ENHANCED BLAST FURNACE PERFORMANCE UNDER A PERIOD OF LOW QUALITY RAW MATERIAL ACHIEVED BY IMPLEMENTING SIP TECHNOLOGY*

Ross Edmond[1]
Rainer Klock[2]
Jiho Juen[3]
Bartosz Smaha[4]
Hauke Bartusch[5]

Abstract

The technology known as Sequence Impulse Process (SIP) injects oxygen with high kinetic energy through the tuyeres on a regular basis. This method improves the local conditions within the raceway of the furnace and enhances its overall performance. In this paper, the principles and key components of this full-scale technology will be introduced, along with some impressive findings from operational results at the world's first blast furnace to use SIP technology, which is operated by thyssenkrupp Steel Europe AG at their Duisburg site in Germany. Previous reports have shown that the use of SIP technology results in a reduction of the total fuel rate and CO_2 emissions, as well as enabling higher productivity and a stable use of increased PCI rates on the blast furnace. The current paper will focus on results from a period where low-quality raw materials were used and will provide new information about the performance of BF1 with SIP technology compared to the minimum fuel rate requirement and the performance of other blast furnaces at the same site during that period.

Keywords: SIP; Oxygen; Permeability; CSR

[1] *Principal Process Engineer, Primetals Technologies Ltd, Stockton-on-Tees, UK.*
[2] *Chief Operating Officer, thyssenkrupp AT.PRO tec GmbH, Essen, Germany*
[3] *Technical Sales Manager, thyssenkrupp AT.PRO tec GmbH, Essen, Germany.*
[4] *Head of Team Reduction Metallurgy, thyssenkrupp Steel Europe AG, Duisburg, Germany.*
[5] *Senior Researcher, VDEh-Betriebsforschungsinstitut GmbH, Düsseldorf, Germany.*

1 INTRODUCTION

The efficient operation of blast furnaces, particularly large units operating near their minimum energy input or reducing agent requirement, relies heavily on the consistent high quality of the raw materials used. In general terms, to achieve the desired nominal output, it is crucial to maintain continuous and consistent operation of a blast furnace. Deviations from the thermodynamic optimum or significant deviations from this condition can result in a rapid decline in raw material efficiency [1,2,3].
Blast furnace operators have always faced increasingly demanding challenges, including the need for high production levels while maintaining consistent iron quality. However, these goals are often pursued amidst operational and process difficulties. The scarcity of high-quality raw materials and the unpredictable properties of available alternatives can lead to less-than-ideal operating conditions, which may impact production targets.
The introduction of a new technology that has already demonstrated positive effects on blast furnace performance, while addressing such challenges, is a valuable addition to the suite of operational tools available at one of the world's leading blast furnace facilities. The Sequence Impulse Process (SIP) is an innovative blast furnace technology which commenced full operation at Schwelgern blast furnace 1 in late 2020. This blast furnace, with an inner volume of 4416m^3, is operated by thyssenkrupp Steel Europe AG (tkSE) at their Duisburg plant in Germany.
SIP technology has proven to significantly enhance blast furnace operation, including during periods of sustained low-quality raw material. The SIP plant has been completely integrated and adopted into blast furnace operating practices at Schwelgern BF1.

Image 1: View from cast house floor at Schwelgern BF1 where SIP Technology is installed

This paper initially provides an overview of the technology principles and describes the plant at Schwelgern BF1, followed by an exploration of its decarbonization credentials and operational results achieved under normal operation thus far. The period of low-quality raw material use at the Duisburg steelworks is then examined in detail. During this time all the blast furnaces were required to receive raw materials of a quality significantly below their standard specification, introducing challenges for operational control and productivity. Similar material qualities were used at each blast furnace - but the impact upon the operations, was not necessarily the same. Of particular interest is a remarkable contrast in the performance of the two large units during this period, one equipped with SIP technology, one without.

2 DISCUSSION

2.1 TECHNOLOGY DEVELOPMENT

SIP technology was initially developed by thyssenkrupp AT.PRO tec GmbH and more lately in partnership with tkSE. The development path has been documented previously [4] and was achieved within a framework of research projects, both at a laboratory and industrial scale. The technology was advanced and successfully adapted for blast furnaces from its origins in foundry furnace application, leading to the full system installation at Schwelgern BF1. Image 1 shows a view from the cast house floor, where dedicated SIP boxes for each tuyere can be seen located above the tuyere platform. An exclusive cooperation agreement with Primetals Technologies makes SIP technology available to the worldwide market enabling operators to use it to stabilize their process and increase the performance of their blast furnace assets

The impact of SIP was initially investigated on a blast furnace through operating tests conducted on a single tuyere at Schwelgern BF1, which was equipped with a dedicated SIP testing facility. To facilitate a comparative analysis, additional examinations were performed on reference tuyeres. Analysis of temperature fields within the raceway revealed that approximately 80% of the pulsed oxygen reacted within the coke bed situated behind the raceway, leading to a substantial improvement in the chemical conversion of injected coal during the pulsation process. Evaluations of numerous material samples extracted from the tuyeres consistently demonstrated a reproducible and significant enlargement of the raceway, expanding from an average of approximately 1.0 m to 1.5 m as shown in image 2.

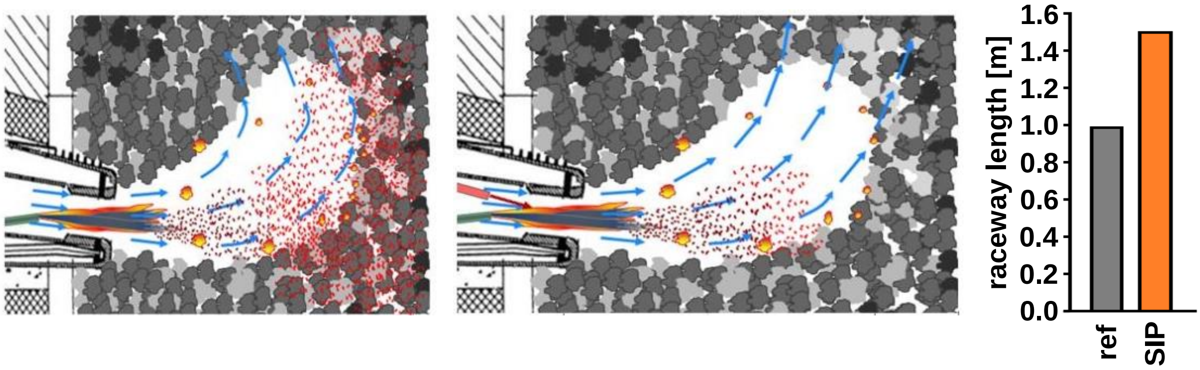

Image 2: Influence of the SIP raceway effect and resulting increase to raceway length

Additionally, a recurring observation involved the presence of a smaller fine fraction and larger equivalent grain diameter of the coke in the transition zone between the raceway and the dead man. Material sample analysis further indicated a shift in the distribution of liquid phases (iron and slag) towards the center of the furnace. Chemical analyses performed on iron and slag samples provided evidence of a shift in the high-temperature range towards the furnace center. Through the application of helium tracing, which involved the introduction of helium into the tuyere and measuring its concentration at the central position of the in-burden probe, a notable alteration in the gas flow attributable to the SIP process towards the furnace center was identified. These studies provided valuable insights into the temporary localized depth effect of SIP oxygen.

2.2 TECHNOLOGY PRINCIPLES

When coal is injected into a blast furnace, the chemical transformation in the raceway is incomplete due to its short retention time and insufficient mixture generation [5]. The concept behind Sequence Impulse Process (SIP) is to generate a supersonic free jet with an unsteady start-up range and a leading shock wave. This condition is used to provide a positive impact on the blast furnace process by enhancing and intensifying the local turbulence in the raceway. As a result, reactive mixtures are formed more effectively, promoting the necessary mass transfer for chemical reactions [6]. The implementation of SIP technology not only improves the ignition condition, but also enhances turbulence itself, leading to the cleaning of the rear area of the raceway. Failure to address these sub-processes typically results in reduced permeability, increased flow resistance, and a shift in gas direction towards the sides of the blast furnace. Furthermore, there is a risk of fine particle deposition in the blast furnace hearth, negatively affecting the flow behavior of the liquid iron and slag along the entire path, from the melting zone to the tap holes. These effects are particularly pronounced when the quality of the coke is inadequate [7,8,9]. Relative to the injected coal mass, the oxygen injected during a pulse contains a surplus of the stoichiometric oxygen required for coal reaction. The transient open jet created by SIP technology improves the conditions for coal-oxygen mixing. As a result, a high level of chemical conversion of the injected coal can occur temporarily during a pulse. Image 2 illustrates the impact of SIP technology on the raceway, comparing the conditions without and with SIP operation.

2.3 SIP PLANT DESCRIPTION

thyssenkrupp Steel Europe operates an integrated steel mill located in Duisburg, Germany. The mill consists of four blast furnaces with a combined maximum hot metal production capacity of 34,000 tons per day. Among these furnaces, Schwelgern BF1 is one of the larger units, boasting an inner volume of 4416 m^3, a hearth diameter of 13.6 m, and 40 tuyeres. Its nominal capacity is 3.5 million tons per year.

The SIP plant utilizes oxygen that was previously employed by the blast furnace, either through conventional stove blast enrichment or oxy-coal injection. The oxygen is sourced from the site's high-pressure network and delivered to the SIP plant. A pressure control station, buffer vessel, and oxygen ring main support the essential components of the SIP plant, which are housed in specialized SIP boxes. Each tuyere of the blast furnace is equipped with a dedicated SIP box located just above the tuyere platform and can be seen in Image 1. These boxes supply oxygen to the SIP injection lances, which are inserted through the blowpipe at each tuyere. SIP technology requires the use of high-pressure oxygen, typically exceeding 20 bar g. Additionally, a nitrogen supply is available primarily for safety purposes, including a filter station and another ring main encircling the blast furnace. Both oxygen and nitrogen are distributed to the 40 specialized SIP boxes.

The primary function of each SIP box is to facilitate the generation of the shockwave and deliver a high kinetic energy oxygen pulse to the dedicated SIP lance inserted through the blowpipe of each tuyere. In addition to the periodic pulses of high-energy oxygen, each lance receives a continuous flow of a "basic load" of oxygen, so to ensure sufficient lance cooling. Nitrogen is also utilized for cooling purposes and is automatically activated as an emergency cooling measure in the absence of oxygen.

The plant is equipped with a safety function that can rapidly divert stored oxygen away from the blast furnace through a vent pipe while introducing a nitrogen purge.
During normal operation, the SIP plant utilizes a short-duration oxygen pulse that is periodically added to the basic-load oxygen at a predetermined frequency. Each pulse is of a very brief duration, typically around 0.5 seconds, but their frequency is regulated by a dedicated control system to ensure regular intervals. The control system allows for flexibility in managing the system and adjusting the admission of oxygen to individual tuyeres according to the specific requirements of the blast furnace operation.
For instance, the pulse pattern, cycle time, and total oxygen flow can be customized to align with production needs. The operator has the freedom to choose how the system is utilized, including the selection of individual tuyeres and the possibility of providing additional oxygen to specific tuyeres if deemed necessary. This level of flexibility is not commonly available in all blast furnaces. The installed SIP plant has the capacity to supply the blast furnace with up to 25,000 Nm^3/h of oxygen.

2.4 PREVIOUS OPERATIONAL RESULTS

Applied at every tuyere, the benefits originating from the raceway provided by SIP such as, increased local permeability, improved flow paths for gas and liquids, and an increase to the raceway length, have translated into benefits for the overall blast furnace process. A reduction in the total fuel rate, reduction of CO_2 emissions, a more stable operation at high PCI rates and the potential to unlock a greater productivity, have all been attributed to the influence of the SIP effect [10].
An example of the impact upon stability can be seen in Figure 1. It shows the differences found between a SIP evaluation period (shown in orange), compared to a reference operating point under similar conditions - but without SIP. It shows the permeability resistance, defined by K, was reduced and that the frequency of high temperatures recorded by skin flow measurements in the blast furnace shaft were dramatically reduced when SIP was in operation. The permeability resistance K is a function of the pressure difference between the bosh and top gas, and other operational measurements [11]. A uniformly distributed gas pressure and low permeability resistance over the furnace cross-section, is a characteristic feature of a stable blast furnace process. Such a change in key blast furnace values gives the potential for new operating points.

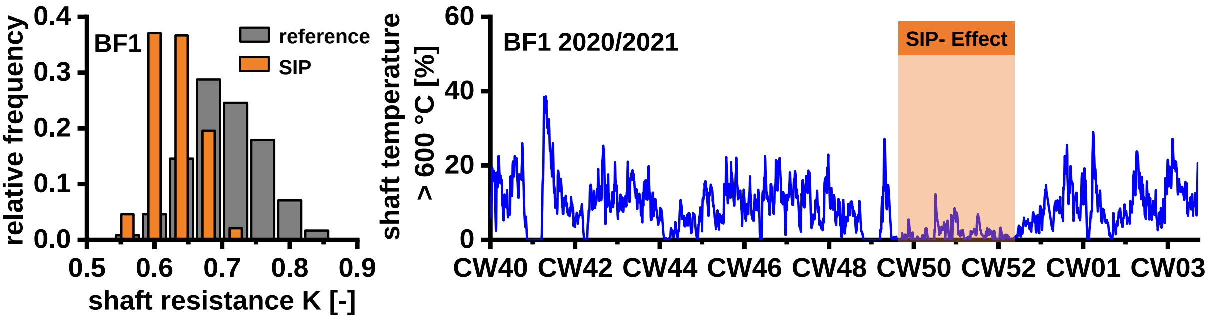

Figure 1: Impact of SIP on reducing the permeability resistance and high wall temperatures experienced in the shaft of BF1

The positive impact SIP has on the ascending gas flow from the lower part of the blast furnace, allows for adjustments to be made to the proportion of central coke charged. By reducing the size of the central coke chimney while still maintaining adequate gas acceptance in the blast furnace, a larger amount of gas can be directed through the coke windows in the cohesive zone, improving gas contact with the descending burden across a larger cross-sectional area. This increased gas utilization leads to a reduction in blast furnace reducing agent consumption.

Figure 2 shows results from the impact of this relationship. A smaller coke chimney radius was targeted from the burden distribution during operation, yet at the same time the gas utilization was improved. Also at the same time, a significantly higher PCI rate could be maintained with stable operation and at a replacement ratio with expensive metallurgical coke in real terms of more than 1:1 given that the additional benefits of SIP resulted in a net reduction of the reducing agent rate (RAR).

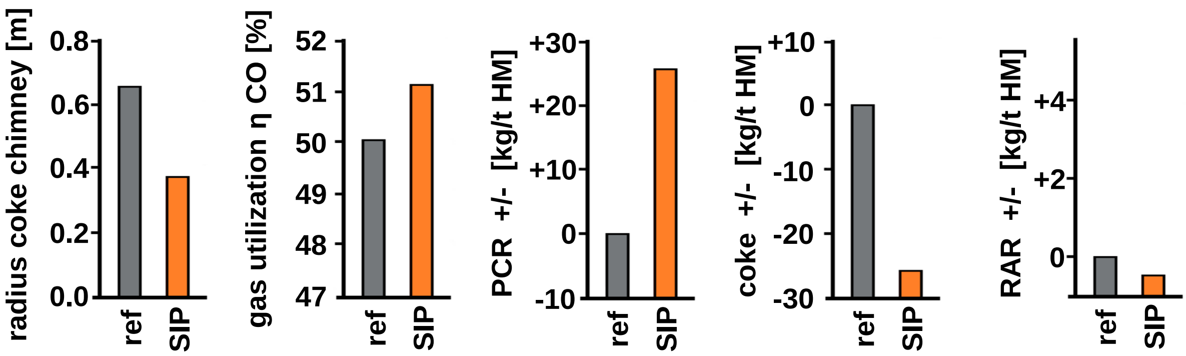

Figure 2: Comparison of average values of reference period with SIP evaluation periods on BF1

Increased gas utilization aligns with a reduced carbon footprint. Figure 3 displays the gas utilization and median specific CO_2 emissions per tHM/h plotted against the achieved increase in production found with SIP. Several SIP evaluation periods have been possible since the start-up of the full system. SIP 1a, 1b, 2a & 2b denote evaluation periods and the determined operating lines of Figure 3 are shown relative to performance during reference periods.

Apart from gas utilization, other factors also influence CO_2 emissions. For instance, the initial SIP 1a period was conducted with conservative operational settings, including a relatively high reducing agent rate. Subsequent SIP periods made more efficient use of the technology's potential. Comparing SIP 1b and 2b with ref1 and ref2 periods of normal operation, a CO_2 reduction ranging from 50 kg/tHM to 100 kg/tHM was observed, depending on production levels.

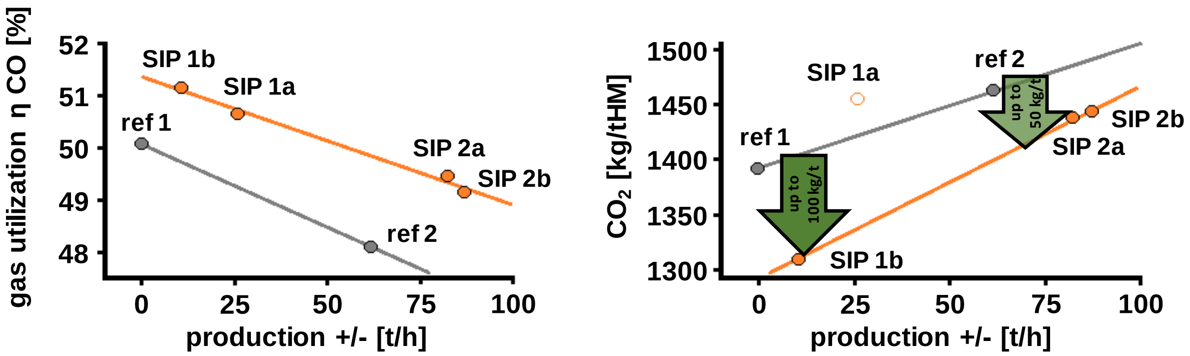

Figure 3: Gas utilization during reference and SIP evaluation periods in relation to production rate (left) and resulting CO2-emission saving potential (right).

2.4 LOW MATERIAL QUALITY PERIOD

There are a total of four blast furnaces operating at the tkSE Duisburg site. The two larger units at the site are Schwelgern BF1 (IV 4,416m3) and Schwelgern BF2 (IV 5,513m3). BF1 as stated is equipped with SIP technology.

A period of reduced burden material quality lasted for approximately six weeks. It was characterized by an overlapping deterioration and increased variation, of coke and sinter properties. In addition, frequent burden changes were necessary with swings in the quantities of pellets and lump ore charged to the blast furnaces required to accommodate the changing chemistry. Table 1 summarizes the low-quality material properties and relative impact upon operation to BF2 and BF1.

Table 1: Raw material quality values charged to BF 2 & BF 1 (with SIP) and blast furnace performance during the period of low material quality, relative to typical values & performance

Raw Material Quality BF1 and BF2		
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

Parameter	BF2	BF1 with SIP
production	low	maximum capacity
blast volume	low	high
PCI	low	typical level
RAR	very high 518-534 kg/tHM	typical level 499-511 kg/tHM
gas utilisation	low 46.6-47.4 %	high 49.2-50.0 %
wall heat load	high	low
permeability	low, unstable	good, stable
channeling	often	not often
checking	often	not often
HM analysis	aim failed and unstable	typical level

The blast furnaces operate a predominately sinter burden and it was necessary to work with a strongly fluctuating sinter basicity introducing unstable conditions. Both large blast furnaces received approximately the same mix from the three sintering plants available and were thus both confronted with a rather demanding situation. During this period, a remarkable decrease in coke quality can be seen - sharply falling CSR and correspondingly rising CRI values. Both blast furnaces had to work with this poor coke quality during this time. A rapid drop in the weighted CSR values to approximately 63% with large fluctuations was caused by the supply of a poor-quality external coke.

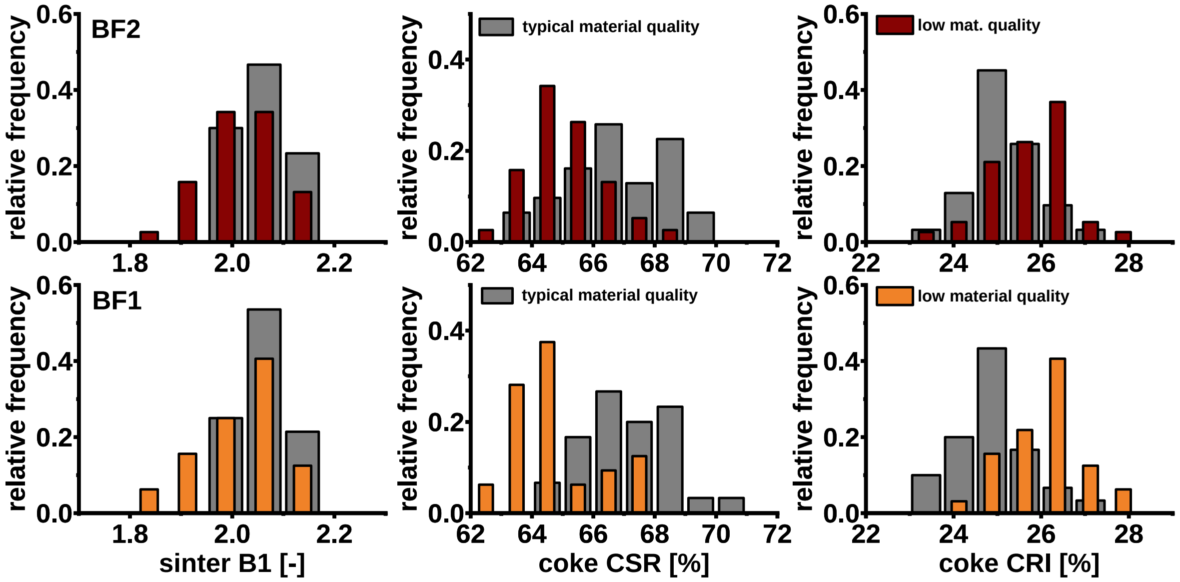

Figure 4: Sinter basicity (B1), Coke CSR & CRI values charged to BF 2 & BF 1 (with SIP) during the period of low material quality compared to typical values

Figure 4, shows three histograms, representing the distributions or frequencies of parameters for sinter (basicity B1) and coke (CSR and CRI) in two different time periods at blast furnaces 1 and 2. This statistical analysis and graphical depiction of data facilitate a straightforward and impactful representation of the disparities between the two sets. The gray bars represent the qualities used in both furnaces during a reference period and can be considered almost identical for both units. The colored bars (dark red for blast furnace 2 and orange for blast furnace 1) represent the same raw material values during a challenging period characterized by fluctuating and deteriorating coke or sinter qualities. In both furnaces, a shift of values towards significantly poorer ranges is observable. On one hand, the colored bars representing basicity values move towards smaller values, and the distribution becomes more left-skewed. On the other hand, the coke qualities, reflected in the CSR values, also shift towards smaller values, with blast furnace 1 exhibiting a much stronger leftward shift. The distribution of data changes, deviating from a normal distribution, indicating particularly pronounced fluctuations during this period. Blast furnace 2 goes through a similar phase and experiences deteriorating CSR values, but the distribution is closer to a normal distribution and thus exhibits considerably less variability. On the other hand, the increasing CRI values correspond to the decreasing CSR values in both blast furnaces, even though these histograms do not show any peculiarities in their distribution pattern or shape.

Figure 5 shows the development over time of process instabilities experienced during period of reduced burden material quality and, in the case of BF1, the start of SIP operation. A description of the full operational phenomena has been given elsewhere [12]. In summary, the direct comparison between a blast furnace operating with SIP technology (BF1) and a similar blast furnace without it (BF2), shows a higher productivity at a lower fuel rate. This performance was accompanied by a smoother furnace operation on BF1, as seen in the dramatic decrease in process instabilities of figure 5 such as hanging, channeling and high heat load events.

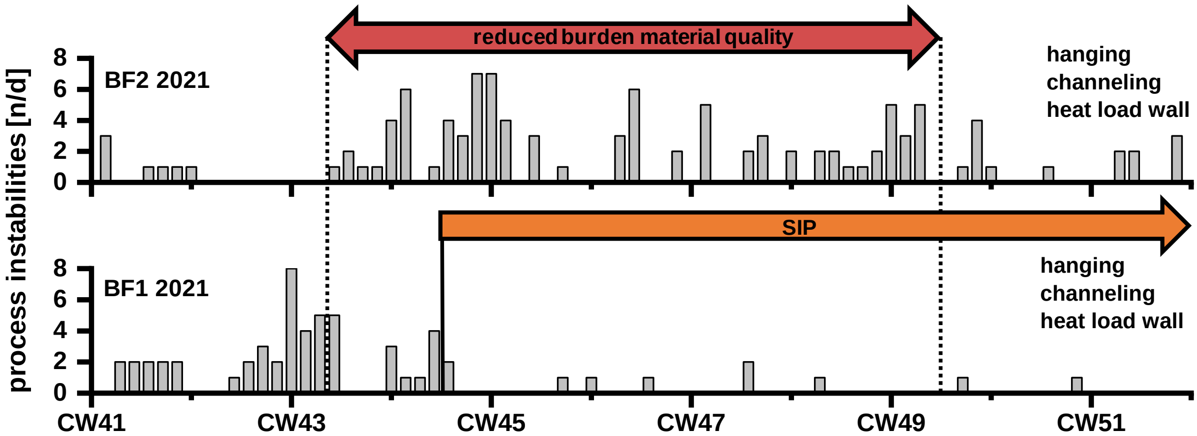

Figure 5: Changes in process instabilities on BF2 and BF1 (with SIP) during the low material quality period characterized by hanging, channeling and high heat load events

A summary of the effects can be seen in Figure 6. It shows the relative frequency of process conditions during the reduced burden material quality period for BF1 and BF2, compared to the conditions outside this period.

At BF2, the situation required a fundamental adjustment of the blast furnace process, particularly due to the frequent instabilities. One of the measures implemented was the reduction of the blast volume. Essentially, this allowed the permeability resistance K to be set to typical values at BF2, However, critical values and process instabilities still occurred. As a result of the raw material quality and adjustments, the productivity of BF2 decreased. On the other hand, a contrasting picture can be seen at BF1 with SIP. The improved permeability of BF1 enabled an acceptance of greater blast volumes leading to an increase in productivity.

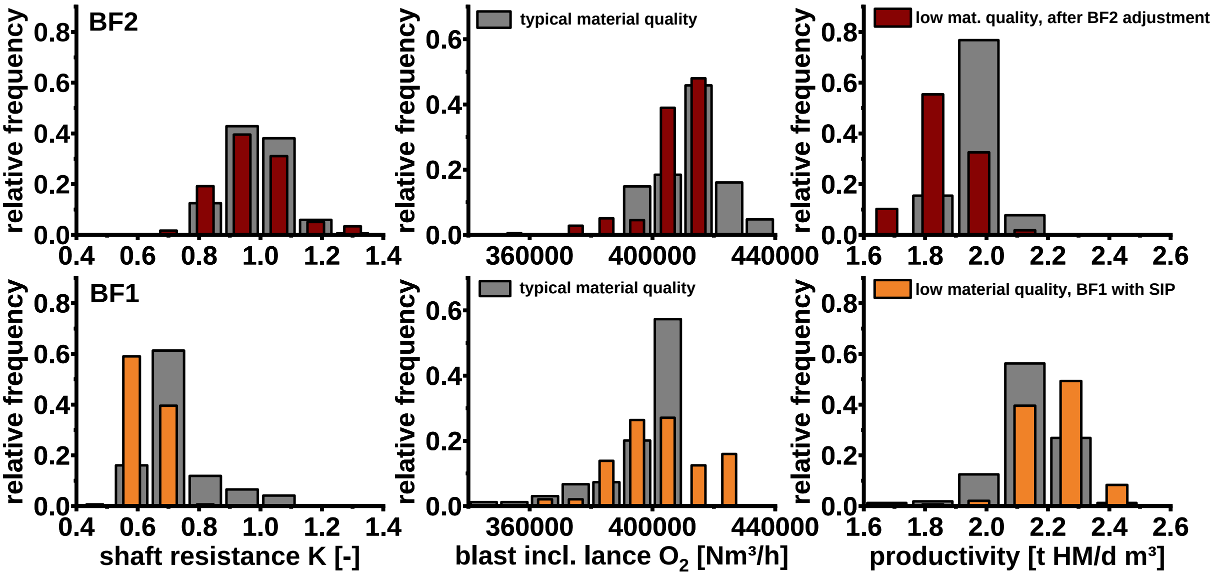

Figure 6: Permeability resistance, blast volume & productivity of BF 2 & BF 1 (with SIP) during reduced burden material quality compared to the performance during typical material quality

Core drill samples taken during trial work [4] have previously shown that on BF1 the raceway length was increased during SIP operation, even with low quality material. It is believed that the same phenomenon contributed to the improved performance seen on BF1 in the current analysis.

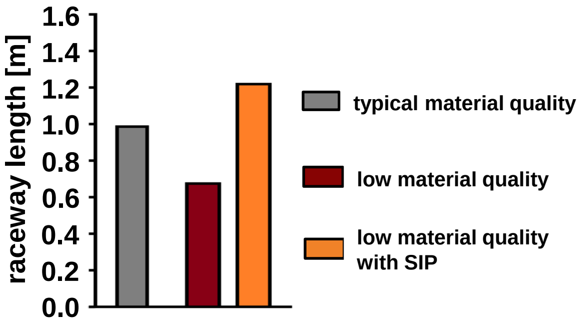

Figure 7: Determined raceway length at BF1 from core drill analysis following operation with (left to right) typical material quality, low material quality and low material quality but with SIP

Figure 8 shows a difference in the occurrence of high wall temperatures in the shafts of the blast furnaces, which often indicates non-ideal gas flow. The measurements represent temperatures from the bosh to the stock line. On BF2, during the reduced burden material quality period, they increased dramatically compared to operation with a typical material quality. However, on BF1 the SIP effect was able to compensate the quality issue with a smoother operation, improved permeability, and a more central gas flow, which is seen as a positive effect of the SIP operation. This led to a reduction in the temperatures, even during the reduced burden material quality period.

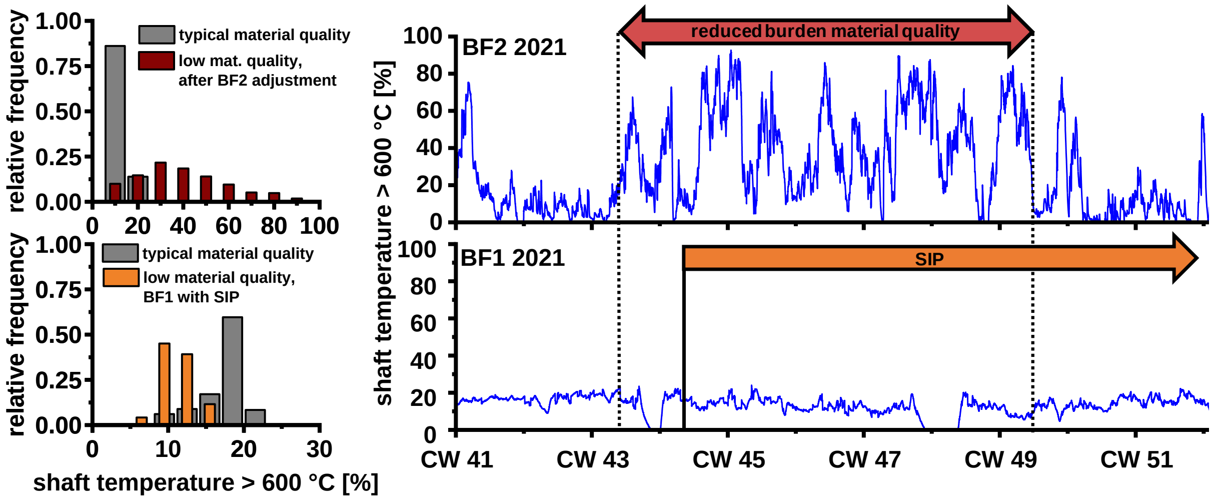

Figure 8: The permeability resistance and wall temperatures experienced in the shaft of BF2 and BF1 (with SIP) during the low material quality period.

2.5 MINIMUM FUEL RATE MODEL

For the blast furnace process optimization, tkSE uses various models developed in-house. To understand the approach to the thermodynamic optimum, is the so-called Minimum Fuel Rate (MKV) model. This model enables the calculation of the metallurgically feasible fuel consumption for the operating state of a blast furnace, under given conditions and its potential for fuel savings. The model illustrates a defined working area, determined by heat and chemical boundaries, using operational data, blast furnace properties, quantities of burden materials, and other measured parameters. The chemical boundary line, established by the gas/wustite equilibrium, and the heat boundary, determined by the required exposure of the burden to the ascending heat of the gas, describe the potential range of operational fuel consumption [13].

The graphical depiction of the model's calculation results can be seen in Figure 9. In this graphic, the left y-axis describes the specific carbon rate required for heating and reducing ores in kg/tHM. The right y-axis represents the actual used total amount of reducing agents. The x-axis shows the proportion of indirect reduction in the total reduction work of the blast furnace.

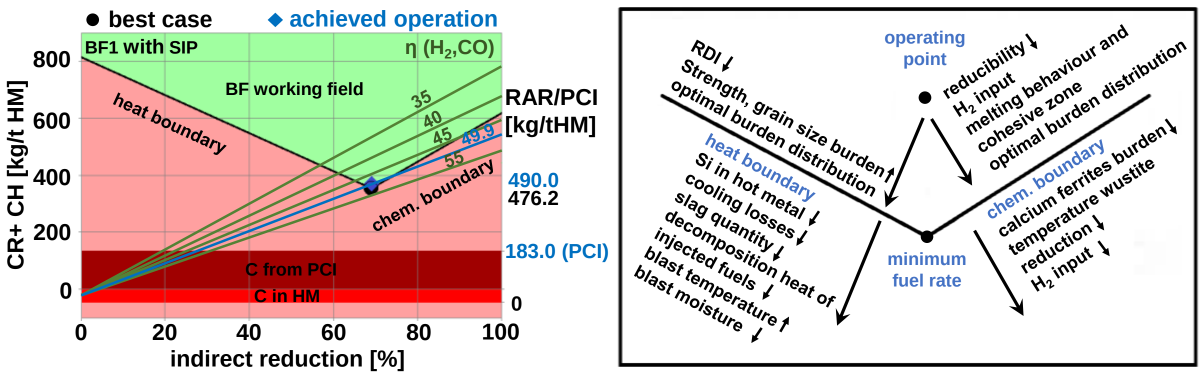

Figure 9: Example view of the graphical presentation of the MKV model results (on the left) with a representation of key model input parameters (on the right)

The lines originating from bottom left to top right represent the possible gas utilization values (at a theoretical constant gas utilization η), and the blue line represents the actual gas utilization. Furthermore, the heat boundary (coming from the top left) and

chemical boundary (rising towards the top right corner) for the given process data, are determined and shown. The intersection of these two lines is important and represents the optimal operating point of the furnace at a given time. This is indicated as the minimum possible fuel consumption. The field that emerges upwards, (shown in green) displays all the possible operating points above these constraints.
Using the MKV model, evaluation periods of the furnaces were extensively examined before, during, and after the use of reduced burden quality material for BF1 and BF2. In the upcoming section, the results of the selected model calculations are presented and discussed.

2.5.1 RESULTS BEFORE LOW QUALITY RAW MATERIAL PERIOD

The initial situation before the use of reduced burden material quality and the operation of BF1 without the SIP system, and BF2 are presented in Figure 10 using the MKV model.

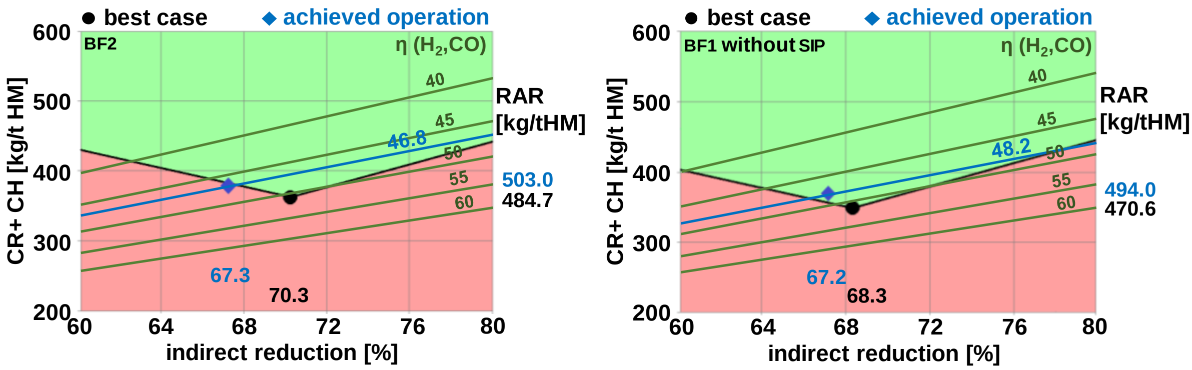

Figure 10: Results of the MKV model (left: BF2, right: BF1) for the initial state before the period of reduced raw material quality, and BF1 without SIP operation.

As both blast furnaces used similar feedstock compositions, the chemical conditions and enthalpies required for the feedstock were equally similar. The generally higher cooling losses of BF2 result in the heat boundary of BF2 being slightly higher. The lower heat demand of BF1 thus leads to a lower theoretical RAR (model best case) of BF1 of approximately 471 kg/tHM, while the model for BF2 has a value of approximately 485 kg/tHM. Due to the better gas utilization of BF1 it also has a lower RAR of 494 kg/tHM compared to 503 kg/tHM at the current operating point. The difference between the optimal RAR and the current RAR of BF1, is higher at 23 kg/tHM than that of BF2 at 18 kg/tHM. However, the current operating point of BF1 is well above the thermal and chemical limit, so its operating point can be considered "stable". In contrast, the operating point of BF2 sitting on the heat boundary is at the thermal limit.

2.5.2 RESULTS DURING LOW QUALITY RAW MATERIAL PERIOD

The situation of BF1 and BF2 during the use of reduced burden material quality with the help of the MKV model is shown in Figure 11. During this period, BF1 was operated with the SIP technology.

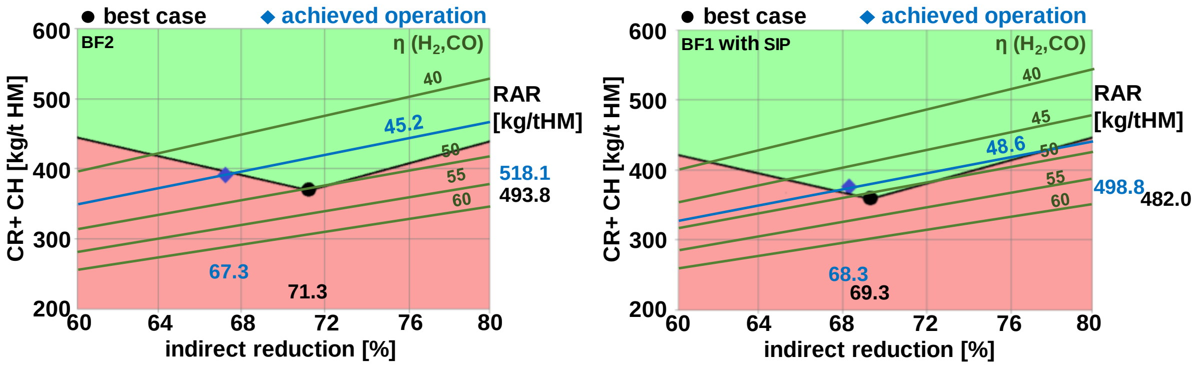

Figure 11: Results of the MKV models (left BF2 and right BF1) for the situation during the period of reduced raw material quality with SIP operation on BF1.

The model data shows that, compared to the initial situation, the heat demands of both BF1 and BF2 have shifted to slightly higher values due to a change in feedstock composition. However, the shift in the thermal limit of BF2 is much more pronounced. The cause of this is the increase of cooling losses in BF2 by more than 60% due to the negative impact of the lower quality raw materials. Thus, the operating range (green area) of BF2 was more strongly restricted and the position of the optimal operating point (model best case) was accordingly negatively influenced. In contrast, no significant increase in the cooling losses were observed for BF1. The reason for this is the improved permeability and blast furnace operation brought about through SIP technology.

The production data evaluation period for BF2 shows a significant decrease in gas utilization of 1.6%-points. The RAR has increased significantly from 503 kg/tHM to 518 kg/tHM compared to the initial situation. Similarly, the distance between the current operating point and the optimal operating point has significantly increased from 18 to 24 kg/tHM. The current operating point is now slightly outside the working range calculated by the model, reflecting the observed unstable state of BF2 during the production data evaluation period.

The operation of BF1 with SIP during the reduced burden material period provides a completely different picture. At or shortly after the beginning of the reduced burden material campaign, BF1 was operated together with the SIP plant. This allowed for the direct investigation of the influence of the SIP technology on the blast furnace working state under a poor raw material situation. The RAR remained almost the same with 499 kg/tHM compared to the initial value of 494 kg/tHM, although the working range was also limited at BF1 due to the altered burden composition. This was achieved by increasing the gas utilization by 0.4%-points and the indirect reduction by 1%-points. The distance between the current operating point and the optimal operating point decreased from 23 kg/tHM to 17 kg/tHM. The current operating point is stable due to sufficient distance from the thermal and chemical limits while still being close to the optimal operating point predicted by the model.

The results achieved at BF1 with the SIP technology are particularly remarkable, considering that the production could be increased despite the raw material problems, while the production level of BF2 could not be maintained. Figure 12 shows the changes in production for all tkSE Duisburg blast furnaces including BF8 and BF9, during the reduced burden material quality period as well as other key performance indicators.

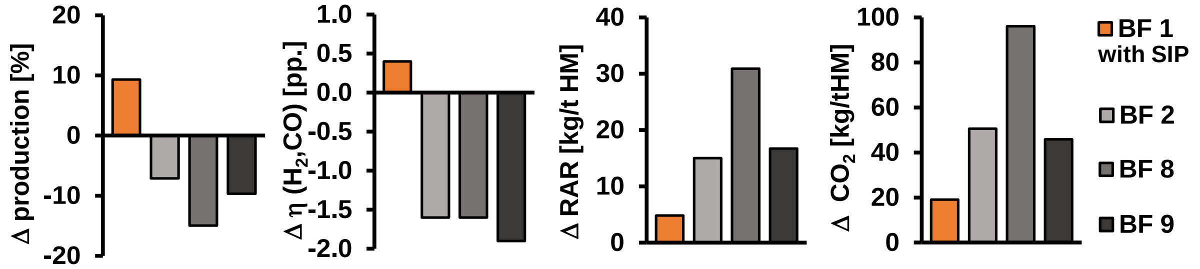

Figure 12: Performance indicators of all four blast furnaces at tkSE during reduced burden material quality period

3 CONCLUSION

Blast furnace operation was positively influenced by SIP technology during a reduced burden material quality period. Comparisons with blast furnaces at the same site, using the same material supply - but without SIP technology, showed they did not perform as favorably.

In contrast to the BF2, at the BF1 with SIP operation it was possible to approach the theoretical minimum fuel rate during this time. In addition, a smoother furnace operation was observed with a dramatic decrease in process instabilities such as hanging, channeling and high heat load events. This introduces possibilities for operators to increase the performance of their blast furnaces during periods of reduced burden material quality through oxygen pulsing technologies, such as SIP

REFERENCES

1 Zhang, S.; Bi, X.:
Theoretical considerations of problems relating to high coal rate injection into blast furnaces
Ironmaking & Steelmaking, 467 (2003), Vol 30, No.6

2 Schmöle, P.:
The mysteries of Fe2O3 reduction
Internal lecture, thyssenkrupp Steel Europe AG, (2015)

3 Schwalbe, R.; Klock, R.; Janhsen, U.; Schmöle, P.; Peters, M.:
Influence of intentionally deteriorated coke properties on performance of blast furnace #2 Schwelgern
Metec and 2nd ESTAD, (2015)

4 Klock, R.; Johnen, A.; Heldt, H.; Kannappel, M.; Thiede, Ch.; Feldhoff, M.; Senk, D.; Greibig, R.; Ramthun, J.:
Automatisierter Sequenz Impulsprozess für Großschachtöfen
BMBF, Abschlussbericht (2011)

5 Carpenter, A .:
Use of PCI in blast furnaces Oxygen Pulsing Technology
IEA Clean Coal Centre, (2006)

6 Gruening, C.; Mayinger, F.:
Experimental investigations of supersonic flame stabilisation based on fuel ignition
Chemical Engineering & Technology No.10, pp. 909-918, (2000)

7 Shen, Y.; Yu, A.; Zulli, P.:
CFD Modelling and Analysis of Pulverized Coal Injection in Blast Furnace: An Overview
Steel Research 82 Nr.5, S.532-537 (2011)

8 Born, S.; Babich, A.; van der Stel; Ho, H. T.; Sert, D.; Ansseau, O.; Plancq, C.; Pierret, J-Ch.; Geyer, R.; Senk, D. Pridhivi, V.:
Char Formation by Coal Injection and Its Behavior in the Blast Furnace
Steel Research International 91(2020)

9 Takahashi, H.; Kawai, H.; Kogo, T.; Sugawara, M.
Permeation and blockage of fine particles transported by updraft through a packed bed
ISIJ International 51 (2011)

10 Edmond, R.; Klock, R.; Smaha, B.; Bartusch, H.:
Improving Blast Furnace Efficiency and Reducing Carbon Emissions with Blast Furnace Oxygen Pulsing Technology
AISTech 2022 Proceedings, 172, Vol 1 (2022)

11 Ishii, K.
Advanced Pulverized Coal Injection Technology and Blast Furnace Operation
Elsevier Science Ltd, Oxford, United Kingdom, pp 149, (2000)

12 Smaha, B., Klock, R., Juen, J., Edmond, R., Smith, M., Bartusch, H.:
Introducing SIP Technology and its Impact on Blast Furnace Operation
SEAISI (2022)

13 Kowalski, W., Bachofen, H., Kreibich K.:
Modelling the inner state of the blast furnace: the Thybas models
Ironmaking & Steelmaking, 324, Vol 23, No.4 (1996)