IMPROVING BLAST FURNACE EFFICIENCY AND REDUCING CARBON EMISSIONS WITH BLAST FURNACE OXYGEN PULSING TECHNOLOGY

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ABSTRACT

The SIP Oxygen Pulsing technology was commissioned in late 2020 on the 40-tuyere thyssenkrupp Steel Europe Schwelgern BF1 in Germany, and demonstrated immediate improvements in eta-CO. The technology reduced the total fuel rate and also allowed an increase in the ratio of PCI to coke. These results demonstrate both a reduction in OPEX as well as a reduction in the carbon emissions from the blast furnace, within a very short payback period. This paper will discuss the technology and the learnings from the Schwelgern BF1 operations with Oxygen Pulsing.

INTRODUCTION

Blast Furnace operators worldwide are often tasked with producing high quality iron, at a high throughput. This, however, must often be achieved against a backdrop of operational and process challenges. The limited availability of high quality raw materials and irregular properties of available alternatives can lead to a departure from ideal operating conditions to a reality under which production targets must be made [1, 2].

Consider further, demands in modern blast furnace ironmaking to reach carbon emission targets and reduce energy costs, whilst also effectively managing blast furnace campaigns, then the task only becomes more challenging, especially when using high PCI rates [3]. A new technology with the potential to provide significant process improvements and help overcome these challenges, is a welcome addition to the tools available to any blast furnace operator.

The Sequence Impulse Process technology, or SIP for short, is such a technology. SIP addresses these problems by improving permeability in the lower part of the blast furnace for gas distribution away from the raceway and liquids drainage to the hearth, resulting in demonstrable benefits to the efficiency and stability of blast furnace operation. Figure 1 depicts in summary how the benefits may be realized in a practical sense, enabling positive adjustments to the blast furnace operating points. This gained process stability paves the road to push the process beyond current limitations. It can be used to either:

i. enhance productivity,

ii. enhance use of low-quality raw materials, or

iii. enhance gas utilization

This pioneering and exciting new technology developed in partnership between thyssenkrupp Steel Europe and thyssenkrupp AT.PRO tec GmbH, for the first blast furnace SIP plant installation at Schwelgern BF1, is now accessible to blast furnace operators worldwide, through the new exclusive cooperation agreement with Primetals Technologies.

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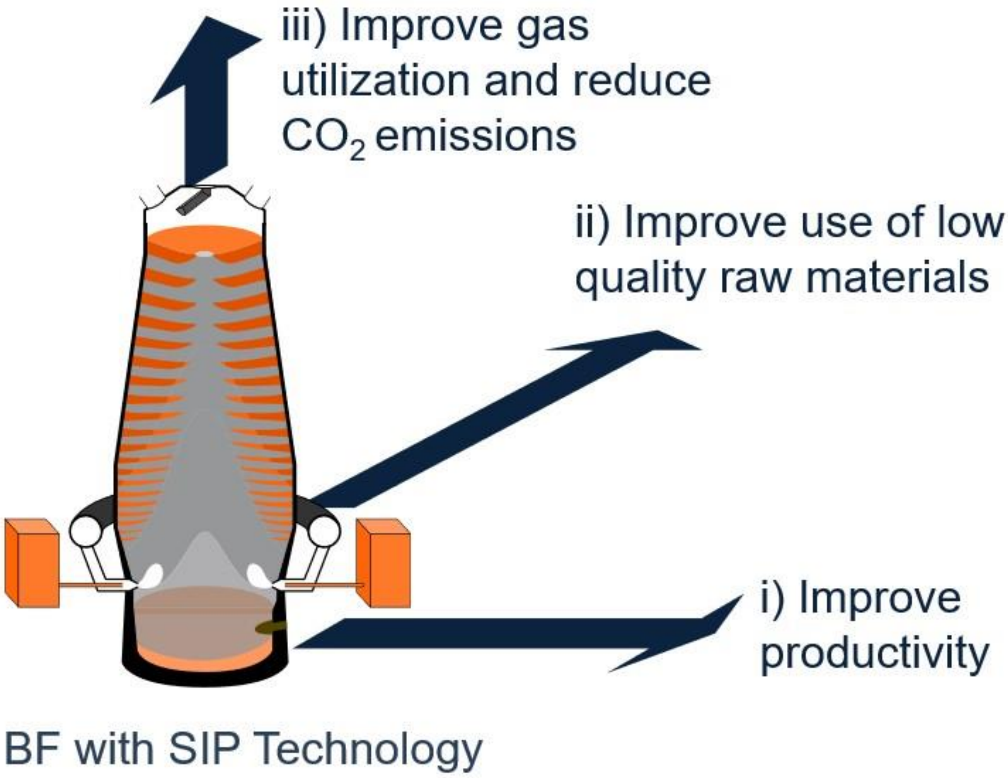

Figure 1: Schematic representation of the potential optimizations of the blast furnace process (i and iii) and extended freedoms in raw material selection (ii)

DISCUSSION

TECHNOLOGY PRINCIPLE OF SIP

The technology development has been based upon a number of comprehensive investigations and operational experiments over several years, in addition to knowledge and experience gained from the application of similar technology on cupola furnaces. A summary of the research results and a description of the technology principles derived from them for blast furnace application, are now discussed.

The gas dynamic phenomena were investigated in cooperation with the shock wave laboratory of the University of Aachen and the mode of action has been optimized for the blast furnace process. It is a supersonic free jet with unsteady start-up range and a leading shock wave. This phenomenon is created by the abrupt relaxation of a small vessel under high pressure, by a special valve which periodically opens and closes extremely quickly.

The characteristic of the shock wave that is beneficial for the blast furnace process is the influence it has on greatly intensifying the local manifestation of turbulence in the raceway. In this way, the formation of reactive mixtures and the necessary mass transfer for the respective chemical reactions, are positively influenced. Shock waves can make a significant contribution to achieving the thermodynamic or thermal conditions that are necessary for the course of a chemical or physico-chemical reaction. Shock waves can also make a considerable contribution to enabling ignition conditions [4, 5]. The shock wave follows the unsteady start-up of the oxygen free jet, with the distinctive leading vortex and marginal turbulence, properties which are characteristic for optimal reaction kinetics behavior. Especially after the transition to the steady supersonic jet, the high pressure of the pulse generators provides a high kinetic energy, with oxygen outflow velocities of about 440 - 460 m/s [6, 7].

EARLY DEVELOPMENTAL & INVESTIGATIVE FINDINGS

The influence of the SIP process was first investigated on a blast furnace by means of operating tests on one tuyere at Schwelgern BF1, which was equipped with a SIP test facility. For a comparative assessment of the results, additional investigations were also carried out on reference tuyeres. The observations of the temperature fields in the raceway showed that 80% of the pulsed oxygen reacts in the coke bed behind the raceway and that the chemical conversion of the injected coal is significantly improved during the pulsing effect. The examinations of the numerous material samples taken from the tuyeres showed that the raceway is reproducibly and significantly enlarged by the pulse oxygen, on average from approx. 1.10m to 1.50m. A smaller fine fraction and larger equivalent grain diameter of the coke, in the transition zone between the raceway and the dead man, were repeatedly observed. Furthermore, a shift in the proportion of liquid phases (iron and slag) towards the center of the furnace was observed from the material samples. The chemical analyses of the iron and slag samples taken indicate a shift of the high temperature range towards the center of the furnace. By means of helium tracing, the addition of helium into the tuyere and measurement of helium concentration in the center position of the in-burden probe, a significant change of the gas flow through the SIP process to the furnace center was detected [5, 8]. These studies clarified the temporary local depth effect of SIP oxygen.

FUNCTIONAL PRINCIPLE OF SIP

For blast furnaces operating with injected coal, it is known that coal is incompletely chemically transformed in the raceway of a blast furnace, due to the short retention time of the injected coal in the raceway and insufficient mixture generation [9]. High injection rates, sub-optimal blast parameters such as O/C ratio and blast temperature amplify this effect. Coal and resulting char particles that do not, or incompletely, undergo reaction in the raceway, are either deposited in the coke bed behind the raceway, or are carried further into the blast furnace. Small particles from coke circulation and degradation in the lower part of the blast furnace, are also deposited behind the raceway and these deposited particles have a negative effect on the gas flow away from the raceway of the blast furnace. These effects considerably reduce permeability, flow resistance rises, and the direction of escaped gas shifts towards the sides of the blast furnace. Moreover, particles can get into the blast furnace hearth. There is a negative effect on the flow behavior of the liquid phases of iron and slag along the entire path, from the melting zone to the tap holes. These effects are even stronger when coke qualities are insufficient [10, 11, 12].

During the set-up of the oxygen impulse system in a blast furnace, the installation of a second lance through the blowpipe and into the nozzle tip of a tuyere is necessary. This will be constantly provided with a continuous flow of oxygen to cool the lance. Due to the positioning of the lance, the oxygen flow comes into direct contact with the flow of coal. A certain amount of optimization of the conversion behavior of the injected coal takes place, from the so-called basic load oxygen as well as from the mixing effects due to this inflow.

In relation to the mass of the injected coal flow, during a pulse, the oxygen injection contains approximately four times the stoichiometric oxygen necessary for a reaction of the injected coal. In addition, the conditions for mixing coal and the injected oxygen are enhanced because of the transient open jet. A high chemical conversion of the injected coal can take place temporarily during a pulse.

As the oxygen advances into the raceway, stationary conditions return behind it. On its way through the raceway, the injected oxygen comes into direct contact with the coke and injected coal particles. These are picked up by the flow and react with the excess oxygen present, thereby forming carbon dioxide.

The transient supersonic open jet has a very high kinetic energy, compared with that in the blast flow. Therefore, most of the oxygen from a pulse can reach the end of the raceway and penetrate the coke bed. Because of the reaction-kinetic conditions, the oxygen and

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carbon dioxide already created, react with, and consume fine particles deposited in the coke bed.

Very high temperatures exist here in the short term – although these are screened from the raceway and the edge of the furnace by the coke bed. The level of porosity in the coke bed increases and permeability rises, as over time more and more char and fine coke particles are consumed when SIP is in operation. The raceway also gradually enlarges. The described conditions in the raceway and the surrounding coke area are shown schematically in Figure 2, depicting raceway conditions created with and without SIP operation.

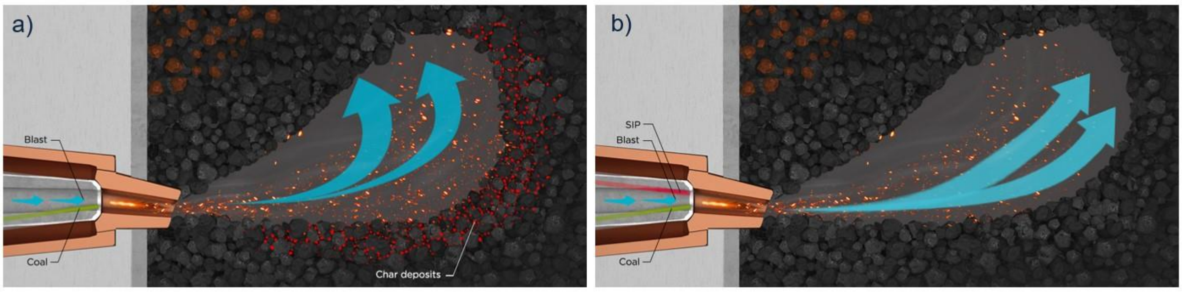

Figure 2: Conditions in the raceway and surrounding coke area a) without SIP, b) with SIP

THE SCHWELGERN BF1 SIP PLANT DESCRIPTION

Thyssenkrupp Steel Europe has an integrated steel mill at Duisburg in Germany with 4 blast furnaces with a maximum hot metal production of 34,000 t/d in total. Schwelgern BF1 has an inner volume of 4416 m^3, a hearth diameter of 13.6 m and 40 tuyeres. It is one of the two large units at the site along with the Schwelgern BF2 and has a nominal capacity of 3.5 million tpy, operating until recently with oxy-coal injection technology.

Following extensive development and research work, the newly developed oxygen technology, the world's first SIP plant, was successfully commissioned at Schwelgern BF1 at the end of 2020.

The provision of the necessary amount of oxygen is made possible by the exchange of amounts previously used mainly by oxy-coal for blast enrichment.

The SIP system consists of the following key plant items:

- Nitrogen supply, including filter station and ring main around the blast furnace
- Oxygen supply, including pressure control station with pulsation dampers and ring main around the blast furnace
- SIP boxes located above the tuyere platform, which provide pulse generation to a dedicated SIP lance inserted through a blowpipe at each tuyere. Figure 3 shows an image of the installed SIP boxes
- PLC system

SIP boxes inject high pressure oxygen into Schwelgern BF 1 using an oxygen impulse system with induced shock waves. Each of the 40 SIP lances is supplied by its own SIP box, with required automatic safety function technology. In addition to the actual periodic injections of pulsed oxygen, the SIP box continuously supplies the lance with the necessary quantity of oxygen between pulses, to ensure cooling of the lance in the hot blast stream. The so-called basic load. Each lance is also supplied with nitrogen via its SIP box, to keep it cool when the oxygen injection is switched off, or in the case of a safety function being activated.

Periodically a pulse is generated in the SIP boxes, which is superimposed onto the basic load quantity at a certain frequency.

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The control of the system, with regards to pulse frequency and the admission of individual tuyeres, is freely selectable and depends on the furnace operation.

The 40 SIP boxes are supplied in total with up to 25,000 m^3 (S.T.P.)/h of oxygen from the site network via a pressure control unit and filter station, with a 50 m^3 buffer tank and a ring main around the blast furnace. The nitrogen supply takes place via a filter station and a ring main that is also distributed by the site network.

The plant is equipped with a safety function which, when required, diverts the oxygen away from the blast furnace via a vent pipe, SIP lances switch to nitrogen cooling and the system is flushed with nitrogen.

Figure 3: Image of Schwelgern BF1 SIP boxes, located on a platform above the tuyere level

THYSSENKRUPP STEEL EUROPE SCHWELGERN BF1 PRACTICE WITH SIP

In total until the end of 2021 three SIP long-term campaigns have taken place. After the second SIP campaign, the relining of Schwelgern BF1 was carried out. After the blast furnace ramp up following the reline was established, the third SIP campaign started. Now the SIP technology is in continuous operation. An overview of the production periods with SIP and statistical analysis periods can be found in Table 1. Further explanation of the SIP campaigns and the reference phase operating conditions is provided in the later section, “Statistical Evaluation of SIP Campaigns”.

Production Periods with SIP		Statistical Evaluation Periods	
		reference 1	27.10.20-05.11.20
1st SIP campaign	19.11.20-28.12.20	SIP 1a	10.12.20.-19.12.20
2nd SIP campaign	16.02.21-27.03.21	SIP 1b	11.03.21-20.03.21
		reference 2	26.10.21-30.10.21
3rd SIP campaign	08.11.21-02.01.22	SIP 2a	10.11.21-14.11.21
		SIP 2b	18.11.21-21.11.21

Table 1: SIP campaigns, evaluation periods and reference periods

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IMPROVING THE PERMEABILITY AND STABILITY OF THE BLAST FURNACE PROCESS

The injected SIP oxygen influences the gas flow profile and thus the temperature profile of the blast furnace. Schwelgern BF1 experience, shows the changes are fully pronounced after approximately 14 days and could be observed in all SIP campaigns and are therefore reproducible.

This is characterized by lower blast furnace wall temperatures and the resulting lower heat load on the cooling elements in the blast furnace shaft, which results from the significantly improved permeability due to the center gas penetration.

A commonly known means of controlling the necessary permeability of the blast furnace is to adjust the burden distribution. As a rule, a large proportion of coke is charged in the center of the shaft, especially at high PCI rates, so that a coke channel is created in the center of the furnace. With the help of the central gas flow in the coke channel, the gas distribution mechanism is to be ensured via the coke windows in the cohesive zone. Good gas distribution across the furnace cross-section leads to an efficient blast furnace process and must be considered indispensable. However, there are certain limits to the control of gas distribution that can be achieved with the help of the burden distribution pattern. This important parameter is checked regularly by recording temperature and gas concentration profiles through measurements with an in or above burden probe.

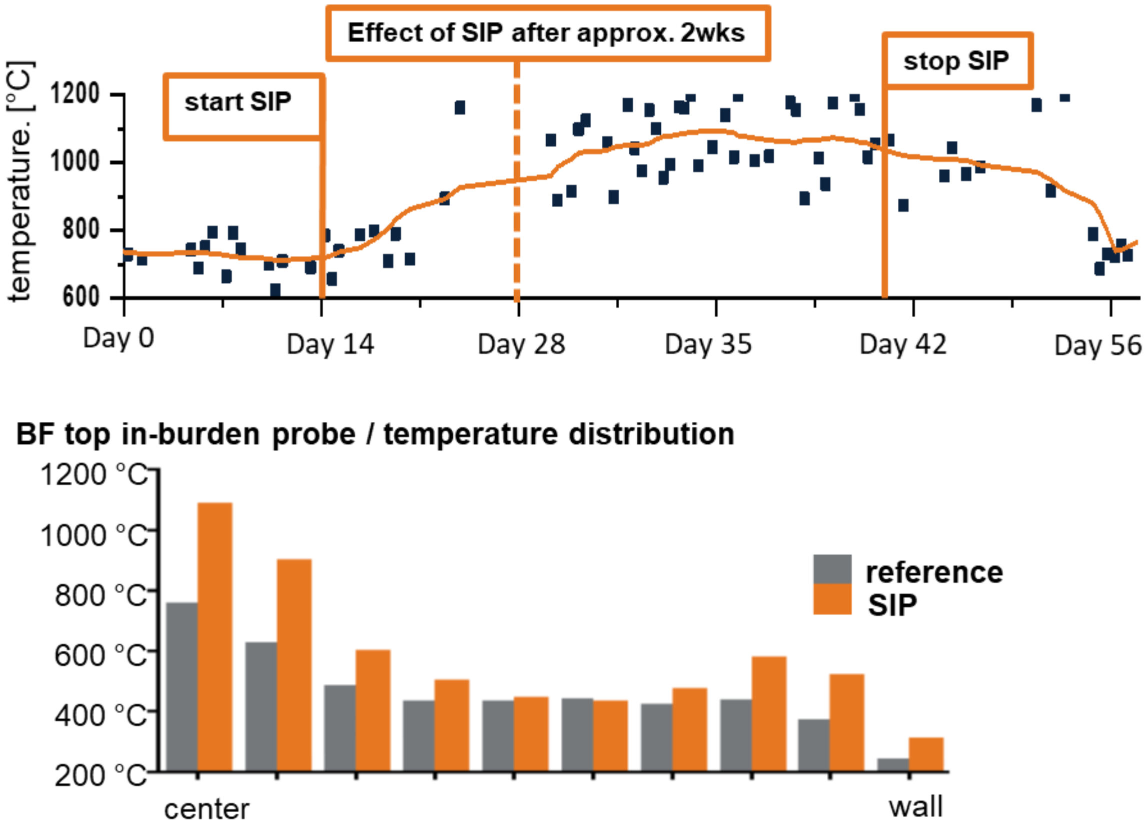

Figure 4: Schwelgern BF 1 in-burden probe (approx. 2 m below stock line level) temperature measurements, without and with SIP at the time of the first campaign. The top image shows development of the blast furnace center temperatures as measured with the in-burden probe, without and with SIP at the time of the first campaign

During the use of the SIP technology, a good gas distribution could be achieved without widening the coke channel by adjusting the burden distribution pattern. Figure 4 shows the measured center temperature of the in-burden probe before and during a SIP campaign. The temperature range was initially at a level between 600°C and 800 °C with an average value of about 700 °C before the campaign. After the start of the SIP system, an increase in temperatures was observed. The temperature level of 1000 °C on average, which experience at Schwelgern BF1 has shown to be conducive to production, was reached after approx. 14 days. This temperature range was measured during the entire test period.

After the end of the SIP campaign, the original temperature level was gradually restored. A time-delayed drop in values with a dip after about 14 days, possibly shows an "echo" reverberation of the SIP technology on the process.

The comparison of the measured temperature profiles of the periods with and without the SIP technology shows that an improved central gas flow was achieved.

An improved central gas flow also implies a lower gas flow at the blast furnace wall, thus also an effect on temperatures at the blast furnace wall. Figure 5 also shows this correlation. The temporal course of the wall temperatures above the tuyere level (14.1 to 31 m) shown here, can already be divided into two areas by a cursory observation. With the start of oxygen injection, the course of the shaft temperatures is increasingly characterized by fewer temperature peaks. Finally, after the already defined approximate period of 14 days of operation, a lower temperature level was reached, with only individually occurring temperature outliers. After the end of the SIP campaign, the original condition was restored after a delay here as well.

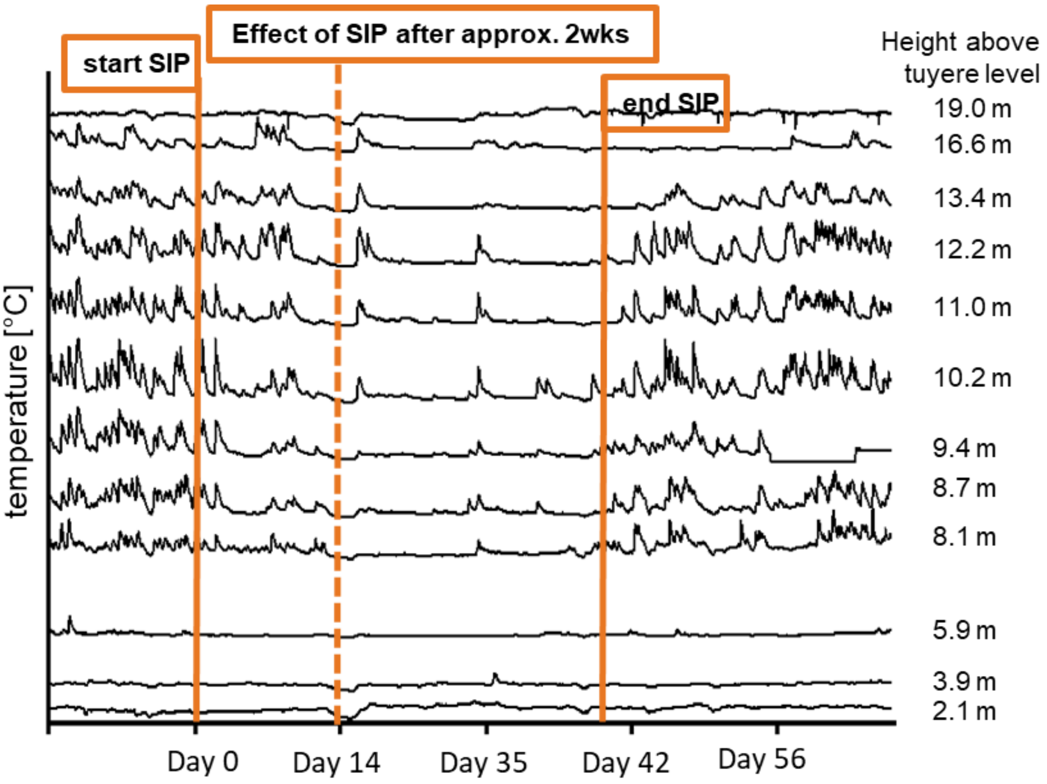

Figure 5: Schwelgern BF 1, wall temperatures above the tuyere level at one vertical measure line (line 5) during the first SIP campaign

The improved central gas flow and the lower temperatures at the blast furnace wall side are an indication of improved permeability. The resistance index K was used to assess permeability [13]

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$$K \sim \frac{p_1^2 - p_{Top}^2}{\left({RGV}/{A_1}\right)^{1,7}}$$

where:

p_1 = bosh gas pressure

p_{Top} = top gas pressure

RGV = bosh gas volume

A_1 = shaft cross-section

This blast furnace specific index describes the pressure difference between the bosh and the top, which is set in relation to the bosh gas volume and the shaft cross-section of the furnace. When interpreting the calculated values, the inverse proportionality to the permeability of the entire material stack in the shaft must be considered. Low resistance indices indicate good gas permeability.

A histogram (Figure 6) is shown of the resistance index K in the reference condition and the blast furnace operation with SIP during the first SIP campaign. The distribution in SIP operation has shifted to significantly lower values, indicating the permeability has improved. The standard deviation of the distribution function - recognizable by the distribution in the SIP 1a evaluation period is also significantly lower.

A uniformly distributed gas pressure over the furnace cross-section is a characteristic feature of a stable blast furnace process. Figure 6 also shows the maximum deviation of the measured shaft pressure differences between four measuring points positioned symmetrically around the furnace. The distribution function of the blast furnace operation with SIP shows a significantly smaller range of variation as well as a shift of the mean value towards smaller values as well, which suggests a significantly more stable process condition in the shaft (smooth blast furnace operation).

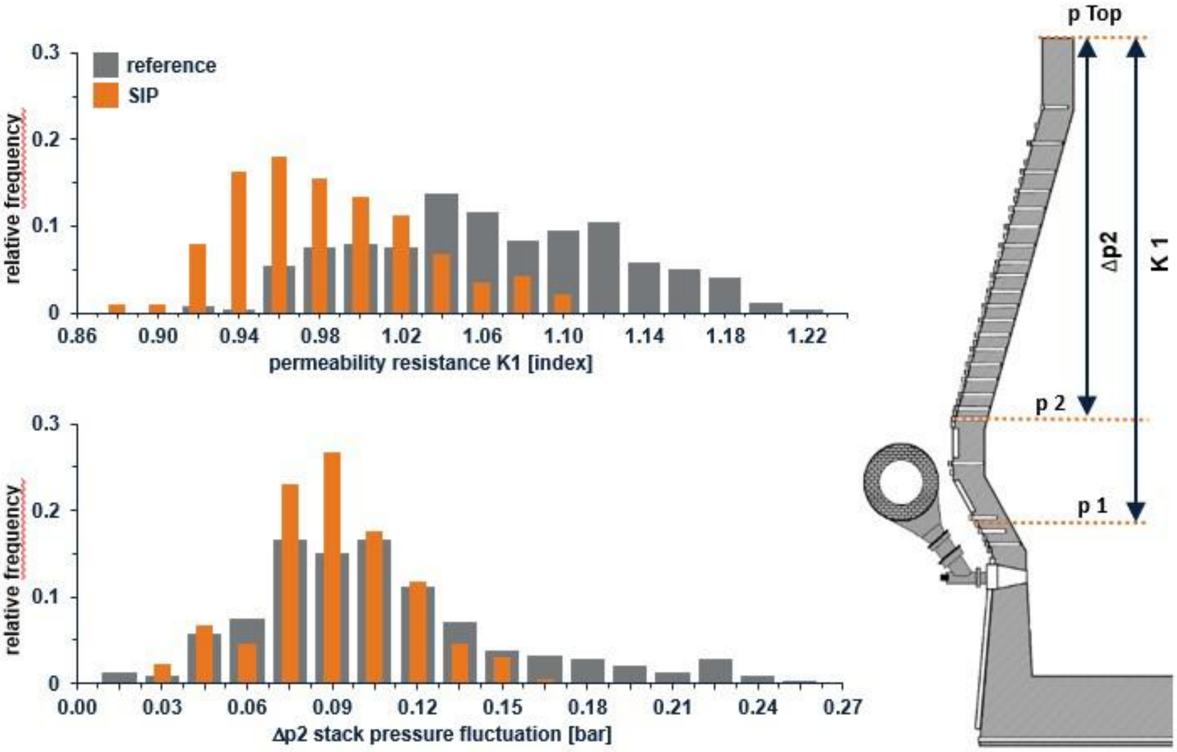

Figure 6: Comparison of the relative frequency distributions for the calculated resistance index K1 and the measured delta p values between the reference phase 1 and the SIP evaluation period 1a

Improvements in the permeability and stability of the blast furnace process create opportunities for optimizing the use of reducing agents, while maintaining the same raw material quality and similar production level, namely:

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- Eta CO optimized “burden distribution”
- Increase in PCI rate

The improved central gas flow is essentially due to the optimized inflow and throughflow of the coke channel in the lower part of the furnace, which is made possible by the lower proportion of fine particles in this area and the enlarged raceway. However, increased gas discharge through the coke channel at the stock line level leads to a reduction in gas utilization, i.e., to higher reducing agent consumption.

GAS UTILIZATION OPTIMIZED BURDEN DISTRIBUTION

The positive effect described for the flow of the ascending gas in the coke area in the lower part of the furnace allows the proportion of central coke to be reduced. As a result of the now reduced coke channel, more gas is diverted through the coke windows in the area of the cohesive zone into the burden layers. As a result of the lower central coke content, the burden is also distributed over a larger area. In this way, gas utilization can be increased and reducing agent consumption reduced.

PCI RATE INCREASE

The cleaner coke area in the lower part of the furnace additionally enables the PCI rate to be raised, an increase in fine particles in this area is deliberately accepted to a certain extent. If necessary, this increase can be compensated by a higher number of oxygen pulses. The burden distribution pattern remains the same, but the amount of coke charged is reduced at the same time due to a higher PCI rate, the coke channel is reduced in size. However, this decrease takes place to a smaller extent than it is in the case of a single coke portion change in the burden distribution. In this way, gas utilization can also be optimized with an increase in the PCI rate.

In the first and second SIP campaigns carried out on Schwelgern BF1, the PCI rate was first increased and then the coke channel was additionally reduced by means of a targeted burden distribution pattern adjustment. Figure 7 shows the development over time of the width of the coke channel, the PCI rate, the coke consumption, and the gas utilization.

In the first SIP campaign, the PCI rate was significantly increased and thus the coke consumption reduced. The first SIP campaign was interrupted by a planned long blast furnace repair shutdown. The PCI and coke consumption were adjusted for this, this adjustment is also clearly visible in the enlargement of the coke channel. After restarting the blast furnace, the PCI rate was quickly and significantly increased to a maximum value, as a result of which the width of the coke channel decreases. In addition, a moderate reduction of the center coke through burden distribution was carried out which resulted in maximization of gas utilization. After the end of the first SIP campaign, such high PCI rates and low coke consumption were no longer achieved.

In the second SIP campaign, the high PCI rate was reproduced, whereby the width of the coke channel also decreased with the increase in PCI quantity (Figure 7). The subsequent significant reduction of the coke channel, to a radius of only about 0.4 m (never used before in Schwelgern BF1 PCI practice), is due to a massive reduction of the center coke in the burden distribution. Gas utilization was maximized in this way while minimizing coke consumption. After the end of the second SIP campaign, the high PCI rates and low coke consumption as before, could again no longer be achieved. Finally, the massive reduction of center coke in the burden distribution had to be reversed.

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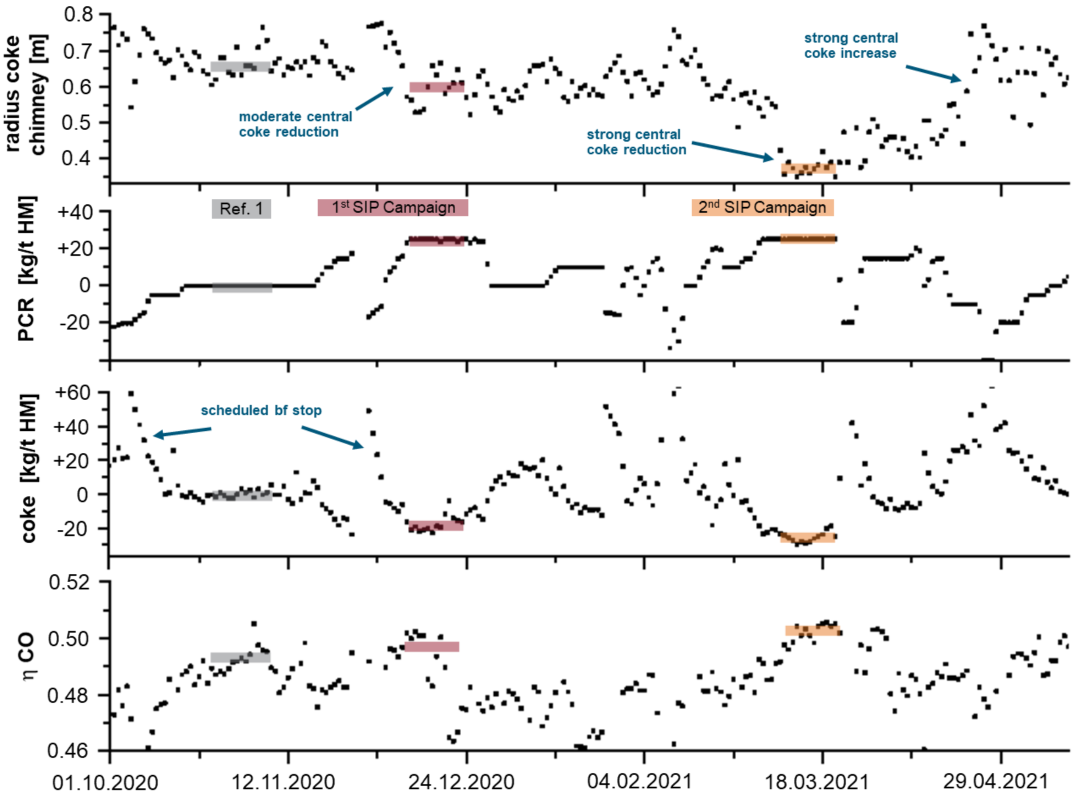

Figure 7: Temporal development of selected operating data of Schwelgern BF1, with colored indication of the periods of reference 1 and the first and second SIP campaigns

In both the SIP campaigns presented here (Figure 7), the PCI rate could be increased significantly, and the coke consumption consequently reduced. The first SIP campaign is characterized by a very good coke replacement ratio resulting from the improved Eta CO. In the second SIP campaign, coke consumption was reduced beyond the increase in the PCI rate, resulting in a coke replacement ratio of greater than 1. This effect can be explained by the further improvement in gas utilization compared to the first SIP campaign, due to the greatly reduced coke channel. The summary diagram in Figure 8, clearly shows the relationship between gas utilization and the width of the coke channel, as well as the achieved reductant agent rates (RAR).

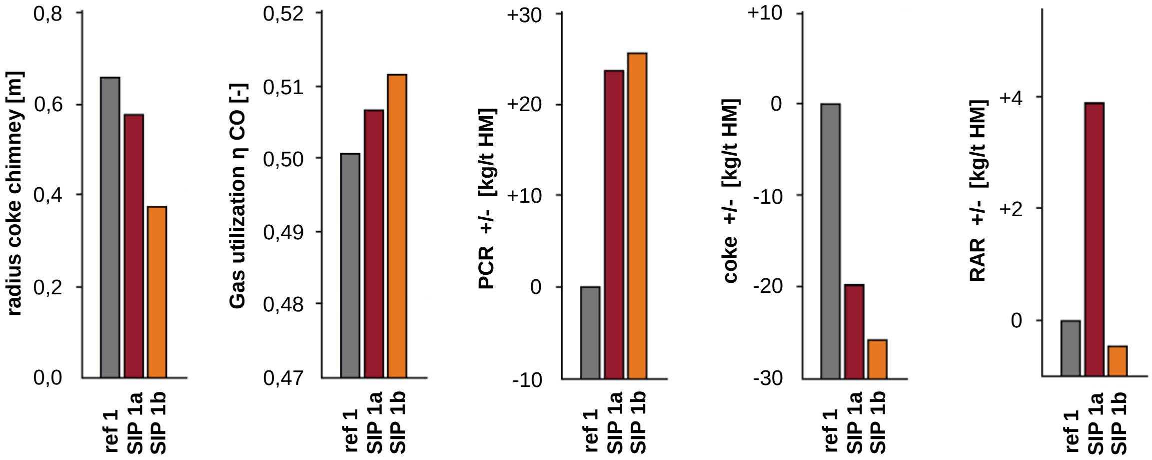

Figure 8: Comparison of average values of reference period with SIP evaluation periods

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After the relining of Schwelgern BF1 and a restart at the beginning of October 2021, the commissioning of the SIP plant and start of the third SIP campaign followed, in a period characterized by unusually poor raw material quality. The international difficulties in the transport industry due to shipping delays, led to adjustments in the compositions of the blends for coke and sinter and thus directly influenced the raw material quality supplied to the blast furnaces at thyssenkrupp Steel Europe.

At this time, only 3 of the 4 blast furnaces, reacted to this situation with significantly worse blast furnace performance and increased reducing agent consumption. For clarification, a comparison between the two larger blast furnaces, Schwelgern BF1 and Schwelgern BF2, is provided in Table 2 for this time, along with a relative description of the raw material quality. It is particularly noticeable that the frequency of blast furnace instabilities (hanging, slipping and channeling) leading to the requirement for a "checking" of a blast furnace, increased at Schwelgern BF2 due to the influence of the raw material quality. However, at Schwelgern BF1, this frequency strongly decreased following the start of the third SIP campaign, despite the poor raw material quality (Figure 9).

Raw Material Quality BF 1 and BF 2		
coke	mean size	low
	I 40	low
	I 10	high
	CSR	low
	CRI	high
sinter	mean size	low
	fines	high
	strength	low
	RDI	high
lump ore	type	change often
pellets	type	change often

a)

Parameter	BF 2	BF 1 with SIP
production	low	maximum capacity
blast volume	low	high
PCR	low	typical level
RAR	very high	typical level
gas utilisation	low	increase
gas temp. profile	insufficient	good, stable
wall heat load	high	low
permeability	low, unstable	good, stable
channelling	often	not often
hanging	often	not often
HM temperature	decrease, unstable	typical level
HM analysis	aim failed, unstable	typical level

b)

Table 2: a) Available blast furnace raw material quality with relative descriptions compared to the thyssenkrupp Steel Europe standards at the time of the third SIP campaign b) relative performance comparison of Schwelgern BF1 and Schwelgern BF2 at the time of the third SIP campaign

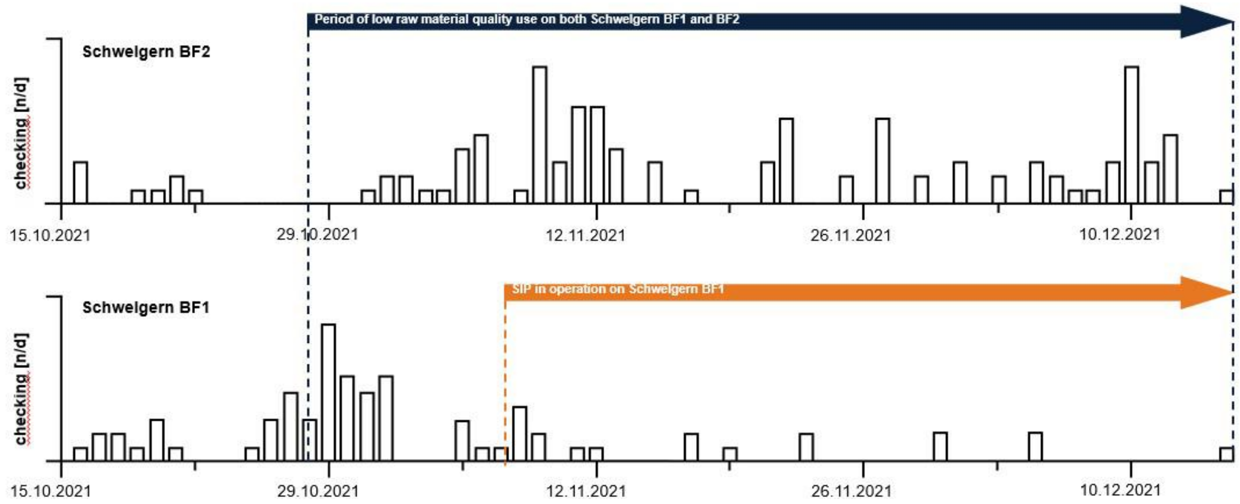

Figure 9: Timeline of the checking processes required per day for Schwelgern BF1 & Schwelgern BF2 during periods of deteriorated raw material quality and the third SIP campaign on Schwelgern BF1

STATISTICAL EVALUATION OF SIP CAMPAIGNS

The SIP campaigns at Schwelgern BF1, were accompanied by statistical data analysis of blast furnace parameters, usually used for evaluation of the process efficiency and by parameters known to be related to the blast furnace operational state. In total, until the end of 2021 three SIP campaigns were established from within which suitable evaluation periods were identified for comparison to periods with similar blast furnace operating parameters - but without SIP. The third campaign was divided into two evaluation periods, due to a blast furnace stoppage in-between: They are as defined in Table 1 previously:

- SIP 1a (10.12.20 – 19.12.20), SIP 1b (11.03.21 – 20.03.21) – established during the 1st and 2nd SIP campaigns
- SIP 2a (10.11.21 – 14.11.21), SIP 2b (18.11.21 – 21.11.21) – established during the 3rd SIP campaign

The SIP campaigns are compared to blast furnace normal operation periods hereinafter referred to as “reference” periods:

- reference 1 (19.11.20 – 28.12.20) – related to SIP 1a & 1b
- reference 2 (26.10.21 – 30.10.21) – related to SIP 2a & 2b

The reference periods were selected as periods with a good blast furnace working state without bigger operational problems for example, severe hanging & slipping or channeling events but also, with as far as possible, comparable operational set points to the SIP evaluation periods.

All statistical evaluations have been executed by comparing the median values of minute-based data from blast furnace parameters, measured during the reference or SIP campaign periods. To also gain an overview of the parameter fluctuations “swarm plots” were used. These plots note on the y-axis the parameter value. Several occurrences of the same value are marked by data points at the same y-level but next to each other in the x-direction. The received visual effect is a distribution plot, where more often-occurring values show a bigger extension in the x-direction, which helps to estimate if certain parameter values are measured only a few times (a thin distribution) or belong to the majority of values (“belly” of the distribution). Also, the minimum and maximum extrema are visible by the distribution “peaks” at top and bottom.

Parameters characterizing the operational set point of a blast furnace are for example, the hot blast flowrate, defining the production rate (at a constant oxygen content) as well as the reducing agent consumption. These parameters are given for the SIP evaluation periods as well as the related references in Figure 10.

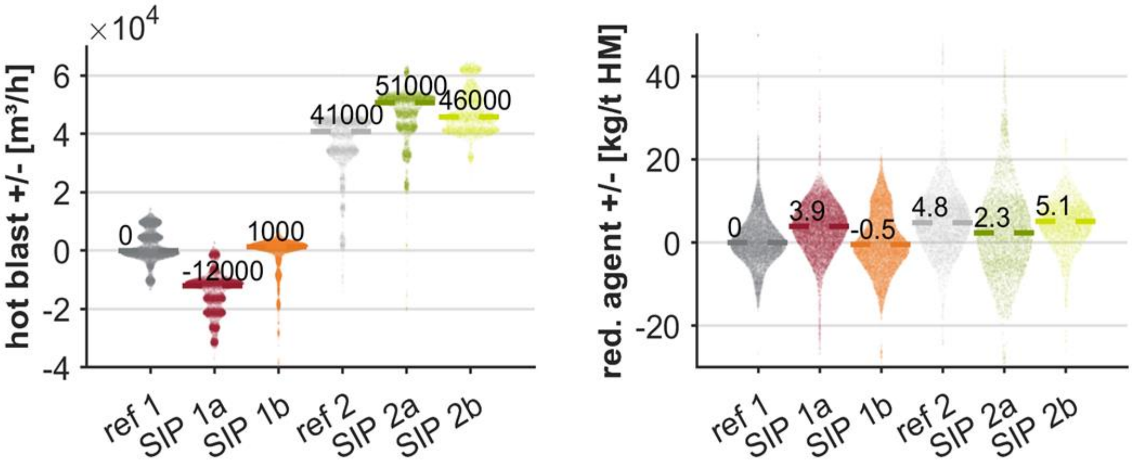

Figure 10: Blast Furnace operational set-points (left: hot blast flowrate, right: reducing agent)

During the first campaign of the SIP technology in evaluation period SIP 1a, the blast furnace set point was conservative. Hot blast flowrate was reduced by 12x10^3 m^3/h compared to the reference 1. Reducing agent rate was slightly increased by 3.9 kg/tHM. After quite positive results (see previous sections) the second SIP campaign with evaluation period 1b, started at a setpoint nearer to the reference state.

In the third SIP campaign, and the evaluation periods (SIP 2a, SIP2b), the blast furnace was in total at a higher production rate with the hot blast flowrate increased by around 4 - 5x10^4 m^3/h. For the reference 2, this also meant an increased reduction agent rate compared to reference 1 by 4.8 kg/tHM. During the evaluation period SIP 2a, reduction agent rate was decreased by 2.5 kg/tHM compared to reference 2 and in SIP 2b, it was around the same level as reference 2.

BF WORKING STATE DURING SIP TRIALS

As already explained in the sections above, the SIP operation has a strong influence on gas flow in the blast furnace and therefore also pressure drop. This is also visible by evaluation using the swarm plots. Due to the operational measures explained in the sections above, during evaluation period SIP 1a the median pressure drop slightly increased, compared to an operation without SIP but a good furnace working state, as during reference 1. But even with this higher median pressure drop the furnace working state was better, as less pressure fluctuations occurred, which would otherwise be a sign for blast furnace working state problems. This is visible in Figure 11. The width in y-direction of the distribution of values from evaluation period SIP 1a is smaller compared to reference 1. For SIP 1a, less extreme values occurred, and the highest pressure drop measured is still below 2 bar, which is less than the highest values of reference 1.

The later SIP 1b evaluation period shows a comparable shape like reference 1, meaning comparable pressure drop fluctuations like a good working state – but the median is at a lower level.

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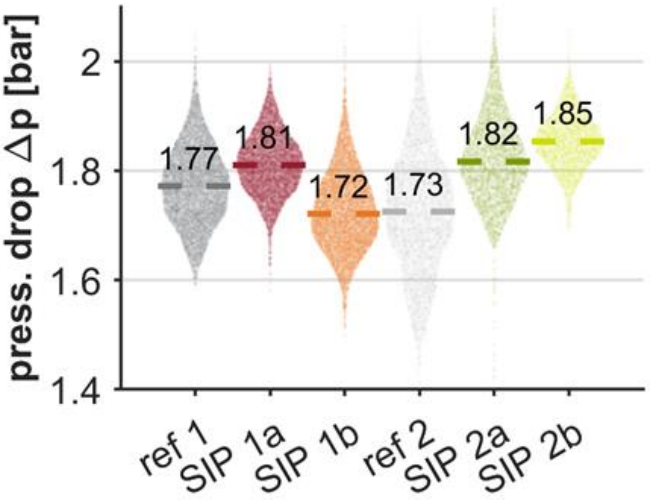

Figure 11: Blast furnace pressure drop (from hot blast to top) during reference state and SIP evaluation periods

A good example for the overall effect of SIP on blast furnace pressure drop is visible by comparison of reference 2, with evaluation periods SIP 2a and SIP 2b. Reference 2 shows an in total lower median value of the pressure drop, of only 1.73 bar. But the value distribution is wide, stretched from values as low as 1.4 bar up to more than 2 bar. This strong fluctuation was caused by lower raw material quality in combination with the increased hot blast flowrate (Figure 11). From reference 2 to evaluation period SIP 2a, the hot blast flowrate was increased by $1x10^4$ m^3/h. This resulted in a total higher median pressure drop, but as already observed for the case of SIP 1a against its reference, the distribution with SIP operation is more compact in y-direction, indicating less pressure drop fluctuations. For SIP 2b this effect is even stronger. Although the median pressure drop is at the highest level of all campaigns, the blast furnace working state is smoother than at all previous campaigns.

POTENTIAL FOR NEW BLAST FURNACE WORKING POINTS

As claimed in Figure 1, SIP enables the potential for new blast furnace operational set points. In the first two SIP campaigns, during the evaluation periods SIP 1a and SIP 1b, the focus was on substituting high-cost raw materials like coke, for more economic pulverized coal injection. From reference 1 to SIP 1a and 1b, the coke rate could be reduced by 20 and 26 kg/tHM respectively (Figure 12). In turn, the coal rate was increased by 23.6 and 25.6 kg/tHM leaving the total reductant rate on a similar level to the reference 1 for SIP 1b and slightly increased for SIP 1a (Figure 10, right).

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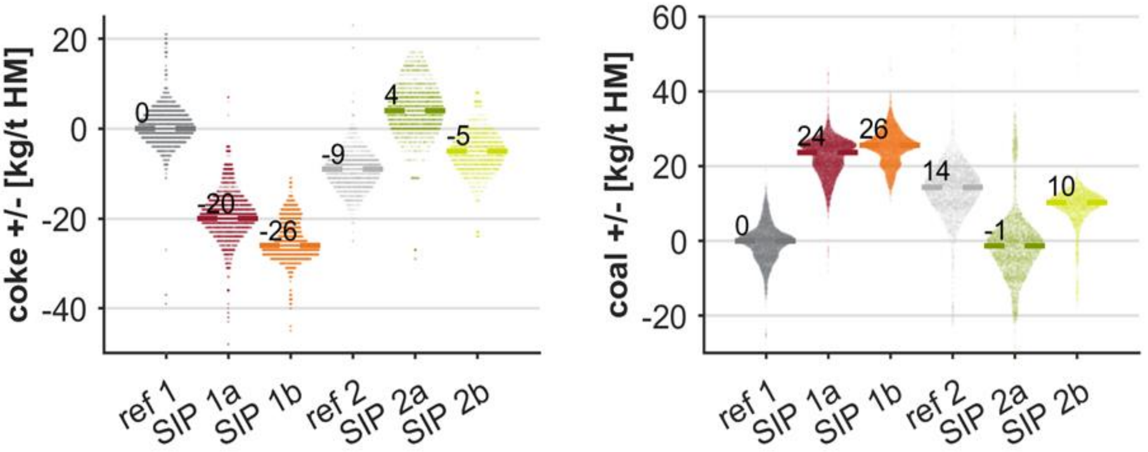

Figure 12: Share of coke (left) and coal (right) rate as reducing agents supply during reference and SIP evaluation periods

During the third SIP campaign, the coke rate was changed to a lesser extent. Evaluation period SIP 2a operated at a slightly higher coke rate and lower coal rate level than reference 2, whereas SIP 2b is comparable to reference 2. The focus in these campaigns were, beside the necessity to use lower raw material qualities, more on the production aspect (Figure 13).

Though total reducing agent supply rate between reference 2 and SIP 2b was untouched and was even slightly lowered for SIP 2a compared to the reference 2 (Figure 12), an increase of production rate could be established. For SIP 2a the production rate increased compared to reference 2 by 20.8 tHM/h and for SIP 2b by 25.5 tHM/h in median (Figure 13). Thereby, SIP 2b had the highest total production of all analyzed periods.

For SIP 1a also a higher production increase was reached compared to reference 1, although the blast furnace operated at a lower hot blast flowrate (Figure 10, left). The additional oxygen required for the higher production and supporting a higher pulverized coal rate, was delivered from the SIP system.

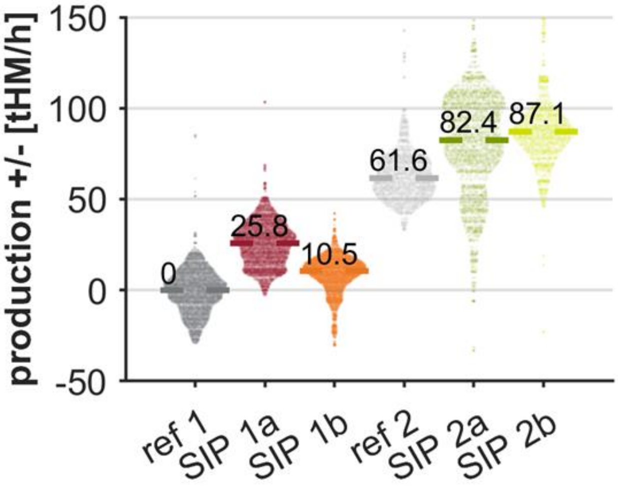

Figure 13: Increase of production rates of all periods compared to reference 1

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EFFECT ON PROCESS EFFICIENCY AND CARBON DIOXIDE EMISSION REDUCTION

SIP substantially changes the gas flow paths in the blast furnace and therefore the location of process reaction zones. This, in combination with operational measures as described in the “thyssenkrupp Steel Europe, Schwelgern BF1 practice with SIP” section, also has an influence on the total blast furnace gas utilization and therefore directly on the efficiency of how the supplied reducing agent is utilized in the process.

During all reference and SIP evaluation periods the gas utilization data defined as, $\eta CO = (CO_2 / (CO + CO_2))$ was gathered from top gas analysis. The value distribution was evaluated according to the same methods as the previously discussed blast furnace parameters. The results are given in Figure 14 (left). Summarizing, for each SIP evaluation period the gas utilization was higher than during the reference periods – even though periods with already good blast furnace working state were chosen as reference.

During the SIP 1a and SIP 1b evaluation periods, compared to the reference 1, the gas utilization was increased by 0.6% and 1% respectively. During the SIP 2a and SIP 2b evaluation periods the gas utilization was increased by 1.4% and 1%. In Figure 14 (left) it is also visible, that the first (reference 1, SIP 1a and SIP 1b) periods and the second periods (reference 2, SIP 2a and SIP 2b) have different total levels of gas utilization. This is caused by the well-known fact, that gas utilization in a blast furnace usually decreases with an increase of production rate. To better visualize this effect Figure 14 (right) shows the gas utilization vs. the increase of production rate in relation to the reference 1, which had the lowest production rate.

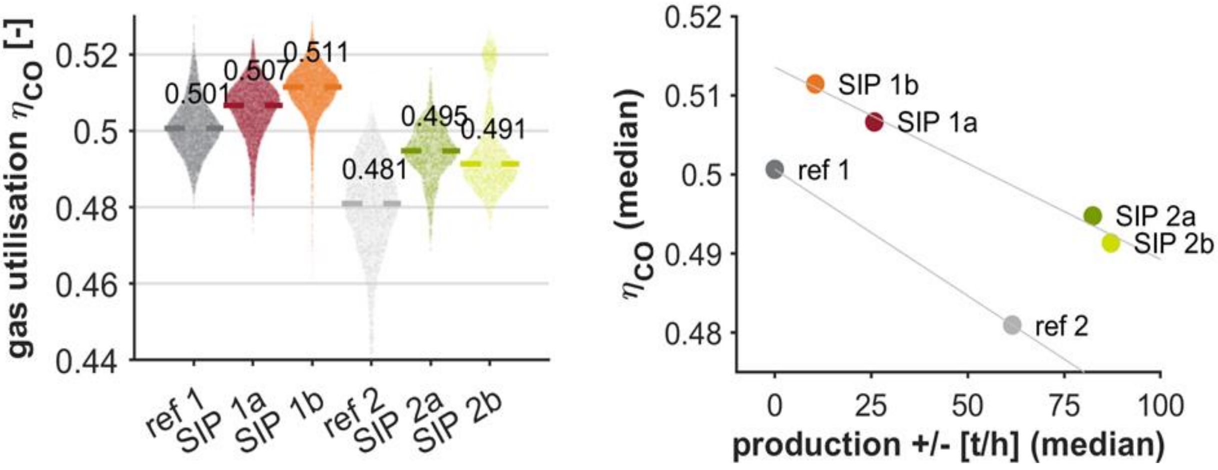

Figure 14: Gas utilization during reference and SIP evaluation periods (left) and in relation to production rate (right)

During reference 1 the gas utilization median value was 0.501 and during reference 2, the median value was 0.481 but with a 61.6 tHM/h increased production rate. This gives a loss of around 0.32% ηCO for each increase of 10 tHM/h production. Also, low production scenarios (not shown in Figure 14), for example, faced by thyssenkrupp Steel Europe during the COVID-19 pandemic situation, lie perfectly on this line, confirming this linear behavior of the blast furnace process for normal operation.

As for the reference periods, the SIP evaluation period operational points can also be linearly connected to a good accuracy as visible in Figure 14. The highest gas utilization median value of 0.511 was achieved during SIP 1b but with the lowest production rate of all SIP evaluation periods. SIP 2b reached the highest production rate of all SIP evaluation periods with 87.1 tHM/h more than reference 1, but in reverse has the lowest gas utilization median value of 0.491. In contrast to the normal operation line, the line for SIP operation is on a higher level and shows a slightly lower declination. Here the loss of gas utilization is only around 0.24% each 10 tHM/h of production increase.

On average, given the same production rates, SIP provides a 1% (at reference 1 production rate) up to 2% (at 100 tHM/h production rate increase) higher gas utilization.

If the production is kept constant, such higher gas utilization rates can be directly converted into CO_2 emission savings. In case of Schwelgern BF1, CO2 emission savings of on average 16 kg/tHM up to savings of 36 kg/tHM in the best case, were established.

CONCLUSIONS

The world's first SIP plant for blast furnace application has been operating at Schwelgern BF1 since November 2020. Fully adopted and incorporated into blast furnace operating practice, it has provided and continues to demonstrate, a huge potential to improve process stability, increase productivity and optimize operating costs.

The main findings from Schwelgern BF1 from the comparison of the value distributions of several measured blast furnace parameters during reference and SIP periods are, that the blast furnace working state, indicated as fluctuations of the pressure drop from hot blast to top, is smoother during SIP operation. Also less hanging & slipping or channeling events occurred during SIP campaigns. This opens the possibility for economic adjustments to blast furnace operational set points:

- Either coke can be exchanged by coal or
- Production can be increased, without the otherwise necessary increase of reduction agent rate

Also, a combination of both is possible. Additionally, SIP introduces the potential for higher gas utilization rates and therefore contribution towards lower CO_2 emissions. Depending on the operational set points, an on average 1%, up to 2% in the best case increased gas utilization was demonstrated. This leads to an average CO_2 emission decrease of 16 kg/tHM on average, or up to 36 kg/tHM in the best case.

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