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THE CARBON COST OF SLAG PRODUCTION IN THE BLAST FURNACE

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Introduction

Today 94 % of the iron produced from iron ore is made by using blast furnaces[1]. A blast furnace (BF) reduces and melts iron ore by hot air and carbon producing a hot metal, which is saturated with carbon, and is separated by the process from a slag consisting of the ashes of the coal used, the gangue of the ores, fluxes and impurities of the raw materials. The process also produces torrents of process gas, which has an energetic value since it still contains high concentrations of carbon monoxide. As the process is carbon based the efficiency of the process is becoming a key concern for climate change. Steel resulting from the decarbonizing of hot metal (HM) from blast furnaces is the second most important man made material with a production of 1.65 billion ton in 2013.

Importance of assessment of the carbon cost of slag

The Carbon Cost of slag is the quantity of CO_2 emissions linked to the production of slag only next to the carbon needed for the production of hot metal in the BF. There are basically four reasons to assess the carbon Cost of slag burden.

- The first reason is to determine one's own process performance compared to the state of the art and how much an individual operator can improve compared with the most efficient in the benchmark. To do this the impact of parameters on which the operator has no control needs to be eliminated. One of these is the amount of slag produced as slag burdens can vary widely from ca. 150 to more than 600 kg/ton HM depending on the pretreatment of the ores and the purity of the iron ores and coals.
- The second reason is to assess the importance of the quality of raw materials in a global carbon reduction strategy. In general there is a choice between concentrating ores (giving rise to tailing ponds which create vast waste lands) and

producing concentrated ore pellets or to take the iron ores and feed them directly into sinter plants where all the fluxes to create an ideal slag chemistry can be added. Unlike the slag of other steel making processes (electric arc furnace, basic oxygen furnace), the blast furnace slag has the right chemistry to become a cement clinker substitute when quenched and ground afterwards and is known as Ground Granulated Blast Furnace Slag (GGBFS). In order for Society to decide on the desirability of making granulated slag the question that should be answered is whether the Carbon Cost of the production of granulated slag is higher or lower than the production of the cement product it can substitute[2].

- A third reason is the evaluation of different steel making routes. When comparing different iron making routes (pellet - blast furnace - basic oxygen furnace; sinter - blast furnace - basic oxygen furnace; pellet - direct reduced iron - electric arc furnace) it is essential to define the system boundaries in a precise way. The total balance of the products and by-products (steel, waste gases and granulated slag) should be compared. Many studies tend to omit upstream production steps or one of the product streams leading to erroneous answers. Also the development of slag valorization methodologies is not possible if there is no criterion to measure the additional value of GBFS[3].
- A fourth issue is the way GBFS is accounted for in Life Cycle Analysis. A commonly used method is the one of 'system expansion' where a by-product is attributed an equal impact as the product it replaces and which is used as a credit for the main product of the process[4]. This method is debatable however because the value depends on an exogenous element and is ultimately linked to the evolution of technologies that have nothing to do with one's own activities. A more acceptable method would be to determine the exact share of emissions linked with the production of slag.

Method to determine the Carbon Cost of slag production

To determine the part of CO_2 linked to the slag in the BF process a differential reasoning was applied. The difference in overall emissions of variation of slag quantity while keeping the HM production constant should give a reliable estimate of the CO_2 impact of the slag quantity.

The idea is simple but the slag quantity in the BF has an impact on the overall functioning of the BF process. If the carbon demand of the BF changes, so will be the amount of waste gases produced. It is generally accepted that steel waste gases are a substitute for natural gas because it the best available alternative when there is no BF gas available, so a credit for an equivalent quantity natural gas corresponding to the change in BF gas is also attributed to the process.

It is also necessary to look at upstream emissions. As the gangue of iron ores and coke are in general acid (high SiO_2-content) it is necessary to add limestone or dolomite to adjust this slag chemistry. The emissions of decarbonizing limestone are usually found in the sinter plant upstream of the blast furnace. In any case these fluxes also create CO_2 emissions which are linked to the slag generation and caused by the chemistry of the gangue material.

The two above aspects are considered being the predominant aspects of the CO_2 cost of a marginal quantity of slag. It is assumed that the impact of other aspects (sulfur or phosphorous content, initial acidity etc.) is of a lower order of magnitude. This needs to be proven by the analysis below. The main question is if there exists one single value that can predict with an acceptable precision (+/- 10 %) and in a sufficient broad range the CO_2 cost of total slag burden in the BF route?

The Mathematical Model of the Blast Furnace (MMBF)[5,6]

The Mathematical Model of the Blast Furnace (MMBF) is the standard overall heat and mass balance model for the ArcelorMittal blast furnaces. The model is built on the principle that there is in the blast furnace a thermal reserve zone, the upper part, in which gas and solids have the same temperature fixed by the coke reactivity. This thermal reserve zone includes a chemical reserve zone in which gas and solids reach a chemical equilibrium ($FeO+CO=Fe+CO_2$).

Due to these simultaneous equilibriums, the lower part (processing zone) of the furnace sets the important operating parameters (fuel and blast rates) while the upper part recovers the available heat and reducing potential of gas to pre-process the burden.

The algorithm adopted to provide the model's results is based on the determination of a linear system, which links different types of operational data. It is capable to model the most diverse operation points and successfully predicts the different output parameters of the BF products given a given set of input data.

Data and Calculations

For the purpose of analyzing the impact of differential slag burdens five different existing BF belonging to different companies with different operating practices (Table 1) were considered, one BF with two operating points. Additionally, a theoretical operation was added corresponding to the reference blast furnace used in the ULCOS project[7,8]. The data used are obtained through an annual data exchange by the European Blast Furnace managers and are mostly on the year 2012. The data were checked on consistency with the MMBF model and some minor adjustments were required to guarantee the thermodynamic equilibrium of the process.

In order to determine the slag effect two calculations are made: one with the standard slag volume and another with a 50 kg slag/ton Hot Metal more. Since all equations (related to slag) are linear this amount itself is not very important but it needs to be high enough to remain unaffected by the noise of calculation precision. The increased slag weight is modeled by varying the quality of the minerals used in sinter while the iron entries in the blast furnace remain the same. Also the consumption ratios of pellets and lump do not change. Calculations are made at a constant flame temperature.

Table 1: Burden composition and fuel rate

	ULCOS (reference)	BFA	BF B	BF C	BF D-1	BF D-2	BF E
Bell sinter	1 000	1 167	1 093	548	1 329	1 329	1 668
Lump ore	150	58	254	8	27	27	14
Pellets	430	392	266	970	441	441	0
Slag volume	**260**	**292**	**297**	**213**	**650**	**525**	**391**
T° blast	1 200	1 149	1 121	1 256	969	969	1 054
Coke rate	283	297	334	283	602	573	488
Coal rate	197	183	162	221	31	43	42
C in hot metal	4.74	4.90	4.80	4.57	4.45	4.29	4.20

There are three steps in the calculation:
1. Blast furnace balance using MMBF which gives coke consumption. MMBF calculates coke rate at a given coal rate (or the opposite depending on the fixed conditions).
2. Calculation of stove consumption using a simplified stove model. By difference with first step this permits to calculate the CO_2 BF credit due to net BF gas export.
3. Upstream requirements for coke production and limestone impact are considered. In this paper the option is taken to adjust the carbon input only via coke since injected fuels can vary in carbon content (oil, coal, natural gas).

In this way a global balance of an iron making plant including coke making and sintering has been performed to account for cross effects of BF operation on upstream processes. Figure 1 presents the model of such a plant and identifies inputs and outputs used for assessment of slag effect.

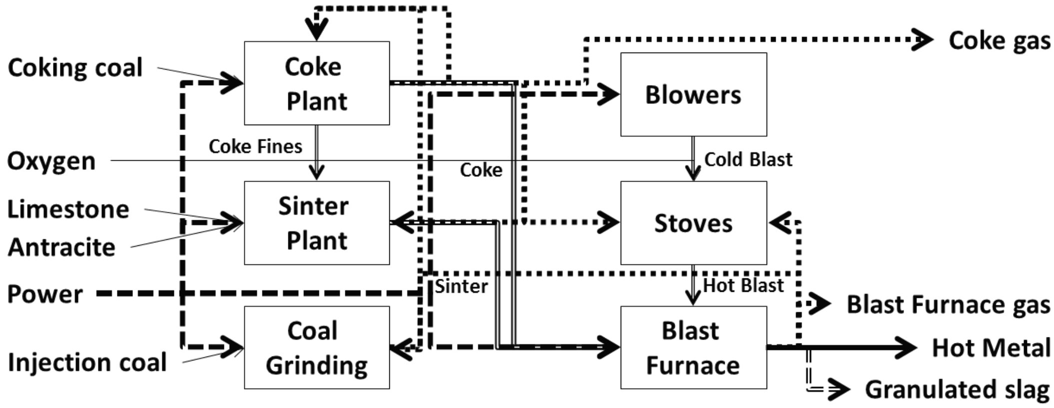

Figure 1: Model of iron making plant for slag effect assessment

Assessment of slag effect results from a differential calculation comparing a reference operation to an operation with a different slag volume; Carbon Cost of slag is equal to the ratio of the CO_2 balance change and the slag volume change.

Results and discussion

The calculation determines the net CO_2 for each operating point; the difference with the reference operation point is the Carbon Cost of Slag. As indicated previously, net CO2 includes effect on BF operation of slag variation, effect due to additional coke production and effect due to the decarbonation of additional limestone at the sinter plant. Table 2 presents the summary of CO_2 needs for the different "raw" streams used for slag production.

Table 2: CO_2 needs for the production of slag.

(kg CO_2/t slag)	ULCOS	BFA	BF B	BF C	BF D-1	BF D-2	BF E
CO_2 needs for Slag production	540	529	555	551	560	580	532

The results of the calculations show a remarkable constant value result for the CO_2 needs of treating gangue and sterile through the Blast Furnace route independent of the quantity or nature of the slag as well of the operating practices.
Figure 2 presents the relation between slag rate and slag rate effect. Slag rate effect seems to be quite constant with an average value of 550 kg CO_2/ t slag (Std dev = 18 kg CO_2/ t slag, i.e. +/- 3 %).

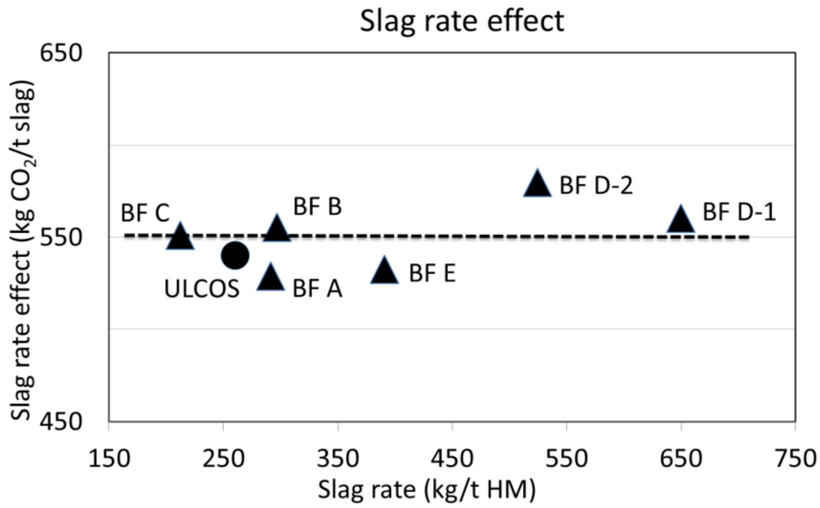

Figure 2: CO_2 effect of slag rate

CaO content of slag is generally about 40 %. This observation permit to estimate CO_2 impact of limestone decarbonation at sinter plant [44/56 (CO_2/CaO) => 786 kg CO_2/t CaO] which is: 40 % of 786 = 315 kg CO_2/ t slag. By difference the impact directly related to BF operation is 225 kg CO_2/ t slag (550-315).

This confirms the hypothesis that the melting of slag and the basicity correction are the most important energy related aspects of the processing of slag and are an order of magnitude more important than other aspects which could also have an impact on the CO_2 cost of the slag treatment.

Conclusions

The present analysis shows that the CO_2 impact of slag on the Blast Furnace process can be estimated by a single value of about 550 kg CO_2/t slag. This value has proven to be rather robust within a wide range of slag burden independent of the nature of the raw materials (sinter, pellets, lump ore) used in the Blast Furnace. By crediting the Blast Furnace process for the production of slag using this value the Carbon Cost of hot metal production of every blast furnace operator can be measured and compared.

Also the value indicates that the cost of producing a ton of slag which is turned into GGBFS is much lower than the benchmark value of 766 kg CO_2/ t clinker for grey cement clinker[9]. This means that the generation of more GGBFS as such is not undesirable as its production does not cause more emissions than the product it could substitute. Moreover, the fact that somewhere in the world less mining tailings need to be stored is an environmental advantage which is however difficult to compare with CO_2 emissions.

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