Energy-efficient and hydrogen-ready technologies for EAF steelmaking

edited by: J. von Schéele, H. Alshawarghi, P. Kwaschny, H. Groiss, J. van Lingen, D. Razzari

The CoJet® gas injection technology was developed and first introduced by Praxair (now Linde) in 1996, more than 25 years ago, and it has revolutionized Electric Arc Furnace (EAF) operation. Today there are more than 170 CoJet installations world-wide, and CoJet technology has become the industry standard for chemical energy input into EAFs. To decarbonise the chemical energy input into EAFs, Linde has developed CoJet injectors, Fluidic Burner, and 3-in-1 Injector, all of which can be operated with hydrogen as a fuel. The excellent results show that hydrogen is the ideal fuel here. The Fluidic Oxyfuel Burner uses a fluidic function to move the flame and melt a larger volume of scrap. This has been found to be particularly beneficial when installed at the slag door or in the EBT area. The functionality of the Fluidic Burner has also been combined into a Fluidic CoJet, where the CoJet lancing capability is combined with a moving flame to cover a larger area in the burner mode. This further improves heating and melting uniformity, increases productivity and enables more efficient use of chemical energy. The concept of 3-in-1 Injector combines oxygen lancing, carbon injection and burner mode. It provides effective carbon injection into the molten bath and at the slag/steel interface from a fixed side wall position, which improves slag foaming and gives better control over steel refining. Additionally, it increases the solid injection efficiency for finer carbon materials – minimizes losses to the fume system – and may be used to also inject DRI fines or lime. The Fluidic Burner uses jets, without mechanically moving parts, to deflect the flame and optimize chemical energy input and melting in the EAF. This has been found to be particularly beneficial when installed at the slag door or in the EBT area to cut and melt-in heavy scrap.

Linde's CoJet injectors and Fluidic Burner may be operated with hydrogen as a fuel to help decarbonize chemical energy input into the EAF. Experiments show that hydrogen is an ideal fuel, better even than standard fossil fuels, at producing a flame shroud for better jet coherency and yielding longer jets.The Fluidic CoJet adds the fluidic flame capability to the CoJet technology. The added feature improves heating and melting uniformity, shortens melt-in time thereby increasing productivity and enables a more efficient use of chemical energy.To further support the optimization of the energy-efficiency, Linde's OPTIVIEW® technology has now also been adapted to EAFs. OPTIVIEW is an image-based system that analyses the flue gas composition. Based on the analysis, OPTIVIEW provides online information to optimize the EAF post combustion to obtain minimum energy losses.This paper includes an overview of these different burner and injection technologies, the results achieved, and how they can support decarbonisation of the EAF. They are all ready to use with hydrogen as fuel.

KEYWORDS: EAF, OXYFUEL, ENERGY, SCRAP, INJECTION, FINES, HYDROGEN

INTRODUCTION

As governments and companies continue to pursue net zero carbon policies, electric steelmaking becomes increasingly strategic important in many countries. We will see a drastic evolution in number of mills using electric melting and a revolution is use of low-carbon fuels, ultimately hydrogen. The introduction of Linde's CoJet® Coherent Jet gas injection technology more than 25 years ago, was the previous revolution in this field, and that technology system continues to develop to include

Joachim von Schéele,
Hamzah Alshawarghi,
Pascal Kwaschny,
Herbert Groiss,
Jeroen van Lingen,
Davide Razzari
Linde GmbH, Germany

new features.

CoJet was a significant step in effectively injecting chemical energy in Electric Arc Furnace (EAF) steel making. This breakthrough technology was the first to introduce the concept of fixed wall mounted injectors, with each injector designed to perform multiple functions including oxyfuel burner, oxygen lancing, post combustion, and carbon injection. With the installation of the first CoJet injector in 1996, Gerdau Macsteel Arkansas became the first EAF in the world to operate with fixed multi-functional sidewall injectors. Today, steel makers worldwide have widely accepted this concept, as the technology has enhanced their efforts to lower costs, improve productivity, and in general, optimize their melting process. Indeed, the industry has shifted to this new standard for chemical energy input in EAFs. Fig. 1 shows a CoJet system in operattion.

The testimony to the wide acceptance of CoJet in the EAF melting process can be summarized as follows:

- Over 170 furnaces authorized to operate this technology worldwide over the last twenty-five years, and perhaps twice as many additional furnaces utilizing the same concept;
- A wide geographical distribution with customers in North and South America, Europe, and Asia;
- Furnaces ranging in capacity from 30 to 400 metric tonnes tap weight;
- The number of injectors installed per furnace ranging from one (1) to four (4);
- Various furnace types that include AC, DC, Shaft, Consteel® and Conarc®;
- Raw material input to the furnace with wide ranging variation - 100% scrap, 100% DRI, a mixture of scrap and DRI, various percentages of hot metal, continuous scrap feeding;
- Furnaces operating under constant flat bath conditions with continuously varying bath heights;
- Inherent burner capacity of 3 MW to 6 MW per injector;
- Designed lancing capability from 600 Nm^3/h to 4750 Nm^3/h;
- A wide spectrum of oxygen practice from 12 Nm^3/ton to 50 Nm^3/ton.

Fig.1 - Four CoJet injectors in operation in an EAF at the Nucor Berkeley plant, USA.

COJET INJECTION TECHNOLOGY

The basic technology

The CoJet technology was developed in North America by Praxair, which merged with Linde to form Linde plc in 2019. Exploratory research on supersonic gas jet behavior by Linde's corporate fellow Dr. John Anderson led to the concept of flame shrouded jets, which become coherent and maintain their exit velocities and momentum over long distances. For example, an optimum flame shroud extends the length of a Mach 2.0 supersonic oxygen jet in ambient air from ~15 times the nozzle diameter to about 70 times the nozzle diameter. With a quantitative understanding of coherency, Praxair then focussed on translating the basic concept to final applications for this novel technology. Subsequently, the first commercial application was launched for electric arc furnaces.

In an EAF, the laser-like oxygen jet from a coherent injector travels significantly farther than an oxygen jet from a conventional supersonic lance. Hence, coherent jet injectors can be positioned well above the bath in the sidewall of the furnace, and still carry out effective bath lancing. Also, when the coherent jet of oxygen produced by the nozzle impinges and penetrates through the slag and into the molten steel bath, the concentrated momentum of the oxygen jet dissipates in the steel as fine bubbles, providing deep penetration and effective slag-metal mixing. This results in high efficiency lancing and decarburization. The principles are illustrated in Fig. 2.

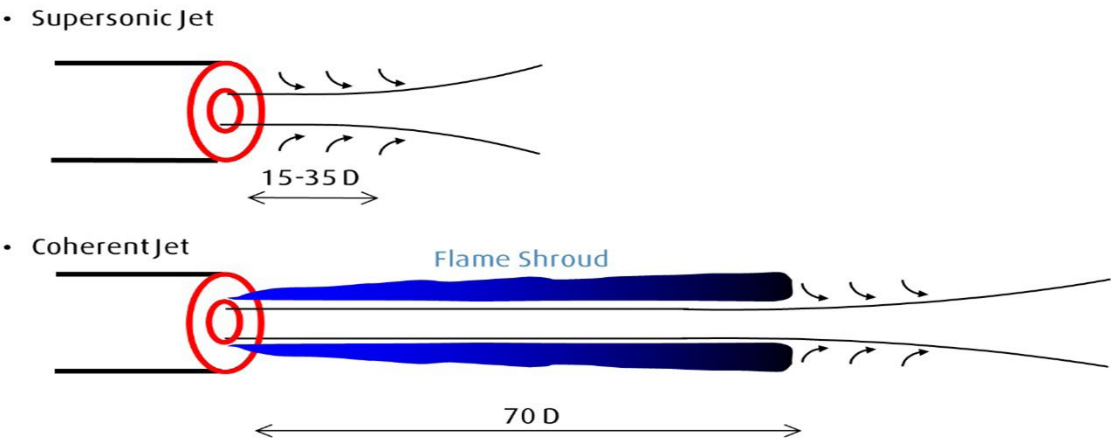

Fig.2 - Schematic comparison of a conventional supersonic jet vs a coherent jet using a flame shroud.

The CoJet injector assembly, in addition to lancing, is also designed to provide other multiple functions. Each injector, as needed during the heat, functions as a burner to melt scrap and to simultaneously inject supplementary oxygen at subsonic velocity to achieve post combustion. The post combustion oxygen is introduced in a controlled fashion at a specific shallow angle and close to the main lance oxygen to achieve maximum benefits, not only during scrap melting, but also during flat bath periods. This results in further reduction in electric power consumption, with concomitant increase in furnace productivity.

Finally, included in the CoJet injector assembly, is the feature to introduce carbon. The carbon is injected in a fully automated mode through a port specifically located to allow for effective slag foaming and reduction. Under proper conditions, this injected carbon can also provide some recarburization of the bath. The benefits resulting from this efficient mode of carbon injection is the excellent slag foaming achieved, with significantly reduced quantity of injected carbon used.

Gas requirement

CoJet technology is fuel flexible in that a wide range of hydrocarbon fuels can be used for the burner and shrouding gas. Natural gas, desulphurized coke-oven gas, LPG, kerosene, and fuel oil have all been commercially deployed. Linde has also developed CoJet technology based on hydrogen fuels. Hydrogen is in fact an ideal fuel to produce coherent jets. Not only does hydrogen produce the longest coherent jets for oxygen lancing (greater than 85 times the nozzle diameter), it also improves the heat transfer efficiency for scrap melting. The existing CoJet burners can be used with hydrogen with minimal modification. Fig. 3 shows a photograph of a CoJet injector with its flame shrouding.

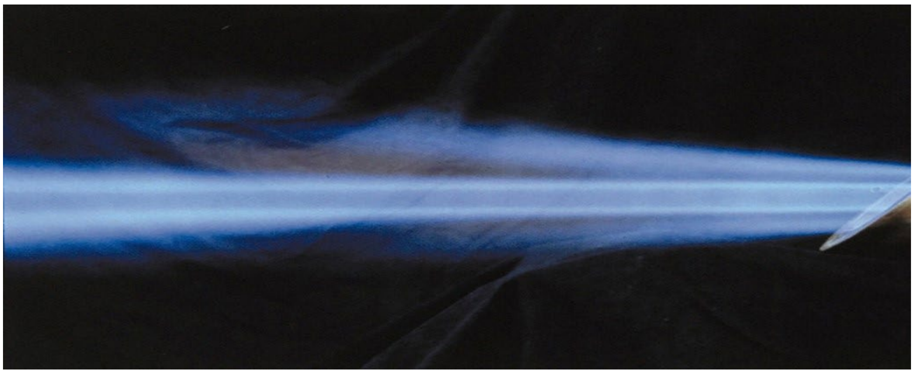

Fig.3 - CoJet system producing extended jet lengths with a fuel shroud. Hydrogen coherent jets have been demonstrated to produce the longest jet lengths. Hydrogen is the ideal fuel to use.

Given the high temperature atmosphere in an EAF, questions are periodically raised about the need for a shroud fuel to produce coherency. While hot ambient conditions do improve jet lengths of a conventional O_2 jet, up to about 35 nozzle diameters, laboratory studies and field experience has shown that they do not produce jet lengths comparable to a perfect coherent jet (>70 nozzle diameters). In addition, the jet length is not consistent throughout the heat, and leads to negative impacts on furnace operation.

The purity of oxygen required is less stringent than for a BOF and can be produced by Vacuum Pressure Swing Adsorption (VPSA) in which most of the nitrogen is 'filtered' out of air by molecular 'sieves' resulting in a gas containing 90-92% oxygen and 4% argon. This is a lower cost method than cryogenic liquification of air.

Operational Features and Benefits

A typical CoJet system includes multiple injectors with associated assemblies for mounting on the sidewall of the furnace, a valve skid to independently meter and control the oxygen and fuel, a programmable logic controller, and an operator station usually located in the furnace pulpit. Historically, conventional EAF operation had been carried out by manual lancing and carbon injection, usually through an open slag door. By using coherent jet technology, the furnace is converted from a manual operation to a fully automated sequenced operation with the slag door closed, as depicted in Fig. 4. In addition, the oxygen and carbon are now uniformly introduced through multiple injectors around the furnace in a homogeneous manner as shown in Figure 4. This allows for the use of higher overall chemical energy with added benefits achieved in return, in addition to improved safety for the operators.

The CoJet coherent jet technology is basically designed to provide a fully automated sequenced operation. Once a bucket charge is added and the roof is closed, the injectors automatically begin to operate in their preprogrammed sequence. With staged firing profiles, the injectors operate to provide different flame shapes. Initially, the injectors function in a low burner mode to melt the scrap. At this stage, a wide flame is used to heat a large area of scrap. Subsequently, a high burner mode is used with a more cutting or penetrating flame, followed by a low lance cutting mode that is deployed to rapidly cut through the heated scrap and facilitate quick melting. After the scrap is melted with this sequenced burner – low lance cutting operation, the injectors automatically switch to high lancing and decarburization. Concurrently, the carbon injection is automatically initiated to inject carbon at the set flow rates. Throughout this run, the post combustion oxygen is continuously added in each mode of operation of the injectors – low burner/high burner/low lance/high lance - refine, at varying flow rates. This allows for a high rate of capture of the CO evolved during the heat, and effective utilization and transfer of this energy to the bath.

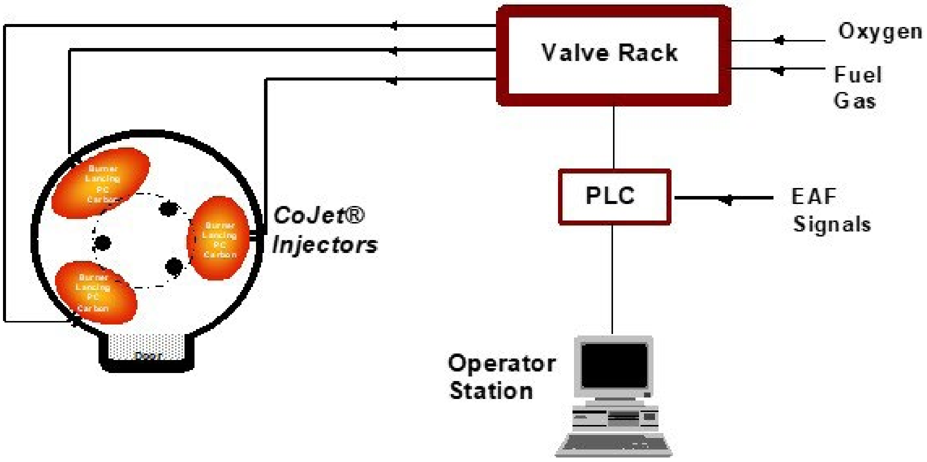

Fig.4 - The general layout of a CoJet system with fixed injectors and oxyfuel burners mounted in the sidewall at the cold spots of the EAF.

A furnace operated with the CoJet system can immediately reap benefits from this technology. Typical cost benefits derived are from a combination of following parameters:

- Reduced power consumption
- Increased productivity
- Elimination of supersonic lances and manipulators
- Significantly reduced maintenance
- Improved yield
- Reduced refractory wear at banks
- Reduced gunning
- Reduced electrode consumption
- Reduced injected carbon
- Improved delta life

Some of the other factors that lend added value to using a coherent jet technology are:

- Automation – less operator dependent
- Consistency – from heat to heat
- Improved slag foaming – higher rate of power input
- Non water-cooled injectors – easy to check
- Total flexibility – option to selectively lance with any injector(s)
- Improved safety

With more than 170 furnaces around the world authorized to use CoJet technology, considerable knowledge has been garnered at Linde from their experience with a wide range of furnace types and operating practices. This could be broken down into several categories, including the jet characteristics, high chemical energy utilization, lancing efficiency and carbon, and maintenance.

Jet Characteristics

It is now clear that coherent jets can be designed for remote location on the sidewall even at a height as high as 1.85 meters above the bath. Concurrently, coherent jet length can be achieved where jet coherency of supersonic speeds can be offered up to 2.5 meters in length from the nozzle face. This factor becomes even more critical when furnaces are operated with hot metal, 100% DRI feed or continuous feeding of scrap. Under these conditions, the furnaces are in a flat bath condition all the time. Given these conditions, where the bath height changes significantly over the extent of the heat, it becomes critical to have accurate quantitative data on jet length. This helps ensure that a truly coherent jet is designed with the appropriate requirements, and with its characteristics maintained over the requisite distances. Such well-designed coherent jets can function effectively in such furnaces with continuous feeding, or even in furnaces where there are bath height changes due to bottom wear.

It is critical to have quantitative data on coherent jet length and "perfect" coherent jets to handle variations in bath height without splashing or creating negative effects on the furnace. Imperfect coherent jets when installed in such furnaces, can render considerable damage to the furnace and negatively impact the operation. Typical problems that can be encountered with imperfect (poorly designed) coherent jets are:

- Excessive splashing
- Excessive overheating of panels
- High delta wear
- High refractory wear
- High levels of FeO
- Poor yield

Another key aspect of coherent jets are the shroud ports, which are integral to the injector design. Maintaining the appropriate gas flows through the flame shroud (fuel gas and shroud oxygen) is critical for proper operation in each of the modes. If the flows to the shroud ports are not independently controlled, the integrity of the coherent jet can be compromised during a campaign. Such occurrences lead to negative effects on the furnace, some of which are listed above. Fig. 5 illustrates the relationship between flame shrouding and penetration depth.

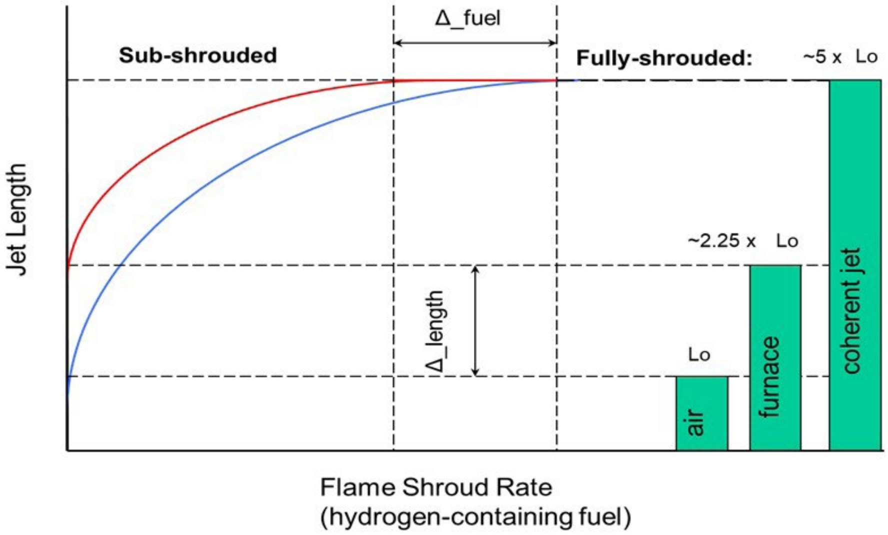

Fig.5 - Production diagram for wire rod and subsequent drawing.

Several customers in countries with high fuel prices often request that the coherent jet offer be made without using shroud fuel. As discussed earlier, this is not advisable, and it results in excessive splashing, loss in yield, longer heat times, increase in O_2 consumption due to lower injection efficiency, and significantly higher carbon injection consumption to combat raised FeO levels. The effects of flame shrouding on the penetration length of a supersonic oxygen jet are huge. Relative to ambient air, the hot furnace increases the natural jet penetration length, however, the application of a flame shroud maximizes the jet penetration to the coherent jet length deployed in Linde's CoJet technology, which is more than doubling the its length inside the hot furnace.

High Chemical Energy Utilization

Another aspect of a well-designed coherent jet system is the significant impact of chemical energy addition. Experience gained shows that CoJet systems can be effectively used even with high oxygen practice. Some customers are operating furnaces at >45 Nm^3/ton of oxygen and still reaping the benefits of improved yield, reduced power consumption, and higher productivity. All this, and with no adverse effects on refractory or electrode consumption. Indeed, the observed general benefit of injecting oxygen into the furnace using a CoJet system, yields a power reduction of about 4-4.5 kWh/Nm^3 of oxygen used. Fig. 6 shows the range of oxygen practice used by some CoJet system customers with the corresponding power consumption. This clearly demonstrates that the coherent jet technology can be used to avail of high chemical energy utilization with positive results. This is mainly due to the following features:

- Multiple injectors offer multi-point injections

- Homogeneous distribution of energy in the furnace
- Uniform early foamy slag generation
- Efficient coherent jets provide better stirring and mixing resulting in lower FeO in the slag

The most striking feature is that high levels of chemical energy have been consistently delivered without compromising on yield or slag FeO levels. A noteworthy comment from one of our early customers who was surprised at the results commented, "you should publish a paper on how to increase oxygen use in EAF and still deliver increased yield."

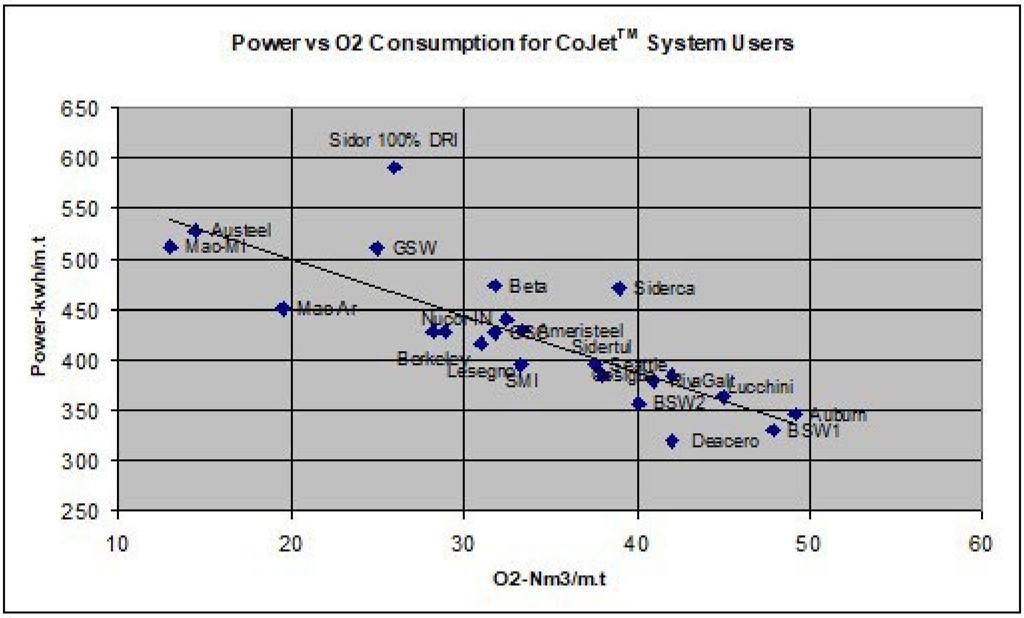

Fig 6. - Range of oxygen practice used by CoJet customers with corresponding power consumption, showing a proven power reduction of 4-4.5 kWh/Nm³.

Lancing efficiency and carbon

It is now quite apparent that when lancing with coherent jets, the decarburization efficiency improves considerably. This aspect becomes a useful tool to reduce refining times, improve productivity, and make concomitant gains in power savings. Generally, carbon injection with the CoJet system has demonstrated that best results are achieved with additions that are less than 5-8 kg/ton. With the slag door closed, the foamy slag generated can be retained and carbon injection proportionally reduced or stopped. Reduced injected carbon consumption is a benefit we routinely deliver to our customers, with up to 60% savings in some cases.

The improvements in jet penetration, uniformity of lancing around the furnace and better slag foaming have also translated into lower N levels in the steel. Reductions up to 10 ppm have been achieved, both in scrap and DRI charged furnaces

Maintenance

A frequent concern of any melt shop is the kind of attention and the level of maintenance necessary for any new system and hardware under consideration for use. This aspect is crucial since any down time needed to carry out maintenance, comes at a price.

At the very outset, this aspect of the CoJet system has been a major benefit to steel makers. The injector itself is non water-cooled and weighs barely 13 kg. A quick inspection of an injector, as timed by some customers, takes about 10 minutes. Generally, such an inspection is advised at least once a week on a down day to ensure the integrity of the nozzle face. However, a special in the operator station is available to alert the operator in case any specific changes occur.

Another key benefit from a maintenance perspective is the life of the coherent jet injector. Experience shows, if adequate cooling water as required is maintained, basic flows and pressures of oxygen and fuel are held and sustained in the various modes - especially during charging, the injector life is significant. Customers have been using CoJet injectors and panels for more than a year, and in some cases, even up to 18 months or more.

FLUIDIC BURNERS

Linde's oxyfuel Fluidic Burner technology produces a powerful, concentrated flame whose direction can be changed remotely by the operator without any physical movement of the burner itself and without any moving parts. This unique feature can be employed to direct the flame over a large volume in front of the burner, and thereby improve the use of chemical energy in the melting of a variety of metals.

The burner incorporates small steering jets using the "Fluidics" principle and the "Coanda" effect to create a significant change in direction of the main flame in any desired direction. This feature is particularly val-uable in an electric arc furnace, where the Fluidic Burner can provide higher scrap melting efficiency by progressively directing the energy from the burner to the colder areas of the furnace, and by preheating a significantly larger volume of scrap in front of the burner. Fig. 7 shows photographs of how the flame is di-rected in the burner.

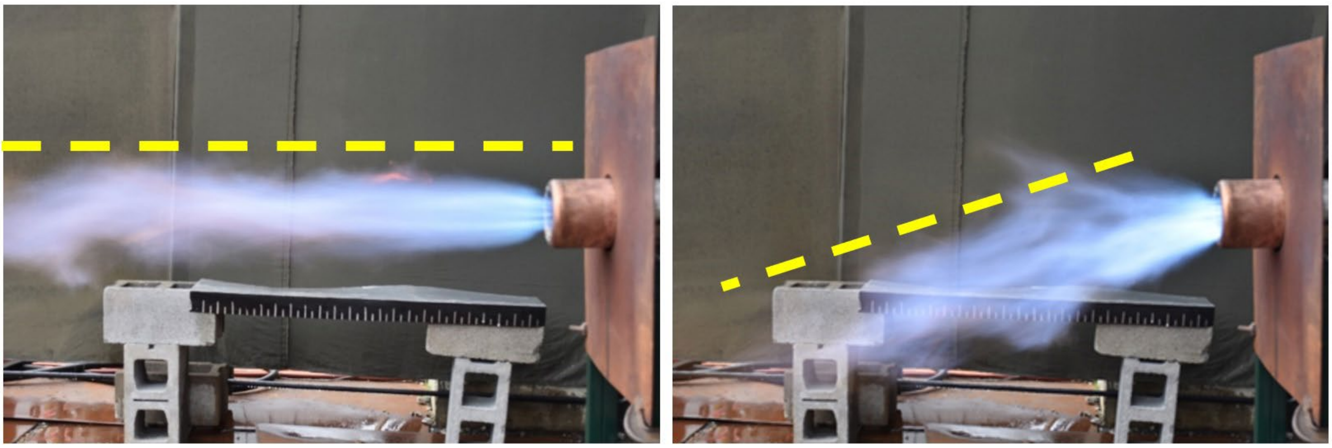

Fig.7 - Fluidic Burner in basic burner mode and when using the fluidics function.

In an EAF, the Fluidic Burner can be mounted on the furnace sidewall along its circumference, in the slag door, and/or in the EBT area, to improve scrap melting efficiency. Flame directionality can be controlled remotely at the touch of a button, without any moving parts, by controlling the flow through steering jets in the burner. The Fluidic Burner a powerful concentrated flame, typically operating at 3-5 MW.

The fluidic function can also be incorporated into a Fluidic CoJet injector so that the same injector performs the fluidic burner function in the burner mode as described above, and it operates as a traditional coherent jet lance in the lancing mode. The Fluidic Burner brings several important benefits to the operation of an EAF, see Tab.1. The configuration with Fluidic Burners and Fluidic CoJet at an existing installation in an EAF is shown in Fig. 8.

Tab.1 - Features and benefits of use of a Fluidic Oxyfuel Burner in an EAF.

FEATURE	BENEFIT
Directional control of the flame	Heating up a larger volume of scrap in front of the burner
	Elimination of cold spots by directing flame towards un-melted scrap
	Improved heating efficiency and uniformity
	Higher firing rates
	Productivity increase
	Power on time reduction
No moving parts to achieve directional adjustments	High serviceability
	Low maintenance combustion system
PLC based combustion control systems	Direction of the flame is changed in pre-programmed cyclic pattern to cover a large volume (heat from side to side and up and down)
	Enabling remote monitoring

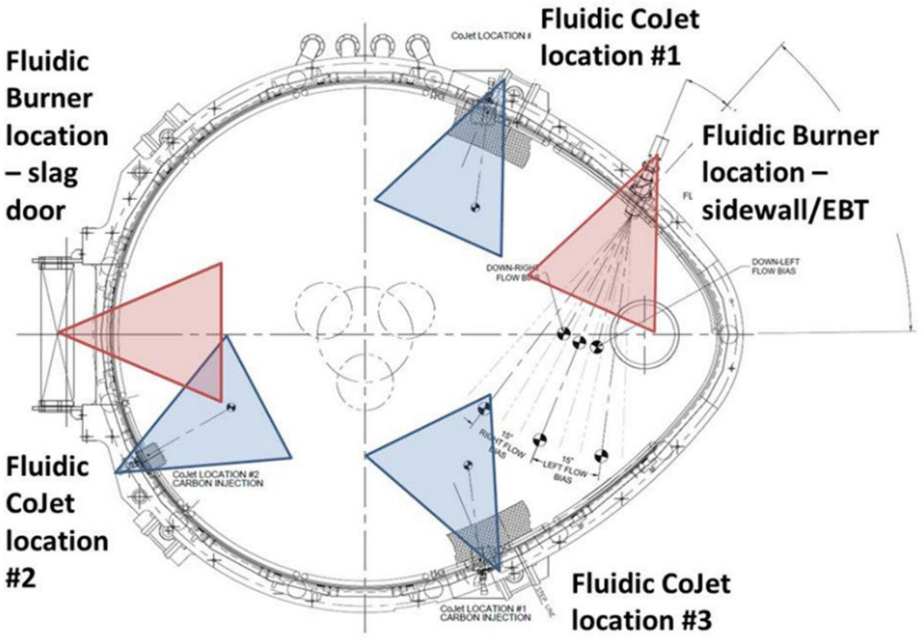

Fig.7 - Configuration of Fluidic Burners and Fluidic CoJet in an existing EAF installation.

3-IN-1 INJECTION

The concept of 3-in-1 Injector combines oxygen lancing, carbon injection and burner mode. It provides ef-fective carbon injection into the molten bath and at the slag/steel interface from a fixed side wall position, which improves slag foaming and gives better control over steel refining. Additionally, it increases the solid injection efficiency for finer carbon materials – minimizes losses to the fume system – and may be used to also inject DRI fines or lime. The CoJet 3-in-1 Injector has been fully tested in EAF operation. Fig. 8 shows a 3-in1 Injector during testing,

Fig.8 - Testing of 3-in1 Injector.

EFFICIENT POST-COMBUSTION

In addition to the topics already mentioned, Linde is also working on thermal post-combustion. A system for this purpose was developed years ago and has now been transferred to the EAF steelmaking sector. If unburned CO leaves the furnace, this leads to energy losses. The Linde OPTIVIEW® system analyses this via a camera installed outside the furnace; the image-based system analyses the flue gas composition. OPTIVIEW provides online information to optimize the EAF post combustion to obtain obtain the maximum energy yield and minimum energy losses.

The online image analysis reliably measures the CO content in the off-gas and based on this information it controls oxygen post combustion through injectors. Photographs from an OPTIVIEW system at an EAF are shown in Fig. 9. It is in operation in EAFs in Brazil and USA, and the results include:

- Power-on time reduction; higher productivity
- Electricity savings
- Optimized oxygen use
- Reliable, practically maintenance-free

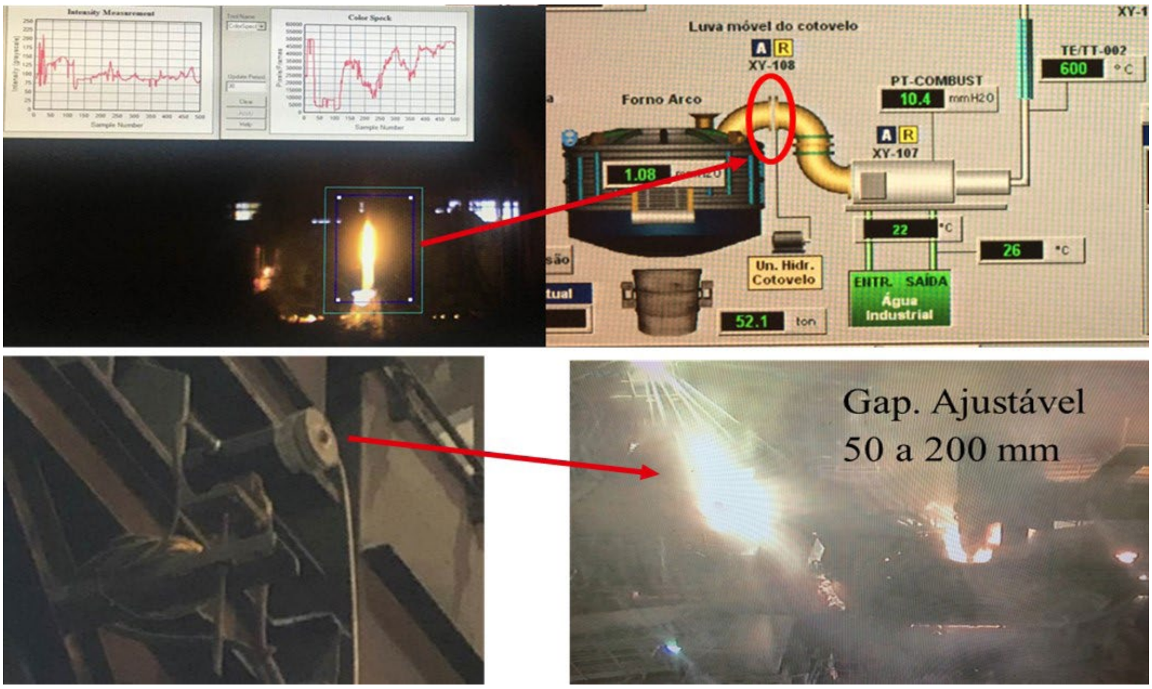

Fig.9 - Photographs from an OPTIVIEW system in operation at an EAF.

HYDROGEN AND SUSTAINABILITY

In recent years the EAF's lower carbon footprint has grown increasingly important compared with the BF-BOF route. For an EAF charging 100% scrap a reduction in energy requirements as high as 75% can be achieved, and scrap is defined as carrying zero CO_2; CO_2 emissions from an EAF charging 100% scrap are in the order of 0.33 tCO_2/t of steel produced.

Over the past 25 years, global EAF output has more than doubled, from below 250 Mt to more tha 500 Mt annually. Total CO_2 emissions are dependent on the carbon emissions relating to electricity generation, the fuel gases used in burners, electrode consumption, carbon injection, etc. If quality requirements demand part charging of primary iron such as DRI, pig iron or hot metal, the CO_2 emissions increase. Indeed, it is impossible to reach zero emissions in any steelmaking process since the steel itself requires carbon as an alloying element. Even DRI produced with 100% hydrogen requires carbon to passivate it to avoid spontaneous combustion on exposure to moisture, unless directly linked via an inert conveyor to the EAF. In the EAF, even if power is generated by 100% renewable energy, emissions will still arise from consumption of the electrodes, the need to inject carbon to create a foaming slag to protect the refractories and cover the arcs, and the need for burners to mitigate against cold spots, an exception to the latter being the use of oxy-hydrogen as the fuel gas.

The ability of CoJet technology to use hydrogen as the shrouding and burner flame without need for conversion of the hardware offers an 'H2 Ready' application for the process and one that will further lower the CO_2 footprint of the EAF once 'green' hydrogen can be supplied at a commercial price.this has been fully verified in multiple trials, where CoJet burners with a power of up to 3 MW have been tested.Use of 100% hydrogen as fuel works very well, actually it was found to deliver better results than any other fuel. In burner mode, a higher flame temperature can be produced, which in turn can reduce melting time or reduce electrical power input at unchanged production rate. When hydrogen is used in injector mode, the shrouding flame is vert stable, and the length of the jet is increased. This can increase the penetration depth and increase the efficiency of the system. It was found that the length of the jet when using 100% hydrogen as fuel was longer than with any other fuel. Compared to a natural gas based shrouding, it increased by 20%. Fig. 10 shows a photograpth from tests with CoJet operating with 100% hydrogen as fuel.

Fig.10 - Test with a Cojet in injection mode using 100% hydrogen as fuel.

CONCLUSIONS AND OUTLOOK

The past decades years has seen a dramatic increase in the production of steel using the electric arc furnace process with a growth in furnace heat size coming close to that of many BOF converters. To alleviate longer tap-to-tap times for refining resulting from the shallower hearth of the EAF compared with the BOF, steelmakers are searching for means of speeding up reaction rates in the EAF. CoJet technology has proved to be an excellent way of achieving this goal. As the proportion of EAF steelmaking increases with the move to decarbonize steel production, CoJet technology is ready to support this decarbonization roadmap.

The introduction more than CoJet 25 years ago changed the industry standard completely, created many learnings that yielded further operational improvements, and formed a platform for the future. CoJet is an excellent example of how to make the world more productive, but it is also providing a tool for decarbonization already today when at same time be ready for the future. In terms of process technology,

Fluidic Burner and multi-injection – with fine-sized injection of carbon and, potentially, DRI and lime – and the use of the OPTIVIEW system for optimized thermal post-combustion in the EAF, are examples of im-portant further developments. Moreover, the fact that all the CoJet burner configurations have been proven for use of up to 100% hydrogen, support an optimistic view on the future of the CoJet system and a posi-tive development of an energy-efficient and sustainable EAF steelmaking.

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