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EAF POST-COMBUSTION CONTROL BY ON-LINE LASER-BASED OFF-GAS MEASUREMENT

STEROWANIE DOPALANIEM GAZÓW W PIECU ŁUKOWYM PRZEZ LASEROWY POMIAR GAZÓW WYLOTOWYCH

At the steel and rolling mill Marienhütte Graz the laser-based off-gas analysis system LINDARC® is installed just behind the gap of the 36 t EAF. High reliability and low response time of the system have been proven. The in-situ measured off-gas compounds in the combustion zone are CO and O_2, as well as the off-gas temperature. To post-combust the evolved CO and H_2 during the melt down period, four PC-lances are installed tangentially at the upper furnace shell (freeboard). A measurement campaign with an additional extractive IR/VIS off-gas analysis system has been performed, to acquire information on the off-gas flow rate and off-gas components including H_2, CO_2 and CH_4, which can not be measured by the laser system, but are important for dynamic control and energy balance calculations. A dynamic closed loop control strategy of the post-combustion injectors based on the laser-based off-gas analysis system was developed and tested successfully. Post-Combustion oxy-gen is injected only if required due to high levels of CO in the off-gas, which increased its energetic efficiency dramatically. The trials were evaluated regarding the total energetic behaviour and the achieved savings by using of energy balance model calculations.
Keywords: Laser-based off-gas analysis, post-combustion, dynamic control, energy balance models

W stalowni i walcowni huty Marienhütte Graz system analizy gazów wylotowych w oparciu o pomiar laserowy LINDARC® jest zainstalowany tuż przy wylocie 36 Mg pieca łukowego. Udowodniona została duża wiarygodność i krótki czas odpowiedzi systemu. W strefie palenia następuje pomiar in-situ zawartości CO i O_2 w mieszaninie gazów wylotowych oraz mierzona jest temperatura gazu. Do pomiaru CO i H_2 podczas trwania wytopu po zapłonie, zainstalowane są stycznie cztery lance PC w górnej części pieca. Pomiary z dodatkowymi analizami IR/VIS gazów wylotowych zostały wykonane, aby zdobyć informacje o szybkości przepływu gazów i jego składzie z uwzględnieniem H_2, CO_2 i CH_4, które nie mogą być mierzone za pomocą lasera, ale są konieczne do sterowania dynamicznego i obliczenia bilansu energii. Dynamiczne sterowanie obwodem zamkniętym inżektorów oparte na systemie analizy gazów wylotowych za pomocą lasera zostało z sukcesem rozwinięte i przetestowane. Tlen po zapłonie jest wdmuchiwany, jeżeli jest wysoki poziom CO w gazie wylotowym, co powoduje wzrost wydajności energetycznej. Próby zostały oszacowane na podstawie zachowania energetycznego i osiągniętych oszczędności przez użycie obliczeń modelowych bilansu energii.

1. Introduction

The main objective of the described work is to increase the efficiency of post-combustion (PC) oxygen to transfer energy to scrap and melt within the EAF process. For a reliable and reproducible achievement of effective oxygen injection and reduced energy consumption, a permanent on-line monitoring and control of the EAF melting process on the basis of an off-gas analysis is necessary. The technical objective is the long-term availability and applicability of the off-gas signals for on-line assessment and control of post-combustion and for comprehensive EAF energy monitoring. For these reasons considerable efforts have been made during the last few years to develop in-situ measurement systems to analyse EAF off-gas concentrations as close as possible to the furnace with a minimum response time. Marienhütte, a steel and rolling mill with a production of 370.000 tons reinforcement steel per year, sets a next step of innovation by implementation of the laser-based off-gas measurement system LINDARC® to enhance the furnace performance by dynamic control of PC injectors.

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TABLE 1

Maximum energy contribution from reactions (injected fuel and oxygen are at 25°C)

	Chemical reaction	kWh/Nm³ O_2 $(\Delta E)_{800°C}$	kWh/Nm³ O_2 $(\Delta E)_{1600°C}$
Injected fuel	$C_{(s)} + {}^1/_2\ O_{2(g)} \rightarrow CO_{(g)}$	2.0	1.3
	$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$	4.1	3.6
	$CH_{4(g)} + 2\ O_{2(g)} \rightarrow CO_{2(g)} + 2\ H_2O_{(g)}$	4.0	3.4
Post-combustion	$CO_{(g)} + {}^1/_2\ O_{2(g)} \rightarrow CO_{2(g)}$	6.2	5.8
	$H_{2(g)} + {}^1/_2\ O_{2(g)} \rightarrow H_2O_{(g)}$	5.4	5.2

2. Fundamentals of post-combustion

If CO and H_2 are present in the furnace gases, their oxidation releases more energy per unit oxygen than burning injected carbon or natural gas. As shown in Table 1, the theoretical limit for post-combustion of CO at bath temperatures (1600°C) is 5.8 kWh/Nm^3 oxygen [1].

Jones [2] published results of different post-combustion practices at several EAFs. Energy savings between 1.2 and 5.04 kWh/Nm^3 oxygen were obtained. The PC oxygen efficiency assumed in the BFI energy model is 2.8 kWh/Nm^3 [3]. Adams [4] expects a thermal efficien-cy of the reaction between hot CO and cold oxygen of 50% at the most, i.e. 3.1 kWh/Nm^3. However, the reported PC efficiencies vary in a wide range, leading to the conclusion that they highly depend on the applied PC technique (injectors, burner stoichiometry,...).

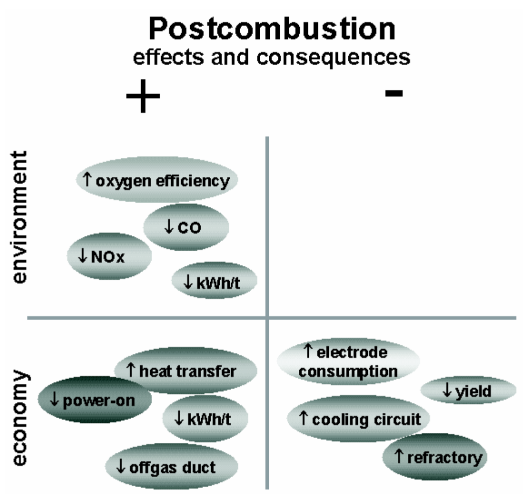


Fig. 1. Effects and consequences of post-combustion practice (↑/↓ increase/decrease)

In figure 1 different positive and also negative effects and consequences of post-combustion are shown, which must be considered when developing a successful PC practice. An excessive use of post-combustion oxygen can result for example in a decreased yield and in an increased electrode consumption. The strain of the water-cooled panels must be considered as well as the refractory lining of the shell. An environ-mental benefit is e.g. a reduction of NO_x emissions due to a lower amount of infiltrated air if oxygen is used for post-combustion. Lower CO emissions due to combustion inside the furnace can be expected, too. A lower amount of CO in the offgas duct also decreases the risk of bag house explosions. Thus post-combustion can be an effective tool but an economical operating practice must be customised at each EAF individually.

3. Description of the Laser-based off-gas analysis system

The off-gas analysis system LINDARC®uses the technique of "Tunable Diode Laser Absorption Spectroscopy" (TDLAS).This single-line spectroscopy measuring technique is based on the selection of one single absorption line in the near infrared spectral range for the specific gas. The spectral width of the diode laser is considerably narrower than the one of the absorption line for the gas chosen. By varying the diode laser current, its wavelength is scanned across the absorption line. The light detected in the receiver unit varies in intensity as a function of wavelength during the scan of the laser, due to the absorption of light from the specific gas molecules in the optical path between diode laser and receiver. The detected shape and size of this single absorption line is used to calculate the amount of gas between the transmitter and the receiver unit. Absorption lines from other gases are not present at this specific wavelength, and therefore will not interfere with the single absorption line or the resulting gas concentration [5, 6]. The laser units are protected by a water-cooled housing. The laser system is installed just behind the gap after the elbow, in order to deliver off gas concentration close to the place of emergence in the furnace (figure 2 and 3). Due to the typically harsh environment of an electric arc furnace, the sensitive transmitter and receiver unit are mounted outside the off gas system to prevent high heat load and even mechanical damage. These parts are additionally cooled by water. To avoid undesirable effects of false air entering from the gap, the path length is reduced by two water-cooled housings. The lances are purged with nitrogen.

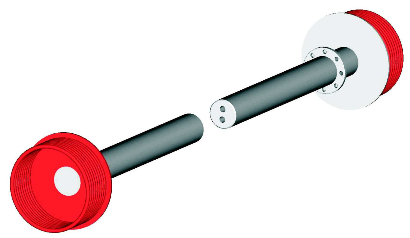


Fig. 2. Water-cooled lances

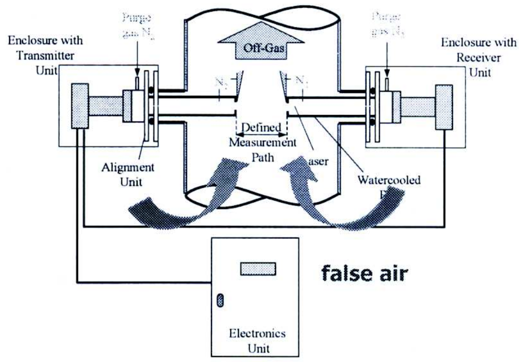


Fig. 3. Installation in the off-gas duct

Conventional measurement techniques are based on an extractive method where the gas to be measured is drawn off from the off-gas stream, cooled, filtered and analysed continuously. CO, CO_2 and CH_4 are determined using an infrared analyser, H_2 via thermal conductivity and oxygen by its paramagnetic behaviour (IR/VIS) [7]. Alternatively a mass spectrometer can be applied to analyse all components in parallel. Disadvantageous is the long response time of more than 20 sec., depending on the distance between probe sampling point and analytical instrumentation. Such a long time delay makes a rapid intervention impossible. Today, the shortest response times can be achieved with the laser measurement technique.

To verify the laser-based analysis values, additional measurements with the extractive IR/VIS method were performed by RWTH, including also the components CO_2, H_2, and CH_4. The measurement point was at the same position as the laser-based sensor, directly behind the gap after the elbow. Additionally CO, CO_2, O_2 flow rate and temperature were measured further down the off-gas stream, to derive information for a dynamic mass and energy balance of the EAF. The measurement locations are indicated in figure 4.

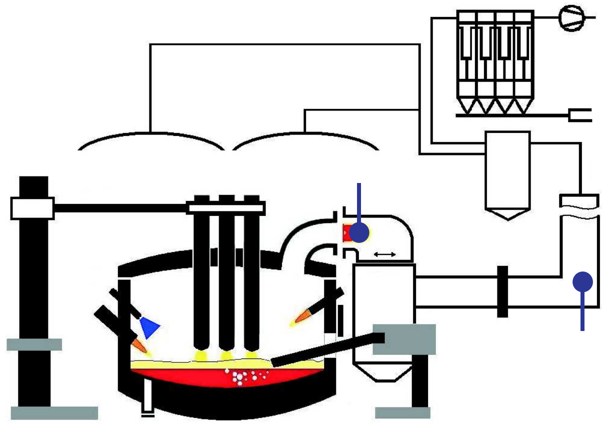


Fig. 4. Off-gas measurement points during RWTH trial campaign at MH EAF

Figure 5 shows a comparison of the off-gas analysis results of the LINDARC® and the RWTH Aachen IR/VIS off-gas measurement systems for an example heat.

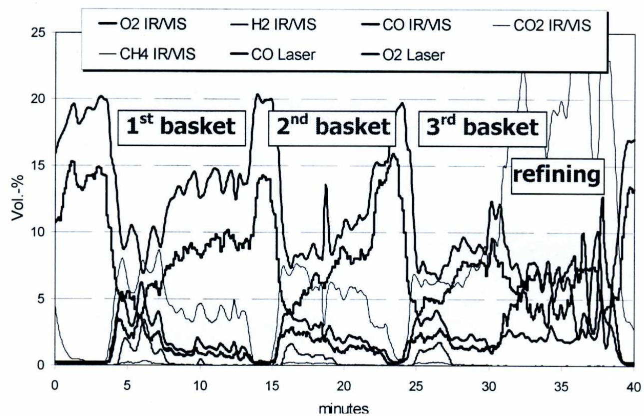


Fig. 5. Off-gas analysis (CO, CO_2, CH_4, H_2, and O_2 concentration)

The measurements of more than 100 heats confirmed the occurrence of high O_2 and CO values at the same time. This thermodynamic disequilibrium can be explained by the small furnace volume and a high offgas velocity (>20 m/s), that preclude sufficient reaction time. As the measurements indicate, the absolute O_2 and CO values of the laser are lower than those of the extractive method, especially in the melting phase. Possible reasons for deviation are:

- *dry gas (extractive) – wet gas (laser):*
  If the gas sample is dried the water molecules are removed and the ratio of all other components increases.
- *measurement point (extractive) – line (laser):*
  The laser technique averages the concentration of the molecules against the measurement path and doesn't fall victim to possible different offgas stratas.

- *insufficient quenching of the extractive sample at high temperatures*
  Probe sampling of CO is increasingly inaccurate at temperatures greater than 1000 K [8].
- *inaccurate laser measurement path due to nitrogen purging*
  If the nitrogen flow rate is too high a nitrogen cushion builds up and reduces the measurement path. On the other hand off-gas (and inherent dust loading) will penetrate the lances if the flow rate is too low.

The comparison of data from the different off-gas analysis techniques shows a good correspondence of the CO/O_2-ratio. In figure 6 the average ratios of 20 heats are shown. This led to the idea to use the CO/O_2-ratio from the laser instrument as basis for development of a dynamic control of post-combustion oxygen. For a sufficient control strategy for the PC-injectors, information on the concentration of further combustible gases like H_2 and CH_4 is required.

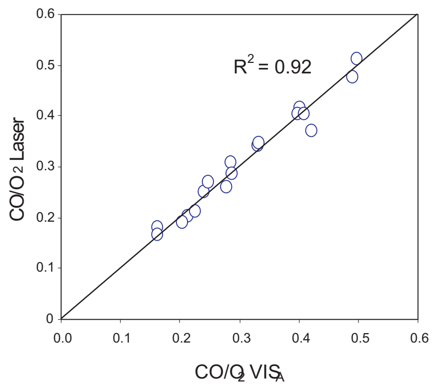


Fig. 6. Correlation of CO/O_2-ratio from laser and IR/VIS measurement

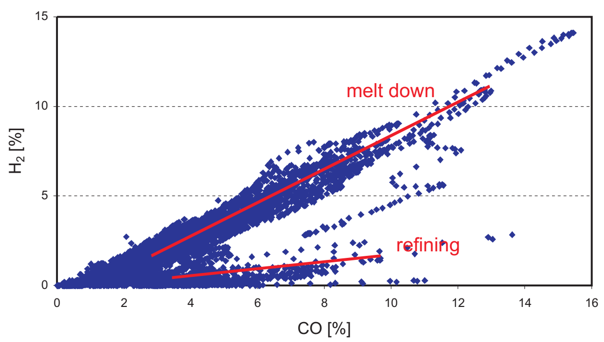


Fig. 7. CO and H_2 (IR/VIS)

With figures 7 and 8 the existence of a relationship between CO and H_2 respectively CH_4 is confirmed for 20 heats. A distinction between the melting and refining phase is identi-fiable. Typical high hydrogen amounts occur during melt down due to several H_2 sources like burner natural gas, organic impurities of the scrap etc. Much less H_2 is recorded during refining when the burners are off and the scrap is already molten down. A possible further source of evolved hydrogen is the water coming from the spray rings to cool the electrodes.

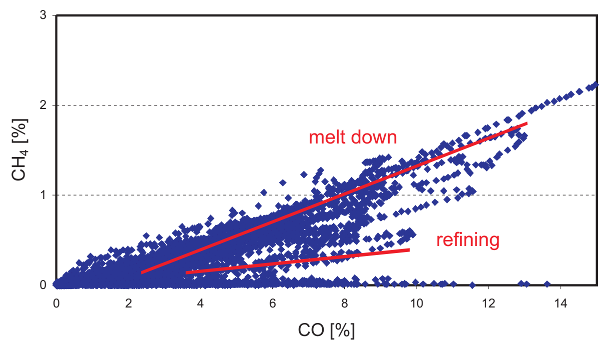


Fig. 8. CO and CH_4 (IR/VIS)

4. Development of the dynamic PC control

The highest efficiency of post combustion is achieved during melt down. Therefore the correlation of average CO, H_2,and CH_4 concentrations during melt down of each basket has been evaluated separately. From the correlation lines for melt down of all three baskets of 20 heats linear equations were derived:

$$g(H_2) = 0.853 \cdot CO - 0.808 \quad (1)$$

$$g(CH_4) = 0.126 \cdot CO - 0.116 \quad (2)$$

Equation (1) and (2) can be used to calculate the ideal CO/O_2-ratio according to equation (3) in order to ensure a stoichiometric combustion.

$$nCO + g(H_2) + g(CH_4) + mO_2 \Leftrightarrow nCO_2 + xH_2O \quad (3)$$

The derived criteria for the dynamic control of the PC-injectors (given in figure 9) contains all coherences of the combustible gases CO, H_2, and CH_4 and negates the need for additional H_2 and CH_4 analyses. The corresponding line shape function is shown in figure 9.

The PC-injectors have to be switched on if the CO/O_2-ratio measured with the laser instrument exceeds the minimum ratio needed for stoichiometric combustion as formulated by the criteria given in figure 9. Otherwise, if the criteria is not fulfilled and the ratio is lower, there is no need to add additional oxygen by the PC-injectors.

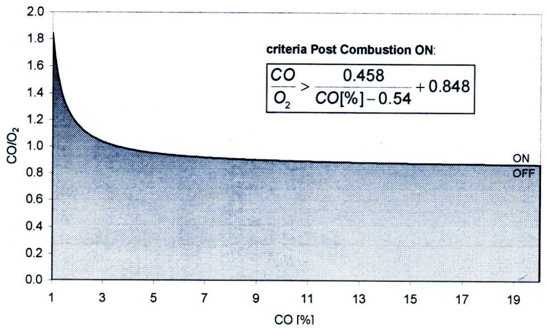


Fig. 9. Line shape function of the PC-criteria

The CO/O_2-ratio is plotted in figure 10 for an example heat together with the operation modes of the PC-injectors, burners, power on, carbon and oxygen lance.

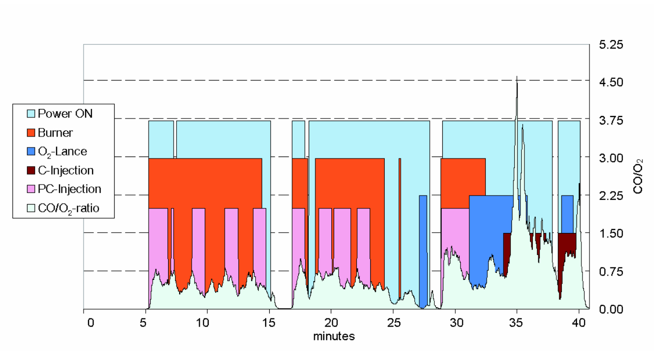


Fig. 10. Operation mode and CO/O_2-ratio

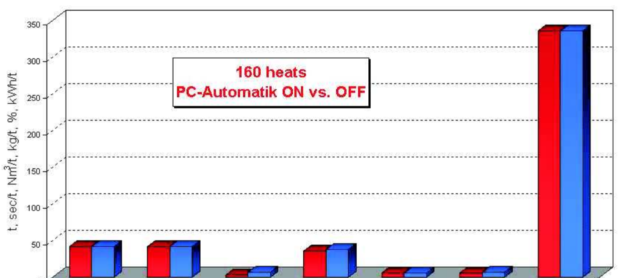
The four PC-injectors are switched on at the beginning of the melt down of each basket. They keep running for a fixed duration of 60 seconds with a flow rate of 300 Nm^3/h oxygen each, because of the typical strong flame evolution. After the first minute the CO/O_2-criteria is the constraint for the PC-injectors. If the ratio is below the criteria the injectors will switch off, otherwise they keep operating for one further minute. In figure 10 the CO/O_2-ratio increases steadily after 7 minutes. When exceeding the criteria, the injectors start for at least one minute. While running, the ratio decreases continuously. After one further minute the ratio is below the criteria and the injectors are switched off again.

The PC-control is only active during melt down. After starting the lancing mode or during the use of the oxygen lance, the PC-oxygen input is switched off, using air to keep the nozzles free. To counter the danger of bag house explosions due to exceeding high CO amounts in the off-gas, an upper limit of the CO/O_2-ratio is considered. If it exceeds the value of 4.0, a moveable sleeve will move back immediately to increase the gap behind the elbow, allowing a higher amount of false air coming into the fourth hole duct. This can be seen in figure 10 after 35 minutes, where carbon is injected to build up the foamy slag and thus the CO/O_2-ratio rises suddenly above 4.0.

5. Examination of the energetic behaviour of the EAF using dynamic PC-control

The objective of a dynamic PC-control is to increase the efficiency of oxygen injection for post combustion and thus to improve the energetic performance of the furnace. By the control strategy described above, PC-oxygen is injected only if required due to the progress of the heat. Higher CO/O_2-ratios result in a higher oxygen consumption because the PC-injectors are operated for a longer time. The dynamic control of the PC-injectors depending on the CO/O_2-ratio leads to a highly varying oxygen consumption of the different heats.

The effect of these varying conditions was evaluated within 160 trial heats. To minimise the influence of different scrap qualities, the trials were performed alternating: One heat was carried out without dynamic control (Auto OFF), where the injectors are operated for five minutes at the beginning of melt down of each basket, the following heat with dynamic control of the PC-system (Auto ON). This method ensured comparable conditions because of similar scrap qualities taken out from the wagons sequentially. In figure 11 the performance of 80 heats operated in Auto ON mode is compared to 80 heats in OFF mode. No significant difference in electrical energy consumption or in power on time is found although the PC oxygen consumption decreased in the Auto ON mode drastically from 6.8 to 3.3 Nm^3/t_{scrap}.



	scrap [t]	power on [sec/t]	PC [Nm³/t]	total O_2 [Nm³/t]	total CH_4 [Nm³/t]	carbon [kg/t]	electric energy [kWh/t]
ON	42.18	42.54	3.32	35.76	6.03	6.50	336.20
OFF	41.77	42.18	6.83	38.33	5.92	6.85	336.00

Fig. 11. Results of alternating trials (PC Automatic ON/OFF) with 160 heats

In figure 12 the daily averages of the electrical energy consumption [kWh/t_{gb}], the tap to tap time and the power on time [min] of 112 production days equal to 3739 heats are correlated to the PC-oxygen consumption [Nm^3/t_{gb}].

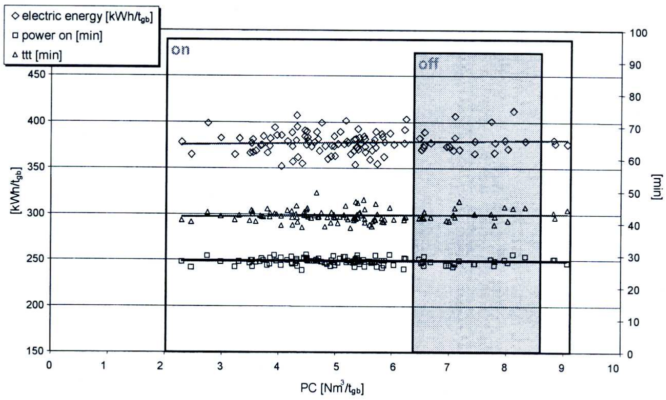


Fig. 12. Electrical energy, power on time and tap to tap time vs. post combustion oxygen

The distribution of the PC-oxygen consumption in the Auto ON mode is between 2 and 9 Nm^3/t_{gb}. For comparison, the range of the Auto OFF mode (between 6.5 and 8.5 Nm^3/t_{gb}) is also indicated in the diagram. With the Auto ON mode the average PC-oxygen consumption spreads out, resulting in a shift of the average consumption to lower values. There was no significant influence noticeable neither to the electric energy consumption nor to the power on and the tap to tap time. Consequently the electrical energy demand seems to be independent of the oxygen input for post combustion.

Results of the trial campaign with PC-oxygen control were also evaluated with the BFI statistical model for the electrical energy de-mand of EAFs given in Table 2 [3]. It takes into account the specific con-sumption of ferrous charge materials, slag formers, burner gas, oxygen for blowing by lance and injectors as well as for

TABLE 2

BFI model for electrical energy demand [3]

$$\frac{W_R}{\mathrm{kWh/t}} = 375 + 400 \cdot \left[\frac{G_E}{G_A} - 1\right] + 1000 \cdot \frac{G_Z}{G_A} + 0.3 \cdot \left[\frac{T_A}{°\mathrm{C}} - 1600\right] + 1 \cdot \frac{t_S + t_N}{\mathrm{min}} - 8 \cdot \frac{M_G}{m^3/t} - 4.3 \cdot \frac{M_L}{m^3/t} - 4.3 \cdot \frac{M_{LJ}}{m^3/t} - 2.8 \cdot \frac{M_N}{m^3/t}$$

G_A	fumace tap weight	t_N	power-off time
G_E	weight of ferrous charge materials	M_G	specific bumer gas
G_Z	weight of slag formers	M_L	specific lance oxygen
T_A	tapping temperature	M_{LJ}	specific injector oxygen
t_S	power-on time	M_N	specific post combustion oxygen

post-combustion, tapping temperature, power-on and power-off time. All consumption values, also the electrical energy consumption for comparison with the calculated demand, are related to the liquid tap weight. With this model, variations of the total energy consumption of the EAF can be analysed.

The average model input data for the trials with Auto ON and OFF mode of PC-control are shown in Table 3. The electrical energy consumption W_E is nearly equal in both cases. Small differences in the input variables (e.g. injector oxygen consumption) are considered when calculating the electrical energy demand W_R, for an objective comparison of the total energy consumption. The significant difference is that the PC-oxygen consumption in the Auto ON mode is by 4.2 Nm^3/t lower than in the Auto OFF mode.

TABLE 3

Input data for BFI statistical model for trials with PC-control

Variable	W_R	W_E	G_A	g_E	g_R	T_A	t_S	t_N	M_G	M_L	M_{LJ}	M_N
Unit	kWh/t	kWh/t	t	kg/t	kg/t	°C	min	min	m^3/t	m^3/t	m^3/t	m^3/t
80 heats with PC Auto OFF	357.9	399.3	35.4	1192	38.7	1618	29.4	11.7	6.8	7.2	16.5	8.1
80 heats with PC Auto ON	367.3	399.4	35.7	1195	36.7	1624	29.9	12.5	6.9	7.4	17.1	3.9

In Figure 13 the expected electrical energy demand W_R is plotted against the actual consumption W_E for both cases of PC-control mode. Their difference is a measure for the energetic performance of the furnace. It is by 8 kWh/t lower for the heats in PC-control Auto ON mode. This amount can be considered as net energy saving due to the automatic PC-control, caused by an energetic efficiency of PC-oxygen which is significantly higher than assumed with 2.8 kWh/Nm^3 in the statistical model.

Additionally it has to be considered that a high PC-oxygen consumption due to a high CO/O_2-ratio corresponds to bad scrap qualities (see figure 14). A large amount of impurities or a scrap quality with bad melting behaviour leads to an insufficient efficiency of the burners and the electrical energy input, resulting in high off-gas temperatures. Therefore much more oxygen is required to compensate these losses. This is demonstrated by figure 15, where the off-gas temperature at a measurement point 35 m downstream in the hot gas duct is correlated to the CO/O_2-ratio.

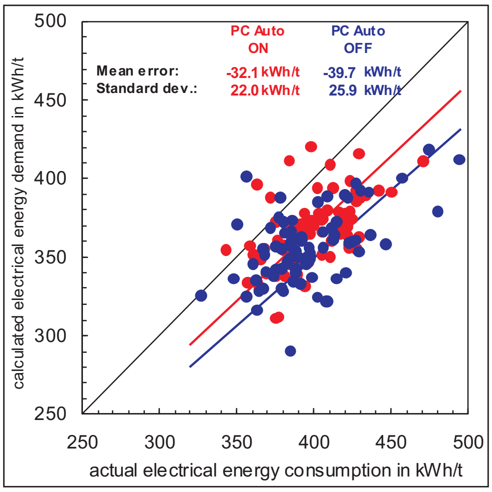


Fig. 13. Calculated vs. actual electrical energy consumption for heats with alternating PC-control mode

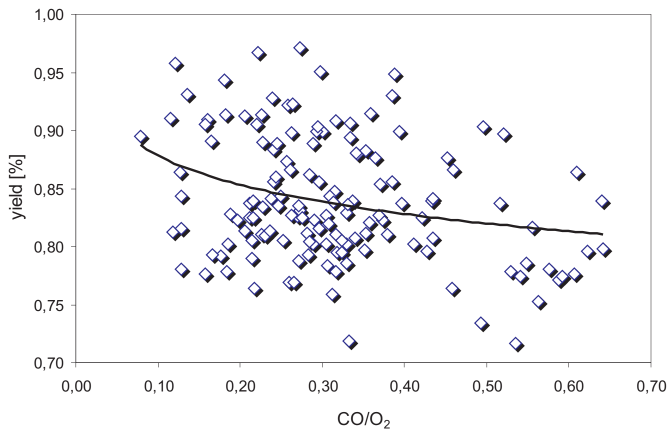


Fig. 14. Metallic yield vs. CO/O_2-ratio

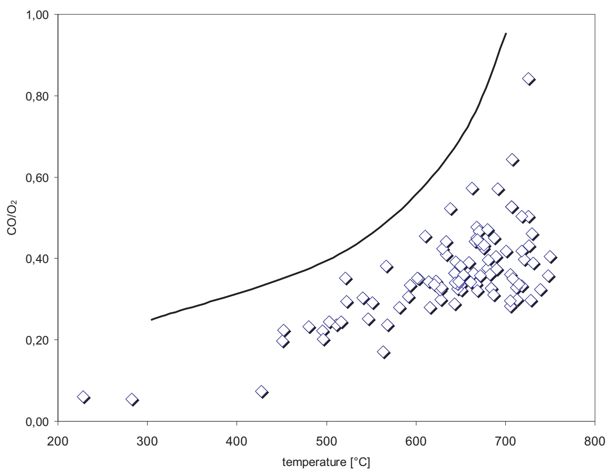


Fig. 15. CO/O_2-ratio vs. off-gas temp.

6. Improvement of the dynamic post-combustion control

The dynamic PC-control described above is only a simple version of a closed loop control. The injectors were set to a fixed flow rate and switched on or off depending on a cer-tain CO/O_2-ratio. This simple control already resulted in an increased PC-oxygen efficiency.

The next step of development aimed at controlling not only the timing but also the flow rate of oxygen input depending on the off-gas composition. Thus it was required to vary the oxygen flow rate of the PC-injectors continuously, adjusting it to the CO and O_2 profile of the off-gas. The oxygen flow rate of each injector is limited between $m_1 = 200$ and $m_2 = 400$ Nm^3/h. The range of the CO/O_2-ratio is between $n_1 = 0.40$ and $n_2 = 0.75$. In that range the flow rate is adjusted linear proportional according to equation (4).

$$Q\left[\frac{Nm^3}{h}\right]_= \frac{m_2 - m_1}{n_2 - n_1} \cdot \left[\frac{CO}{O_2}\right]_{n_1}^{n_2} + \left[m_1 - n_1 \cdot \left(\frac{m_2 - m_1}{n_2 - n_1}\right)\right] \tag{4}$$

If the CO/O_2-ratio exceeds 0.75 the flow rate remains at 400 Nm^3/h. If the ratio is below 0.40 the injectors are switched off. This control regime is shown in figure 16.

For any trials and improvements the boundaries m_1, m_2, n_1 and n_2 can be adapted easily. A large number of heats was performed with the settings described above. In figure 17 the calculated oxygen flow rate according to equation (4) and the actual flow rate of the PC-injector 1 is shown for an example heat with a three bucket charging sequence. The operation mode of KT-burners, oxygen-lance, PC-system, carbon injection and power-on is also figured against the progress of the heat.

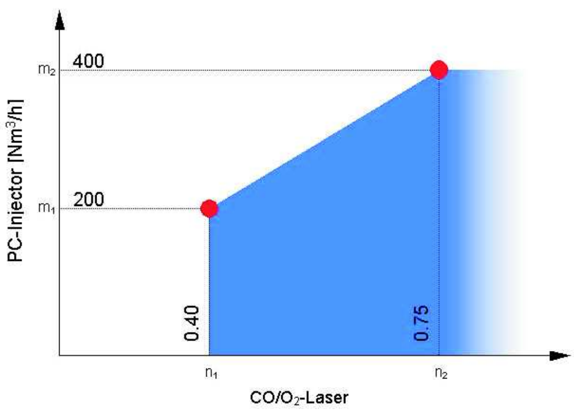


Fig. 16. Linear proportional PC-control strategy

In the beginning the PC-injector flow rate is set to its maximum of 400 Nm^3/h, as described in the previous dynamic PC-control. After a lapse of time the flow rate is determined according to equ. (4). The minimum operating time of the PC-injectors is set to 30 seconds to protect the valves against mechani-cal wear. For example, if the CO/O_2-ratio goes below n_1, the flow rate will retain at the value m_1 for at least 30 seconds.

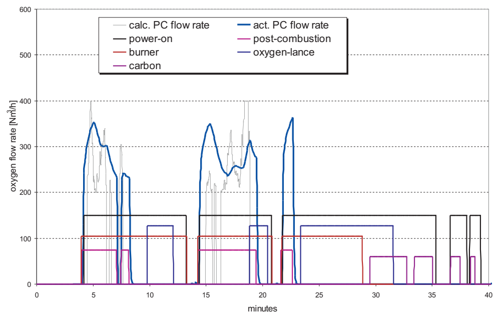


Fig. 17. O_2 flow rate of PC-injector 1 with dynamic control

The deviation between calculated and actual flow rate can be explained by the attenuation factor of the regulation controller. Figure 18 shows the total oxygen and natural gas input for the three bucket sequence heat, the off-gas profile is plotted in figure 19.

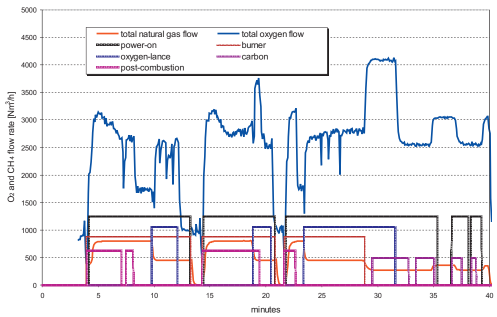


Fig. 18. Total oxygen and natural gas

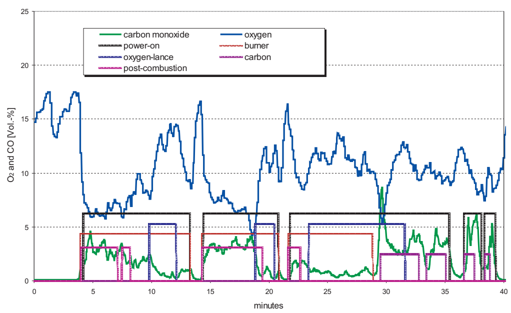


Fig. 19. CO and O_2 profile

7. Conclusions

A dynamic closed loop control strategy of the post-combustion oxygen injectors based on a laser-based off-gas analysis system was developed and tested successfully. High reliability and low response time of the system were proven. Post-combustion oxygen is injected only if required due to high levels of CO in the off-gas. Due to the dynamic control depending on the evolved CO, the PC oxygen efficiency was increased drastically. A reduction of up to 40% PC-oxygen without negative influence on electrical energy consumption was obtained, leading to a net energy saving of about 8 kWh/t liquid steel.

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