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Energy Savings and Additional Benefits of Inert Gas Stirring in Electric Arc Furnaces with a Focus on Green Steelmaking

New electric arc furnaces (EAFs) with large melt volumes are expected to meet the required steel production capacity at minimum CO_2 intensity during the green steel transformation period. As the impact of oxygen injectors on bath mixing decreases with increasing melt volume, additional stirring technologies are required for an optimum EAF process. Inert gas stirring is an established method for improving process control, energy efficiency, metal yield, and melting time. In the following paper, the benefits of RHI Magnesita's gas purging technology in EAFs are highlighted with a special focus on the influence of steel flow on refractory wear and hearth mix consumption. The process improvements observed are presented in industrial case studies covering EAFs fed by steel scrap, direct reduced iron, and/or hot metal. Furthermore, the gas purging benefits shown were achieved without an increase in refractory consumption, which is in contrast to competing EAF stirring technologies.

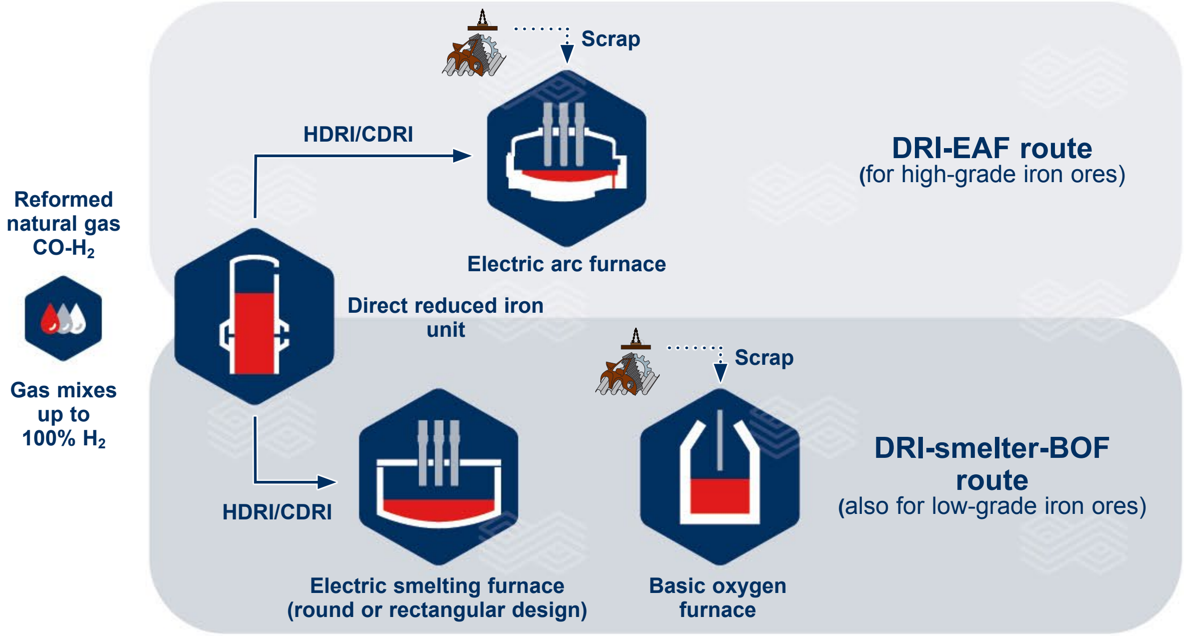
Introduction

The European Green Deal initiatives define the path towards an industry-based European economy with net CO_2 emissions close to zero by 2040–2050 and all steel producing companies in Europe have provided roadmaps, initiatives, R&D consortiums, and detailed action plans to fulfil the objectives. The electric arc furnace (EAF) represents the dominant technology in green steelmaking on a European and global level with the increased use of direct reduced iron (DRI) and recycled steel scrap (Figure 1), supplemented by an optional share of hot metal (HM) during the transition period of steel plants with blast furnaces (see page 10). Decreased CO_2 emission figures are achieved by replacing coke in blast furnaces with reformed natural gas (i.e., CO and H_2) or using H_2 as a reducing agent in direct reduction plants, as well as by decreasing the CO_2 intensity of electrical energy. However, the beneficial high flexibility of EAF steelmaking for various ferrous raw materials, varying market demands, and production volumes increase the conversion costs. This is mainly due to electrical energy costs and, to a lesser degree, increased specific refractory consumption figures.

The high production levels of typical integrated steel plants require EAFs with large melting volumes of 150 tonnes to >350 tonnes (including the hot heel). However, with an increasing EAF melt volume, the need for additional melt mixing technologies increases as the electric arcs and oxygen injectors, sources of momentum for melt mixing, are restricted to the melt surface covered with slag. The established and efficient technologies for increased melt mixing are inert gas stirring and electromagnetic stirring (EMS), a technology rarely used for the EAF until recently.

Figure 1.

Two options for green steelmaking using direct reduction: Electric arc furnace (EAF) plant based on hot and/or cold DRI (HDRI/CDRI) and a direct reduced iron (DRI) unit combined with a continuous electric smelting furnace (ESF), followed by the basic oxygen furnace (BOF) process (see page 10).



Process Improvements Through Enhanced Melt Movement in the Electric Arc Furnace

Some of the typical problems observed during the EAF daily operation are:

- Skull formation resulting in a variable melting volume due to low temperature and dead flow volumes.
- Reduced eccentric bottom tapping (EBT) opening rate due to cold spots near the EBT area.
- Unmelted input material from the slag pot decreasing metal yield.
- Hot spots located in the slag line area, which are critical for refractory wear.
- Carbon boiling especially observed when adding input materials with a high carbon content, such as pig iron, HM, or DRI.
- Low temperatures and sample reliability resulting in additional processing time during the secondary metallurgy.
- High slag zone wear rate due to a high oxidation state of the slag.
- High hearth mix wear rate due to cold spots (i.e., thermal imbalance).

Such problems mainly come from an improper thermal and chemical bath homogeneity and they directly affect the refractory performance.

In general, there are two possible sources of bath agitation or momentum to move and mix the steel melt and slag in the EAF: Electric arcs and the resulting material jets below the electrodes, and oxygen lances that induce melt flow through the impinging gas jets. However, both sources only affect the surface of the steel with restricted efficiency, due to a viscous slag layer covering the steel melt, and with increasing EAF sizes and melt volumes, as expected for the green steelmaking transformation, the impact of oxygen injectors and electrodes on bath mixing may not be enough. Therefore, in order to reduce the unbalanced thermal and chemical distribution in the furnace, it is necessary to improve bath agitation and melt homogenisation by adding other stirring sources.

Inert gas stirring is established as the most common method for improving process control, energy efficiency, metal yield, and process time in EAFs, converters, and ladles. The gas purging plugs, with a multihole design for safe gas injection into the steel melt, are the most common purging systems globally in EAFs, for example the RHI Magnesita direct purging plug (RADEX DPP) series (Figure 2). Further details regarding the technical and refractory concept of RHI Magnesita's purging plugs have been previously published [1,2]. RHI Magnesita has more than 50 references worldwide in carbon steel and stainless steel plants that currently use EAF inert gas stirring, and many of them have applied inert gas purging for decades [3–9].

In the following sections, process optimisations and improvements that have been observed in the field due to inert gas purging will be described. It is important to note that these benefits were realised even though the focus was on electricity savings.

Increased Thermal Homogeneity in the Steel Melt

Due to the improved bath movement, and thus bath mixing, the efficiency of heat transfer increases and the metallic input sources, scrap, and DRI melt faster, thereby avoiding unmelted residues and a varying furnace melt volume. Consequently, both the specific energy consumption and the power-on time of the furnace decrease (Figure 3). On the one hand, the energy savings decrease scope 2 CO_2 emissions and, on the other hand, the lower tap-to-tap time increases plant productivity. The reduction in power-on and process time also help to decrease the electrode graphite consumption.

Improved Control of Steel Tapping Temperature

The steel temperature at tapping was consecutively measured for a 75-tonne EAF before and after installing three gas purging plugs. The results showed that the standard deviation of the temperatures measured decreased from 21 °C to 7 °C with inert gas stirring. This higher temperature control at tapping leads to a better process control in the secondary metallurgy.

Figure 2.

Increased melt mixing by inert gas purging plugs in the EAF hearth.

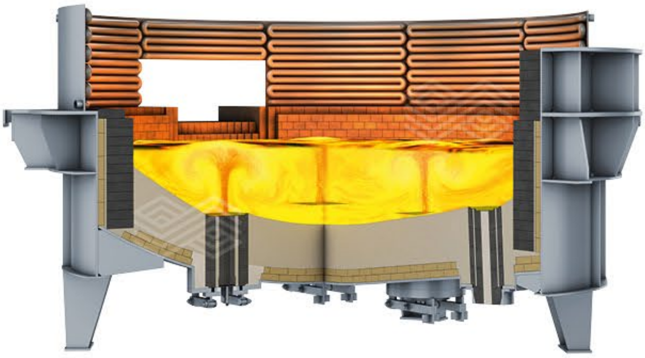
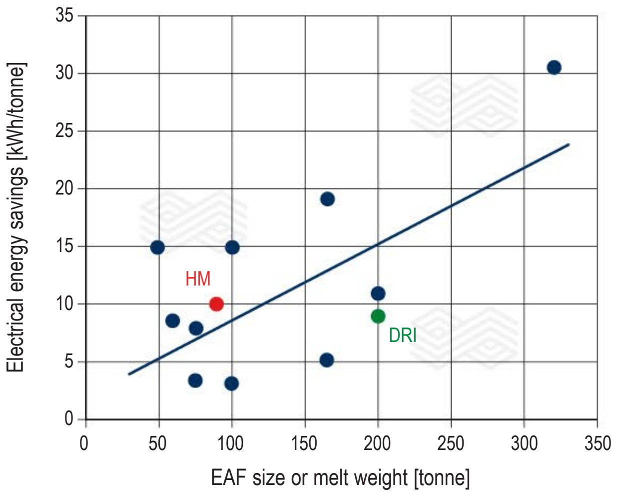


Figure 3.

Electrical energy savings with inert gas purging for different EAF sizes or melt weights: Savings in power-on time and scope 2 CO_2 emissions are proportional to the electrical energy savings. EAFs were charged with 100% steel scrap (blue), hot metal and scrap (red), or ~95% DRI (green).



Increased Chemical Homogeneity in the Steel Melt

At high chemical energy input, the instantaneous or retarded CO boiling due to the addition of high carbon-containing iron carriers, such as HM or DRI, is avoided by the continuously inserted bottom stirring gases. Furthermore, inert gas stirring significantly improves the control of FeO in the slag through an increased mass transfer between the slag and melt, as well as improved mixing of dissolved carbon and oxygen in the steel melt. The same process improvements also increase the metal yield in the case of alloyed steel production. Furthermore, dephosphorisation and the removal of nitrogen are increased with argon gas stirring. Nitrogen levels are further controlled by improved regular CO degassing.

Figure 4.

Productivity increases with inert gas purging for different EAF sizes or melt weights due to improved metal yield and a lower power-on time.

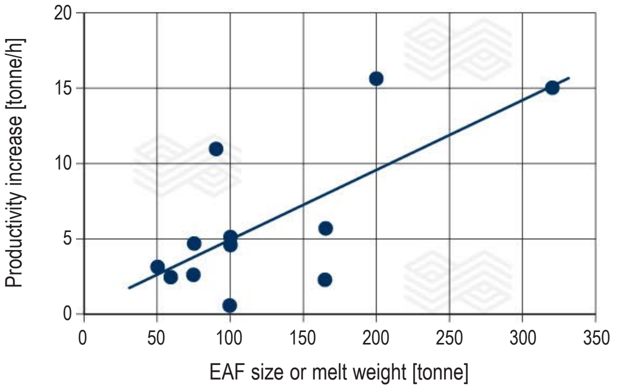
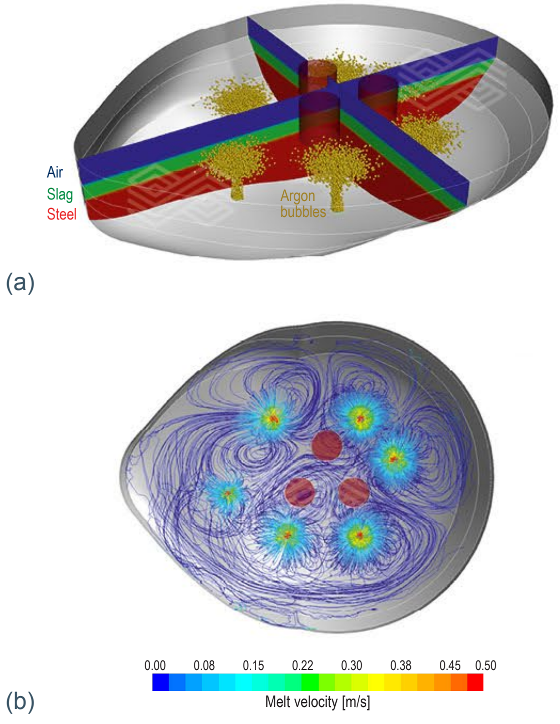


Figure 5.

(a) schematic showing the 1:1 computational model of a 250-tonne EAF with the various fluid phases, six bottom purging plugs, and three electrodes and (b) streamlines of the well-agitated steel melt indicate an absence of dead volumes.



Besides achieving the customer-specific targets, metal yield improvements in the range of a few percent and lower melting times result in a systematic productivity increase of EAFs with inert gas stirring (Figure 4). In general, Figures 3 and 4 corroborate the increased performance associated with gas purging for increasing EAF melting weights.

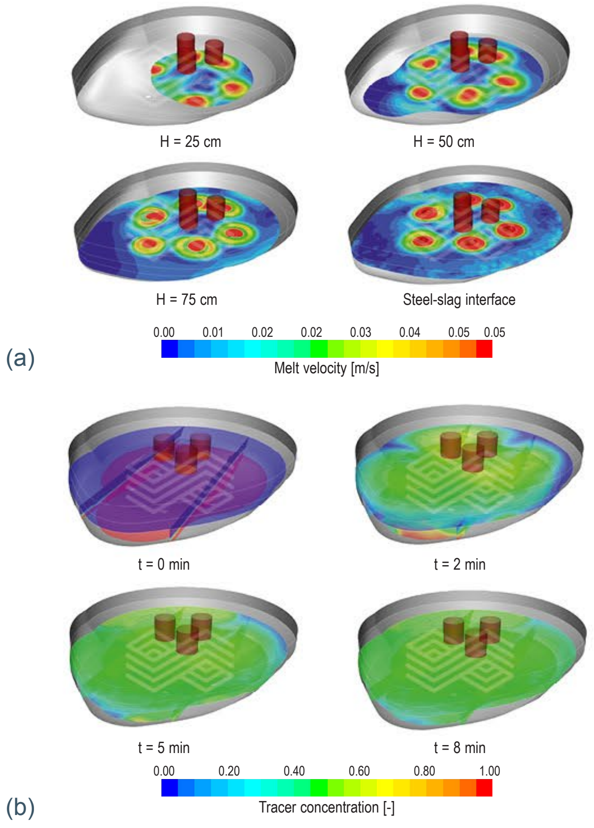
Flow Characteristics with Inert Gas Purging Plugs

A modernly designed EAF with a 250-tonne total melt weight was simulated to visualise the steel flow due to inert gas stirring using six bottom purging plugs. Transient computational fluid dynamics (CFD) methods for a multiphase modelling approach were used, namely a volume-of-fluid model combined with a discrete particle method. The maximum volume flow rates applied were 150 litre/minute per plug or 54 m^3/hour in total for six purging plugs, namely 0.216 m^3/tonne for a 60 minute tap-to-tap time. However, it is important to note that the actual gas consumption would be lower than 0.2 m^3/tonne as a result of process dependent and optimised flow programs.

Figure 5 shows the characteristic flow pattern developing in the steel bath after 8 minutes purging. This swirling and complex three-dimensional velocity field are indicative of good mixing efficiency within the steel bath and no dead volumes are observed. While the rising bubbles induce maximum steel velocities of up to 1 m/s, the average velocity is much slower, in the range of 10^{-2} m/s. The melt velocity modelling in Figure 6a depicts effective mixing

Figure 6.

Modelled steel flow in a 250-tonne EAF with six bottom purging plugs showing (a) effective mixing between the lower and upper volumes by rising steel mass flows and (b) tracer concentrations show the homogeneous mixing in the first few minutes.



between the lower and upper volumes due to rising steel mass flows and the tracer concentrations (Figure 6b) indicate homogenous mixing in the first few minutes of inert gas purging.

Wall Shear Stress Pattern and Implications on Refractory Wear

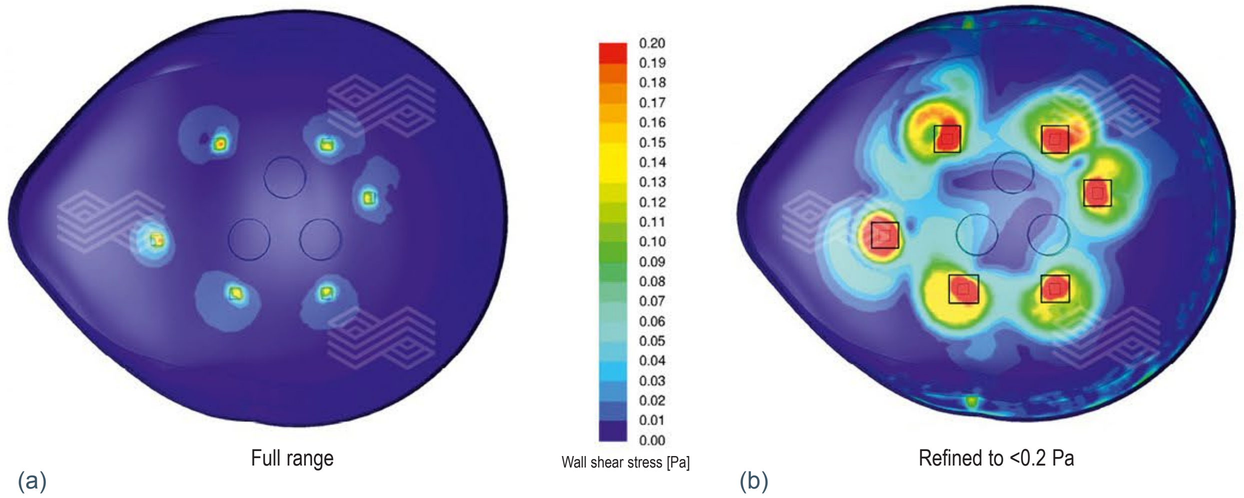
In this simulation study, the impact of increased melt movement on refractory hearth wear is directly related to the wall shear stresses from the liquid steel movement in the vicinity of the EAF hearth. Obviously, this approach only considers the erosion component and not the effect of chemical corrosion by slag. Figure 7 depicts wall shear stress levels on the hot side of an EAF hearth surface. In Figure 7a the scale is from zero to a maximum stress value of ~2 Pa, and the high stresses are clearly restricted to the plugs' hot face area (consisting of the top quality MgO-C DPPs and the surrounding MgO-C block depicted in Figure 8). In contrast, the compacted refractory hearth mix is exposed to rather low shear forces, as can be seen in Figure 7b, where the scale is refined to values below 0.2 Pa.

Influence on Hearth Mix Consumption

In addition to no increase in EAF hearth mix consumption having been observed with inert gas purging, the defined standard purging plug installation with surrounding blocks in the EAF hearth (see Figure 8) are special top-quality MgO-C products optimised for minimum wear rates and maximum lifetimes. In contrast, EMS introduces the momentum for melt movement in the lowest part of the steel melt directly on the refractory hearth in the entire area of the installed coils. The compensating mass flow in the upper melt volume results in a single roll flow regime [10]. As a result, the steel flow generated by EMS causes significantly higher shear stress patterns and erosion on the part of the EAF hearth affected. Increased hearth mix consumption after installation of an EMS system has been reported by two customers, with up to a 30% increase for one customer, and a third customer prefers a bricked MgO-C EAF hearth with EMS.

Figure 7.

Shear stress exerted by the agitated steel melt on the refractory hearth is restricted to the purging plug area. (a) full range of stress values (0–2 Pa) and (b) stress values refined to <0.2 Pa.

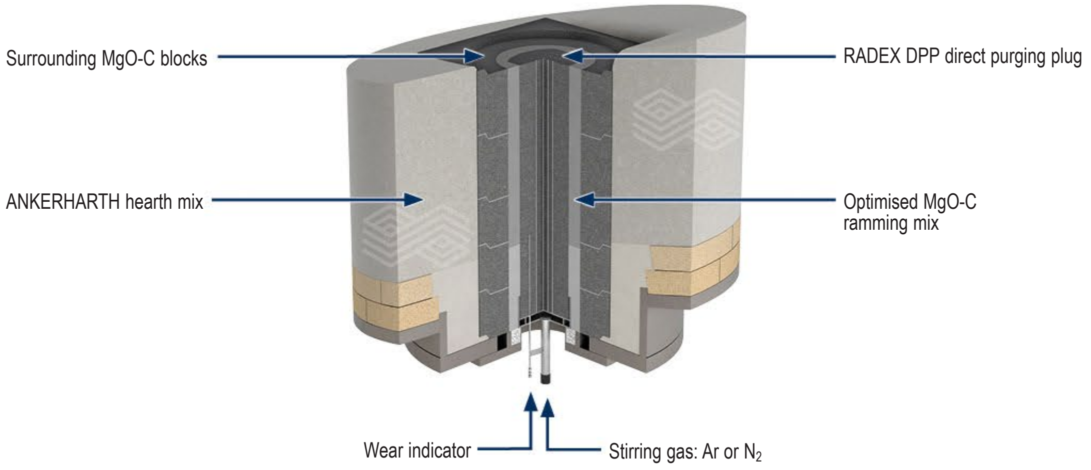


(a) Full range

(b) Refined to <0.2 Pa

Figure 8.

Standard installation of a RADEX DPP gas purging plug with surrounding MgO-C blocks to provide maximum stability and easy exchange of the plug with minimum hearth material losses at the end of the EAF production campaign.



Modern Gas Control Units

RHI Magnesita can provide the entire gas purging system consisting of the refractory bricks and mixes, the installation procedure, process support, and the gas control unit. The gas control unit was newly developed based on decades of experience with gas purging. A typical gas control station supplying one to six RADEX DPPs in the EAF is shown in Figure 9. Each plug is controlled separately and nitrogen and/or argon is used as the purging gas. The gas flow rates can be regulated independently of the EAF control using specific EAF operating parameters or they can be incorporated into the EAF control system.

The RADEX DPP gas purging system significantly increases the availability and reliability of gas purging during the entire EAF campaign. Some of the technical advantages of the state-of-the-art gas purging systems from RHI Magnesita include:

- Modular, maintenance-friendly design (Figure 10).
- 100% leak-free system due to O-ring sealed standard blocks instead of pipes.
- Possibilities for improving the stirring efficiency.
- Option for visualisation of all input and output signals.
- Error reports with failure detection.
- Transfer of process data to customer data storage or via the Internet.
- Remote troubleshooting using a built-in modem.
- Siemens and Rockwell programmable logic controllers (PLCs) available.
- Accurate and individual flow control for multiplug purging systems.

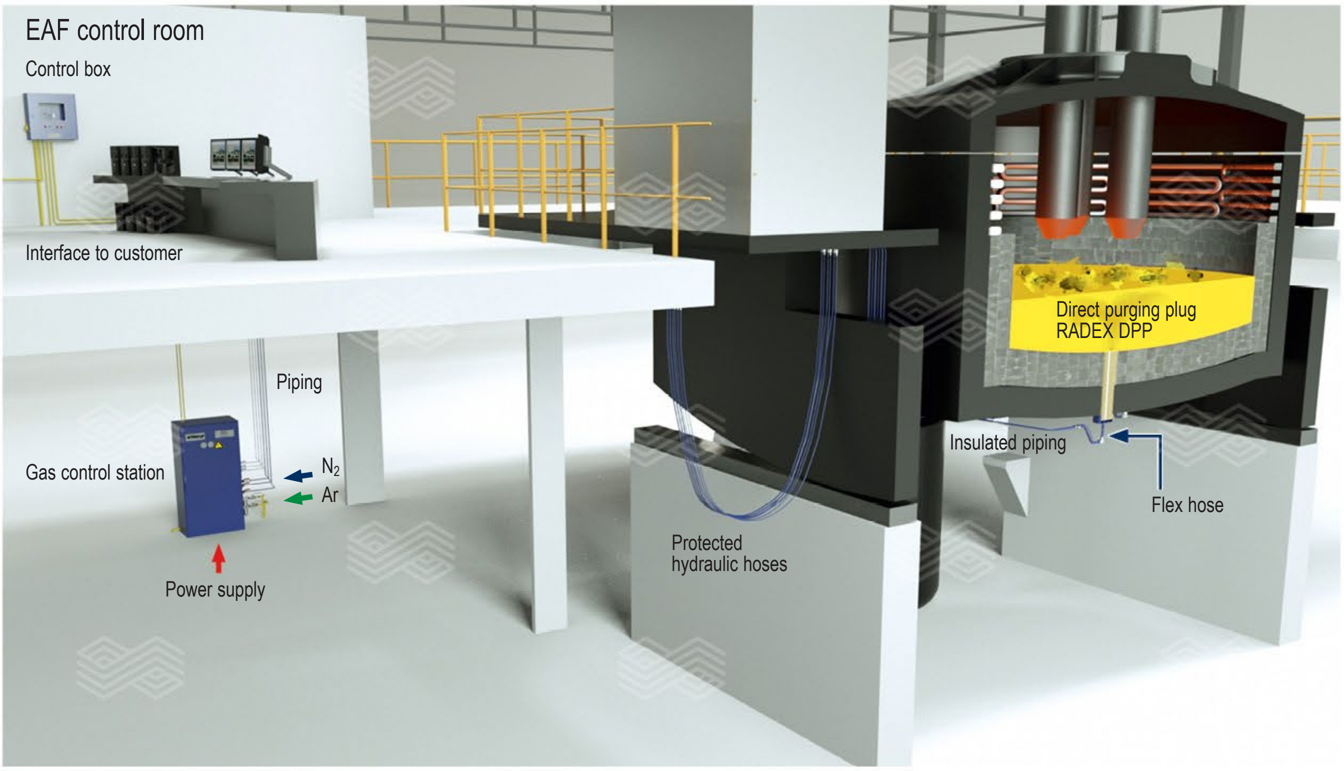
The parameters of a RHI Magnesita gas purging system typically guaranteed are:

- 100% leak-free system.
- Accuracy of +/- 1.5%.
- Setting time <500 ms.

The general characteristics of the RHI Magnesita gas purging systems for EAFs and secondary metallurgy are:

- The entire gas purging technology from refractory to valve control and the purging strategy.
- One-stop project management for systems and refractories.
- Technical support by experts with process knowledge.
- Combined excellence of top suppliers, gas control systems, and refractory solutions.
- More than state-of-the-art technical solutions.

Figure 9.
Overview of INTERSTOP compact gas control station near the EAF platform.



- Fully integrated in the customers' process control systems from Level 0 to Level 2.
- Simple and cost-effective serviceability due to the modular design.
- Highly precise mass flow control and the latest generation of mass flow controllers (MFCs).
- Quick response of flow rate to set value.
- Integrated solutions from gas supply and control to purging plugs and metallurgical know-how.
- User-friendly, intuitive control panel and visualisation.
- Very compact design means a very low space requirement.
- Customer-specific software solutions.
- Exact adjustability of purging gas type and flow rate during the entire heat.
- Programmable gas flow rates for specific steel grades or production programs.
- Innovative solutions for the early detection of purging plug wear based on monitoring back pressure in the wear indication lines.

The compact design of the gas control unit, the standardised solutions for data connection to the EAF control systems, a series of purging plug solutions available for small or large EAFs, and the standard installation design of the purging plugs on the EAF steel shell provide the opportunity to revamp the inert gas stirring system of any EAF.

Conclusion and Prospects

With the upcoming transformation of the global steel industry to green steelmaking with comparable production capacities, the number of large EAF installations will increase in the next few decades. Providing additional melt movement is crucial for a highly productive EAF process with maximum raw material conversion efficiency and minimum energy demand, especially for EAFs with a >150-tonne tap weight. The state-of-the-art technologies available for improved melt mixing are inert gas stirring and EMS. The benefits and savings in terms of energy and process time reported depend on the specific process conditions (e.g., carbon steelmaking or high-alloyed stainless steelmaking), and the carbon content of the applied raw materials (i.e., steel scrap, DRI, and/or HM), but are more or less in the same range for both approaches as a result of comparable improvements in melt mixing.

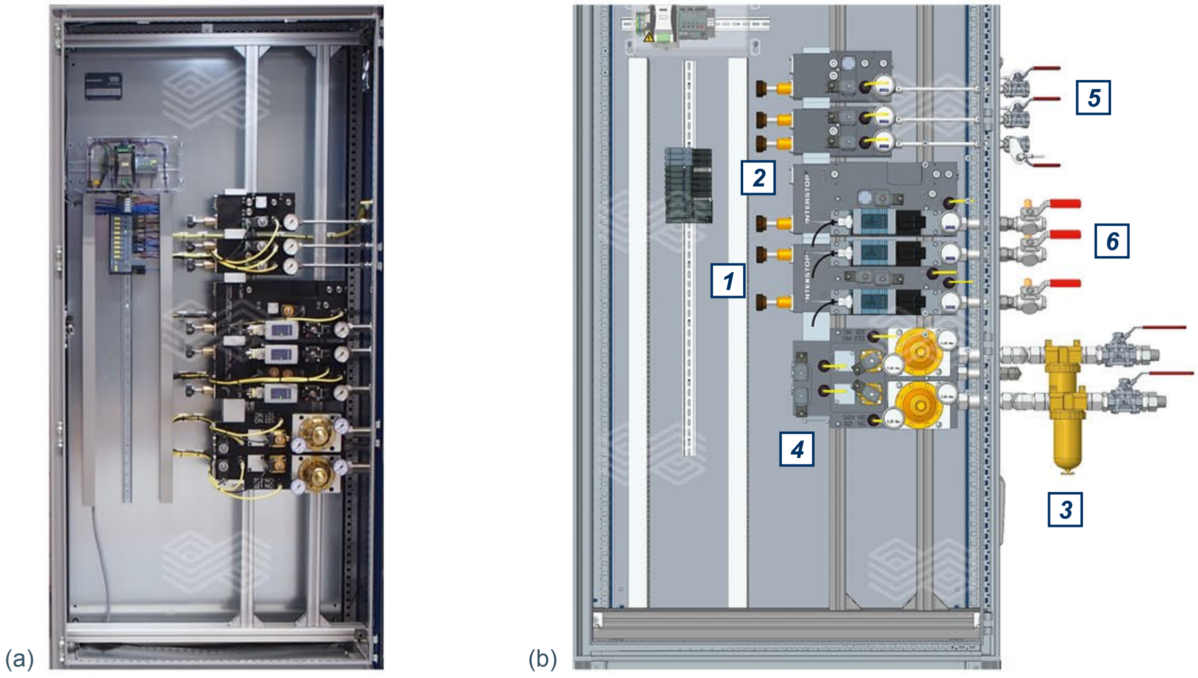
While numerous case studies have confirmed energy savings between 5–30 kWh/tonne, which increase with EAF size, a closer look at the characteristics and benefits of the two technologies provide some decisive differences between the two stirring technologies, for example the impact on hearth wear, CAPEX, and installation effort. These details are summarised in Table I, which highlights that inert gas purging provides a large series of EAF process benefits at comparably low costs and a fast return on investment within a few months.

The topics currently being investigated to further develop inert gas purging systems include:

- The use of CO_2 gas mixtures or metallurgically reactive gases as bottom purging gases.
- Automatic control algorithms.
- Fully automated performance reporting.

Figure 10.

(a) photograph and (b) schematic of the modular and compact gas control station for easy installation and maintenance.



1. Modular design
2. O-ring sealed aluminium blocks
3. Duplex filters at each inlet line
4. Release valve to avoid nitrogen contamination of argon line
5. Wear indicator line to purging plug
6. Monitored 3/2-way ball valves on each outlet line to prevent any inert gas flow during relining of the furnace, for safety reasons

Table I.

Comparison of an inert gas purging system with electromagnetic stirring. Weighting (W): Low importance = 0 and high importance = 10. Rating (R): Unsatisfactory = 0 and very good = 4.

Criteria		Inert gas stirring			Electromagnetic stirring		
	Weighting	Rating		W x R	Rating		W x R
Design							
Low construction effort for new EAF	7	+ + + +	4	28	+	1	7
Low construction effort for EAF revamp	5	+ + + +	4	20		0	0
Low influence on shell weight	6	+ + + +	4	24	+	1	6
Number of installations	3	+ + +	3	9	+	1	3
Low maintenance	7	+ +	2	14	+ + +	3	21
Thermal effect							
Reduction in electrical energy [kWh/tonne]	7	+ +	2	14	+ + +	3	21
Reduction in power on	7	+ +	2	14	+ + +	3	21
Increased tap temperature control	7	+ + +	3	21	+ + +	3	21
Lower superheat	7	+ + +	3	21	+ + +	3	21
Improved EBT opening rate	7	+ +	2	14	+ + +	3	21
Reduction of scrap cave in	7	+ +	2	14	+ +	2	14
Improved melting of heavy scrap	8	+ +	2	16	+ +	2	16
Improved melting of HBI/DRI	8	+ +	2	16	+ +	2	16
Reduction of skull formation	8	+ +	2	16	+ + +	3	24
Chemical effect							
Improved bath mixing/mixing time	7	+ +	2	14	+ + +	3	21
Improved yield [%]	7	+ +	2	14	+ +	2	14
Lower FeO in slag	7	+ +	2	14	+ +	2	14
Low refractory hearth wear	7	+ + + +	4	28	+ +	2	14
Improved alloy yield	8	+ + +	3	24	+ + +	3	24
Increase in decarburisation rate	8	+ + +	3	24	+ + +	3	24
Lower oxygen in steel (closer to equilibrium)	7	+ + +	3	21	+ + +	3	21
Reduced P level	8	+ + +	3	24	+ +	2	16
Reduced N level	8	+ + +	3	24	+	1	8
Possible CO_2 utilisation	2	+ + +	3	6		0	0
OPEX							
No need for special refractories	2	+ +	2	4	+ + + +	4	8
Low stirring gas consumption	2	+ +	2	4	+ + + +	4	8
Low system energy consumption (kWh)	5	+ + + +	4	20	+	1	5
CAPEX							
Low CAPEX	8	+ + + +	4	32		0	0
Return on investment							
Fast return on investment	7	+ + +	3	21	+	1	7
			Total	515		**Total**	396

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