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Reactive Pulverized Coal Injection

A quite and simple but very effective idea

Pulverized coal injection (PCI) is a very effective way to improve total fuel costs of the blast furnace. Hence the optimization of PCI technology still has a significant impact on the profitability. In this regard Küttner has developed a new technology called Reactive PCI and Reactive Oxycoal, which will be presented and discussed within this article. The idea behind Reactive PCI/Oxycoal is quite simple but very effective.

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At present, the blast furnace process is still the most important process to produce crude iron and (via oxygen converter) steel. But, especially European steel producers are faced with high economic pressure created by the global steel market. On top of this carbon trading and developing decarbonization put additional economical and technical pressure on European steel producers. One important measure to deal with this situation is to optimize the technology of the existing installations in order to reduce the total costs. This creates some opportunities to further develop new technologies (e.g. Carbon2Chem [1]) which are able to significantly improve the carbon footprint with simultaneous consideration of a competitive iron and steel production.

The required process energy of the blast furnace is mainly covered by expensive coke. A significant measure to optimize cost effectiveness by reducing the blast furnace coke rate is the injection of cheaper auxiliary reducing agents like pulverized coal, oil or natural gas into the raceway of the blast furnace. The greatest influence on cost effectiveness using auxiliary reducing agents is the price difference between coke and the auxiliary reducing agent and the maximal possible injection rate converted in the blast furnace process. Most blast furnaces in the world use pulverized coal as an auxiliary reducing agent as the cost-efficiency enhancement is the best in their cases [2-4]. Consequently, main requirement for the PCI technology is to ensure the highest possible injection rate which is converted in the blast furnace process. In order to achieve this target, the consideration starts with the pulverized coal gasification process within the tuyère and the raceway of the blast furnace [3].

For an optimal blast furnace operation using pulverized coal injection, it is necessary to ensure that nearly the whole amount of injected coal is gasified as fast and best as possible. For this purpose, only 10-20 milli-seconds are available after pulverized coal is injected into the hot blast within the tuyère, and before the pulverized coal is entering the coke layers at the end of the raceway. In this short time, the injected coal particles heat up to ignition temperature and gasify. Pyrolysis, combustion of pyrolysis-gases, and gasifying of generated semi-coke occur simultaneously. A portion of the generated semi-coke enters the coke layer at the end of the raceway, where it then gasifies. This amount should be as small as possible, otherwise, it could negatively affect the permeability of the blast furnace. The physical and kinetic limits of coke substitution for pulverized coal are the permeability of the blast furnace if the injected pulverized coal does not gasify completely, a minimum coke rate to secure the permeability of the blast furnace, and/or an increasing amount of unconverted pulverized coal in the top gas dust. Hence, the injected pulverized coal rate can be increased, and the coke rate can be simultaneously decreased (according to the replacement ratio coke/coal), as long as pressure drop in the blast furnace or the carbon rate in the top gas dust does not increase significantly.

Consequently, the pulverized coal injection technology should be developed with a vision of the best possible gasification of injected pulverized coal within the tuyère and raceway of the blast furnace. In this respect some important developments can be found in a paper from 2016 [3]. In this regard Reactive Pulverized Coal Injection and Reactive Oxycoal are the latest developments of PCI optimization technologies.

What is Reactive Pulverized Coal Injection / Reactive Oxycoal?

The target of Reactive PCI and Reactive Oxycoal is to improve the gasification of injected pulverized coal. This can be realized by first reducing the time until the PC gasification reactions starts after injection and second accelerating PC gasifying reactions during flight time in tuyère and raceway of the blast furnace (10-20 milli-seconds). The main idea behind Reactive PCI and Reactive Oxycoal to achieve this target is to save the time of pulverized coal degassing by means of added reactive gases which undertake the function of degassed volatiles during PC injection process.

All kind of gases or gas mixtures which participate in the coal gasification reactions can be used as reactive gases. Pure hydrogen and/or carbon monoxide are most effective. Practically coke oven gas, converter off gas and blast furnace top gas can be used. These reactive gases will be added to the pulverized coal flow as a part of transport gas before injection. The necessary amount of reactive gas is advantageously quite small. As a consequence pulverized coal injection process can be realized in dense phase conditions in order to additionally use the PCI dense phase advantages (compare [2-3]). The concepts of Reactive PCI and Reactive Oxycoal are shown schematically in Figure 1 and can be explained as follows: Pulverized coal is injected via single lances or coaxial lances in the tuyères of the blast furnace. The used transport gas is a mixture of reactive gas and nitrogen. The total amount of transport gas is small enough to realize still high transport gas loadings and still small injection velocities (typical features of dense phase injection). The key effect is that immediately after the mixture of pulverized coal and transport gas has left the injection lance the reactive gases will react and ignite with the oxygen of the hot blast (Reactive PCI) or the oxygen of the coaxial lance (Reactive Oxycoal) at the interface layer between PC injection jet and the hot blast jet or respectively coaxial oxygen jet. This reaction increases the available energy for coal gasification at this interface layer which leads in the end to a significant acceleration of pulverized coal gasification reactions during the flight time through the tuyère and the raceway of the blast furnace. A possible increase of PCI rate in association with a related decrease of coke rate is the consequence which creates an additional boost in reduction of total fuel costs of the blast furnace.

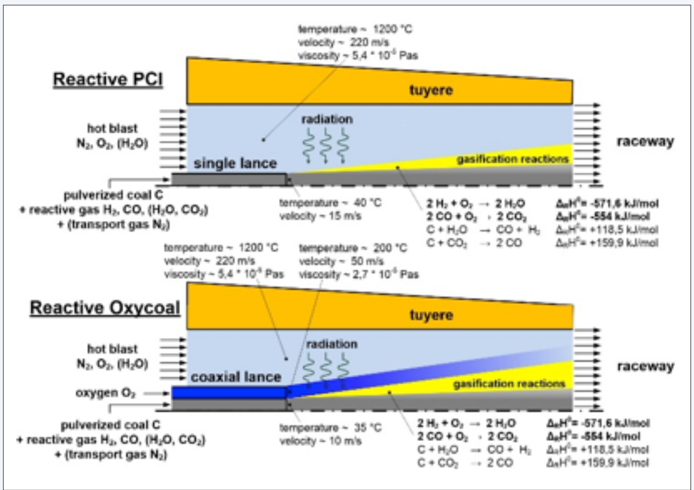

Figure 1: Concept of Küttners Reactive PCI and Reactive Oxycoal

The next step of developing Reactive PCI and Reactive Oxycoal was to verify the expected positive impact on PC gasification during the injection process. For this purpose Küttner performed numerical simulations of the injection process in the tuyère and the raceway of the blast furnace as well as industrial trials testing Reactive PCI and Reactive Oxycoal at one tuyère of BF No.1 at ThyssenKrupp Steel Europe.

Numerical simulations

For the numerical simulations Küttners CFD gas flow and PCI process model of the tuyère and the raceway [5] was used. Figure 2 exemplarily shows the results of two Reactive PCI simulations, one for standard dense phase PC injection and one for Reactive PCI with coke oven gas. The standard dense phase PCI simulation acts as reference. This means that this simulation is fitted to a real dense phase PCI operation at a blast furnace. Furthermore it is important that the injected amount of pulverized coal, the amount of transport gas nitrogen, the amount of added reactive gases and all hot blast parameter are the same for all numerical simulations. The only variation between the simulations is the composition of the reactive gas amount. The results of the numerical simulations in Figure 2 are illustrated on a two-dimensional plane in the middle of the reaction space within the tuyère and the raceway. These results show the temperature distribution, indicating the burning of injected pulverized coal.

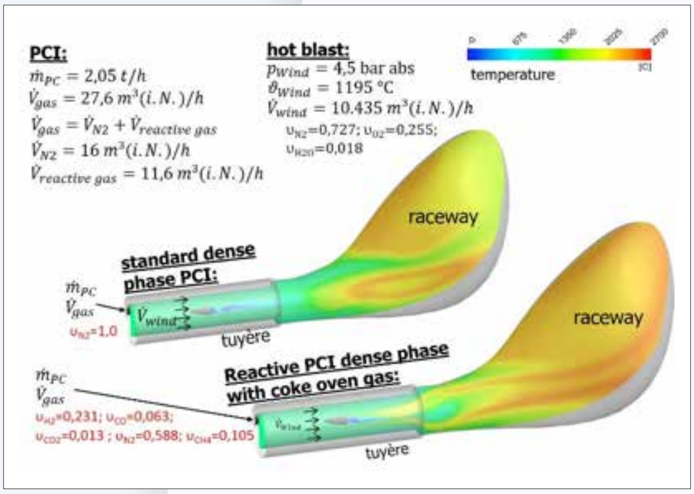

Figure 2: Simulation results of Reactive PCI – gas temperatures in tuyère and raceway

Regarding the temperature distribution, it can be seen that an increase of temperature due to ignition of pulverized coal using only dense phase PCI occurs as expected next to the tuyère but within the raceway. By using Reactive PCI with coke oven gas, the increase of temperature due to ignition of pulverized coal occurs already within the tuyère. That means the simulations predict an earlier ignition of injected pulverized coal in the tuyère using only a small amount of coke oven gas as reactive gas. This is a very interesting result which can be verified experimentally. Up to now an early ignition of injected pulverized coal in the tuyère could only be observed using the Oxycoal technology [2-5].

Another consequence of the results shown in Figure 2 is that there should be more time left for a complete gasification of the injected coal particles within the tuyère and the raceway of the blast furnace using Reactive PCI. For this reason numerical simulations have also been evaluated to quantify the more complete gasification of injected coal particles using standard dense phase PCI and Reactive PCI technology. In doing so the not converted coal particles at the end of the raceway just before entering the coke layer in the blast furnace are counted. This is shown in Figure 3 where the amount of completely and incompletely gasified coal particles within the tuyère and raceway is evaluated. For standard dense phase PCI simulation (reference) 316.4 g/s of altogether 524.6 g/s of injected pulverized coal is gasified completely in the tuyère and raceway. The remaining not completely gasified 208.2 g/s of injected pulverized coal enter the coke layer at the end of the raceway. Remember the reference simulation was fitted to a real dense phase PCI operation at the blast furnace. This implies that the blast furnace process is able to cope with the amount of not completely converted pulverized coal particles of 208.2 g/s entering the coke layer at the end of the raceway. If now Reactive PCI is used by adding a small amount of coke oven gas to the dense phase coal flow, the numerical results in Figure 3 show that the amount pulverized coal converted completely in the tuyère and raceway increased from 316.4 g/s (dense phase PCI) to 341.3 g/s (Reactive PCI) while the amount of not completely converted pulverized coal entering the coke layer at the end of the raceway decreased from 208.2 g/s (dense phase PCI) to 183.3 g/s (Reactive PCI). From this it can be concluded that a minimal increase of PCI rate changing dense phase PCI to Reactive PCI of 24.9 g/s (or 4,5%) is possible as the blast furnace process can cope with 208.2 g/s of not completely converted pulverized coal entering the coke layer at the end of the raceway (reference). In this evaluation the minimal amount of additionally injected pulverized coal of 24.9 g/s is not gasified in the tuyère and raceway. However, it is very probable that this additional amount of injected pulverized coal is also gasified according to the ratio converted to not converted coal using Reactive PCI. From this it follows that a maximum increase of PCI rate of 71.3 g/s (or 11.9 %) using Reactive PCI instead of dense phase PCI can be reached. The practical increase of PCI rate will lie in the given range between minimum and maximum.

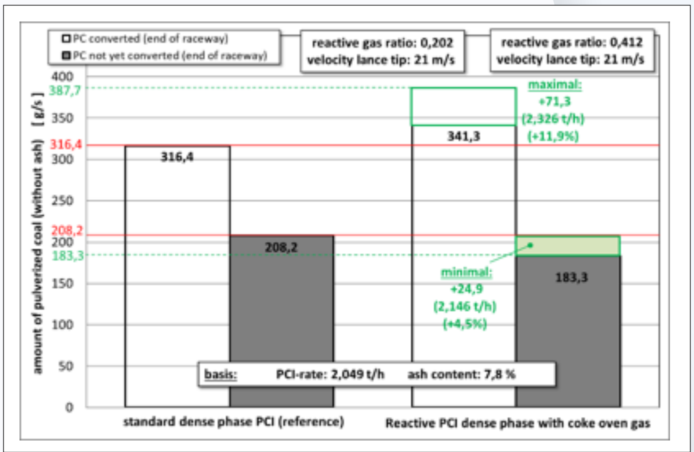

Figure 3: Improved coal gasification from dense phase PCI versus Reactive PCI with coke oven gas

Industrial trials

These promising simulation results encouraged to test and evaluate experimentally Reactive PCI and Reactive Oxycoal at one tuyère of a blast furnace. Thyssenkrupp Steel Europe thankfully allowed to perform and supported the industrial trials of Reactive PCI and Reactive Oxycoal at one tuyère of their blast furnace no. 1 at Duisburg, Schwelgern. Figure 4 shows schematically the concept flow sheet of Reactive PCI/Oxycoal for one tuyère of the blast furnace. Thyssenkrupp Europe operates a lock hopper PCI system with discrete fluidizing chambers for their blast furnace no.1 in Duisburg, Schwelgern. The PCI plant is designed for dense phase operation. It is additionally equipped with the Oxycoal technology which covers the injected pulverized coal with pure oxygen [2,3]. In this PCI system each injection lance at the tuyère is connected via a single pipe with a discrete fluidizing chamber. The injection vessel is kept under the necessary pressure which is depending on the injection rate, the transport distance and the counter pressure of the blast furnace. The Reactive PCI and Reactive Oxycoal industrial trials at the blast furnace were performed with different reactive gases or gas mixtures. For adjusting the desired amount and composition of reactive gas an experimental mixing station was built and installed. This mixing station was able to adjust and mix three different pure reactive gases. These pure reactive gases were provided by gas bottles. Table 1 summarizes all examined reactive pure gases and reactive gas mixtures.

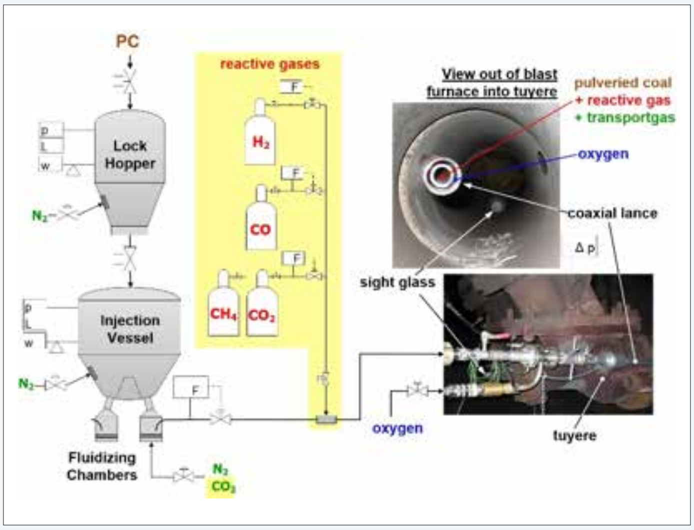

Figure 4: Concept flow sheet of Reactive PCI and Reactive Oxycoal

COMPOSITION	CO	H_2	CH_4	CO_2
carbon monoxide	1	0	0	0
hydrogen	0	1	0	0
methane	0	0	1	0
gas mixture similar to top gas	0,2	0,05	0	*0,75*
converter off gas	0,7	0	0	0,3
gas mixture similar to coke oven gas	*0*	0,55	0,25	*0,2*

Table 1: Examined reactive gases

Due to the fact that only three pure gases could be mixed the composition of the examined coke oven gas and blast furnace top gas were adjusted to only similar compositions but similar enough to show the Reactive PCI/Oxycoal effect. After adjusting the desired reactive gas composition this mixture was added to the coal flow via a sinter metal tube in the single pipe. After that the mixture of pulverized coal, transport gas and reactive gas was injected via a single lance (Reactive PCI) or a coaxial lance (Reactive Oxycoal) into the tuyère of the blast furnace. The injection process at the injection lance tip in the tuyère was observed through the sight glass either with an optical camera combined with a pyrometer or with a thermovision camera. Figure 5 shows photos of the used experimental equipment: The mixing station on the left hand side and the measuring equipment on the right hand side.

Figure 5: Experimental equipment

Experimental results

The purpose of the industrial trials was to evaluate the concept of Reactive PCI and Reactive Oxycoal together with the verification of the numerical simulation results. Especially the simulation prognosis of PC ignition in the tuyère of the blast furnace not using the Oxycoal technology should be evaluated and verified experimentally. With this in mind the injection process in the tuyère of the blast furnace was observed through the sight glass with an optical camera combined with a pyrometer temperature measurement. In addition a thermovision camera was used to measure and to observe the temperatures in the tuyère during the injection process. The big advantage of the thermovision camera is that all temperatures at each different location in the tuyère can be measured at the same time while the pyrometer can only measure the temperature at one spot. A number of industrial Reactive PCI and Reactive Oxycoal trials were performed whereby the amount, the type and the composition of the additionally injected reactive gas were varied.

Figure 6 shows photos of the PC injection process in the tuyère of the blast furnace recorded either with the optical camera (photos above) or with the thermovision camera (photos below) for first standard dense phase PCI, second Reactive PCI and third Reactive Oxycoal. For Reactive PCI and Reactive Oxycoal pure carbon monoxide was used as additionally injected reactive gas. The volume fraction of reactive gas in transport gas was measured between 0.36 and 0.4. The PCI rate was measured around 1650 kg/h. Standard dense phase PCI is the reference case to evaluate the changes of flame appearance and temperatures using Reactive PCI or Reactive Oxycoal.

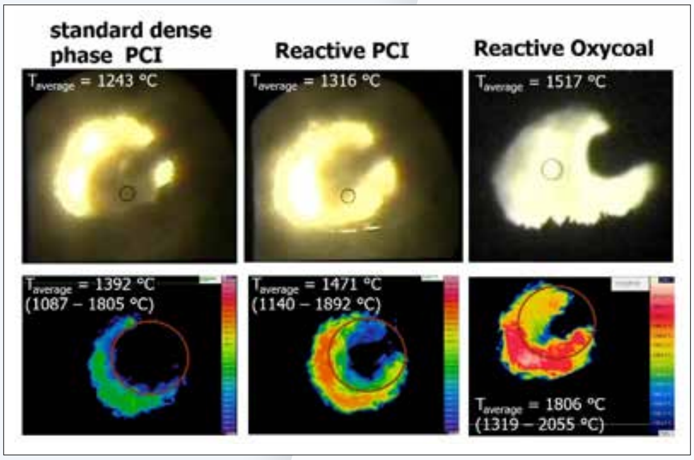

Figure 6: PC injection process in the tuyère observed with an optical and a thermovisions camera

The photos of standard dense phase PCI show as expected a dark not ignited pulverized coal cloud in the tuyère at the lance tip. The measured temperature with the pyrometer at the marked spot showed an average temperature of 1243 °C. The measured temperatures with the thermovision camera in the marked area showed an average temperature of 1392 °C. When using Reactive PCI the photos in Figure 6 show that the injected pulverized coal cloud in the tuyère is partly ignited. In this context it must be mentioned that the ignition of the pulverized coal due to reactive gases showed fluctuations during some trials. In sum this result confirms the simulation prognosis of an ignition of injected pulverized coal in the tuyère of the blast furnace not using the Oxycoal technology (compare Figure 2). Moreover the measured temperature in the tuyère shows an increase of about 75 °C compared to standard dense phase PCI. Reactive Oxycoal is the combination of Reactive PCI and Oxycoal. The photos in Figure 6 show a complete ignition of the injected pulverized coal in the tuyère of the blast furnace. This result was expected as the Oxycoal technology already ensures a stable ignition of the injected pulverized coal in the tuyère of the blast furnace [5]. Compared to standard dense phase PCI the measured temperature shows an increase between roughly 280 °C (pyrometer) and 410 °C (thermovision camera).

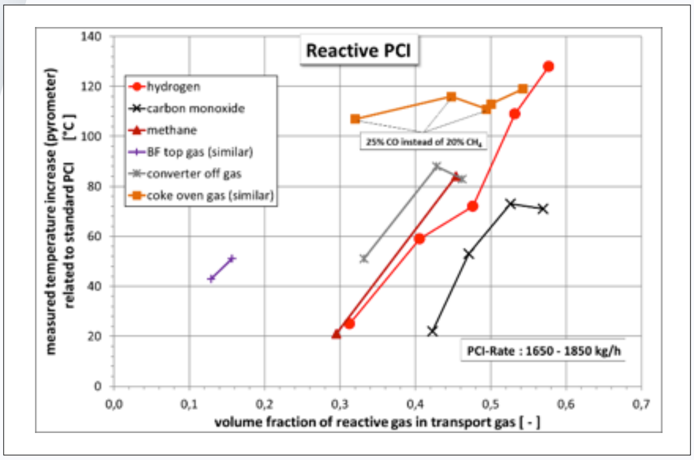

Figure 7: Temperature increase in the tuyère using Reactive PCI observed by pyrometer

The temperature measurements recorded by pyrometer and thermovision camera were evaluated in more detail. Regarding Reactive PCI one important result is that for all examined reactive gases a temperature increase in the tuyère of the blast furnace was determined compared to standard dense phase PCI. Figure 7 shows this temperature increase depending on the volume fraction of reactive gas in the PC transport gas for all examined reactive gases observed by pyrometer. Figure 8 shows the same correlations based on the temperature measurements by the thermovision camera.

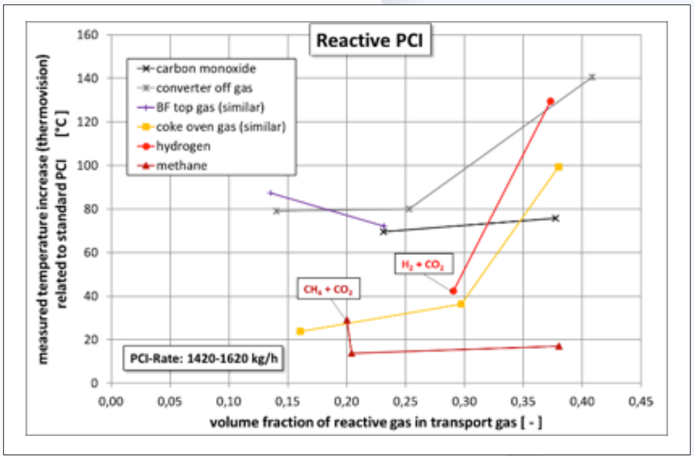

Figure 8: Temperature increase in the tuyère using Reactive PCI observed by thermovision camera

The data in Figure 7 and 8 show that the level of temperature increase depends on on the type and the volume fraction of the used reactive gas in the transport gas. But, for an accurate interpretation of these results it has to be considered that the injection velocity, the total amount of injected pulverized coal and the total amount of transport gas, which correlates with the volume fraction of the reactive gas are depending on each other. As a consequence these parameters influence the level of temperature increase in the tuyère at the same time. Therefore the interpretation of these results needs a more detailed evaluation and separation of the different influencing factors. However, it can be stated that Reactive PCI affects an early ignition of PC and an additional temperature increase in the tuyère of the blast furnace compared to using only standard dense phase PCI. From this, it follows that there is a positive affect on pulverized coal gasification in the tuyère and the raceway of the blast furnace. To be exact a small part of this temperature increase is caused by the oxidation of the reactive gases, but the biggest part is caused by the oxidation of pulverized coal in the tuyère. To show this temperature increase caused by oxidation of the whole amount of added and injected reactive gas was theoretically calculated and subtracted from the measured temperature increase. The resulting temperature increase shown in Figure 9 can only be caused by additional oxidation of the injected pulverized coal in the tuyère compared to standard dense phase PCI. Only injected methane does not show an additional temperature increase caused by PC oxidation. It is known that natural gas injection into the tuyère of the blast furnace lowers the raceway adiabatic flame temperature (RAFT) as methane the main component of natural gas will first be cracked after injection. This requires energy which explains the decrease of RAFT. Having this in mind, the temperature decrease using methane as reactive gas becomes explicable.

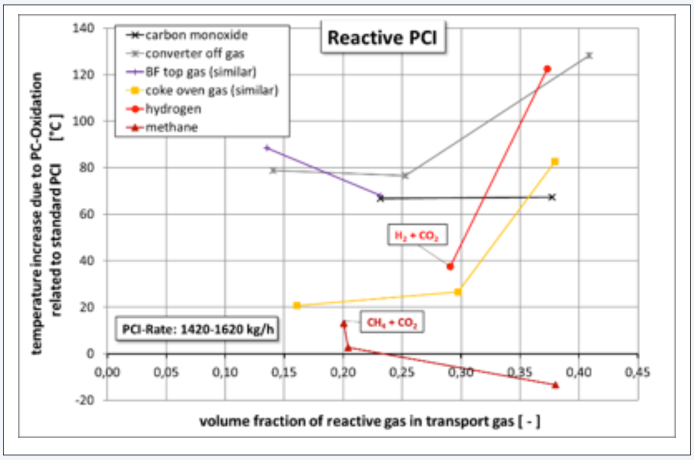

Figure 9: Temperature increase in the tuyère due to PC oxidation using Reactive PCI

At first sight, the evaluation results of the industrial trials using Reactive Oxycoal in Figure 10 are surprising. Most trials show a temperature decrease in the tuyère of the blast furnace compared to standard Oxycoal operation. For volume fractions of reactive gas in the transport gas below 0,5 only hydrogen or hydrogen rich reactive gases show a temperature increase in the tuyère. For the interpretation of these results the pulverized coal gasification mechanism of reaction and the relating temperature- and pressure-dependent equilibria [7] have to be taken into account. In this regard, it is important to remember that the temperature level in the tuyère using Reactive Oxycoal is about 300-400 °C higher than using Reactive PCI. Especially the endothermic Boudouard and heterogenous water-gas reactions are active at this temperature level which seems to have an impact on measured temperature in the tuyère using Reactive Oxycoal. But, from this it follows as predicted that Reactive Oxycoal affects an earlier start of pulverized coal gasification in the tuyère of the blast furnace compared to only using Oxycoal. Hence Reactive Oxycoal enables

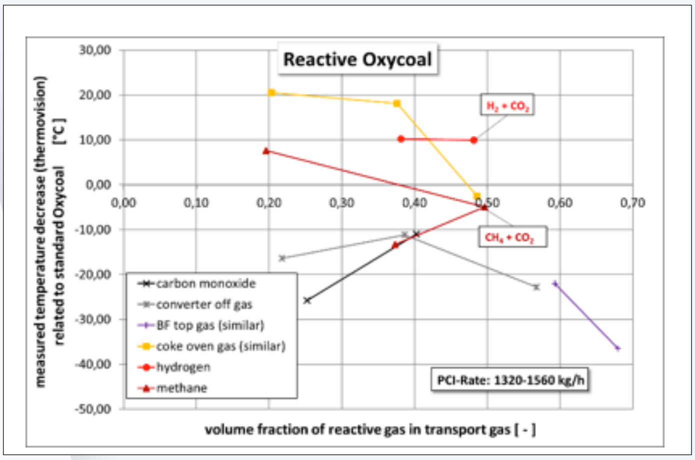

Figure 10: Temperature decrease in the tuyère using Reactive Oxycoal

to gasify more pulverized coal in the tuyère of the blast furnace compared to using only Oxycoal. This leads to an increase of the converted PCI-rate and to a decrease of the coke rate according to the exchange ratio.

Conclusion

The substitution of a significant amount of expensive coke in the blast furnace process by injection of cheaper pulverized coal into the tuyère and the raceway is a decisive measure to reduce the blast furnace total fuel costs. In summary, the higher the converted PCI-rate in the blast furnace process, the higher the cost effectiveness. For this reason, PCI technology should enable the best possible gasification of injected pulverized coal within the tuyère and raceway to avoid a negative impact on the permeability of the blast furnace. In this regard, Reactive Pulverized Coal Injection and Reactive Oxycoal are the latest developments of PCI optimization technologies. The concept of Reactive PCI and Reactive Oxycoal is to add a small amount of a reactive gas to the dense phase transport of pulverized coal conveyed and injected in the tuyère and the raceway of the blast furnace. Hereby the PCI process is improved first by reducing the time until the PC gasification reactions starts and second by accelerating PC gasifying reactions during flight time in tuyère and raceway of the blast furnace.

In order to verify the effect mechanism of Reactive PCI and Reactive Oxycoal numerical simulations of the injection as well as industrial trials at one tuyère of BF No.1 at ThyssenKrupp Steel Europe were performed. The numerical simulations show an early ignition of injected PC already within the tuyère of the blast furnace using Reactive PCI. Following this an increase of PCI-rate of approx. 10 % due to improvement of PC-gasification is possible. The industrial trials confirm the early ignition of PC already within the tuyère of the blast furnace using Reactive PCI. Beyond that, the evaluations of the temperature measurement during the industrial trials show the thermal footprint of accelerated PC gasification reactions. In summary, it can be stated that Reactive PCI increases the temperature in the tuyère of the blast furnace compared to only using standard dense phase PCI and Reactive Oxycoal decreases the temperature in the tuyère of the blast furnace compared to using only Oxycoal. Both can be explained with the pulverized coal gasification mechanism of reaction and the relating temperature- and pressure-dependent equilibria. It has to be taken into account that the injection velocity, the total amount of injected pulverized coal, the total amount of transport gas which correlates with the volume fraction of the reactive gas in the transport gas and the temperature level in the tuyère are depending on each other and have an impact on the effect of Reactive PCI or Reactive Oxycoal.

Altogether, the possible increase of PCI-rate associated with a decrease of coke rate using Reactive PCI or Reactive Oxycoal gives the blast furnace operator the boost on the profitability. The next step to realize this boost on the profitability will be the installation of Reactive PCI or Reactive Oxycoal at all tuyères of a blast furnace.

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Abbreviations

BF	blast furnace
CFD	computational fluid dynamics
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
H_2O	water (steam)
	mass flow rate
N_2	nitrogen
p	pressure
O_2	oxygen
PC	pulverized coal
PCI	pulverized coal injection
RAFT	raceway adiabatic flame temperature
T	temperature
υ	volume fraction
	volume flow rate
v	velocity
wind	blast furnace hot blast
	standard reaction enthalpy
	temperature

References

[1] Carbon2Chem: 1. Konferenz zur nachhaltigen chemischen Konversion in der Industrie. 20./21. November 2017 in Düsseldorf

[2] Schott, R: State-of-the-Art PCI Technology for Blast Furnace Ensured by Continuous Technological and Economical Improvement; Iron & Steel Technology, March 2013, p. 63-75

[3] Schott, R.: Optimization strategies for pulverized coal injection into the blast furnace. stahl und eisen 136, 2016, Nr.3, p. 39-47

[4] Schott, R.; Malek, C.; Schott, H.-K.: Effizienzsteigerung des Reduktionsmitteleinsatzes im Hochofen zur CO_2-Minderung und Kostenersparnis (Efficiency Enhancement of Reductants Use in the Blast Furnace to Reduce CO_2 Emissions and Costs); Chemie Ingenieur Technik 2012, 84, No.7, p. 1076-1084

[5] Schott, R.; Schumacher, M.: Modellierung von effizientem Kohlenstaubeinblasen in den Hochofen mittels der Oxycoal-Technik (Modelling of efficient pulverized coal injection into the blast furnace by means of the Oxycoal technology); stahl und eisen 134, 2014, Nr.5, p. 29-38

[6] Schott, H.-K.: Das Küttner Dichtstromverfahren. STEEL & METALS Magazine, Vol. 27, No. 4, 1989, p. 272-277

[7] Schilling, H.-D.; Bonn, B.; Krauß, U.: Kohlenvergasung Bestehende Verfahren und neue Entwicklungen. Verlag Glückauf GmbH, Essen, 1981 p. 10-21