

EFFICIENCY IMPROVEMENT OF REDUCING AGENTS IN THE BLAST FURNACE TO REDUCE CO₂ EMISSIONS AND COSTS*

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Abstract

The blast furnace process is the most important process to produce pig iron. The necessary process energy is mainly covered by coke. But the production of coke is connected with CO₂-emissions and high costs. A significant measure to reduce the coke rate and with it the CO₂-emissions plus costs is pulverized coal injection (PCI) through the tuyeres into the blast furnace. A further increase to substitute coke by coal can be achieved by using the Oxycoal+ technology. This article compares and shows the cost effectiveness and the decrease of CO₂-emissions with the help of simplified energy balances for the only coke operation of the blast furnace, the operation using pulverized coal injection and the operation using the Oxycoal+ technology.

Keywords: Blast furnace; Substitute fuel; Pulverized coal injection (PCI); Reduction in costs.

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1 INTRODUCTION

The worldwide energy requirement for the year 2010 was approx. 12 billion tons oil equivalent [1]. This corresponds to approx. 140 billion MWh/a. The enormous energy consumption is, among other things, due to the increasing industrialisation, as well as the economic growth of many developing countries and emerging countries in recent years.

The world's energy hunger is essentially divided between industry, business and services, households, and traffic. Ranked directly after the chemical industry, the iron and steel industry has the 2nd largest industrial energy requirement [2].

In the year 2010, approx. 1.42 billion tons of steel were produced worldwide. This value represents a virtual doubling of steel production from 1990 to 2010 [3]. Steel can be manufactured through various production paths. In 2010, 69 % of steel produced was manufactured via blast furnace plants and oxygen steelworks, 29 % was manufactured via the electric arc furnace manufacturing path, and just 2 % was manufactured via the traditional, historic Siemens-Martin furnace. Looking back to the year 1990 the percentage of electric arc furnaces has remained constant and the decline of the Siemens-Martin furnace represents a shift in favour of blast furnace hot metal production. Assuming a mean specific energy consumption for an integrated steel-making based on iron ore via blast furnace and BOF steelmaking of approx. 30 GJ/t steel [4] and steelmaking in an electric arc furnace of approx. 15 GJ/t steel [4], an annual total energy input of approx. 10 billion MWh/a can be estimated. This rough estimate shows that approx. 7 % of the world's entire energy requirement is consumed in the steel industry, and thus underlines the significance of energy use in the steel industry. Since fossil energy sources are predominantly used in the steel industry, thus the emitted CO₂ quantities are also directly linked with the steel industry. Today steel production is approximately based 30 % on scrap and approx. 70 % on iron ore.

If development of the specific consumption of reducing agents in the blast furnace is considered over the past decades, then up to 1000 kg of carbon carriers per ton of iron were still required in 1950 [5]. Through a wide variety of procedures for optimising the blast furnace, a reducing agent requirement of less than 500 kg carbon carriers per ton of hot metal is achieved today. In terms of energy, in the blast furnace this means an energy use of reducing agents in the amount of approx. 15,500 kJ per kilogram of generated pig iron.

On one hand, the research projects conducted internationally deal with further energy optimisation of production flows, and on the other hand with reduction of CO₂-emissions in steel production. An overview of various activities is provided in [6]. The latest research results were reported at the "1st International Conference on Energy Efficiency and CO₂ Reduction in the Steel Industry" (EECR Steel 2011, Düsseldorf).

Worldwide research activities can be roughly divided into the following approaches:

- Use of "less C-containing" fuels, such as hydrogen and natural gas, as reducing agents
- Process optimisation to increase the efficiency of reducing agents, e.g. through the ULCOS "Top Gas Recycling Technology" program [7] or heat recovery from auxiliary systems and by-products of steel production, as well as the use of CCS technology (Carbon Capture and Storage)
- Development of a fused-salt electrolysis for greater independence from fossil fuels in the long-term.

Many of the solution approaches of the American, European or also Japanese research platforms are currently still on the laboratory scale or pilot scale. It can be assumed that commercial implementation is still another 20-30 years away.

In the meantime one approach that has been realised on a commercial scale is injection of carbon carriers via the tuyere of the blast furnace. In this regard injection of oil, gas or fine pulverised coal is established technology. Due to the low oil prices in the 1960s heavy oil was predominantly injected into the blast furnace. Then due to the oil crisis in the early 1980s injection of pulverised coals into the blast furnace prevailed [8]. Through substitution of expensive coke, on one hand cost savings occur due to the lower-priced fuels. On the other hand, by using "less C-containing" fuels and through coke minimisation, the CO₂ balance of the blast furnace or of the coking plant can be improved.

The pulverized coal injection technology itself as well as its effect on CO₂ and cost reduction in steel production are presented below.

2 MATERIAL AND METHODS

2.1 Injection of Pulverised Coal into the Blast Furnace.

A pulverised coal injection system with Oxycoal+ technology is presented in Fig. 1. In this process the pulverised coal is conveyed pneumatically in the dense phase with nitrogen as carrier gas, out of a pressurised injection vessel, and over longer distances into a distributor in the vicinity of the blast furnace. The delivery rate is detected via a mass flow measurement and adjusted via a ceramic regulating valve. In the distributor, the pulverised coal is uniformly split over multiple individual lines of the same length that run to each individual tuyere. This is where the pulverised coal is injected into the turbulence zone of the blast furnace through the tuyere. Iron oxide is reduced in the blast furnace, essentially by the reduction gases CO and H₂ via heterogeneous gas-solid reactions. When injecting pulverised coal into the blast furnace, to the extent possible all the pulverised coal must be transferred in the flight phase. Approx. 10-20 ms are available for this [9]. This is the time period from entry of the pulverised coal particles into the hot gas stream until the end of the turbulence zone (i.e. into the boundary area of the coke bed).

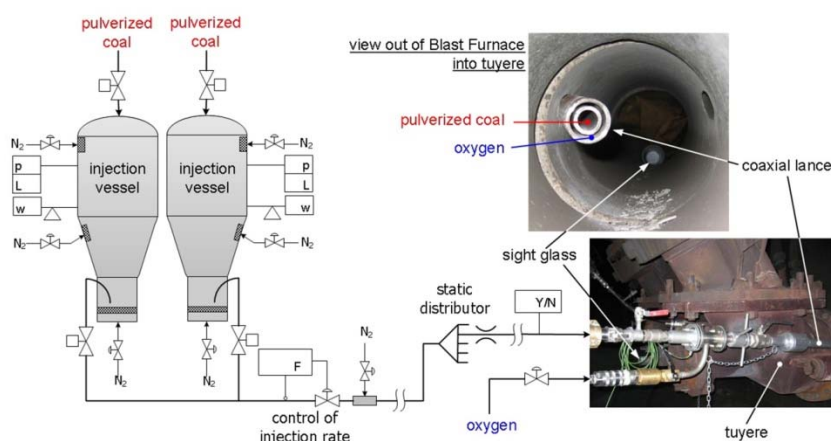


Fig 1. Pulverised coal injection system with Oxycoal+ technology

In this short period of time the following reaction steps take place: First, the injected particles of pulverised coal are heated up to ignition temperature. This occurs

through convective heat transfer from the hot blast and through radiant heat transfer from the tuyere wall, as well as through irradiation from the turbulence zone. In this regard, first the boundary areas of the injected jet of pulverised coal are heated up, since here a blending with the hot blast has not yet taken place, and the outer pulverised coal particles shield the inner pulverised coal particles against radiation. Depending on the temperature achieved, first the residual surface moisture of the pulverised coal is evaporated. Then the pyrolysis of the heated pulverised coal starts, wherein the pyrolysis gases are combusted to CO₂ and H₂O due to the speed of the gas-gas reactions with the oxygen of the hot blast. The reaction heats occurring through these processes help other heat-up procedures run faster. The oxygen that is still present in the oxygen and steam of the hot blast, as well as the combustion products CO₂ and H₂O, are gasification agents for the semicoke (carbon skeleton remaining after pyrolysis), which is now gasified depending on the temperature. CO₂, H₂O, CO and H₂ are formed as reaction products, whereby CO₂ and H₂O disassociate depending on the temperature. Because the injected pulverised coal is not ideally distributed in the hot blast, but rather is present as "compact" jet, all processes occur in parallel, as soon as the ignition of the first pyrolysis gases starts. Escape of the pyrolysis gases from the coal particles transfers a pulse to the coal particles, whereby its movement direction can change, and overall a mixture of the injected pulverised coal with the hot blast occurs. However, a portion of the semicoke that is formed in the coke bed of the blast furnace is only converted here. This portion should be as small as possible.

Injecting pulverised coal into the turbulence zone of the blast furnace via the tuyeres requires oxygen enrichment in the blast depending on the proportion of volatile matters of the coal for adjustment of the raceway temperature (RAFT) in the turbulence zone to the desired level. Without oxygen enrichment the raceway temperature would collapse due to the energies necessary for decomposition. Normally, the entire oxygen enrichment is fed into the cold blast upstream of the hot blast stoves. In this regard, the hot blast quantity is reduced by the quantity whose proportion of oxygen equals the quantity of oxygen enrichment. Otherwise, if the hot blast quantity is maintained, with addition of oxygen a capacity increase of the blast furnace would occur.

The limit for injection of pulverised coal is the beginning of incomplete conversion of the pulverised coal in the lower furnace. This becomes noticeable when semicoke appears from non-converted pulverised coal in the top gas dust and/or so-called "bird nest" zones occur (these are fine coal deposits in the edge zones of the dead man). If these "bird nest zones" cannot be gasified fast enough due to the lower partial pressure of the gasification agents here, this can cause a fault in the gas flow through the discharge column in the blast furnace. Excessive pressure loss that can no longer be compensated by the cold blast blowers and a deflection of the raceway into the edge zones of the blast furnace above the tuyeres are the consequence. At the same time the fluid drainage of dripping iron and slag is disturbed.

The objective when injecting pulverised coal into the turbulence zone of the blast furnace is to replace as much "expensive" coke as possible with the "cheaper" substitute fuel, coal, at the same overall energy consumption of the blast furnace. Injection rates from 160-180 kg/tHM at a total fuel consumption of below 500 kg/tHM can be considered as the state of the technology today.

3 RESULTS AND DISCUSSION

3.1 Optimized use of Coal as Substitute Fuel in the Blast Furnace Process

The OXYCOAL+ technology is a further development of the pulverised coal injection technology. With this technology a portion of the oxygen necessary for enrichment of the blast is directly injected together with the pulverised coal into the tuyeres of the blast furnace via coaxial lances. A coaxial lance essentially consists of two straight pipes, one inserted and centred into the other; the pulverised coal is conveyed through the inner pipe with nitrogen as carrier gas and the oxygen is conveyed in the coaxial gap between the inner pipe and outer pipe. The important thing is that the oxygen must only come into contact with the pulverised coal in the hot blast stream in the tuyere (see Fig. 1).

Directly after the "cold" oxygen exits the coaxial lance there is no spontaneous mixing of the hot blast with the cold oxygen, because the viscosities that are dependent on the temperature (blast: 5.36×10^{-5} Pas, oxygen: 2.66×10^{-5} Pas) vary significantly. In this manner the jet of pulverised coal is surrounded with an oxygen sheath. It follows that the partial oxygen pressure is high in the direct vicinity of the pulverised coal particles in the boundary area of the jet of pulverised coal that is important for ignition. The result is an accelerated conversion speed of the injected pulverised coal. Moreover the "sheathing" of the grains of pulverised coal with oxygen causes a lowering of the ignition temperature of the injection coal, i.e. an improvement of the local ignition conditions, whereby the start time of the conversion of the pulverised coal is shortened [10]. The conversion of injection coal already begins within the tuyere after ignition. An accompanying aspect is that a temperature increase in the tuyeres can be expected.

Fig. 2 shows four photos that were taken through the inspection glass of tuyere no. 8 of blast furnace 5 of the Dillinger/ROGESA that Küttner equipped with the dense phase and Oxycoal+ technology. This inspection glass is arranged in such a way that a view into the raceway in front of the tuyere of the blast furnace is possible. The photos on the left side show the pulverised coal injected into the tuyere at an injection rate of 800 kg/h (top left) and at an injection rate of 2000 kg/h (bottom left). In both photos a black cloud of pulverised coal that has not yet ignited in the tuyere is easy to see. On the right side, two photos are presented that show the same tuyere at the same injection rate and for which in addition 280 Nm³/h oxygen is injected with the aid of the Oxycoal+ technology. The combustion of the volatile components evaporating from the injection coal directly on the tip of the lance after entry into the hot blast stream can clearly be seen. This means that the injected pulverised coal already ignites in the tuyere and carbon conversion starts. Customer measurements and our calculations indicate that when using the Oxycoal+ technology in the tuyere, temperatures higher than 2400 °C can occur [9]. In dense phase operation, and with oxygen enrichment of the hot blast, the injected pulverised coal does not ignite in the tuyere, but it only combusts/gasifies in the raceway. As Fig. 2 shows in the photos on the left, the ignition temperature of the coal jet also in the boundary areas on the approx. 300 mm long path within the tuyere from the tip of the lance until into the raceway is not achieved.

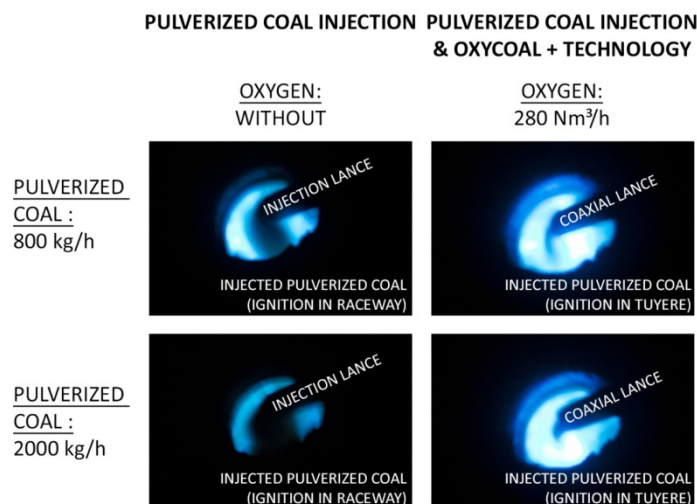


Fig. 2: Influence of the Oxycoal+ technology on the conversion of the injected pulverised coal

Overall for the Oxycoal+ technology less time is needed for carbon conversion due to the earlier onset of ignition of the pulverised coal. Thus an additional increase in the injection rate can be achieved with accompanying substitution of coke through the additionally injected pulverised coal. Experiences of our customers and our own calculations show that with the Oxycoal+ technology, the injection quantity can be increased by approx. 10 % relative to the "conventional" injection technology at conditions which are otherwise the same.

3.2 Simplified Balancing of the Blast Furnace Process for Different Operating Modes

The increased efficiency of the use of reducing agents in blast furnace operation relative to reduction of CO₂ emissions and costs savings are illustrated below by means of simplified energy considerations of the blast furnace process for coke-only operation, operation with injection of pulverised coal and operation using the Oxycoal+ technology. For these energy balances, a separate static blast furnace model is used that simultaneously solves the conservation equations for mass and energy for four different balancing groups in and around the blast furnace for an operating point in each case.

Fig. 3 schematically shows the four different balancing groups of the blast furnace model, as well as the material flows fed into and discharged from the blast furnace. Thermodynamic data, material values and enthalpies of reaction necessary for the blast furnace model were taken from [11], [12] and [13]. The modelling of the blast furnace process is based on the following premises:

- The entire oxygen that is fed into the blast furnace via the tuyeres will be converted to CO.
- The entire CO₂ and H₂O in the top gas are formed in indirect reduction via CO and H₂. The exceptions in this regard are the evaporated water from the burden, the hydration water and the CO₂ from the carbonates.
- A "reserve zone" exists on the "wüstite corner" [14], [15]. The equilibrium on the "wüstite corner" is only achieved to approx. 90%. The gas temperature on the "wüstite corner" is approx. 20 °C higher than the solid matter temperature. The minimum temperature of the reserve zone is determined through a thermal balance around the upper furnace.

- The Boudouard reaction and the heterogeneous water-gas reaction freeze at 1,000 °C.
- The homogeneous water-gas reaction freezes at 800 °C, at lower temperatures; the equilibrium is no longer achieved.
- Sulphur distribution (% S in the slag)/[% S in the pig iron] is approx. 50 – 100 [16]. Approximately 50 ppm goes into the top gas.

The blast furnace model defines four balance groups (see Fig. 3). Balance group 1 includes the tuyere and the turbulence zone of the blast furnace. In this regard, a fictive temperature is calculated on the volume surface of the balance group in the blast furnace, which occurs if the total of the raceway is converted into carbon monoxide via the tuyeres and the oxygen supplied to the coke. Only the gaseous reaction products CO, H₂, COS, as well as N₂ occur from the balance group from and in the lower furnace. Balance group 2 comprises the lower furnace, including the reserve zone. This is where the direct and indirect reduction takes place of FeO_{1.05} and the metalloids (MnO, MgO, P₂O₅, TiO₂, SiO₂, V₂O₅) as well as the de-acidification of the carbonates (FeCO₃, MgCO₃, MnCO₃, CaCO₃). Balance group 3 includes the entire top furnace that is characterised by the indirect reduction of Fe₂O₃ and Fe₃O₄, as well as the separation of hydration water, the expelling of annealing losses and water evaporation. Balance group 4 includes the entire blast furnace.

The blast furnace model takes the following equilibrium reactions and their energy influence into account:

- Fe₃O₄ – CO equilibrium
- Fe₃O₄ – H₂ equilibrium
- FeO – CO equilibrium
- FeO – H₂ equilibrium
- Boudouard equilibrium
- Heterogeneous water-gas equilibrium
- Homogeneous water-gas equilibrium (Fe₂O₃ is already reduced to Fe₃O₄ at low reduction gas contents.)

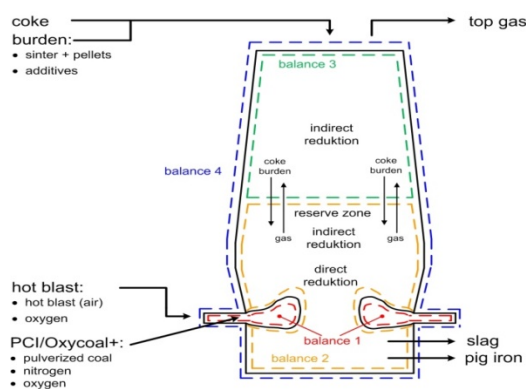


Fig. 3: Schematic representation of the blast furnace model

For correct comparison of the three operating modes of the blast furnace cited above the values listed in Table 1 are held constant for all simulation calculations. For the simulation calculations a blast furnace with a daily capacity of 10,000 t of pig iron is assumed. In this regard the forming gas temperature and the gas utilization on the furnace top have special significance as important key indicators for the blast furnace operator. The gas utilisation of carbon monoxide at the furnace top is defined as quantity of reduction gas carbon dioxide based on the total of carbon monoxide and

carbon dioxide at the top of the furnace $\eta_{CO} = CO_2/(CO+CO_2)$ and describes the quality of the productive blast furnace operation.

Gas utilisation of carbon monoxide at the top of the furnace is determined by the ratio of direct reduction under consumption of solid carbon via the Boudouard reaction and indirect reduction with conversion of CO (H₂) into CO₂ (H₂O) and the achieved proximity to the equilibrium on the "wüstite corner" [14], [15]. The lines of the "Heugabel curve" of the Bauer-Glaessner diagram mark the equilibrium [17]. Here, each of the proportions of CO₂ (H₂O) of the totals of CO₂ and CO (H₂O and H₂) are in equilibrium with two phases of the oxidation stages of the iron. Direct reduction takes place in a temperature range from forming gas temperature to approximately 1,000 °C in the bosh and belly of the lower furnace. Below approx. 1000 °C the Boudouard reaction freezes and indicates the end of the direct reduction. At decreasing temperatures, FeO is further directly reduced with CO (H₂) by the increase of the CO₂ (H₂O) until the equilibrium curve is reached. In the temperature range of approx. 800 – 850 °C the homogeneous water-gas equilibrium is the determining factor for conversion of CO into CO₂ (or H₂ into H₂O). Below 800 °C the reactions increasingly slow down. The indirect reduction takes place in a temperature range from 400 – 950 °C mainly in the upper part of the furnace [9]. The oxidation levels of the iron Fe₂O₃ and Fe₃O₄ are already completely reduced at temperatures less than 850 °C. Small amounts of the reduction gases CO and H₂ which are always present are already sufficient for this.

Table 1: Values of the blast furnace simulation calculations that are kept constant

Smelting capacity of the blast furnace	10.000	t _{HM} / d	Smelting capacity of the blast furnace	10.000	t _{HM} / d
Quantity of ore consisting of sinter and pellets	1.571,2	kg / t _{HM}	Quantity of ore consisting of sinter and pellets	1.571,2	kg / t _{HM}
Quantity of additives	10	kg / t _{HM}	Quantity of additives	10	kg / t _{HM}
Forming gas temperature	2.150	°C	Forming gas temperature	2.150	°C
Top gas temperature	110	°C	Top gas temperature	110	°C

For the blast furnace simulation calculations, coke quantity, hot blast quantity, blast temperature, oxygen enrichment in the hot blast, the quantity of injected pulverised coal, and the quantity of the oxygen when using the Oxycoal+ technology are varied in such a manner that the blast furnace process for the respective operating point of the considered blast furnace operating mode is in equilibrium. Simultaneously, through specification of the values from Table 1 held constant, a comparability of all simulated operating points is ensured. The product quality of the pig iron is not influenced by injection of pulverised coal into the blast furnace, as compared with coke-only operation in the first approximation. From the material balance perspective, in this regard only coke is replaced by the injected pulverised coal; note that beside the volatile matters, coke and injection coal do not have significant material differences. In Table 2 the results of the simulation calculation are cited for the three blast furnace operating modes compared. Tables and Figures (drawings, schemes, flowcharts, photographs, graphs etc.) must be numbered in Arabic numbers, consecutively, in the order of appearance in the text. Should be cited in the text, next to the place they should be located. Their sources should be cited in the references. Below an example of Figure (Figure 1).

Table 2: Results of the blast furnace simulation calculations

Blast furnace 10,000 t _{HM} /d	Coke-only operation			Injection of pulverised coal			Oxycoal+ technology					
	Mass flow		temp. °C	Energy MJ/t _{HM}	Mass flow		temp. °C	Energy MJ/t _{HM}	Mass flow		temp. °C	Energy MJ/t _{HM}
	kg/t _{HM}	m ³			kg/t _{HM}	m ³			kg/t _{HM}	m ³		
Supply:												
Coke	490,5	-	15		296,2	-	15		282,5	-	15	
Burden:												
Sinter + pellets	1.571,	-	15	14.776,2	1.571,	-	15	8.930,5	1.571,2	-	15	8.517,6
Additives	10	-	15		10	-	15		10	-	15	
Blast furnace blast:												
Blast (air)	-	1.200	947	1.569,6	-	900	1.200	1.602,4	-	823	1.200	1.423,4
Supplemental oxygen	-	-	-		-	46,3	1.200		-	43,8	1.200	
Pulverised coal/ Oxycoal+:												
Pulverised coal	-	-	-		178,2	-	30		195	-	30	
Transport nitrogen	-	-	-	-	-	4,5	30	5.840	-	5,2	30	6.391
Oxygen	-	-	-		-	-	-		-	20	30	
Discharge:												
Pig iron	1.000	-	1.500	-1.294,2	1.000	-	1.500	-1.294,2	1.000	-	1.500	-1.294,2
Slag	243,5	-	1.510	-444,1	237,7	-	1.510	-433,5	237,4	-	1.510	-432,9
Top gas	-	1.726	110	-5.111,6	-	1.521,5	110	-5.199,7	-	1.479,3	110	-5.144,6
Heat losses	-	-	-	-550	-	-	-	-550	-	-	-	-550
Blast furnace process	-	-	-	-8.945,9	-	-	-	-8.895,5	-	-	-	-8.910,3

3.2.1 Coke-Only Operation

Accordingly, for coke-only operation at a blast furnace capacity of 10,000 t of pig iron per day, 490.5 kg/t_{HM} of dry coke and a blast quantity of 1,200 m³ (STP)/t_{HM} at a blast temperature of 947 °C are required. Overall an amount of energy consisting of thermal and chemical energy of 14,776.2 MJ/t_{HM} is fed into the blast furnace via the burden, and 1,596.6 MJ/t_{HM} is fed into the blast furnace via the hot blast. The simulation calculation shows the discharged, thermal and chemical energy quantities of -5,111.6 MJ/t_{HM} in the top gas, -444.1 MJ/t_{HM} in the slag and -1,294.2 MJ/t_{HM} in the pig iron. The difference of the supplied and discharged energy quantities describes the energy quantity necessary for all of the inner reaction processes that take place in the blast furnace. For coke-only operation overall there is an energy quantity of the inner reaction processes of -8,945.9 MJ/t_{HM}.

3.2.2 Injection of Pulverised Coal

With injection of pulverised coal into the raceway of the blast furnace via the tuyeres, now a portion of the coke in the burden is replaced by injection coal. Now 296.2 kg/t_{HM} of coke is supplied via the burden and 178.2 kg/t_{HM} injected pulverised coal is supplied via the tuyeres. In addition 4.5 m³ (STP)/t_{HM} nitrogen as transport gas is injected into the blast furnace via the tuyeres. The supplemental fuel through the tuyere requires oxygen enrichment in the blast of 46.3 m³ (STP)/t_{HM} to maintain the raceway temperature. In this case, merely increasing the blast temperature to 1,200 °C, does not suffice. The required blast quantity is 900 m³ (STP)/t_{HM}. Thus overall the tangible and chemical energy cited in Table 2 is supplied to and discharged from the blast furnace.

An increase of the hot blast temperature can only occur up to the capacity limit of the hot blast stoves. At a higher blast temperature, more energy is fed into the blast furnace. This causes a higher raceway temperature. If this higher raceway temperature still does not suffice, an enrichment of the blast with oxygen is required. Due to the higher oxygen content of the blast, more coke is combusted and a boost in the smelting capacity is achieved. If an increase in smelting capacity should not occur, the blast quantity enriched with oxygen per tHM is taken back.

3.2.3 The Oxycoal+ technology

With use of the Oxycoal+ technology the substitution of coke through pulverised coal can be further increased. Operational experience of our customers shows that by using the Oxycoal+ technology the pulverised coal injection rate can be increased by approx. 10 %. This is also substantiated by our own calculations with a physical model especially developed for this purpose, which describes and also simulates the procedures for blowing pulverised coal into the tuyere and raceway of the blast furnace when using the Oxycoal+ technology, and with the aid of numeric flow simulations. The effect of an increased injection rate using the Oxycoal+ technology on the efficiency increase of the reduction agents used in the blast furnace for reducing costs and CO₂ is illustrated in this article. Consequently, an approximately 10 % increase in the pulverised coal injection rate is assumed. In this regard 282.5 kg/tHM of coke are charged with the burden and 195 kg/tHM of pulverised coal are injected through the tuyeres. In addition 5.2 m³ (STP)/tHM nitrogen as transport gas and 20 m³ (STP)/tHM oxygen are injected into the blast furnace via the tuyeres. The hot blast must be enriched with 43.8 m³ (STP)/tHM oxygen. The higher oxygen supply of 63.8 m³(STP)/tHM as compared with 46.3 m³ (STP)/tHM is based on maintaining of the mathematical raceway temperature of 2,150 °C at the increased rate of pulverised coal injection. The blast quantity is 823 m³ (STP)/tHM at a blast temperature of 1200 °C. Thus, overall the thermal and chemical energy cited in Table 2 are supplied to and discharged from the blast furnace.

4 CONCLUSION

To present the increased efficiency of reducing agent use, blast furnace operating modes injection of pulverised coal and use of the Oxycoal+ technology, are compared with coke-only operation. To evaluate the efficiency of reducing agent use, at this point the carbon dioxide emissions and the costs are considered.

Reduction of coke use in the blast furnace results in a reduction of the carbon dioxide emissions mainly in the coking plant, because less coke must be produced. Approx. 1.3 t of coking coal must be processed for each tone of coke. To quantify the CO₂ savings a carbon balance is created around the blast furnace and the coking plant in which the entire quantity of carbon carriers required for production of the specified quantity of pig iron is converted to CO₂. In this process the fact that a portion of the CO₂ emissions result from the combustion of coke oven gas and blast furnace gas that accrue in the production of the specified quantity of pig iron in the considered balance space, but are used outside of the balance space is not considered (see [18]). For calculation of the CO₂ savings the changed requirement of electrical energy for the additional oxygen enrichment and the reduced blast compaction were not taken into account.

The essential cost reducing lever is substitution of coke with injected coal, as compared with coke-only operation of the blast furnace. The reason for this is the significant price difference between coke and coal, delivered to the blast furnace. It

must be considered that the cost situation differs for each blast furnace plant and depends on the economic situation. At this point a sample calculation is provided with the costs for coke of 350 €/t, for injection coal of 170 €/t, for oxygen of 40 €/1000m³ (STP), for blast heating of 9 €/GJ and for blast compaction of 6 €/1000 m³ (STP) as well as a top gas credit of 6 €/GJ, taken from [19]. A basic credit of 8 €/t is assessed for the saved CO₂. Current credits for CO₂ certificates are provided in [20].

Table 3: Efficiency increase of the reducing agent use 1 year is assessed at 350 work days)

Blast furnace 10,000 tHM/d	Coke-only operation versus injection of pulverised coal	Injection of pulverised coal versus Oxycoal+ technology
Increase of the injection rate	178.2 kg/tHM (= 623,700 t/a)	16.8 kg/tHM (= 58,800 t/a)
Coke savings	194.3 kg/tHM (= 680,050 t/a)	13.7 kg/tHM (= 47,900 t/a)
CO ₂ emissions reduction (Mainly in the coking plant)	385.88 kg/tHM (= 1,350,580 t/a)	14.37 kg/tHM (= 50,295 t/a)
Increased oxygen consumption	46.3 m ³ (STP)/t _{HM} (= 162.05 x 10 ⁶ m ³ (STP)/a)	17.5 m ³ (STP)/ t _{HM} (61.25 x 10 ⁶ m ³ (STP)/a)
Energy savings – hot blast	-32.8 MJ/tHM (= -114,800 GJ/a)	179,0 MJ/tHM (= 626,500 GJ/a)
Quantity reduction – hot blast	300 m ³ (STP)/t _{HM} (= 1.05 x 10 ⁹ m ³ (STP)/a)	77,0 m ³ (STP)/t _{HM} (= 269.5 x 10 ⁶ m ³ (STP)/a)
Energy gain – top gas	88.1 MJ/t _{HM} (= 308,350 GJ/a)	-55.1 MJ/t _{HM} (= -192,850 GJ/a)
Cost savings	40.08844 €/ t _{HM} (= 140,309,540 €/a)	3.01236 €/ t _{HM} (= 10,543,260 €/a)

In Table 3 the results of the efficiency increase of the reducing agent use on the blast furnace are cited. In the first column, coke-only operation of the blast furnace is compared with blast furnace operation based on pulverised coal injection. In this regard it is evident that the coke savings are higher than the injection rate increase. The reasons for this are: In addition to coke savings through the injected pulverised coal, an increase in thermal energy is introduced through the higher blast temperature in the blast furnace, which partially replaces the combustion of the so-called heating coke for the generation of the process energy. The raceway temperature also increases with the hot blast temperature. Based on the above, in the second column blast furnace operation with injection of pulverised coal is compared with blast furnace operation using the Oxycoal+ technology.

The results of the sample calculation in Table 3 show that through installation of a pulverised coal injection system for a 10,000 tHM/d blast furnace, a significant reduction of CO₂ emissions of 385.88 kg/tHM or 17 % of the total CO₂ emissions of blast furnace and coking plant, as well as a significant cost reduction of 40.09 €/tHM can be achieved. Then in accordance with the example in Table 3, if the existing pulverised coal injection system is equipped with the Oxycoal+ technology, the efficiency of reducing agent use can be further increased. In this case there is an additional reduction of CO₂ emissions of 14.37 kg/tHM or approx. 0.8 % of the total CO₂ emissions of blast furnace and coking plant, as well as additional cost savings of 3.01 €/tHM. At this point express reference is again made to the sample character of the above economic consideration. In particular, the 175 €/t price difference [15] between coke and injected coal appears to be quite high. But even if the price difference of coke and pulverised coal is halved to 87.50 €/t, there is still a

considerable cost reduction of 23.09 €/tHM that can be calculated for installation of a pulverised coal injection system and an additional cost reduction of 1.81 €/tHM when using the Oxycoal+ technology.

In Table 3 only the essential influence parameters are generalised. Each iron and steel plant has different boundary conditions that influence profitability. However, Table 3 does show general tendencies. Moreover, the experience of the last 25 years and 80 plants already installed shows that injection of pulverised coal into the blast furnace and the Oxycoal+ technology can be procedures that are economical as well as profitable from the aspect of reducing CO₂ emissions.

A consistent further development of the injection technology based on a further CO₂ emissions reduction is the injection of substitute reducing agents from renewable raw materials. The use of renewable substitute fuels is countered by the availability of sufficient quantities, the low calorific value, and the possible burden of contaminants. The question of whether use of renewable substitute fuels is ecologically and economically worthwhile is currently being investigated in a self-financed R&D project.

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