by °C in ith skip

Similarly for superheating period, we applied following calculations:
$Q_{g\_s\_sensible\_SH} = C_g / 860 \times F_{g\_SH} \times T_{g\_S\_SH} \times D_{SH} /60$

Since our operational data lacked $T_{g\_S,i}$ and $T_{g\_S\_SH}$, we had to make few assumptions. We assumed that temperature of off-gases in shaft depends on the energy released by exothermic reactions occurring in furnace due to oxidation of carbon. The value of T_{g_S} was assumed to be more for particular stage, if Q_c is above assumed threshold for that stage.

Regarding estimation of latent heat of off-gases in shaft, we will use same procedure as was discussed for calculation of $Q_{g\_f\_latent}$.

Hence we estimated Q_{g_s} for all stages of POT as follows:

Melting Period of POT	Superheating Period of POT
$Q_{g\_s,i} = Q_{g\_s\_sensible,i} + Q_{g\_s\_latent,i}$	$Q_{g\_s\_SH} = Q_{g\_s\_sensible\_SH} + Q_{g\_s\_latent\_SH}$

3) Heat losses through water cooling panels in shaft part($Q_{wl\_s,i}$)

To calculate Q_{wl_s} for all stages of POT, we assumed wasted heat per ton due to water cooling panels, based on domain expert opinion. Using this assumed value, we calculated wasted heat per minute denoted by **"$Q_{wl\_s/m}$".** Using this quantity, we find Q_{wl_s} *for all stages of POT as follows:*

Melting Period of POT	Superheating Period of POT
$Q_{wl\_s,i} = Q_{wl\_s/m} \text{ x } D_{Scip,i} /60$	$Q_{wl\_s\_SH} = Q_{wl\_s/m} \text{ x } D_{SH} /60$

5. Optimization

As can be seen from description of previous section, we try to find two hidden parameters using optimization for each stage of POT that are:

1. Gas flow rate denoted by F_g($F_{g,i}$ for each scip of melting period and F_{g_SH} for superheating period)
2. Efficiency of heat exchange of off-gases in the shaft denoted by η_{scrap} ($\eta_{scrap,i}$ for each scip of melting period and η_{scrap_SH} for superheating period)

The program was developed in MATLAB in which all calculations were made. The connectivity with MySQL(where whole operational data resides) made it possible for us to use SQL queries in MATLAB environment.

Our program used MATLAB optimization facility to find minimum of nonlinear multivariable function [12]. The function was formulated in terms of the two parameters mentioned above. The optimization was subjected to following constraints.

1. Gas flow rate(F_g) value ranging from 0 to *maxGasFlowRate (the value recommended by domain expert)*
2. Efficiency of heat exchange of off-gases in the shaft(η_{scrap}) ranging from 0 to 1

The formulation of function was based on law of conservation of energy. The two zones should completely satisfy this law and therefore if OF is our objective function, it will try to minimize the energy differences in furnace and shaft.

$$OF = \sqrt{[(\text{Input energy of Furnace} - \text{Output energy of Furnace})^2 + (\text{Input energy of Shaft} - \text{Output energy of shaft})^2]}$$

The ideal value of OF should be zero. Now we will show how we formulated this OF at stage level in terms of the two hidden parameters. The unexpanded OF for different stages of POT is as follows:

Melting Period of POT	Superheating Period of POT
$OF_{scip,i} = \sqrt{[(Q_{in\_f,i} - Q_{out\_f,i})^2 + (Q_{in\_s,i} - Q_{out\_s,i})^2]}$	$OF_{SH} = \sqrt{[(Q_{in\_f\_SH} - Q_{out\_f\,SH})^2 + (Q_{in\_s\,SH} - Q_{out\_s\,SH})^2]}$

Where all variables present in the two equations are already explained in Section 3.4.
Now we need to expand those variables of unexpanded OF that have either F_g *or* η_{scrap} or both in their summands. Hence Q_{in_f} needs not to be expanded. Q_{out_f}, Q_{in_s} and Q_{out_s} will be expanded as values of Q_{g_f}, Q_{p_s} and Q_{g_s} are based on F_g and/or η_{scrap}. After expanding Q_{out_f}, Q_{in_s} and Q_{out_s} and then further expanding Q_{g_f}, Q_{p_s} and Q_{g_s}, we came out with objective function formulated in terms of F_g *and* η_{scrap}.

6. Results

This section basically will discuss the results in following dimensions:

1. How well our optimization program behaved for data of different *heats*. In other words, how many times were the values of OF_i closed to zero while satisfying all constraints.
2. What type of values of F_g *or* η_{scrap} were achieved.

Our operational data consisted of data of 606 heats with 13 stages (12 scips and a superheating stage).Hence, our optimization program had to minimize 7,878 objective functions or OF (606 heats x 13 stages). It should be noticed that OF is formulated in the way that it always yields results equal to or greater than zero. We used threshold of 1 as criterion to classify successful and unsuccessful optimization. Hence if value of OF for particular stage exist in the interval spanned by [0,1], the optimization for that stage was considered as successful. This can be thought as fairly strict criterion as the values of input and output heat at different stages are rather high (thousands of kWh) and reach their maximum values in the superheating period.

The optimization algorithm was unable to minimize only few of these objective functions. Table 2 demonstrates the result of our program for the 7,878 OF.

Table 2. Percentage of success of optimization at heat and stage level

Total number of *heats*	606
Total number of objective functions to be minimized	7,878{=(606 heats x 13 stages)}
Total number of *heats* in which OF for at least one stage lie in (1,+∞)	259
Total number of objective functions or OF that lie in (1,+∞)	522
Percentage of *heats* with OF for all stages that lie in **[0,1]**	57.26 % {=(606 - 259) /606 x 100}
Percentage of stages with OF that lie in **[0,1]**	93.37% {=(7878-522)/7878 x 100}

It seems that our optimization program was able to come out with optimized values of hidden parameters for most of stages (93.37%). However since stages are not independent entity i.e. a stage depends upon previous stage so if our optimization program is unable to find optimized values of hidden parameters in earlier stages of heat , then the forwarded values of different parameters for the next stages will not be accurate one and even if our optimization program finds the optimized values of the hidden parameters for these stages, it is highly probable that these values does not represent the correct situation of furnace and shaft. Table 3 shows the total number of unsuccessful optimizations by adding direct and indirect optimization failures.

Table 3. Total Number of unsuccessful Optimizations

Stage No i	No of stages with value of OF in $(1,+\infty)$ A	No of *heats* encountering optimization failure first time in i^{th} Stage B	Indirectly affected optimizations $C = (13- i) \times B$	Total $D = A+C$
1	1	1	12	13
2	1	1	11	12
3	1	1	10	11
4	3	2	18	21
5	67	64	512	579
6	44	22	154	198
7	48	31	186	234
8	41	20	100	141
9	38	16	64	102
10	68	38	114	182
11	84	26	52	136
12	69	9	9	78
13	57	28	0	57
Total	522	259	1242	**1764**

It can be deduced from Table 3 that number of OF that were successfully minimized according to our criterion, are actually 6114 (7878 total stages-1764 stage with optimization failure) that is 78% of all stages rather than 93.37% as described in Table 2. After analyzing the data of those *heats* with unsuccessful optimization, we found that

1. Our optimization algorithm did not get trapped in any local minima.
2. The parameter(s) stuck to extreme values of the constraints boundaries.

It means that we do not have to look for other optimization techniques as the optimization algorithm that we used, worked fine. We think that better results can be achieved by improving:

1. Assumptions/approximations used in formulating the energy balance model.
2. Objective function

The implication of successful optimization is the discovery of optimal estimates of hidden parameters. Our objective function was formulated in terms of F_g *or* η_{scrap}. We are interested in finding out the average values of these parameters for all thirteen stages of POT. Since our optimization was successful in all stages of 347 *heats*, we will use the data from the 347 *heats* to demonstrate the parameters.

Table 4 and Fig.4 shows the average of these two parameters for the 13 stages. It can be seen that average efficiency of heat exchange from off-gases to scrap present in the shaft(η_{scrap}) is almost same in all stages, beginning with peak average value in first stage and after gradual decrease in few consecutive stages, again begin to increase as the POT approaches its end. The result matches our intuition as this shows the cyclic nature of the parameter that will repeat same behavior in every *heat*.

The average gas flow rate through the furnace exit exhibits almost same cyclic behavior with the exception that in the first two scips, the flow rate seems to increase. Understanding possible reasons for such type of behavior require careful analysis of operational data.

Table 4. Average Values of Discovered Parameters for 13 stages

Stage No i	Average of η_{scrap}	Average of F_g Nm^3/min
1	0.3883	997.9715
2	0.3872	1055.1450
3	0.3845	755.4829
4	0.3731	529.1050
5	0.3551	448.4356
6	0.3563	550.1913
7	0.3626	699.0399
8	0.3677	749.0932
9	0.3724	857.9486
10	0.3804	1049.9917
11	0.3812	1091.6690
12	0.3830	1113.9723
13	0.3883	1189.9183

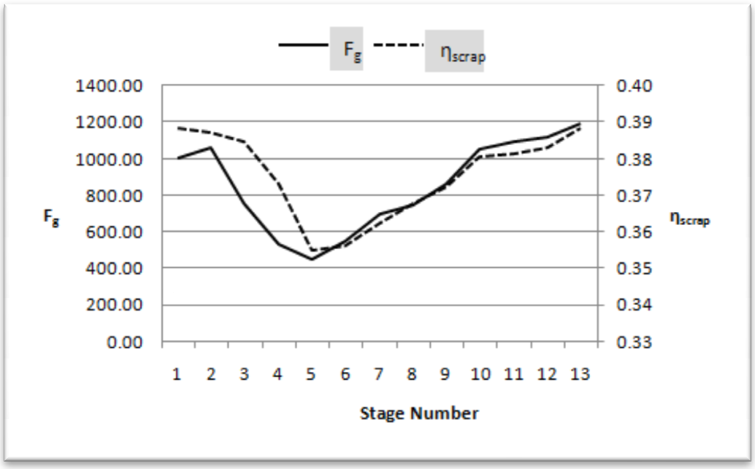

Figure4. Average Values of hidden Parameters for all 13 stages of POT

7. Conclusion

The better understanding of operations of EAF can lead to saving of energy. The understanding can be enhanced by estimating the parameters that are inaccessible to operator due to different reasons. In this work, we developed a stage-based spatial-temporal energy balance model with few quantities expressed in terms of hidden parameter(s). The two hidden parameters are as follows:

1. The average gas flow rate through the furnace exit into the shaft for a stage of *heat*
2. The average efficiency of heat exchange from off-gases to scrap for a stage of *heat*

The objective function, formulated on the basis of this constructed model, contained the above-mentioned two hidden parameters. When optimization was applied to minimize the objective function, we were able to discover the estimates for these hidden parameters. The optimization was successful to minimize the objective functions according to our criterion for most of stages but to get objective function minimized for all stages; we need to improve our energy balance model. The discovered estimates of two hidden parameters reveal their cyclic behavior. This matches our intuition since when the new *heat* is to start; the parameters' values should return to similar position that was at the beginning of previous *heat*. The availability of the values of the hidden parameters throughout different stages of POT of a *heat* will help the operator to take required steps to improve performance of operation.

We used operational data for ECOARC ^{TM} furnace for this purpose. The output of this work i.e. the constructed energy balance model and data comprising of discovered estimates of the two hidden parameters for every stage of number of *heats* are the precious resources and the potential input of our future work.

The purpose of this work was to find values of hidden parameters so that better understanding and improvement of EAF operations can be achieved. In future, we envision proceeding in following three directions:

1. Further improvement in energy model with addition of more hidden parameters in optimization problem.
2. Application of data mining techniques on these discovered values to find good rules for improvement of EAF operation
3. Synthetic generation of EAF operation data and manipulation of different parameters to check different rules expected to improve performance of EAF operation.

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