PROCESS OPTIMIZATION BY PNEUMATIC INJECTION OF SLAG BUILDERS IN THE ELECTRIC ARC FURNACE

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Abstract

Compared to other traditional charging methods, pneumatic injection of slag builders is a well-known practice to improve the Electric Arc Furnace process. The injection of powdered reactants generates a much cleaner shop environment. Therefore, dusty discharging bin practices and the use of maintenance demanding conveyor belts can be reduced.

Unlike conveyor belts, pneumatic injection systems are dedicated units that can be integrated into modern control systems to adapt to the EAF process requirements. These change frequently due to uncertain variable conditions, such as the metallic charge mix.

Slag analysis is readily available. With flux pneumatic injection systems, the information about slag chemistry can be automatically integrated in a closed loop control for the early adjustment of the routine slag building practice. Ideal slag foamability conditions and MgO saturation are obtained; therefore allowing the EAF melting operations to keep the arc radiation shielded. This increases the power input stability, dramatically enhancing the heat input efficiency and overall refractory lifetime, Ultimately, these enhancements improve the long term conversion costs.

This paper will provide insights into the following: injection system equipment, the automatic management of fluxes by process control systems (these dramatically adapt to EAF operating conditions), meltshop practices and operating results from steel plants utilizing these technological packages.

Introduction

In modern steelmaking, slag quality is the keystone of the metallurgical process. Steel melting is faster and heat power intensive like never before. With power-on times as short as 30 min, dosing slag builders in the proper quantity and at the right time, is crucial to provide slag foaming during meltdown promptly. Foamed slag shields the panels from the intense arc radiation, therefore redirecting the heat towards the melt. Foamed slag also mitigates the current swings, improves the operative reactance and protects the expensive refractories from overheating and chemical attacks. All these benefits are crucial for enhancing the EAF productivity and ultimately lead to reaching the best conversion costs.

The increasing demand of pneumatic flux injection systems for EAF steelmaking is the result of several improvements such as: the progresses in the conveying systems reliability, the availability of more efficient injection equipment and specific flow-optimized flux products. Lime and dolomite injections have proven to be the most efficient method to control the slag basicity and viscosity. This practice has not only been widely accepted by the steelmaking community but also sought after.

Typically, the addition of slag builders into the EAF can be done in different ways:

1. Stratified in the bucket with scrap
2. Transported via a conveyor belt and charged through a bin placed on the EAF roof
3. Pneumatically conveyed and injected through the EAF roof
4. Pneumatically conveyed and injected through EAF sidewall injectors

Each individual practice has its "pros" and "cons". Therefore it is important for steelmakers to evaluate the most suitable system for their specific operations carefully.

Bulky materials are cheaper, but at the same time, they are less reactive with the slag. They also require longer melting times, have a higher fraction of carbonates in the core, which can accumulate and eventually cause non-conductive contact at the electrode tips. Finer grain sized fluxes have a faster reaction rate, but the larger dust fraction leads to higher losses in the drop-out box and in the baghouse. Steelmakers should aim to use properly sized and sieved material to attain noticeable metallurgical results.

Charging the fluxes into the bucket (Figure 1) is probably the most widespread practice in traditional meltshops. Likely due to easy integration in the scrap yard, where there is typically plenty of space. The main drawback is that loading super sacks of fluxes directly into the bucket by a crane is a very expensive and manpower intensive practice (typically 100 sacks/day, 4 sacks/hour). The most common solution to overcome this problem, is to add fluxes, via a conveyor bin, which are filled with a predetermined quantity from a storage silo. The bin load is then discharged into the bucket over the scrap. This occurs while in route from the charging bay to the meltshop. Despite the apparent simplicity and the lower capital expenditure, there are a lot of process drawbacks related to such a practice.

It is of upmost importance to, not only store fluxes in a dry atmosphere, but also to have the capacity to dose them accurately. This ensures for proper laying with the scrap in the bucket. Ideally, the fluxes should be placed on the sides of the bucket in its lower half. This is not a very practical operation, as it would call for a repeated movement of the bucket car back and forth, reducing the scrap yard productivity. With incorrect or erratic stratification of the material, material losses and electrode breakages may occur.

Moreover, silos and conveyors in the scrap yard are expensive pieces of equipment that may create issues with maintenance and housekeeping due to dust generation. Besides that, they don't allow any dynamic correction of the slag chemistry during the melting operations.

Figure 1 – Examples of flux addition systems for bucket charge

An alternative option is to load the fluxes through the EAF roof with a conveyor belt (Figure 2). This solution allows for the loading of the fluxes during the scrap melting operations. Thus eliminating the related workload at the scrap yard. In this case, the raw material handling system (RMH) should be properly designed for this purpose, as it is has to prepare the alloy recipes for the tapping stage. Very often, the availability to load the fluxes into the furnace is very limited because the RMH is engaged with the ladle treatment. This makes it difficult to plan the additions, with a proper schedule and feed rate. Hastening to complete the charging of fluxes into the EAF on time causes early additions with high feed rates. Consequently, flux material is building up with late melting during the heat.

The design and position of the convey bin on the roof may be critical. With alloy plants located at the draft side of the EAF, the most common position is close to the elbow. A properly sloped feeding pipe, aiming at the furnace center, can be properly designed in most of the layouts. A vertical material drop is not convenient, as the material will end up in a cold spot, building-up large skulls on the EAF walls. These skulls melt late or sometimes cave into the heel. This generates a lot of slag slopping and dropping down the bath temperature. The elbow draft creates a cross flow of hot fumes that drag out the finer fraction of the loaded materials. In these cases, it is often reported to suffer from material stratification in the drop-out box, with very high concentrations of CaO in the baghouse dust (12% to 20%).

Another frequent convey bin location is between the C phase and the sump. This is the worst condition experienced, as the early batches of slag builders may end up with C phase electrode breakages, while the late ones tend to pack in the EBT area originating tapping delays.

The location between A and B phases is a frequent solution when the alloy system is located behind the transformer side. In this case, it is even more important to slope the bin and the charging pipe towards the center of the furnace, as late batches are likely to be quickly lost during natural slag off.

Another relevant limitation of the roof charging practice, that it is not usually possible to tilt the furnace until the charging cycle has been completed. Tilting the furnace 2-3° towards the sump is a well-established operative practice to retain slag and to promote the melting in the sump area, which is typically a cold spot. This practice obliges the operators to load all the fluxes very early at high feed rates, which is not intrinsically negative unless it creates build-ups. Resulting in oversaturated slag becoming thicker and crusty.

Figure 2 – EAF top charge by a convey bin from the roof

An alternative, also through the roof, is pneumatically conveying the materials from a dedicated pressure vessel, through a water cooled lance (Figure 3). The same considerations previously described for the roof addition are still valid, but this solution instead has a number of improvements. It is a dedicated feeding system that is able to control quantities and feed rates precisely. This enables the integration with the process adaptive control. The design of the water cooled lance and its piping, is fairly more compact than the one for the convey bin. This makes positioning the injection point to , aim at the furnace hot spot very easy and ultimately protects the refractories. It is a solution that is convenient for EAFs that have a very small capacity, where the space available on the walls is really restricted. The main limitation of injecting the material through the roof ,is its yield. Most of the fines will be dragged away by the plant off-gas system, due to the large distance to the slag level.

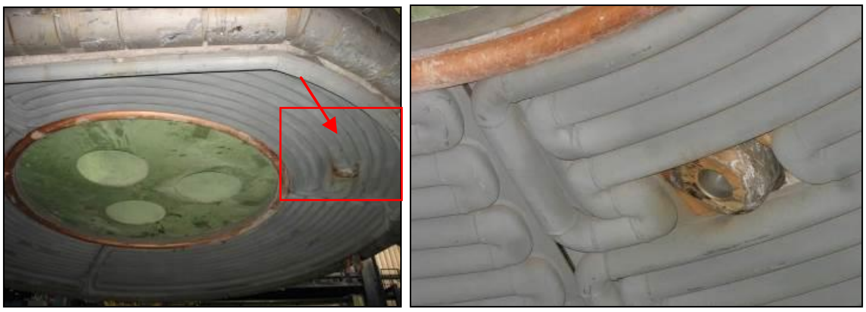

Figure 3 – EAF top charge: pneumatic fluxes convening through a water cooled pipe

Charging fluxes from the sidewall panels (figure 4) can overcome the drawbacks as described above. It is a complete automatic system, consisting of a dry storage (indoor day-bin or sealed outdoor silo). The silo feeds, by gravity, a pressure vessel installed below it. This vessel is continuously weighed to control the feed rate through a regulating knife valve. Material is then pneumatically conveyed to dedicated sidewall injectors. The fact that the slag formers are injected very close to the slag, increases the injected material yield. Having the capacity to control the amounts and feed rates precisely ensures optimal results. Moreover, this solution allows slag to stay balances in terms of saturation, viscosity and rate of reaction. An ideal scenario from the metallurgical point of view.

Figure 4 – Sidewall pneumatic fluxes conveying through injectors

Pneumatic conveying of solids – background information

Pneumatic conveying is the movement of solids through a pipeline using a carrier gas, usually air. The flow regime in the pipeline depends on the ratio of solid material to gas, and the type of material being conveyed.

Compared to conveyor belt systems, there are several advantages to moving solids pneumatically:

- Material can be transported with minimal degradation and minimal exposure to the environment for relatively long distances
- The development of the pipeline route is simpler, especially when elevation changes
- System reliability is much higher having fewer movable parts involved

Pneumatic transportation of solids can be done either with a Dilute or Dense phase (Figure 5):

- The Dilute phase conveying system moves the suspended material in air at high speed
- The Dense phase conveying system moves the material at low velocity in a slug flow mode

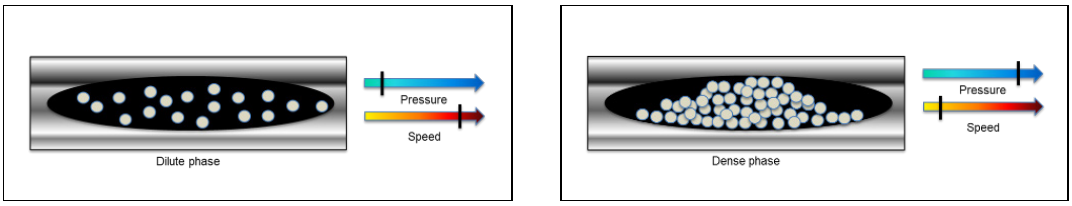

Figure 5 – Dilute phase versus dense phase pneumatic conveying, conceptual scheme

For the specific application of flux injection into the EAF, the dense phase transportation is not a viable option because the flux materials have a saltation velocity as high as 20 m/s (65 ft/s). Therefore they tend to pack along the pipeline whenever they decelerate at lower speeds. The coarser particles easily accumulate or segregate at the walls, creating porous lumps that do not move at all and easily block the material transportation. When this happens, conveying air starts to increase the back pressure. When the material dust has filled all the gaps, it completely blocks the pipe.

Moreover, the injection of fluxes requires a fast response time, in order to react with the changing conditions during melting. Typically, the distance between the pressure vessel, where the feed rate is controlled, and the furnace is in the range of 50 – 70 m (160 – 230 ft). Considering a reasonable speed of 25 – 35 m/s (82 – 115 ft/s) [2, 3, 4, 5] in dilute phase conveying mode, the response time will result in 2 sec approximately. While in dense phase mode, at a speed of 2 m/s (6 ft/s), it would take 25 to 35 sec to initiate the change. Additionally, in dilute phase mode, the time to clear the pipeline is typically 20-30 sec. It may take 10 times longer with the dense phase mode.

Furthermore, the termination speed plays a very important role in delivering the material to the furnace efficiently. For flux injection, it is mandatory to exceed the speed of 40 – 50 m/s (131 – 164 ft/s) at the injector exit in order to penetrate the slag surface sufficiently. A low termination speed would give rise to huge material losses to the dedusting system or material build-ups on the furnace walls.

The conveying air flow rate depends on the solid material mass, sieve distribution and density. Typically for flux injection, it is not possible to exceed a load factor of 20 kg_{solid}/kg_{air} (44 lb_{solid}/lb_{air}) and ratios of 14 kg_{solid}/kg_{air} (30 lb_{solid}/lb_{air}) are usually considered in the design stage to be on the safe side. Experience has shown it is not advisable to exceed a feed rate of 180 – 200 kg/min (400 – 450 lb/min) for each injection point. With this kind of flow, the conveying air required is in the range of 750 – 800 Nm^3/h (465 – 500 scfm). This is a significant amount of air to be released into the furnace but it could be optimized during the commissioning stage of the system when it can be evaluated with the real pressure increase in the pipeline. Moreover, the air blowing into the furnace can be optimized by controlling the material flow rate precisely and by reducing its flow to a minimum value during standby injection phases.

The conveying air pressure depends highly on the pipeline route and design; the length, the number of elbows and the elevation which are the most important variables to consider during the engineering stage [6, 7].

For pneumatic injection, fans are not feasible because they provide a pressure head as low as 3.000 – 3500 Pa (0,03 - 0,04 bar_g; 0.43 – 0.58 psi) which is insufficient to move the coarse materials for slag foaming. Volumetric blowers (Figure 6-left) are able to provide a pressure head of about 30.000 – 40.000 Pa (0,3 – 0,4 bar_g; 4.35 – 5.80 psi) which is sufficient for short routes, but requires oversized pipework to contain the pressure drop. The pneumatic conveying systems adopting blowers as air movers are typically conveying material through 6''– 8'' pipes therefore, in order to exceed the saltation velocity, the air consumption has to be very high. This high amount of cool air blowing into the furnace is hindering the EAF thermal efficiency and affecting the electrode consumption. The solid to air ratio is limited. For all these reasons, the installation of blower-type conveying systems are not commonly used for this kind of applications. They are only suitable to be used to deliver material from the main storage silo to a day-bin unit or where the availability of compressed air is limited and the pipeline between silo and day-bin is linear and short.

Air compressors (Figures 6-right) are most suitable for the pneumatic conveying of materials because they can provide the air media with a pressure head ranging between 6 and 10 bar_g (87 – 145 psi). With proper coordination of the duty cycle, they are not going to be affected by the pressure drop variation between the injection and the standby phases.

Figure 6 – Blower (left) and compressor room (right)

Design concepts for an efficient pneumatic conveying system to add slag builders through sidewall injectors

There are many variables and constraints to consider when designing an efficient pneumatic conveying system for slag builders through sidewall injectors. The size and design of the EAF and the steel making process obviously plays an important role in defining the quantity, quality and feed rates of the slag builders but it is also important to verify the availability of proper materials to be procured in appropriate amounts and in a sustainable way. The amount of materials required to cover the needs of an EAF are huge and, as a consequence, the storage volumes are large too, requiring a preliminary study of the layout and logistics involved in the operations (Figure 7).

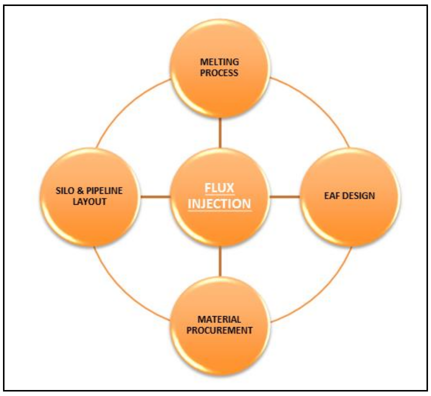

Figure 7 – Slag builders injection project: factors affecting the design process

In basic steelmaking, lime (CaO) is the mandatory slag builder to provide steel dephosphoration and acids saturation. Very often, whenever they are locally available, magnesia binders are also integrated in the process. Dual saturation of silicates, alumina and wustite lead to optimal conditions for the foaming slag, reducing the surface tension and elevating the effectiveness of slag viscosity, as pioneered by E. Pretorius [1]. In addition, MgO slag saturation is limiting the pickup from the refractory walls, prolonging the lining lifetime in a tangible way.

The overall quantity to be used and the fact that one or two materials will be injected will define the design of the storage silos.

Silo lay-out

When only one material is used, the system lay-out is quite straightforward because there will be one main storage silo and one injector to be installed in the EAF (Figure 8a). If the power-on time is very short and the melting practice requires a high quantity of lime to be injected (more than 200 kg/min, 450 lb/min), then it is better to split the flow between two injectors (Figure 8b) to spread the material on a wider slag surface area. To increase the storage volume available, or to reduce the silo diameter to fit into a limited footprint, sometimes two silos are installed.

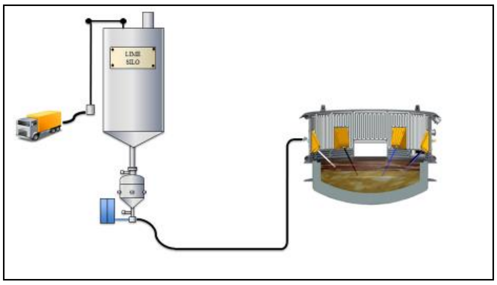

Figure 8a
Single storage silo, single dispenser, single injection point

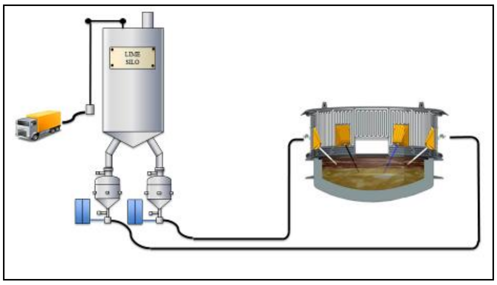

Figure 8b
Single storage silo, double dispenser, double injection point

Whenever two materials are available for injection, two storage silos are required. If power-on time is long enough to add the required quantities with a feed rate not exceeding 200 kg/min (450 lb/min), it will be possible to use a single dispenser, loaded with a stratification of the two materials. This solution is more economical than the one adopting two dedicated dispensers but it will limit operation flexibility. In fact, preloading the two materials in given quantities inside the dispenser, the injected material quantity cannot be dynamically corrected during the heat (Figure 9).

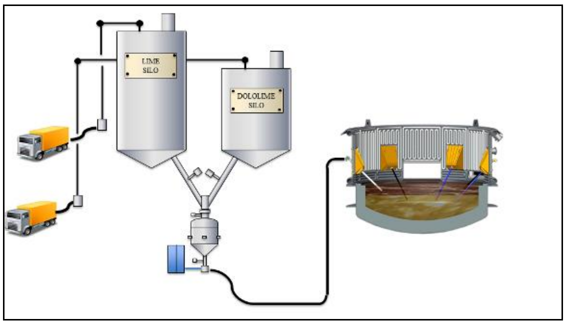

Figure 9 – Double storage silo, single dispenser, single injection point

In order to gain flexibility in the control of the slag chemistry, two independent dispensers are recommended (Figure 10a). However, if the EAF size is not suitable for the installation of two independent sidewall injectors, then one converter pneumatic valve can be used to switch the two lines (Figure 10b).

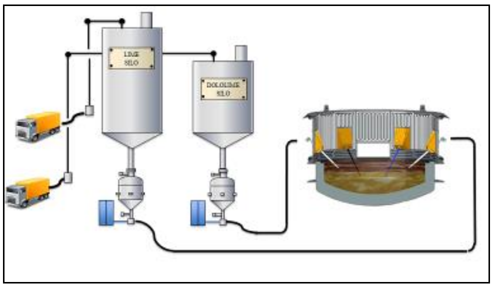

Figure 10a
Double storage silo, double dispenser, double injection point

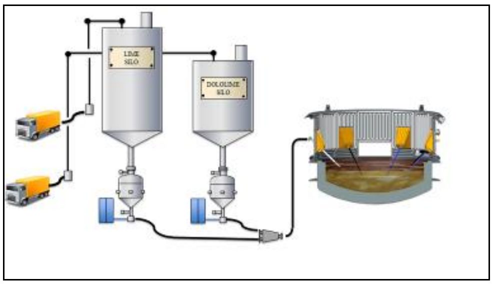

Figure 10b
Double storage silo, double dispenser, single injection point

In specific cases, when the quantity of two materials to be injected is not the same and EAF power-on time is quite short, it happens that injection time is unbalanced. The solution schematically represented in Figure-10c considers to reserve one injection point to the most utilized material (usually lime) while the other one will be used to feed independently two materials (usually lime or dolomite) according to the specific process requirements by simply acting on a converter valve [8].

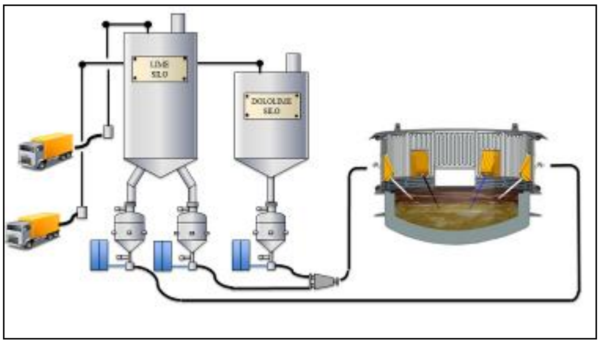

Figure 10c - Double storage silo, three dispensers, double injection point

Ideally, the silos and dispensers for lime and dolomite addition should be installed close to the EAF, possibly at the plancher level or in a mezzanine. This solution is minimizing the pipework extension and reduces the risk for the material chokes approaching a long vertical rise. The lower the transport air pressure build-up during material conveying is, the higher the feed rate achievable is having the full availability and reliability of the system. Unfortunately, it is quite difficult to fit the storage equipment inside a meltshop (especially in existing plants); the storage silos occupy quite a considerable area not only for the structures but also to allow the loading trucks to approach them. Truck loading operations require quite a lot of time and space, therefore, special care should be given to plan docking and undocking activities without jamming other operations in the area.

To overcome these limits, it is therefore very common to have the main storage silos placed outdoors along the meltshop building walls (where the main road is wider) or inside a service bay (Figure 11); both solutions have the storage silos quite far from the EAF.

Figure 11 – Storage silos and material truck unloading operations

Practical experience acquired with dozens of installations, says that 100m (328 ft) of pipeline between dispenser and injector is a good limit for conveying flux material efficiently, especially when there is an elevation of 15 – 20m (50 – 65 ft) to reach the furnace and no more than 5 to 7 elbows are used for direction changes. With a material flow rate of 100 – 120 kg/min (220 – 270 lb/min), it is possible to calculate, by practical correlations, that in this case the carrier gas pressure is exceeding 3 bar_g (43 psi) at the pickup point, leaving quite a small margin for the flow regulating valve to recover in case of choking events.

Whenever the main storage silos have to be installed at a distance exceeding 100m (328 ft) from the EAF, the best option is to introduce a smaller intermediate daily storage closer to the furnace. Reloading dispensers are automatically conveying the materials from the main storage silos to the daily bins whenever triggered by the level sensors. The time available for the refilling operations is a lot more than the injection time in the furnace. Therefore the reloading dispensers can be trimmed on lower feed rates and serve a fairly longer route to shorten the distance between the daily bins and the furnace as much as possible. (Figure 12).

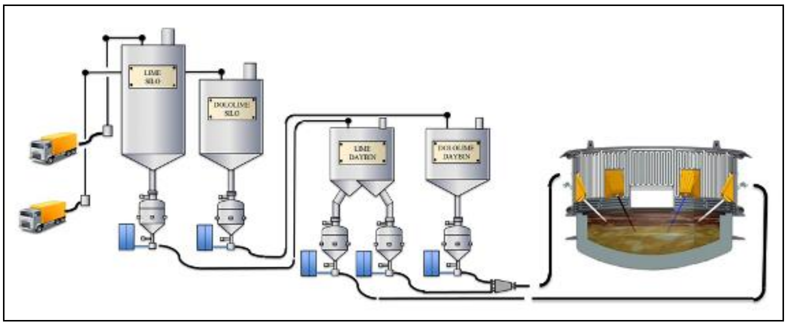

Figure 12 - Double storage silo, reloading dispensers, day bins, three dispensers, double injection point

Injectors lay-out

Fluxes are energy demanding materials and have a high melting point. This aspect has to be always kept in mind whenever considering the injectors placement along the furnace shell. They should be arranged along the hot spots of the furnace, to take advantage of the faster scrap melting. The starting time of flux injection should be evaluated carefully because injecting materials too early will extend scarp meltdown times while delaying it too much could lead to late foaming slag reactions and the refractories will be attacked by the aggressive acidic slag. Usually, the starting of the flux injection could be set between 140 and 160 kWh/t_{ch}, depending also on the oxy-fuel thermal input, the specific electrical active power and arc radiation.

The cooling action generated by the flux material input can be used to proactively shield the hot spot region of the furnace shell (figure 13). Refractory vulnerable spots, worn by excessive arc radiation, can be effectively protected by localized flux injection. The input of basic materials produces very fast slag building reaction, increasing the slag specific volume and naturally shielding the radiation heat flow. As a consequence, the surface temperature of the refractory bricks exposed to the furnace atmosphere drops down. The raise in slag basicity increases its melting temperature and drops the surface tension [9], therefore reducing the capillarity and infiltration capacity in the composite matrix of the refractories. Additions of magnesia binders will furthermore reduce the MgO grain solubility.

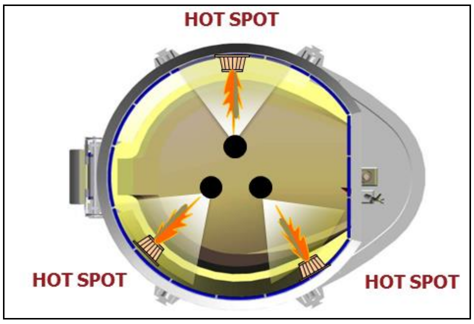

Figure 13 – Conceptual placement of flux injectors to protect the shell hot spots

In AC furnaces, the B phase is usually the most vulnerable, especially with flat bath operations, typical of continuous scrap charging furnaces. With DRI/HBI top feed charging, the A phase is an area that is prone to early erosion and the lime/dolomite injection can be efficiently used to produce slag neutralization as soon as the acidic slag is streaming from the metallic drop spot, intercepting the stream along its path to the slag pit. In DC furnaces, the longer arc length and the magnetic arc deflection frequently highlight a refractory hot spot. Linings and panels are suffering highly from localized wild arc aggression in the area opposite the transformer side, slightly towards tapping. Careful evaluation in the design stage will tremendously enhance the refractory lifetime, reducing planned gunning time and eliminating unplanned delays due to lining repair requirements. In most applications, these benefits are enough to payback the capital expenditure in few months.

In the pioneering years of flux injection in the electric arc furnaces, little attention was dedicated to a proper injector installation on the sidewall panels. It was very common to put a simple pipe, arranged through a gap opened through a panel, fixed with a steel plate and eventually protected by a water jacket or a small tile panel to deflect scrap. Such a rough arrangement was unfit to properly manage the fluxes addition efficiently. In fact, it built a very bad reputation, still holding in many steelmakers.

Substantial experience in the installation of flux injectors has demonstrated that :

- Installation of injectors on flat tile boxes are not recommended because lime and dolomite are insulating materials, they hardly melt so if they are injected too close to the panels their fines are creating a coating around the injector where the electric voltage difference is likely to initiate arcing to the panel pipes giving rise to hazardous water spills (Figure 14);

Figure 14 – Lime injector aligned with the panel – arcing damages repaired by spot welding

- Installation of injectors inside copper bulged blocks (figure 15) is recommended to shorten the free stream distance to the slag, keeping the injector nozzle away from the refractory and protruding it inside the panel to start material injection earlier, avoiding the flux material accumulation within the scrap pile or towards the water cooled panels. The short travelling path limits material losses to the off-gas evacuation system and contemporarily enhances the penetration of the material into the slag. Consumptions savings and less dust load to the baghouse are direct benefits of the high material recovery.

Figure 15 – Lime injectors inside copper bulged blocks

- Lime/dolomite injectors should be able to shroud the material flow at least with oxygen but even better with a premixed swirled shrouding flame (Figure 16). This feature is mandatory to keep the injectors tip clean from build-ups in any given conditions, especially when aiming to install the injector very close to the slag line. At the early stages, the flame thermal input is very beneficial to help melt down the scrap quickly and to provide space for the injection of slag builders. Moreover, a shrouding flame sustains the stream of solids, confining the dust in a more coherent and focused jet towards the slag, therefore minimizing the losses to the off-gas system.

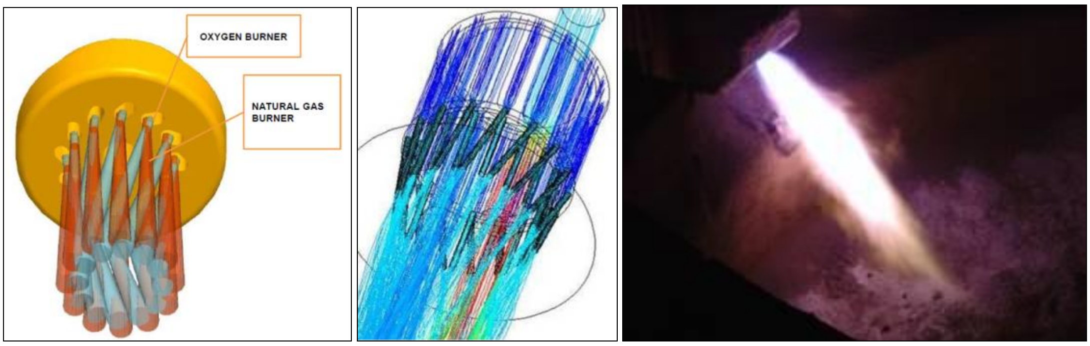

Figure 16 – Premixed swirled flame: design, gas dynamics and real flame in action

- Lime/dolomite injectors (Figure 17a) should be designed to inject grain sized slag builders having an appropriate grain size distribution and diameter lower than 20 mm (0.866 in). Typically, the feed rate can be between 50 kg/min and 200 kg/min (110 - 450 lb/min). The particles should reach a terminal speed of 60 to 80 m/s (164 – 262 ft/s), (Figure 17b), sufficiently high to penetrate the thick slag layer.

Figure 17a

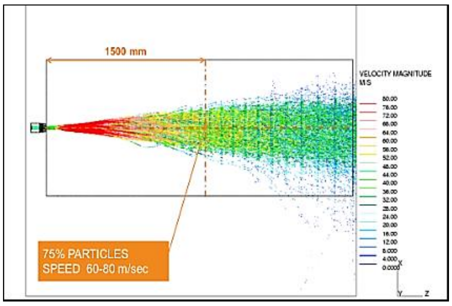

Figure 17b

- The material yield is largely influenced by the distance from the injector tip to the slag level. The stream velocity can help dust recovery but it is prone to lose momentum because distance and the free jet is hugely affected by thermal buoyancy and cross flows; proper installation of injectors leads to a reduction in the CaO concentration in the baghouse dust. Hereinafter some data collected before and after an installation in a steelmaking plant in Australia in 2012 (Figure 18a, b).

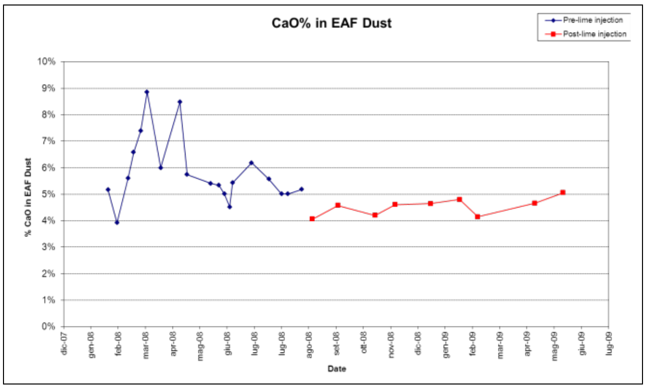

Figure 18a
CaO concentration in the baghouse dust prior and after injection

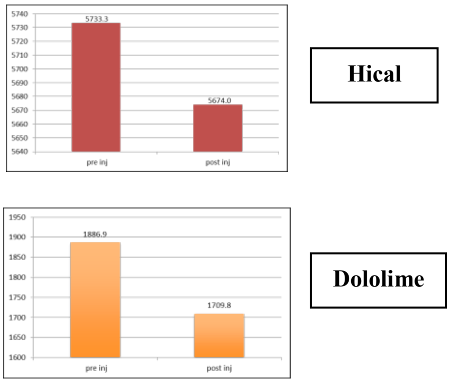

Figure 18b
Hical and dololime consumptions prior and after injection

Pneumatic dispensers

The pressure dispenser (Figure 19) and the inherent flow control equipment is the core of the pneumatic conveying system.

The dispenser must have a capacity big enough to store the fluxes to be injected during power-on times and it will automatically reload from the silo or day-bin installed above when needed. The dispenser tank is suspended on three compression load cells to continuously monitor and control its weight. The material feed rate control is based on a pressurization system and a proportional knife valve that has the ability to change the outflow cross section. Poor material flow control is adjusted by opening the knife valve or increasing the internal tank pressure progressively. A fluidification system, fit at the bin discharging cone, is aimed to reduce the wall friction and it consists of pulsing vibration pads that release air to compensate the internal pressure losses due to the material transportation. The pressure vessel discharging cone has to be designed inside with antifriction material in order to limit the risk of producing cohesive arcs or material settlement to guarantee smooth operations.

Figure 19 – lime dispenser

It is paramount for an efficient pneumatic injection system to control the carrier gas flow rate with a proportional flow regulation servo-valve (Fig. 20) because it will allow to reduce the carrier gas flow during the purging periods when material injection is not required. Moreover, this kind of regulation will automatically adjust the carrier gas flow rate as a function of the material feed rate to cope with the appropriate solid to gas ratio and in case of a line pressure increase, the material flow will be stopped and the flow regulating valve will be fully opened to clear the line before it blocks.

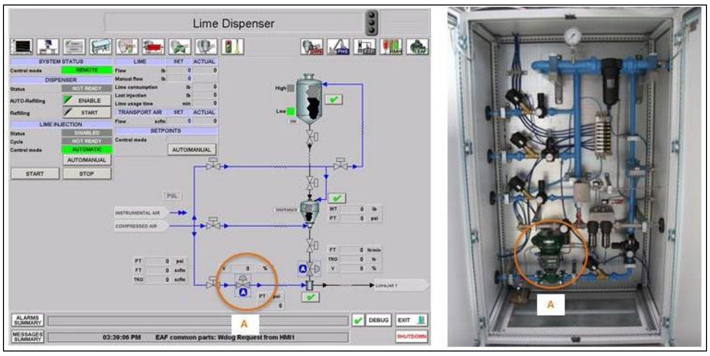

Figure 20 –proportional flow regulation servo valve

Material characteristics

The quality of the slag builders plays a key role in the overall system performance of pneumatic injection in terms of process efficiency, system availability and equipment reliability.

Chemical analysis is crucial to the slag metallurgy [10]. The chemical composition can be easily analyzed in a chemical laboratory by widely available XRF instruments. CaO and MgO concentration should be maximized, as all other components are substantially acidic and act as a burden to the steelmaking process, affecting the metallic yield. The LOI (loss of ignition) test determines the calcination degree and the moisture content. CO_2 and H_2O are energy consuming and have a negative effect on the furnace heat balance. However, the boil produced by the released gases help the stones disaggregation and the dissolution of small crystals into the slag [11]. Gas bubbles are useful for the initiation of foaming reactions [12]. Quite relevant to the kinetics of metallurgical reactions is the reactivity or the efficacy of flux material to be dissolved in the slag. This can be achieved with soft powdered solids composed by small sized crystals with high porosity [14].

The physical properties are equally relevant. Among the others, the grain size distribution can be easily determined by a sieve test and used to tune the dosing and conveying system. Coarser fractions require oversized regulation devices and piping to avoid interlocking arcs and plugs. Saltation and choking velocity raise exponentially for larger stones, increasing the demand of carrier gas flow to avoid settlement. It also causes significant limitations in the conveying route extension.

Size distribution			Chemical analysis		
Grain size (Ø)		[%]	Description	HiCal Lime	Dololime
0 < Ø < ¾"	0 < Ø < 20 [mm]	100	CaO	92	58
Mesh #9 and down	0 < Ø < 2.0 [mm]	20 min	MgO	1,5	35
Mesh #3 to 0.6 inch.	5 < Ø < 15 [mm]	50 min	SiO_2	2	2,5
Mesh #30 and down	0 < Ø < 0.6 [mm]	20 max	Al_2O_3	0	0,5
			Fe_2O_3	1	1,5
			CO_2	2,5	2
			Moisture	< 1	< 1
			Density	1000 Kg/m³ [62 lb/ft³]	1000 Kg/m³ [62 lb/ft³]

Table 1- material characteristics

Dust is easily dragged into the off-gas evacuation system hindering the injected material yield. Finer fractions easily segregate, increasing the wall friction and increasing the risk to produce cohesive arcs and cause dispenser blockages [15] [16]. Powdery material may coat the pipes inner surface and the impact of coarser stones usually breaks and reduces this coated layer but when the phenomenon is excessively large, the coating may keep growing until it blocks the line (Figure 21).

Figure 21 – pipes coated by lime fines

However, a limited fraction of fine grained material is not only tolerated, but it can also be beneficial for pneumatic transportation.

The impact strength characteristic of the bulk material also has an effect on dust generation (Figure 22). Between the truck loading operation, transportation, storage refilling and pneumatic conveying, the solid material undergoes continuous impacts which degrades the grains into dust giving rise to poor flow controls and frequent blockages during pneumatic transportation.

Figure 22 – Different material sieves

OPERATIONAL RESULTS

Lime injection offers several evident operational advantages (in particular on the lining lifetime), but are difficult to ponder in their impact on the EAF consumption and performance figures.

The introduction of pneumatic flux injection cuts the operational costs involved with the alternative methods for storing and handling slag builder materials combined with less material losses and less manpower needed for maintenance and housekeeping.

Power-on time can benefit from the utilization of higher arc power in situations where the transformer usage is limited by the hot spot radiation. On a smaller magnitude, some benefits can be achieved from a more stable foaming slag where reduced power-on time consequently reduces the electrode tip consumption by increasing the arc impedance.

Adding fluxes injection in the EAF have been proven in practice by excellent results achieved in several plants (Table 2), where at the original injectors lay-out was added a sidewall lime injection system.

METRIC	**PLANT "A" Country USA AC EBT EAF - 130t**			**PLANT "B" Country USA AC EBT EAF - 160t**			**PLANT "C" Country USA DC EBT EAF - 160t**		
	Before	After	%	Before	After	%	Before	After	%
Power-on time [min]	44,7	43,5	-2,7	39,0	38,0	-2,6	33,0	32,0	-3,0
Electrical energy [kWh/t]	422	401	-5,0	331	320	-3,3	338	312	-7,7
Lime /Dolomite [kg/t]	93,0	90,0	-3,2	55,0	51,0	-7,3	66,2	52,3	-21,0
Refractory life [weeks]	6	9	+50	8	10	+25%	NA	NA	NA
Bottom patching [kg/t]	NA	NA	NA	1,38	0,94	-31,9	NA	NA	NA
Gunning [kg/t]	NA	NA	NA	1,34	1,06	-20,9	NA	NA	NA

IMPERIAL	**PLANT "A" Country USA AC EBT EAF - 145t**			**PLANT "B" Country USA AC EBT EAF - 175t**			**PLANT "C" Country USA DC EBT EAF - 175t**		
	Before	After	%	Before	After	%	Before	After	%
Power-on time [min]	44,7	43,5	-2,7	39,0	38,0	-2,6	33,0	32,0	-3,0
Electrical energy [kWh/t]	383	364	-5,0	301	291	-3,3	307	283	-7,7
Lime /Dolomite [lbs/t]	186	180	-3,2	110	102	-7,3	132	105	-21,0
Refractory life [weeks]	6	9	+50	8	10	+25%	NA	NA	NA
Bottom patching [lbs/t]	NA	NA	NA	2.76	1.88	-31,9	NA	NA	NA
Gunning [lbs/t]	NA	NA	NA	2.68	2.12	-20,9	NA	NA	NA

Table 2 – operating results before/after pneumatic lime injection

CONCLUSIONS

Pneumatic injection of fluxes has improved over the recent years and nowadays is a reliable system that enables the steelmaker to considerably improve operations and to integrate slag management in the process control closing the loop with slag analysis and electric arc regulation. New categories of recycled materials are currently considered and tested for injection in the slag, for instance, crushed magnesia bricks or ladle recycled slag have already been successfully tested.

Among others, the main benefits of the slag building materials addition via pneumatic injection are:

- Elimination/reduction of all fluxes charged through the EAF roof;
- Furnace bay environment improvement reducing the environmental footprint;
- Low operating and maintenance costs;
- Reduction of conversion costs;
- A better yield of the material being injected directly into the slag;
- Metallurgical process optimization due to faster reaction of lime and/or dolomite;
- Efficient dephosphorization;
- Continuous foaming slag formation with higher volume and longer endurance;
- Better bath insulation with reduced temperature losses and less nitrogen pick-up;
- Arc stability improvement due to earlier foamed slag formation which creates arc stability (lower impedance) and higher active power;
- Hot spot protection enhancing the refractory lifetime and eliminating delays due to patching.

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