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Inert Gas Stirring in Electric Arc Furnaces: Metallurgical Benefits and Raw Material Strategies for Green Steelmaking

Numerous new electric arc furnaces (EAFs) are currently being designed and installed globally to reduce the CO_2 intensity of steelmaking, using steel scrap, direct reduced iron, and/or hot briquetted iron, and occasionally hot metal in integrated steel plants. The planned melting weights (including tapped steel weight and hot heel) are generally larger than the average of existing EAFs, requiring additional stirring technologies to achieve optimum productivity. With the installation of new EAFs in integrated steel plants, partly substituting hot metal production from blast furnaces, the metallurgical requirements will also increase. Inert gas stirring is an established method for improving process control, energy efficiency, metal yield, melting time, and metallurgical performance in EAF steelmaking areas such as oxygen control and dephosphorisation. To support these benefits and meet the increasing demands of larger EAFs, RHI Magnesita's portfolio of purging plugs has been expanded to meet the higher flow rates. The improvements in EAF process efficiency and metallurgy achieved with inert gas stirring are presented in industrial case studies covering EAFs charged with steel scrap, direct reduced iron, and/or hot metal.

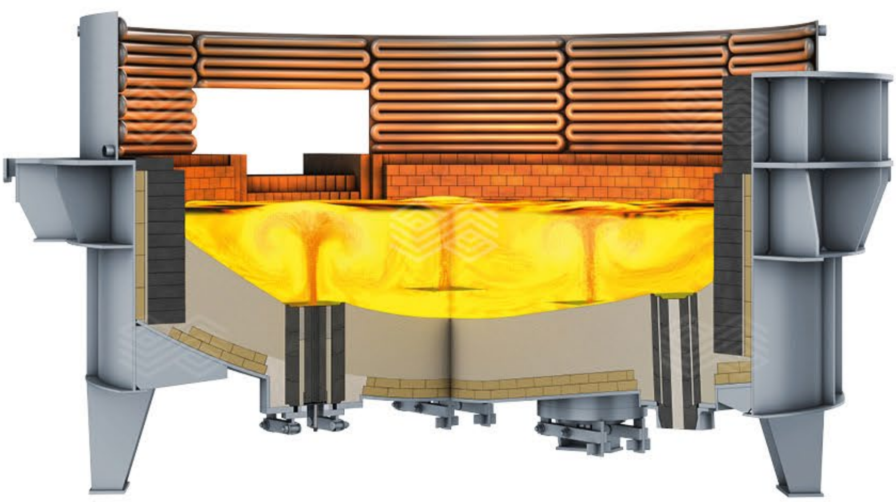
Introduction

The global initiatives for low- and ultimately net-zero CO_2 emission steelmaking are based on an increased share of steel scrap and direct reduced iron (DRI), with DRI-based electric arc furnace (EAF) steelmaking gradually replacing the conventional blast furnace–basic oxygen furnace (BF–BOF) route. Plant suppliers are currently designing and planning numerous new EAFs for both greenfield and brownfield projects worldwide. In medium- and large-scale integrated steel plants, new EAFs are being designed with melting weights of 200 up to 400 tonnes (tapped steel weight plus hot heel)—significantly larger than the current average EAF size—in order to provide the necessary mass flow for the existing secondary steelmaking and casting infrastructure of integrated steel plants.

Although mainly designed for charging with steel scrap, these EAF projects also consider the use of DRI in cold or hot conditions, hot briquetted iron (HBI), and hot metal during the transition period in steel plants with BFs. Replacing coke as the reducing agent in BFs with reformed natural gas (i.e., CO–H_2 gas mixtures) or, later, with 100% H_2 in direct reduction plants, together with the decreasing CO_2 intensity of electrical energy, contributes to lower total CO_2 emissions. The high flexibility of the EAF for various raw materials and changing market demands, combined with the higher cost of electrical energy, however, increases conversion costs and underscores the need to reduce them.

With increasing steel tap weights, the demand for efficient mixing of the steel melt in the EAF also rises. The mixing impact of the electric arcs and oxygen injectors is restricted to the melt surface covered with slag. The most efficient and well-established technology for increasing melt mixing in EAFs, BOFs, and ladles is inert gas stirring (Figure 1). Electromagnetic stirring has been introduced recently for EAFs, but it involves significantly higher CAPEX with only comparable process improvement figures.

Figure 1.
Increased melt mixing using inert gas purging plugs installed in the EAF hearth.



For inert gas stirring in EAFs, gas purging plugs with a multi-hole design for safe gas injection into the steel melt are the most commonly used technology worldwide (Figure 2). RHI Magnesita has more than 70 EAF references globally, spanning from carbon steelmaking based on steel scrap, DRI, and hot metal to alloyed and high-alloyed stainless steelmaking, besides numerous references for inert gas purging in BOFs and nonferrous metallurgical plants. Many of the current customers have been applying inert gas stirring in EAFs with direct purging plugs (e.g., RADEX DPP) for decades [1–9].

Process Improvements

Inert gas purging of the steel melt provides both effective mixing of the melt volume and metallurgical benefits due to the presence of argon or nitrogen bubbles. Mixing the steel melt is improved by the uprising gas–melt mixture of reduced density above the purging plugs. Temperature gradients between hot spots around the electric arcs and lower melt volumes near the EAF hearth are reduced. Increased melt movement accelerates the melting of larger scrap pieces and both energy transfer efficiency and melting time (power-on time) are improved. A second benefit of the enhanced mass transfer in the melt volume is the more homogeneous distribution of dissolved elements in the steel.

Figure 2.

RADEX DPP purging plug featuring a multi-hole design and integrated wear indicator. Constructed from a MgO-C body with a density of 2.9–3.0 g/cm^3, and low open porosity of 0.7–4.0% comparable to high-quality MgO-C bricks used in EAF sidewalls.

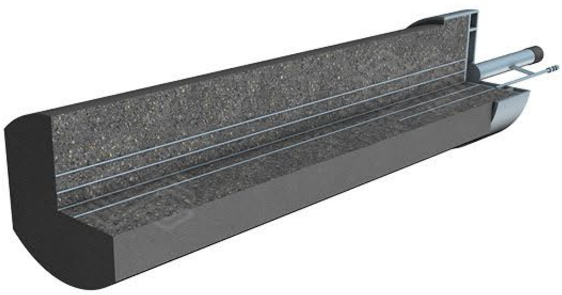
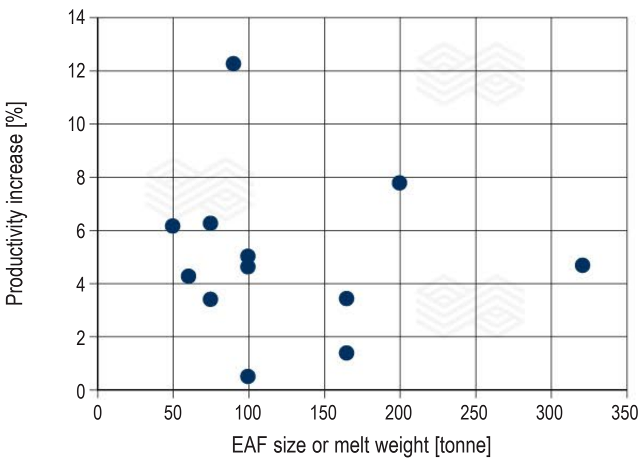


Figure 3.

Productivity increases from inert gas purging for various EAF sizes or melt weights, resulting from higher metal yield and reduced tap-to-tap time.



Metal yield increases due to the avoidance of overoxidation and reduced formation and loss of FeO into the slag. Together, these effects of inert gas stirring increase EAF productivity by a few percent, with examples shown in Figure 3.

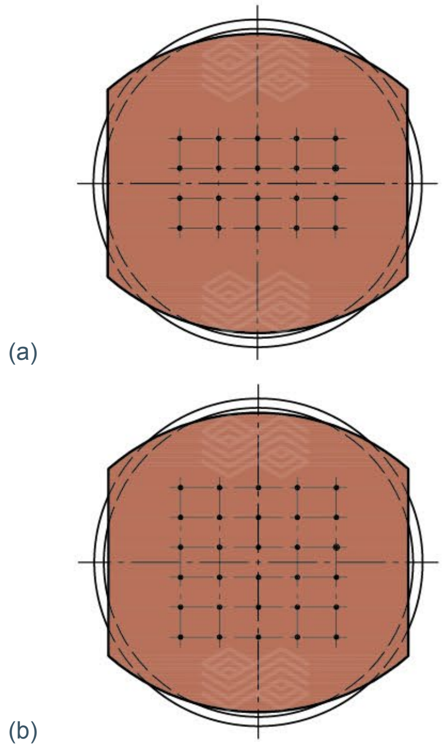
High productivity through efficient gas stirring is crucial, especially at full plant capacity utilisation, and resulting energy savings consistently lead to cost reductions and scope 2 CO_2 savings [10]. Additional metallurgical benefits due to the presence of argon or nitrogen bubbles in the raw steel melt are described in a later section, as these aspects are becoming increasingly important for new DRI-based production of top-quality steel grades, which will gradually replace BOF-based steel production in the coming years.

RADEX Directional Porosity Plugs

The standard RADEX DPPs consist of 19 steel pipes that deliver inert gas to the steel melt without any loss in the EAF hearth (Figure 4a). The typical flow range of current RADEX DPP references is between 30 L/min (default free flow) and up to 100 or 120 L/min. However, the design of new large EAFs—intended to replace converters at integrated steel plants in Europe and Asia, with melt weights up to 400 tonnes—requires a higher gas flow rate per plug to achieve the necessary mixing. For this purpose, a RADEX DPP plug with 29 pipes has been designed (Figure 4b), allowing higher gas flow rates while maintaining moderate gas pressures (e.g., 3–6 bar), compatible with typical gas supply networks.

Figure 4.

Steel tube configuration of the (a) 19-pipe RADEX DPP28 and (b) 29-pipe RADEX DPP29 designs.



(a)

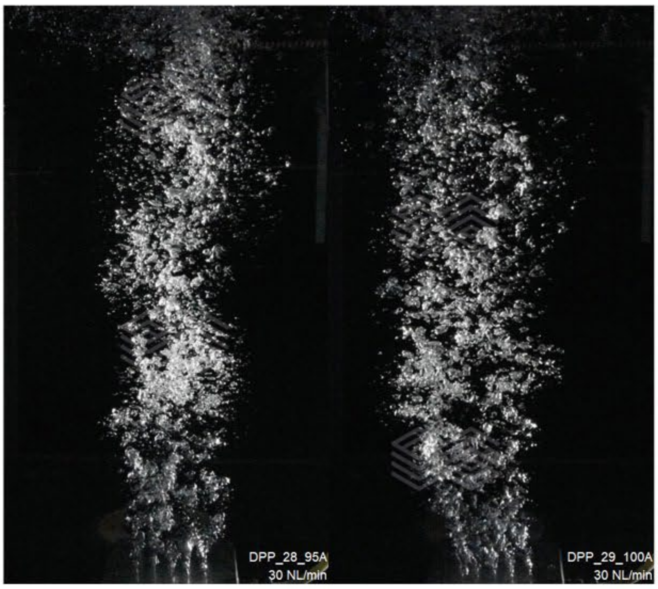
(b)

Water Model Investigations of Multi-Hole Plugs for EAFs

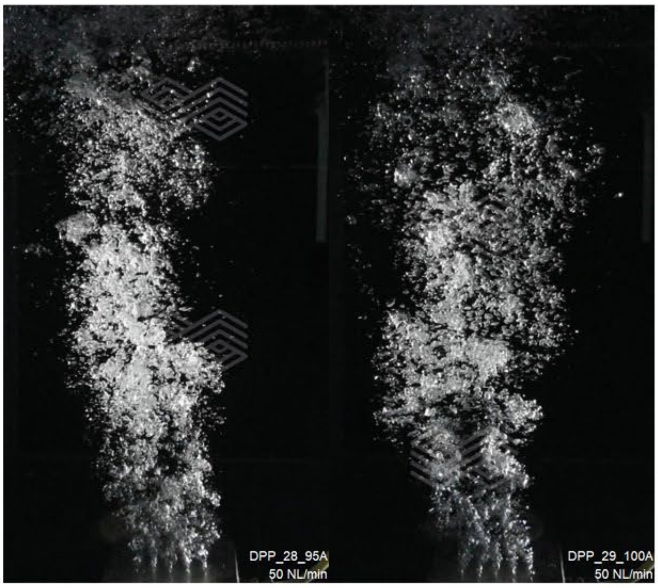
Water model investigations have been established for steel metallurgical phenomena, since the viscosity of liquid steel and water are in the same range, making Reynolds similarity achievable at room temperature. In this case, the formation and evolution of bubbles (air as an analogue for nitrogen) have been investigated at typical gas flow rates of 30, 50, 100, and 150 L/min. It is clearly visible that the multi-hole plug with 29 pipes provides a more homogeneous distribution of bubbles than the standard 19-pipe design at all gas flow rates, due to the additional 10 pipes (Figure 5).

Figure 5.

Instantaneous bubble distribution above a 19-pipe DPP28 (left) and a 29-pipe DPP29 (right) at gas flow rates of (a) 30 L/min, (b) 50 L/min, (c) 100 L/min, and (d) 150 L/min.



(a)



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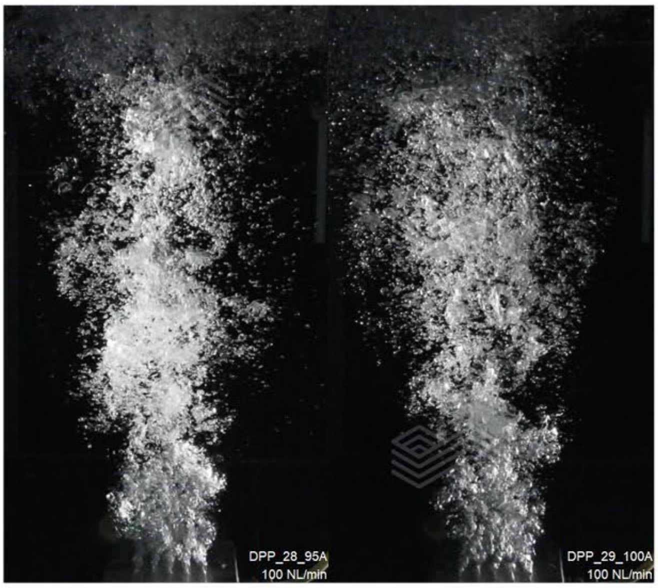

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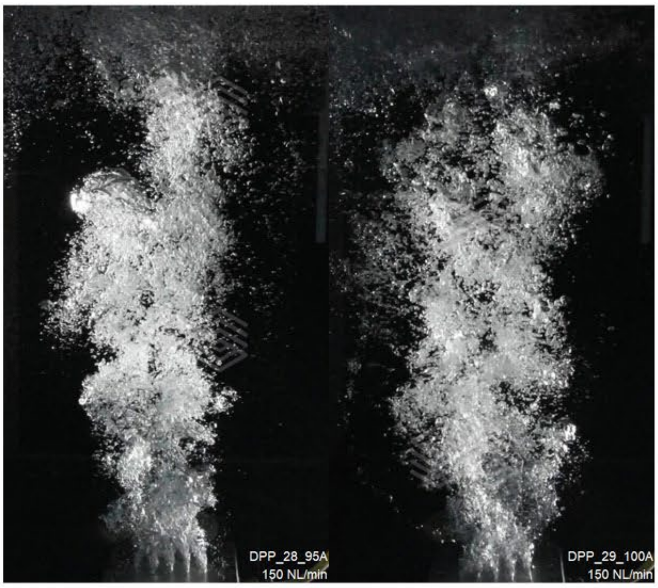


d

The flow regime of the uprising plume over the plug is turbulent and highly dynamic over time. Pulsation of the compressible gas flow at the pipe mouths is typical and causes back-attack of water—namely steel melt—on the hot face of the plug. Both agglomeration of bubbles and disintegration of larger bubbles into smaller ones occur (see Figure 5). When integrating the bubble evolution over time, a clearer picture of their distribution as a function of gas flow rate emerges (Figure 6).

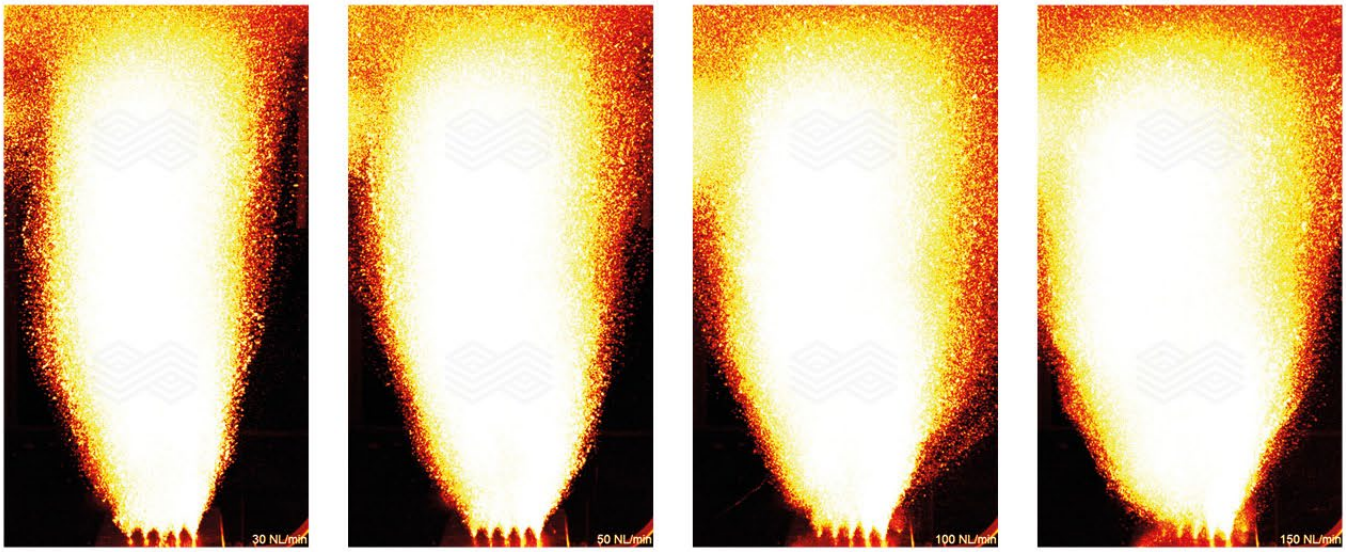
At all four gas flow rates investigated, the bubble area was larger for 29 pipes than for 19 pipes, indicating a higher proportion of small, well-distributed bubbles and a larger interface between inert gas and water (i.e., steel melt). However, the effect of improved bubble distribution with a larger number of pipes diminished at elevated gas flow rates (i.e., above 100 L/min). The likely reason is the increasing upward velocity of the bubble columns with increased total flow rates. At such high rates, the time available for bubble distribution decreases, and the influence of pipe number becomes less significant.

Consequently, the 29-pipe DPP29 is expected to provide advantages for metallurgical benefits such as hydrogen degassing and nitrogen removal through the steel–gas interface at low to moderate gas flow rates up to 100 L/min, whereas at higher flow rates (i.e., 150 L/min and above) mixing of the steel melt becomes increasingly important (e.g., decarburisation and dephosphorisation via steel slag interaction).

Figure 6.

Integrated bubble distribution over time for increasing gas flow rates: (a) 19-pipe DPP28 and (b) 29-pipe DPP29. Percentages indicate relative areas of bubble volumes (white, yellow, and red areas) as an analogue for the gas–steel interface.

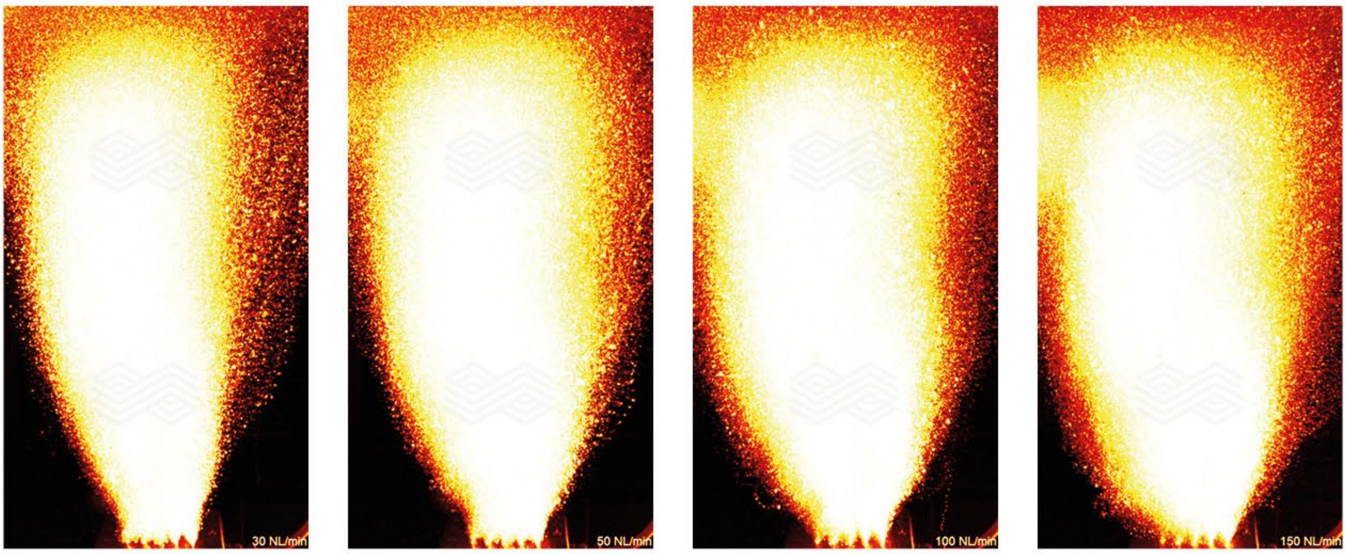
80% 88% 95% 100%



30 L/min 50 L/min 100 L/min 150 L/min

(a)

96% 103% 108% 110%



30 L/min 50 L/min 100 L/min 150 L/min

(b)

Evolution of Inert Gas Flow Rates for EAF Bottom Stirring

After the implementation of inert gas stirring systems in numerous EAFs worldwide in the 1990s—driven by the limited efficiency of oxygen door lance injection—inert gas flow rates decreased from 70–150 L/min levels to 30–120 L/min in order to reduce gas costs and increase plug lifetime (Figure 7). The improved efficiency of multiple supersonic oxygen sidewall injectors further reduced the need for highly intense inert gas stirring.

The upcoming increased use of steel scrap, DRI, HBI, and hot metal in EAFs to achieve lower emission figures will, however, increase the need for efficient mass and energy transfer in modern EAFs, because the carbon input and the need for efficient decarburisation will increase at high productivity levels. A carbon content of 4% from hot metal or 2% from DRI will significantly increase the carbon supply. However, as DRI also introduces a few percent of FeO ($C + FeO \rightarrow Fe + CO$), the amount of oxygen that must be injected may not need to be increased to remove the additional carbon from DRI charging. Therefore, insufficient melt movement will still remain a bottleneck for achieving high EAF productivity when scrap is replaced by DRI and/or hot metal.

The number of purging plugs in the EAF is restricted to the central hearth to avoid erosion of the banks and prevent interference of the stirring spots with arc control. Increasing the total inert gas flow rate will therefore require raising the flow rate per plug to 150 L/min or higher (see Figure 7). The DPP with 29 pipes instead of 19 pipes has been especially designed for applications with increased inert gas flow rates at moderate gas pressures.

A comparison of specific total maximum gas flow rates in EAFs and BOFs highlights the limitation of inert gas stirring in the EAF: 0.15–0.2 m^3/hour/tonne for EAFs versus 1–4 m^3/hour/tonne for BOFs (Table I). This difference arises

Figure 7.

Evolution of the applied inert gas flow rates and representative melt bath images for a 19-pipe DPP28/80A purging plug in (a) 1990s at 70–150 L/min [9] and (b) the 2020s for a range of 30–120 L/min. The forecasted 2030s inert gas flow rates with a 29-pipe RADEX DPP29 purging plug are 30–200 L/min.

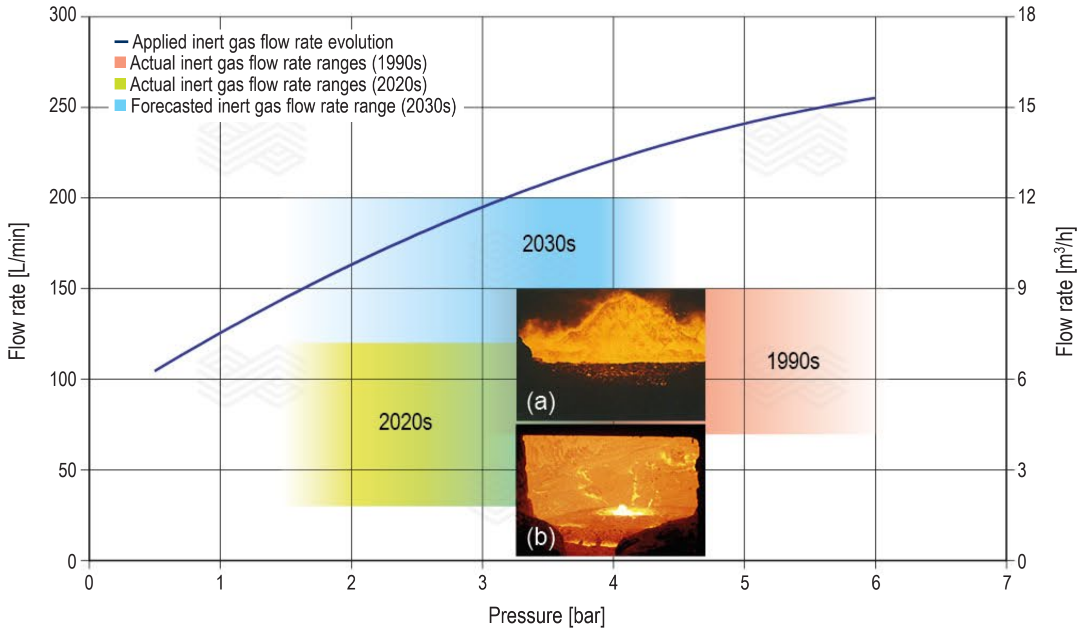


Table I.

Examples of maximum inert gas flow rates, in typical flow programmes, and specific inert gas consumption at BOF and EAF steel plants worldwide.

Furnace	Maximum gas flow rate per plug [L/min]	Number of plugs	Total gas flow rate [m³/hour]	Specific total gas flow rate [m³/hour/tonne]
125-tonne BOF	600	8	288	2.3
170-tonne BOF	1000	12	720	4.2
250-tonne BOF	660	10	396	1.6
330-tonne BOF	2000	9	1080	3.3
100-tonne EAF	80	3	14.5	0.15
180-tonne EAF	120	4	28.8	0.16
300-tonne EAF	120	6	43.2	0.15
New 300-tonne EAF	200	6	72.0	0.24

from the lining design and, more importantly, due to electric arc control by arc-length regulation near the steel bath surface. Inert gas flow rates are therefore expected to remain restricted to around 200 L/min per plug, in order to not disturb the arc control through steel bath elevation. An example of the negative impact was observed during the early EAF standard operation, when electrodes were elevated during intense oxygen door lance injection and inert gas stirring. New EAF designs with increased melt volumes provide more space for optimal plug positioning and increased number, enabling efficient mixing at an appropriate distance from the electric arcs. This supports the state-of-the-art continuous power-on strategy while minimising impact on the hearth lining.

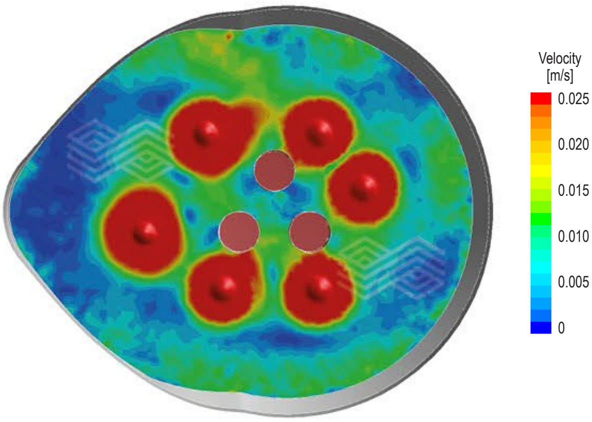
In general, although melt movement in the EAF, and bottom stirring in particular, is restricted by EAF-specific process and refractory lining conditions, it is crucial to ensure sufficient mixing of the large melt volumes in new EAFs for maximum productivity under low-emission steelmaking conditions. Increased mixing through higher total gas flow rates can be achieved by installing an increased number of plugs (Figure 8), and by operating with higher gas flow rates per plug. Increased flow rates per plug are enabled by new plugs designs (e.g., 29-pipe RADEX DPP29), and by further improvements in refractory grades for purging plugs.

Metallurgical Benefits of Inert Gas Stirring in EAFs

EAF inert gas stirring uses nitrogen and/or argon, depending on availability, metallurgical requirements, and costs. The continuous inert gas bubble columns provide several metallurgical benefits in the EAF: Increased metal yield, increased dephosphorisation, lower nitrogen levels with argon gas stirring, better control of the FeO content in the slag, and most importantly, the avoidance of overoxidised slags.

Figure 8.

CFD-generated velocity pattern of a large new EAF design with 6 purging plugs (150 L/min flow rate per plug) [10].



Inert gas purging with a multi-hole plug design (see Figure 4) provides metallurgically efficient gas–metal interfaces in the bubble columns, while also creating a complex mixing flow pattern through buoyancy-driven uprising mass flows of lower density. Increased argon gas–metal interfaces in the steel melt decrease nitrogen content and enhance the degassing of dissolved CO. The lower CO partial pressure in the steel melt, achieved with argon or nitrogen gases, further decreases O and C in the melt by shifting towards equilibrium concentrations. Today, inert gas stirring is state-of-the-art in high-grade steelmaking, particularly in BOFs worldwide, due to its clear benefits for the cost-effective productivity of high-grade steels.

An early study on gas stirring in a 55-tonne EAF with 3 plugs and a nitrogen flow rate of 67–80 L/min per plug showed a decrease in slag FeO, improved Mn yield, a decrease of oxygen levels in the tapped steel from 900 ppm to 700 ppm, and a controlled nitrogen pickup from 57 ppm to 62 ppm (i.e., an increase of 9%) [8]. Additionally, a recent case study in a 90-tonne EAF with 3 plugs and 50 L/min argon gas flow rate per plug demonstrated a sustained nitrogen decrease of approximately 10% (Table II) over a 3-month period, reducing the impact of varying scrap quality on nitrogen levels. Both case studies were carried out in European EAFs with 100% steel scrap charging.

A RADEX DPP study in Asia on a 55-tonne furnace charged with approximately 80% hot metal and 20% steel scrap and equipped with 2 plugs for a 50–125 L/min nitrogen flow rate per plug, showed no increase in nitrogen levels: 62.5 ppm (σ = 6.1 ppm) versus 62.7 ppm (σ = 8.8 ppm) with nitrogen gas purging. This was attributed to the high amount of CO gas generated in the hot metal bath during oxygen lancing. The lifetime of the plugs was 850 heats.

Table II.

Example of reduced nitrogen concentrations in tapped steel with argon stirring (3 plugs x 50 L/min flow rate) and 100% steel scrap charges in a 90-tonne EAF.

Month	Average nitrogen steel concentration without stirring [ppm]	Average nitrogen steel concentration with argon stirring [ppm]
June	87.0	
July	86.6	
August		76.7
September		79.1
October		77.8

Steel production based on DRI melting in the EAF is already the dominant process in the Arab region. The process improvements of inert gas stirring observed in a 250-tonne EAF, charged with approximately 90% DRI and 10% steel scrap, are given in Table III, where argon stirring decreased electrical energy consumption and power-on time. Additionally, the temperature at the ladle furnace arrival was higher with gas stirring and the dissolved oxygen content was slightly lower.

Hot metal is used as a ferrous material input for EAFs in some steel plants, particularly in India and China. Several case studies have been published regarding the benefits of inert gas stirring for hot metal charges [3,6,7], showing clear improvements in the steel melt decarburisation rate—from 0.04%/minute to 0.1%/minute [3]—as well as reductions in tap-to-tap time by approximately 4 minutes [3] and 2 minutes [6,7]. Additional reported benefits include electrical energy savings, improved dephosphorisation (Table IV), and decreased FeO content in the slag [3,6,7]. In one reported case, the lifetime of the bottom purging plugs was 688 heats, lasting the entire EAF production campaign [3].

Conclusions

The demand for large-volume EAF steelmaking of top-quality steel grades, with evolving raw material concepts, is expected to increase as the global steel industry transitions towards green steelmaking at corresponding production capacities. Providing additional melt movement through inert gas purging is crucial for achieving a highly productive EAF process with maximum raw material conversion efficiency, especially for EAFs with tap weights exceeding 150-tonne. RHI Magnesita's established purging plug portfolio has been expanded with a new purging plug design, which improves metallurgical performance by increasing the steel–melt interface and enables elevated gas flow rates at moderate gas counter-pressures in new EAFs with large melting volumes.

The application of inert gas, ranging from low to high flow rates for large EAF sizes (typically 30–150 L/min and potentially 200 L/min with the new RADEX DPP29 design) requires very precise flow control, for example by modern mass flow controllers. RHI Magnesita provides the entire gas purging system including plugs, gas control unit, and services—as a one-stop shop [10].

Besides improved melting of steel scrap and DRI charges, the metallurgical benefits of inert gas bubble columns on nitrogen and oxygen levels, as well as improved dephosphorisation of hot metal charges, have been demonstrated in various industrial case studies and corresponding cost savings are in the range of 1–4 €/tonne$_{\text{liquid steel}}$.

In summary, inert gas purging offers a wide range of EAF process benefits across different raw material strategies—steel scrap, DRI/HBI, and hot metal—while maintaining comparably low costs and achieving a fast return on investment within just a few months.

Table III.

Process improvements in a 250-tonne EAF observed with inert gas stirring (4 plugs x 125 L/min flow rate) during DRI heats.

Parameter	Without argon stirring	With argon stirring	Benefit with argon stirring
Electrical energy consumption [kWh/tonne]	623	614	-9
Power-on time [minute]	109.4	108.2	-1.2
Heats <1560 °C on arrival at ladle furnace [%]	53	35	-18
Heats <800 ppm oxygen at tapping [%]	65	67	+2

Table IV.

Process improvements in a 75-tonne EAF observed with inert gas stirring (3 plugs x 50 L/min flow rate) during heats with steel scrap and hot metal [6]. * The phosphorus slag/metal partition ratio was calculated from the published data.

Parameter	Without stirring	With stirring	Benefit with stirring
P concentration in slag [%]	0.51	0.78	+0.27
P content in steel [%]	0.008–0.030	0.007–0.026	
Phosphorus slag/metal partition ratio*	17–64	30–111	+75%
FeO concentration in slag [%]	23.4	19.3	-4.1

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