An Improved Approximation of Metal Accumulation in Electric Arc Furnaces for Ferrosilicon Production

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***Abstract*— Accurate estimation of metal accumulation in electric arc furnaces (EAFs) is critical for maintaining stable ferrosilicon (FeSi) production and ensuring effective process monitoring. Direct measurement of accumulated metal is currently not feasible due to extreme operating temperatures and the uneven distribution of molten material at the bottom of the furnace. Consequently, accumulation must be estimated through theoretical calculations, which directly influence production planning and operational decisions. This study proposes an improved methodology for approximating metal accumulation based on an enhanced mass balance formulation. Several modifications were introduced to increase estimation accuracy and responsiveness to process dynamics. The proposed improvements result in a smoother and more stable moving average of metal accumulation. Additionally, comparisons with theoretical input–output balances demonstrate improved consistency with expected furnace behaviour. The methodology provides a reliable estimation tool that can support operational decision-making and enhance production control in industrial EAF processes.**

I. Introduction

Ferrosilicon is an alloy commonly used as an additive in steelmaking. It is produced in an electric arc furnace (EAF) [8] using raw materials such as wood chips, quartz, scrap metal, and coal, heated to temperatures of approximately 2,000°C. During this process, the raw materials are transformed into ferrosilicon, which is subsequently cast from the furnace as molten metal.

A major challenge in this production process is that the molten metal is rarely completely removed from the furnace during a single casting operation. This occurs for several reasons: part of the metal may lose fluidity before casting is complete, and residual metal may gradually accumulate inside the furnace. This accumulation introduces significant difficulties, as it alters the chemical composition of the furnace contents. Since maintaining a precise silicon percentage in the final product is critical, any variation caused by residual metal can lead to deviations in composition and, ultimately, to defective (scrap) castings.

Ideally, the exact quantity of accumulated metal would be known; however, accurately measuring this quantity is not feasible in practice. The extreme temperatures inside the furnace prevent the use of conventional sensors, and the large size of the furnace—spanning several meters—results in accumulation that is unevenly distributed across its surface. Consequently, the quantity of accumulated metal must be estimated indirectly. While the literature on EAFs has extensively addressed topics such as energy consumption [3], [7] and process modeling and simulation [4], [10], relatively less attention has been given to accurately estimating metal accumulation within the furnace.

Variations in chemical composition directly impact production recipes, requiring adjustments in the proportions of raw materials added to the furnace to achieve the desired silicon content. Therefore, obtaining a reliable estimate of the accumulated metal is essential for effective process control. At the Canadian facility considered in this study, a function is currently used to approximate this accumulation; however, it lacks important input parameters, leading to poor estimation accuracy. The objective of this project is to refine this approximation in order to improve control over ferrosilicon production.

In addition to metal accumulation, the EAF process generates dust [5], a by-product containing multiple metallic elements that is collected to prevent buildup within the furnace. The generation of dust is directly linked to the mass balance of the EAF [6]. Without detailing the underlying chemical reactions, the silicon mass balance must account not only for raw material inputs but also for all transformation pathways, including both dust generation and metal accumulation. Despite this, the current mass-balance-based model used to estimate metal accumulation does not consider dust production, limiting its accuracy. This project aims to improve the existing approximation of metal accumulation in the EAF, as well as the graphical tools used by furnace operators for decision-making. These improvements are designed to integrate with the current system without disrupting established operational practices.

The remainder of this paper is organized as follows. Section II describes the EAF process and the problems associated with metal accumulation. Section III presents the proposed methodology to refine the accumulation estimate. Section IV discusses the results, and Section V concludes with final remarks.

II. Electric Arc Furnace

This Section explains briefly the ferrosilicon production and the metal accumulation in the furnace.

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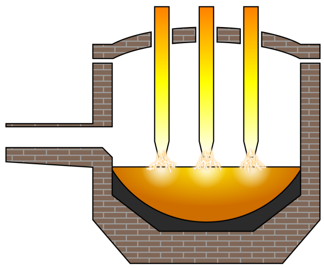

Fig. 1. Electric Arc Furnace [1]

A. Ferrosilicon production

An Electric Arc Furnace consists of a molten bath, where the metal is in fusion and three electrodes, given it is powered by three phases, as shown on Fig.1. An electric current is induced in the electrodes, causing arcs, and hence melting the raw materials into ferrosilicon. During the process, dust [9] is created and contains multiple metallic elements, for example, lead, iron and zinc [2]. The ferrosilicon coming out of the EAF never has the same exact chemistry. It can also happen that the metal does not come out of the EAF, leading to metal accumulation. Once the metal is extracted from the furnace, additives are mixed in the molten metal to obtain the right chemistry. These quantities are evaluated by the previous casting's chemical analysis.

B. Metal accumulation

Ferrosilicon is produced by carbothermic reduction of silicon and iron oxide using carbon in an EAF [11]. When the reduction is not complete, it can cause the metal to accumulate in the EAF since it is not totally extracted from the furnace during the cast.

Metal accumulation in the EAF occurs when the sum of the metal cast with the dust is lower than the quantity of the raw material added to the furnace:

$$ACC = Si_{raw} - Si_{dust} - Si_{cast}, \quad (1)$$

where ACC is the accumulation of metal in the EAF in kg, Si_{raw} is the quantity of silicon in the raw material in kg, Si_{dust} is the quantity of silicon in the dust in kg and Si_{cast} is the quantity of silicon in the cast in kg.

When the cast is complete, elements like Magnesium are added to the ferrosilicon in fusion, and are named recipes. The quantity of metal accumulation in the EAF has a direct impact on the chemistry of an alloy recipe. For example, if there is more metal in fusion in the cast than expected, then the recipe is not exact and could cause a reduction of the percentage of silicon, for example, in the final product. Therefore, it is better to know as precisely as possible the quantity of metal accumulation in the EAF in order to tune the recipes.

C. Current metal approximation

Currently, at the ferrosilicon producer's factory, there is a system that approximates the metal accumulation in the EAF

The goal of this project is to refine the approximation of metal accumulation in order to improve its accuracy and enhance the operation of the EAF and its associated recipes.

III. Methodology

The current computer software in place cannot be changed, but it can be improved. As the graphics and calculations are used in all daily operations, the proposed methodology refines the calculations, without changing anything for the end-user.

The following modifications are proposed:

A) Approximate the metal accumulation when there is a cast, instead of per hour.
B) Add the iron Fe to the approximation.
C) Add the latency period of the raw materials addition.
D) Add the type of $FeSi$ currently in production.
E) Improve the user interface.

The following subsections detail the changes.

A. Approximate the metal accumulation when there is a cast, instead of per hour

The electric arc furnace (EAF) produces a cast approximately every 45 to 60 minutes, resulting in zero to two casts per hour depending on operating conditions such as power input and overall energy consumption. Because the production process is inherently batch-based, with each cast representing a discrete removal of molten metal from the furnace, it is more physically meaningful to express the evolution of metal accumulation on a per-cast basis rather than per unit of time.

From a physical standpoint, the accumulation of metal inside the furnace is directly linked to the mass balance between inputs and outputs during each casting cycle. Each cast corresponds to a well-defined event where a portion of molten metal is tapped, while the remaining metal stays in the furnace. Between casts, raw materials are continuously added and transformed, contributing to the buildup of molten metal. However, the actual change in accumulation only becomes observable when a cast occurs, since this is when material leaves the system in a measurable way.

In contrast, using a time-based discretization (e.g., hourly updates) introduces inaccuracies because it does not align with the underlying physical process. The rate of melting and metal production is not constant over time; it depends on factors such as variations in electrical power, raw material composition, and furnace conditions. As a result, two time intervals of equal duration may correspond to very different amounts of metal production and accumulation.

By updating the calculation at each cast [2], the model remains synchronized with the true physical dynamics of the system, capturing the discrete nature of material removal and reducing the uncertainty associated with variable production rates. This leads to a more accurate and physically consistent approximation of metal accumulation within the furnace.

B. Add the iron Fe to the approximation

In the actual calculation, only the quantity of Si is used, but iron is an important component as it is the second most present element in the $FeSi$. Therefore, incorporating this element in the approximation will lead to an increased approximation.

C. Add the latency period of raw materials additions

When raw materials are added to the EAF, they are not instantly consumed and there is a time delay before they start melting and integrate the metal in fusion. Currently, this time is not considered but is of upmost importance, since it takes a certain time in practice for the raw material to make it to the EAF. Therefore, the latency period of the raw materials is considered in the new approximation.

In Eq. (3), Eq. (4) and Eq. (5), parameter l_b specifies the latency period of the ferrosilicon type changes in production. When the type of ferrosilicon production changes, the latency period changes, since different weights of raw materials are added to the EAF (quart, wood chips, scrap metal, coal), given different types of ferrosilicon.

The actual calculation does not integrate this latency period and the raw materials are consumed within the hours in the calculation, but that is not the case.

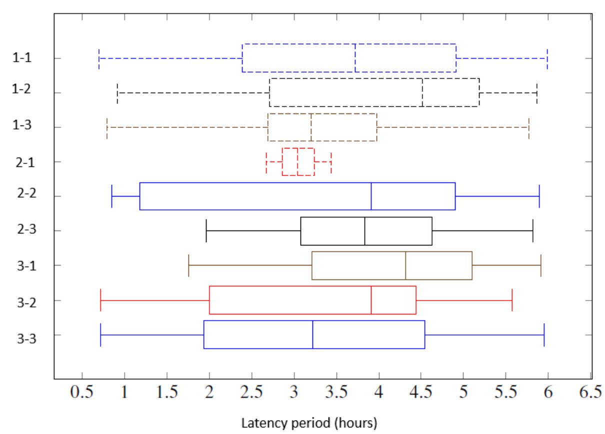

Fig. 2. Production changes on the y-axis and latency period on the x-axis.

The database of historical data was used to determine the latency periods when raw material is added to the EAF. Fig. 2 shows the latency times to consider, depending on the production changes on the y-axis. There are three types of ferrosilicon, 1, 2 and 3. When the type changes, for example 1 to 2, it is noted as 1-2 on the y-axis. These types represent different percentages of ferrosilicon as the final product.

One can notice that the latency times are between 3 and 5 hours (median), therefore there was a huge loss of information in the raw material consumption in the actual approximation of metal accumulation. This new latency period is added to the approximation.

D. Add the type of $FeSi$ currently in production

The ferrosilicon producer produces different types of $FeSi$, more precisely three different percentages of Si in the alloy can be produced at the factory. Currently the calculation does not consider different products. The new calculation considers these three possibilities, thus different values of Fe and Si in the raw materials incorporated to the EAF.

E. Improve the user interface

The current user interface displays the metal accumulation graph alongside other production graphs. The proposed improvement consists of creating a dedicated graph that focuses solely on metal accumulation, making it easier for operators to interpret and support decision-making in EAF operations.

F. New calculation of the metal accumulation

The following notation is used.

Sets are given by:

N = $\{1,2,\ldots,n\}$	Type of raw material
B = $\{1,2,\ldots,b\}$	Type of ferrosilicon in production
T = $\{1,2,\ldots,t\}$	Hours

Parameters are given by:

x_{nt}	Weight (kg) of raw material of type n at time t
l_b	Latency period of the ferrosilicon in production
S_n	Percentage of Si in the raw material $n \in N$
F_n	Percentage of Fe in the raw material $n \in N$
y_t	Weight (kg) of the dust at time $t \in T$
z_t	Weight (kg) of the cast at time $t \in T$

The new metal accumulation calculation at time t is given by Eq. (2).

$$ACC_{new\,t} = SiMP_t - SiP_t - SiC_t, \tag{2}$$

where

$$SiMP_t = \sum_{i=t-l_b}^{t} \sum_{j=1}^{n} (S_j + F_j) x_{ij} \tag{3}$$

$$SiP_t = \sum_{i=t-l_b}^{t} (S_i + F_i) y_i \tag{4}$$

$$SiC_t = \sum_{i=t-l_b}^{t} (S_i + F_i) z_i \tag{5}$$

Eq. (3) provides the quantity of Fe and Si in the raw material. Eq. (4) provides the total quantity of Fe and Si in the dust and Eq. (5) the quantities of Fe and Si in the cast.

To calculate the total metal accumulation in the EAF and not only at time t, the approximation is added to the 23 previous casts, as shown in Eq. (6) to create a moving average.

$$ACC_{total} = \sum_{n=t-23}^{t} ACC_{new\,n} \tag{6}$$

IV. Results

As direct measurement of metal accumulation in the EAF is not feasible, validation of the proposed approximation relies on comparisons with known operating states. Specifically, results are presented for periods where no accumulation is known to occur, as well as for periods where accumulation is confirmed.

The ferrosilicon producer provided access to historical data from the years 2020 and 2021, enabling a comparison between the new and previous approximations. In addition, a senior engineering metallurgist identified specific dates corresponding to conditions with no accumulation and others where accumulation was known to be present, providing a reliable basis for validation.

A. No metal accumulation

1) January 12th 2020: The metallurgist searched through the database to extract days where the production was normal, with constant production and no accumulation in the EAF. Production day of January 12th 2020 was a normal production day.

TABLE I
PRODUCTION STATISTICS JANUARY 12th 2020

Number of casts	27
Sum of S_i and F_e added in EAF	177.15 Tons
Sum of S_i and F_e output in EAF	177.85 Tons
Total weight of casts	176.56 Tons

The theoretical difference between the output versus the input taken from TableI gives a difference of 0.7 Tons, which means it is in normal operations. A difference value between -1 and 1 indicates there are little to no accumulation, which is the case for this day.

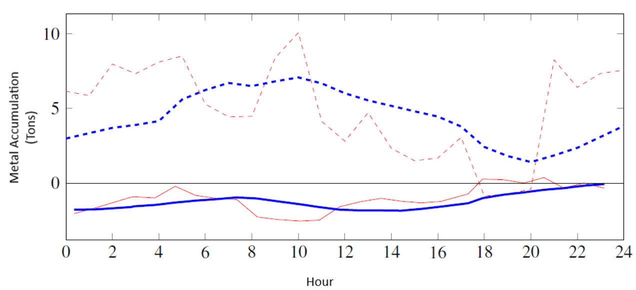

Fig. 3. Zero accumulation day (Jan 12th). The red dashed-line is the old accumulation approximation and the red line is the new accumulation approximation. The blue dashed-line is the old moving average and the blue line is the new moving average.

Fig.3 shows the comparison between the old and new approximation on a zero accumulation day. The red-dashed line is the old approximation and the red line is the new one. It is a lot smoother, and one can notice that the accumulation is either under 0 or very close to 0, which is representative of a no accumulation day. The old accumulation approximation gave an overestimation of the approximation. As for the moving average, the blue dashed-line is the old calculation with the 23 last hours and the blue line is the new calculation with the 23 last casts, giving again a value a lot closer to reality as the old calculation also over approximated the metal accumulation in the EAF.

TABLE II
OLD VS. NEW METAL ACCUMULATION APPROXIMATION

Accumulation	**Old (tons)**	**New (tons)**
Instantaneous minimum	-0.87	-4.77
Instantaneous maximum	10.09	2.08
Moving average minimum	1.41	-2.86
Moving average maximum	7.08	0.39
Start-of-day instantaneous	6.15	-1.55
End-of-day instantaneous	7.58	-2.24
Start-of-day moving average	2.99	-1.35
End-of-day moving average	3.83	-1.23

Results in Table II demonstrate that the new approximation no longer indicates metal accumulation, whereas the previous method did. Since production was confirmed to be operating under standard conditions, this supports the conclusion that the new approximation is more accurate.

2) March 15th 2020: This day was also flagged as a normal production day with no accumulation. Productions statistics are shown in Table III.

TABLE III
PRODUCTION STATISTICS MARCH 15th 2020

Number of casts	26
Sum of S_i and F_e added in EAF	108.55 Tons
Sum of S_i and F_e output in EAF	112.69 Tons
Total weight of casts	111.88 Tons

In this case, the difference between outputs and inputs is greater than 1, but the type of ferrosilicon in production changed, leading to these differences. The experience of the metallurgist is of upmost importance to give insight on these changes.

Fig.4 presents the new calculations in the same fashion as previously. Again, the the moving average is a lot smoother and shows that there is no metal accumulation at the end of the day, which was not the case with the old calculations.

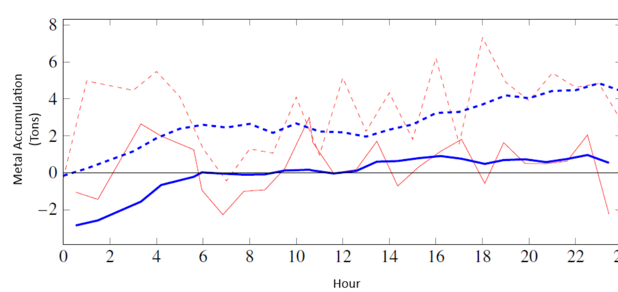

Fig. 4. Zero accumulation day (March 15th). The red dashed-line is the old accumulation approximation and the red line is the new accumulation approximation. The blue dashed-line is the old moving average and the blue line is the new moving average.

The results are further confirmed by Table IV. The maximum accumulation values are significantly reduced compared to the previous approximation, and no accumulation is observed at the end of the day, as expected.

TABLE IV

OLD VS. NEW METAL ACCUMULATION APPROXIMATION

Accumulation	Old (tons)	New (tons)
Instantaneous minimum	-3.95	-4.56
Instantaneous maximum	13.23	2.30
Moving average minimum	-1.32	-2.27
Moving average maximum	4.69	1.57
Start-of-day instantaneous	4.43	-0.58
End-of-day instantaneous	-3.95	-0.56
Start-of-day moving average	-1.32	-1.36
End-of-day moving average	-0.58	-2.27

TABLE VI

OLD VS. NEW METAL ACCUMULATION APPROXIMATION

Accumulation	Old (tons)	New (tons)
Instantaneous minimum	-5.79	-2.77
Instantaneous maximum	5.42	7.45
Moving average minimum	-3.55	-4.58
Moving average maximum	1.42	5.40
Start-of-day instantaneous	-4.00	-2.77
End-of-day instantaneous	4.47	4.08
Start-of-day moving average	-2.64	-4.58
End-of-day moving average	1.42	3.86

B. Metal accumulation

1) December 4^{th} 2020: On the day of December 4^{th} 2020, the metallurgist flagged the day as a known accumulation of metal in the EAF, since it affected the production process. The hypothesis they based on was that on the day before, the production was under the target, whereas on the 4^{th}, they had a record production day.

Production statistics are shown in TableV.

TABLE V

PRODUCTION STATISTICS DECEMBER 4^{th} 2020

Number of casts	23
Sum of S_i and F_e added in EAF	99.54 Tons
Sum of S_i and F_e output in EAF	96.07 Tons
Total weight of casts	93.455 Tons

TableV shows that there is a theoretical accumulation in the EAF, given the input is higher than the output.

Fig.5 shows the comparison between the old approximation of accumulation in the EAF and the new approximation. First, the new calculation is a lot smoother. The moving average (blue line) is a lot smoother for the new approximation, since the 23 last casts are used in the moving average instead of the 23 last hours for the old approximation. As for the accumulation approximation, the red line show that the new approximation is higher than the old one, thus representing more precisely the metal accumulation in the EAF.

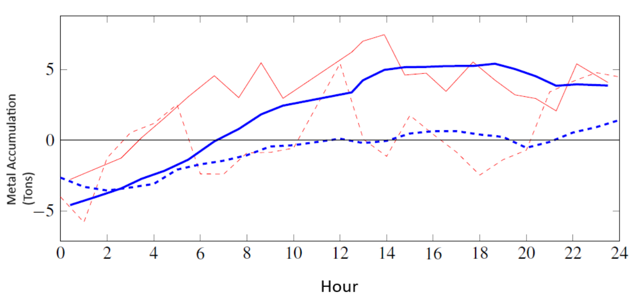

Fig. 5. Accumulation day (December 4^{th}). The red dashed-line is the old accumulation approximation and the red line is the new accumulation approximation. The blue dashed-line is the old moving average and the blue line is the new moving average.

Results in Table VI show a more balanced and physically consistent behavior. Although some maximum values are slightly higher, the overall accumulation remains within a more realistic range, and extreme variations are reduced. In addition, the start- and end-of-day values are more coherent, indicating a more stable and reliable estimation of metal accumulation.

2) June 1^{st} 2021: This day was identified as an accumulation day. Production statistics are shown in TableVII.

TABLE VII

PRODUCTION STATISTICS JUNE 1^{st} 2021

Number of casts	25
Sum of S_i and F_e added in EAF	108.98 Tons
Sum of S_i and F_e output in EAF	101.63 Tons
Total weight of casts	98.17 Tons

The theoretical difference is more than 7 Tons between the inputs-outputs, and the metallurgist also confirmed this accumulation day.

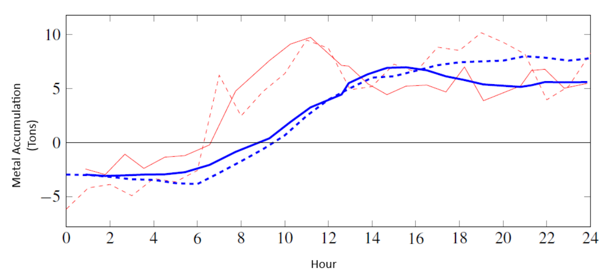

Fig. 6. Accumulation day (June 1^{st}). The red dashed-line is the old accumulation approximation and the red line is the new accumulation approximation. The blue dashed-line is the old moving average and the blue line is the new moving average.

Fig.6 presents the results and shows that the new calculation is close the the old calculation, but has a lower moving average at the end of the day, thus representing more accurately the actual quantity of metal in the EAF.

TABLE VIII

OLD VS. NEW METAL ACCUMULATION APPROXIMATION

Accumulation	Old (tons)	New (tons)
Instantaneous minimum	-6.14	-2.95
Instantaneous maximum	10.17	9.74
Moving average minimum	-3.83	-3.08
Moving average maximum	8.00	6.98
Start-of-day instantaneous	-6.14	-2.43
End-of-day instantaneous	8.27	5.48
Start-of-day moving average	-2.95	-2.95
End-of-day moving average	7.81	5.60

The new results, shown in Table VIII are improved because they show lower and more realistic accumulation levels, avoiding the excessive peaks observed with the previous method. In addition, the accumulation at the end of the day is reduced, which is more consistent with normal furnace operation. Overall, the behavior is more stable and better reflects the physical process, indicating a more accurate approximation.

C. Discussion

The new user interface and improved metal accumulation estimate are currently deployed at the ferrosilicon production facility, enabling more accurate evaluation of metal accumulation in the EAF and supporting better operational decision-making.

Variations in the composition of raw materials, such as moisture or carbon content, can affect the accuracy of the metal accumulation estimate. For example, higher moisture requires additional energy for evaporation, reducing the energy available for melting and leading to lower actual metal production than expected. Similarly, changes in carbon content influence the reduction reactions and the amount of silicon produced. As a result, the same nominal input can yield different amounts of molten metal, introducing uncertainty into the mass balance. Neglecting these variations may therefore lead to systematic errors in the estimation of accumulated metal. Although these variations are not considered in the proposed estimate, it still provides a better approximation than the previous approach and can be further improved in the future by accounting for these uncertainties.

V. Conclusion

This work presents a novel methodology to approximate metal accumulation in an EAF. Currently, direct measurement of metal accumulation is not feasible because of the extreme temperature conditions and the uneven distribution of molten metal at the bottom of the furnace. Consequently, accumulation must be estimated through theoretical calculations, as it significantly influences the production of FeSi. Several improvements have been introduced to the existing calculation framework.

First, the approximation is now performed at each casting event rather than on an hourly basis, allowing for a more precise representation of process dynamics. Second, iron contributions have been incorporated into the theoretical mass balance. Third, the latency period associated with raw material additions has been integrated into the formulation. Finally, the methodology accounts for the specific FeSi grade currently being produced.

These enhancements significantly improve the stability and reliability of the estimated accumulation. In particular, the resulting moving average is smoother and more consistent with operational behavior. Moreover, when theoretical input–output mass balance calculations are performed for the EAF, the proposed methodology provides results that more accurately reflect actual production condition. Future work based on this project would involve determining the quantities of raw material to add to the EAF in a blackbox optimization context.

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