Energy efficiency of Electric Arc Furnace

Dr. Andreas Opfermann
Dirk Riedinger
Badische Stahl Engineering GmbH
13 Robert-Koch Strasse
Kehl, 77694, Germany
Phone - +4978518770
Fax - +497851877133

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INTRODUCTION

Usually the meaning of efficiency is to run a process by consuming minimum resources while still generating the optimum output or to utilize more power with the same amount of resources. Examples are recuperator for reheating furnaces or less consumption of fossil energy due to improved technology.

The electric arc furnace process consumes a huge amount of resources such as electrical and chemical energy (oxygen, natural gas, oil, carbon) but also cooling water to melt metal. It is a very energy-intensive process.

The challenge is to optimize the arc furnace process in such a way that for given frame conditions the maximum output can be achieved with minimum consumption of resources.

The maximum output or productivity can be achieved by using the maximum available electrical power and chemical energy input (e.g. oxygen, gas, alloys). The more power is put into the EAF, the faster the metal will be molten. The question is, how much of the energy input is really melting the metal and how much is wasted. To be efficient the waste part of the equation has to be minimized.

The most efficient energy input is reached by decreasing all the losses during operation to a minimum. From the operational view losses can be divided into losses during arcing times and POFF-times of the furnace i.e. the losses during tapping, turnaround and charging (set-up-times).

In this paper the main focus is laid on the PON-time, though POFF-times also depend on different variables which can be optimized by decreasing delay times, decrease charging times i.e. by increasing crane speed or optimization of the turnaround times.

The PON-times are described by different variables like furnace type, transformer power, input material and injection tools and the optimized operation of the whole system. For reaching the optimum performance the electrical but also the chemical energy input must be optimized (see Figure 1)

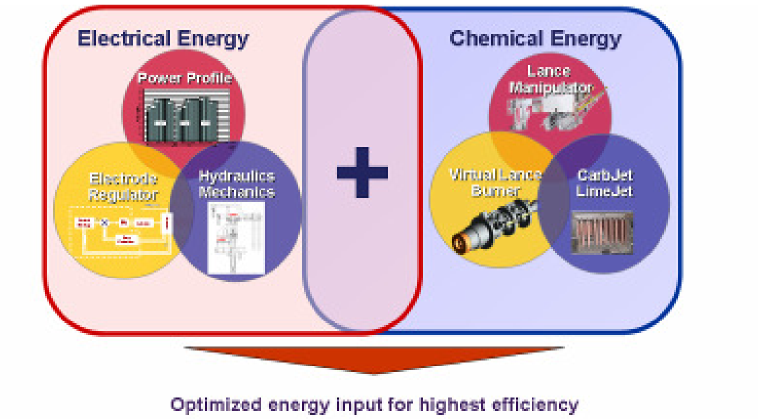


Figure 1: Optimized combination of electrical and chemical energy input gives highest efficiency of EAF during PON

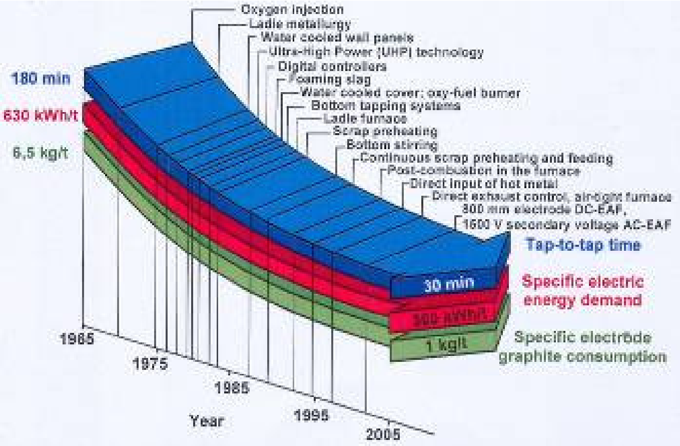


Figure 2: Development of TTT-times, electrical power consumption and electrode consumption /1/

Since the 1960s various changes in operation resulted in a reduction of TTT-Times, electrical power consumption, and electrode consumption as shown in Figure 2.

Today electrical energy consumption can reach a value of 300 kWh/t and TTT-time is reduced to 30 min depending on raw material input (Scrap, DRI, Hot Metal and mixtures), furnace type (AC or DC; scrap preheating), or melting practices. In this wide field of technical changes also the increase of the chemical energy and the foamy slag practice have a major influence on the decrease of PON-Times.

The main focus of this paper is the optimization of the PON-times by efficient input of chemical energy in addition to the electrical energy. For this aim simulations of chemical energy input will be shown and the efficiency for oxygen lancing will be compared to operational results.

BSE is on the one hand supplier for consulting services specialized in Mini Mills, and on the other hand a hardware supplier of highly efficient chemical energy tools up to furnace revamping in the EAF and LF area. The experience of 40 years of steel making at Badische Stahlwerke (BSW) is the driving force for an optimization of all areas in the steel plant and rolling mills.

INFLUENCES ON ENERGY CONSUMPTION AT THE EAF

In **Figure 3** numbers for losses per minute are shown /6/. Largest losses are found during refining of the furnace i.e. in the flat bath phase the losses by radiation are maximized. By own measurements from BSE a temperature loss of approx. 3,3 K/min was found in the furnace during waiting period; with a heating factor of 0,5 kWh/(K*ton) in average also here 1,7 kWh/(t*min) were detected.

	kWh/(t*min)
During melting	0,4
During refining (= Flat bath)	1,7
Between heats < 30min	0,5
Between heats > 30min	0,2

Figure 3: Losses in the EAF in kWh/ (t*min)/6/

POFF-Times:

The main losses during POFF times can be found during delay and set up times of the furnace. In this period the furnace including the hot heel is cooling down (in most cases below 30 min with 0,5 kWh/t*min). Additionally losses are found if the furnace is waiting for tapping. In this case the heat is cooling down and additional energy is needed at the LF for reheating. Between an excellent furnace operation with POFF-times of 11 min (BSW) and a furnace with room for improvement with a POFF-Time of 25 min a loss of 7 kWh/t can be calculated.

The main aim is to shorten the POFF-times by optimization of the whole melting process, which is disturbed by planned and unplanned downtimes and by the necessary setup times. Planned and unplanned downtimes are related to maintenance and equipment, setup times depend on the operational excellence and logistic restrictions.

PON-Times:

Losses are proportional to the melting time but increase with inefficient energy input, either chemical and/or electrical. Optimized energy input guarantees minimized losses due to a short operational time but also the minimized input of different energy sources like electrical energy, oxygen and gas. **Figure 4** /1/ displays all influencing factors.

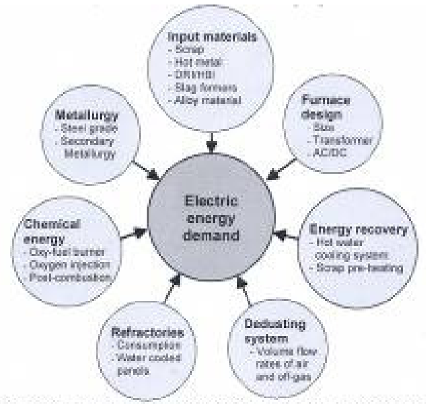


Fig. 2: Influence of various process parameters to the electric energy demand of EAF [4]

Figure 4: Factors influencing the electric energy demand /1/

The primary energy input is electrical and chemical while a secondary energy can be added by scrap preheating in the shaft or on the belt. Also the input from hot metal and hot DRI can be taken as a secondary energy input in the furnace. Losses can be caused by cooling or off gas, but also the non efficient input from electrical energy (e.g. bad foamy slag) or non efficient chemical energy tools can be counted as losses. The biggest influence can be found in the input material which defines mostly the yield, the slag amount (and the amount of fluxes) and the melting behavior (skull build up).

But also the preparation of the scrap like cutting, and layering in the basket, leads to substantial differences in the energy consumption. In Figure 5 the basics of scrap loading are shown.

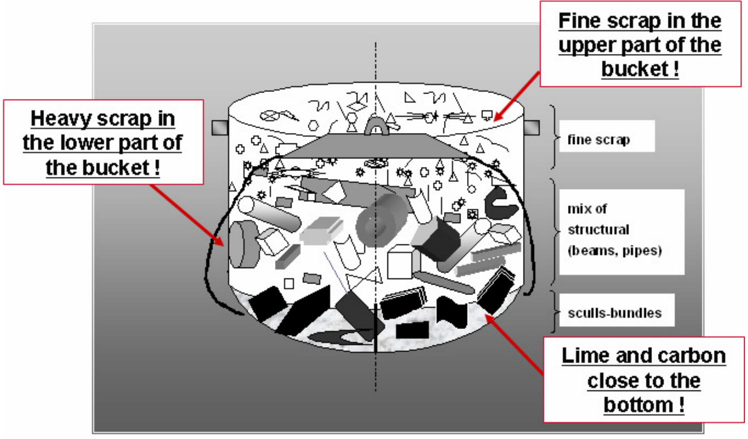


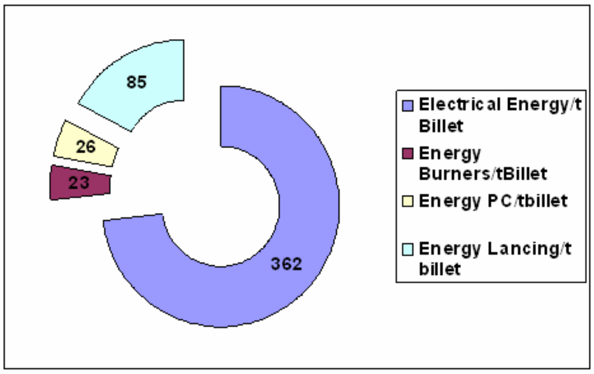
Figure 5: Optimization of the scrap loading practice influences meltdown behavior and power consumption

With the installation of chemical energy tools the aim is the optimization of the energy input from melting to refining but also the minimization of losses. Additionally with a shortage of the process time the losses can be reduced.

In usual installations the raw material as the other big influence remains unchanged and the process has to be optimized for this operation. The worldwide BSE-installations for chemical energy input were performed considering the different raw material inputs from DRI to hot metal. All these big differences make customer specific design necessary to reach the best performance.

Chemical power input:

For low electrical energy consumption with a defined raw material input the efficient input of chemical energy is the leading factor influencing the furnace operation from the homogeneous meltdown down to fast refining with a good foamy slag for a high yield of electrical energy.



Energy from lancing	3,8	kWh/Nm^3
Energy from burner	6,5	kWh/Nm^3
Energy from PC	3,3	kWh/Nm^3

Input at BSW in Nm3/t billet	
3,5	Nm^3/t Gas with 6,5 kWh/Nm^3 (=70% Yield)
7,8	Nm^3/t O2 with 3,3 kWh/Nm^3 O_2 (=50% Yield)
22,2	Nm^3/t metallurgical O_2 with 3,8 kWh/Nm^3 O2 (with 90% yield from LM, 85% yield from VLB)

Figure 6: Energy balance of BSW no. 2 furnace

For scrap based furnaces the meltdown can be accelerated and made more homogeneous for all raw material input with efficient burner operation. In the refining phase of each furnace and irrespective of the input material the oxygen injection has to provide additional energy, bath stirring, and homogenization. In addition with carbon injection points a good foaming is produced allowing an efficient electrical power input.

In Figure 6 the energy balance for the furnace No. 2 of BSW for the year 2007 is shown as an example for the energy reaching the bath. In this case the total energy input of 496 kWh/t_{billet} is reached by 362 kWh/t_{billet} electrical energy and another 134 kWh/t_{billet} in total for chemical reactions. In this case the efficiency of the tools VLB and lance manipulator are taken into consideration i.e. just the energy reaching the bath is counted. In this case a chemical input of 27 % of the total energy input is reached. Also in other balances the amount of chemical reactions in total is in a range of 30 % to 60 % of the total energy input/2,3/. These amounts make the significance of the chemical energy obvious.

The priority of BSE oxygen technology is the effective use of chemical energy in the melting down and the refining stage to reach a highly productive furnace operation. For this aim a large variety of tools are used.

The lance manipulators are used for oxygen and solid injection like carbon and DRI-fines through the slag door. The side wall VLBs are multi functional tools for burner and lancing function running in fully automated mode. These are used either in the side wall or in the EBT area. The solid material injectors in sidewall or EBT platform are used for the injection of lime and carbon close to the slag line.

The tools are designed as components in order to allow a free arrangement in the furnace. This modular way is necessary to fit the different furnace styles and also to solve the specific problems of each customer’s furnace.

Highest efficiency of injection through pipe:

This type of injection either of oxygen or solid particles guarantees the highest yield of material. It is obvious that the injection of oxygen for lancing, carbon and lime for the slag or DRI-fines as additional charge inputs through pipes is the most efficient way to get solid material and gases to the steel bath as there are no losses on the way from the nozzle to the bath. With minimized losses it is possible to inject oxygen and solids into the slag and steel.
In **Figure 7** the lance manipulator is shown in operation during the melting down and refining phase. The challenge is to cut the scrap in lower parts of the furnace and create reactions between hot heel and scrap. In addition the door area can also be cleaned easily by the lances.

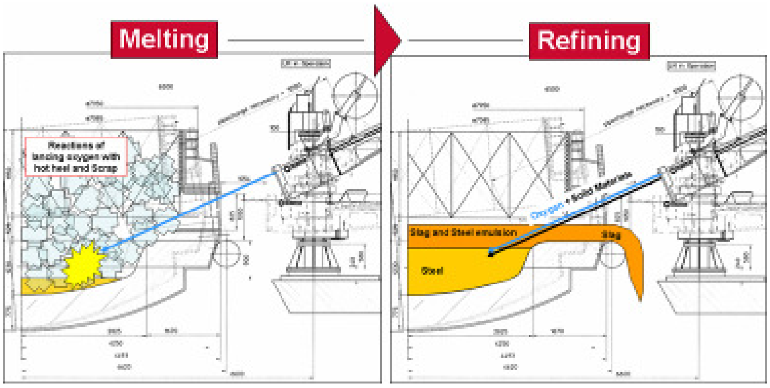


Figure 7: Lance manipulator in melting down and refining

In the refining phase O_2 and carbon are injected between slag and liquid steel. Up to 2x 2000 Nm^3/h oxygen are injected for fast refining and bath stirring. Solid material like carbon or DRI-fines can be injected and with this tool also the injection of carbon <u>in</u> the steel bath is possible to increase the carbon content in a reasonable time and lower the oxygen activity, which is not possible with sidewall installations.

Sidewall tools due to the electrically unbalanced operation in melting

The left drawing in **Figure 8** shows the usual electrical energy distribution in an AC-Furnace. It is obvious that three hot spots are produced in the cross section and large areas are kept cold (grey marked). The electric arc furnace is unbalanced with regard to the electrical power input. The intensity of the hot spots is depending on energy input, transformer power and furnace diameter. In DC-furnaces there is just one hot spot depending on the arc deflection.
But in both cases large areas of the furnace are kept cold especially during melting down. Key aspects of activity for melting down is to reach the flat bath phase quickly where the electrical energy can be brought in the steel with foamy slag and high energetic yield. To avoid a skull build up (which might fall in the liquid steel during refining or which is stable and lowers the volume of the furnace) the melt down has to be optimized by the scrap mixture and layering in the furnace and to be homogenized by chemical energy. As the furnace cannot be designed with three slag doors to have an optimized O_2 + carbon input through lances this problem can be solved by combined burner/injector tools.
The drawing on the right side of **Figure 8** shows the furnace with integrated tools in the side wall and the door. In this case the cold spots are heated up by VLBs in burner mode during melting and with chemical energy during refining. In the special case of BSW an additional VLB is installed in the hot spot on the right side of the door due to the off gas cooling stream.

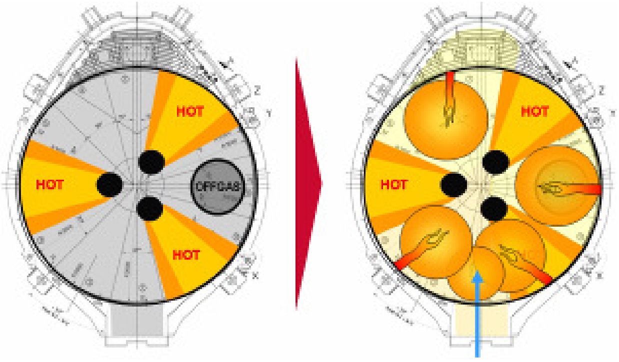


Figure 8: Hot spots in the AC EAF (Example furnace BSW)

Side wall tools for melting

With the input of chemical energy in burner mode the meltdown process is thermally balanced. Usually the burners are mounted in the cold spot areas of the furnace or additionally in special areas e.g. below the lime charging point. The exact location for the tools in each furnace has to be figured out separately.

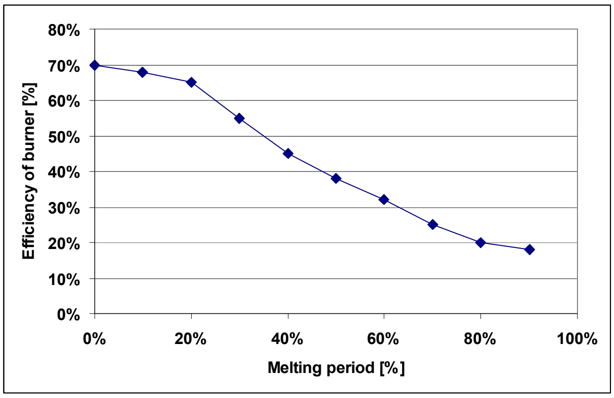
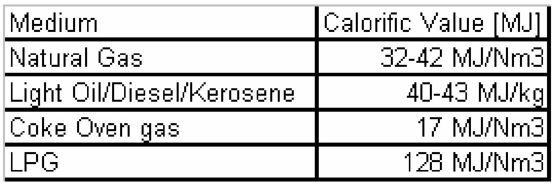


Figure 9: Melting efficiency of conventional burners /4/



Medium	Calorific Value [MJ]
Natural Gas	32-42 MJ/Nm3
Light Oil/Diesel/Kerosene	40-43 MJ/kg
Coke Oven gas	17 MJ/Nm3
LPG	128 MJ/Nm3

Figure 10: Melting efficiency of conventional burners /4/

Electrical energy reduction between 30-50 kWh/t can be reached for the EAF/4/. But what has to be taken into consideration for the input calculation is the loss of effectiveness during the melting phase of scrap by conventional burners as shown in **Figure 9**. In the beginning of the melting phase the burner is fully covered with scrap and most of the heat is used. The longer the melting down period is running the more free the short burner flame is burning and the energy is wasted.

The main aim for the installation of the burner in the EAF must therefore be to keep the efficiency high as long as possible but not leaving cold spots (over the burner for example) where skulls can be built up. The arrangement in the furnace is varying due to specific problems of the operation: A large diameter EAF with a small transformer needs another arrangement than a small furnace with a large power transformer. The aim is therefore to design tailor made solutions for customer wishes and experiences.

Burners can be used with different fuels together with oxygen to reach a high flame temperature. The usable fuels for the chemical energy tools of BSE are shown in **Figure 10** with the calorific values /4/.

Sidewall tools for refining:

In the refining stage the metallurgical reactions in the steel bath with slag provide the highest amount of the chemical energy for the process. For the production of oxygen the energy of 0,5-1 kWh/Nm^3 has to be used so the electrical energy consumption of the furnace can be decreased by higher oxygen injection with gaining up to 5 kWh/Nm^3 O_2 in the furnace in average for all reactions/5/. The main exothermic reactions are shown in **Table 1**. As can be seen, Silicon has the highest energy input with 11,2 kWh/m^3 O_2 and the free energy is coming down to the carbon combustion to CO with 2,73 kWh/m^3 O_2. In the refining stage Si, P, and Al are burned completely due to their high oxygen affinity, Fe, Mn, Cr, and Mo are oxidized with higher oxygen partial pressure. The total energy input by chemical reactions varies from 50 kWh/t to 300 kWh/t depending on the input materials/7/. The total energy per Nm^3/Oxygen varies depending on the input material e.g. hot metal or just scrap. The range of energy given in literature varies between 3,2 kWh/Nm^3 O_2 up to 6,8 kWh/Nm^3 O_2/6/. Especially if a large amount of Si (e.g. from Hot Metal) is available the specific energy per Nm^3 of oxygen is increasing.

Table 1: Chemical exothermic reactions during refining in EAF /7/

Chemical reactions in the steel melt					Reaction enthalpy	
Si	+	O_2	→	SiO_2	- 8.94 kWh/kg$_{Si}$	- 11.20 kWh/m^3 O_2
Mn	+	0.5 O_2	→	MnO	- 1.93 kWh/kg$_{Mn}$	- 9.48 kWh/m^3 O_2
2 Cr	+	1.5 O_2	→	Cr_2O_3	- 3.05 kWh/kg$_{Cr}$	- 9.42 kWh/m^3 O_2
2 Fe	+	1.5 O_2	→	Fe_2O_3	- 2.05 kWh/kg$_{Fe}$	- 6.80 kWh/m^3 O_2
Fe	+	0.5 O_2	→	FeO	- 1.32 kWh/kg$_{Fe}$	- 6.58 kWh/m^3 O_2
C	+	0.5 O_2	→	CO	- 2.55 kWh/kg$_{C}$	- 2.73 kWh/m^3 O_2
2 Al	+	1.5 O_2	→	Al_2O_3	- 5.29 kWh/kg$_{Al}$	- 13.84 kWh/m^3 O_2
Mo	+	O_2	→	MoO_2	- 1.70 kWh/kg$_{Mo}$	- 7.29 kWh/m^3 O_2
S	+	O_2	→	SO_2	- 2.75 kWh/kg$_{S}$	- 3.94 kWh/m^3 O_2
2 P	+	2.5 O_2	→	P_2O_5	- 5.54 kWh/kg$_{P}$	- 8.58 kWh/m^3 O_2
Chemical reactions in the gas phase					Reaction enthalpy	
C	+	O_2	→	CO_2	- 9.10 kWh/kg$_{C}$	- 4.88 kWh/m^3 O_2
CO	+	0.5 O_2	→	CO_2		- 7.01 kWh/m^3 O_2
H_2	+	0.5 O_2	→	H_2O		- 5.99 kWh/m^3 O_2

In the flat bath phase the aim is a fast refining, bath stirring and an increase of the electrical energy input by foaming the slag homogeneously on the steel bath surface. With just one tool through the door the yield of oxygen is very high and local over-oxidization, overheating, and a non-homogeneously mixed bath can result. In case of furnaces with continuous feeding of material (scrap at Consteel, DRI, Hot Metal by launder) it will be difficult to reach the bath surface in the beginning of the flat bath phase due to the low level of steel in the furnace.

The solution is therefore a combination of side wall lances to be operated automatically and a door lance usage for this always cold spot. The door lance is additionally recommended to reach this critical area (sample as early as possible, temperature measurement). Also for the addition of strongly exothermic materials for example Al-Ash for additional energy input the door lance or an injection close to the VLB copper panels (combined VLB + solid material injection panel) from a higher level is recommended.

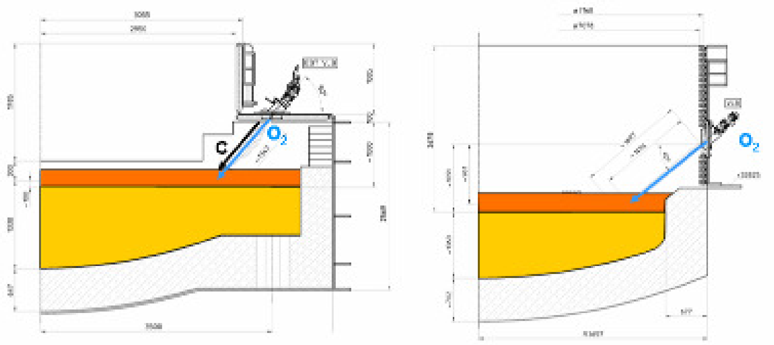


Figure 11: Virtual lance burners in EBT and side wall

For refining the VLBs are used in the side wall as supersonic coherent jets. The philosophy of BSE is to reach the highest yield of oxygen without reduction of the furnace volume or risk of water leakages of copper boxes hit by heavy scrap. Therefore the VLBs are placed in the sidewall in water cooled boxes without extending inside the furnace. It is BSE philosophy to avoid refractory consumption and to reach a long lifetime of the VLB and copper panel. In **Figure 11** the positions are shown as an example on a DRI-melting furnace (150t).

Electrical power input and foamy slag

Around 40-70 % of the total energy input is transferred in the electric arc furnace by electrical power. The aim of the optimized power input is the fast melting and refining i.e. during melting the optimized arc operation should melt down the scrap in a stable operation while in the refining phase a fast heating is reached by high power input in the liquid bath. In both cases the optimum operational parameters of the transformer and the regulation have to be reached.

EAF regulation system

The arc furnace regulation system influences all important parameters of the furnace operation such as active power input, electrical energy consumption, power-on time, electrode consumption, stress of electrical equipment, arc radiation and refractory wear.

The electrode regulation must be an open system with free access to all parameters. It is obligatory that the regulating system must be adjusted in order to achieve the optimal melting process results. Nevertheless experience shows that often it is just the contrary: the regulation is left untouched from commissioning on and the continuous optimization of the complex arc furnace system is neglected. Reasons for that are either missing knowledge (understanding of EAF process and regulating system) or constrained systems (black box regulation, obsolete algorithms).

The two diagrams (**Figure 12** and **Figure 13**) display electrode current frequency distributions indicating a good and a not optimal performance.

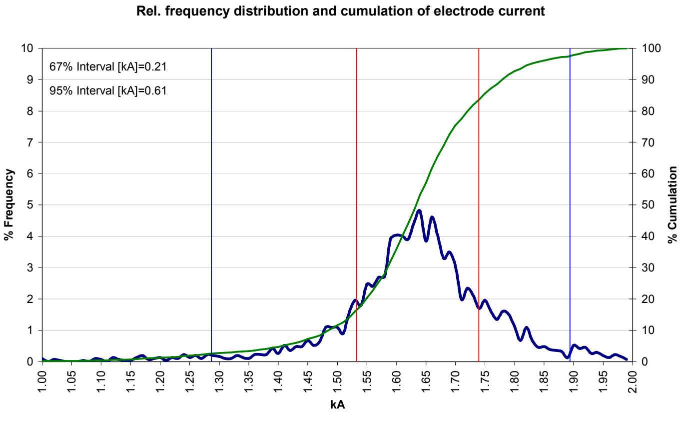


Figure 12: Non-optimized regulating performance with high amount of fluctuations

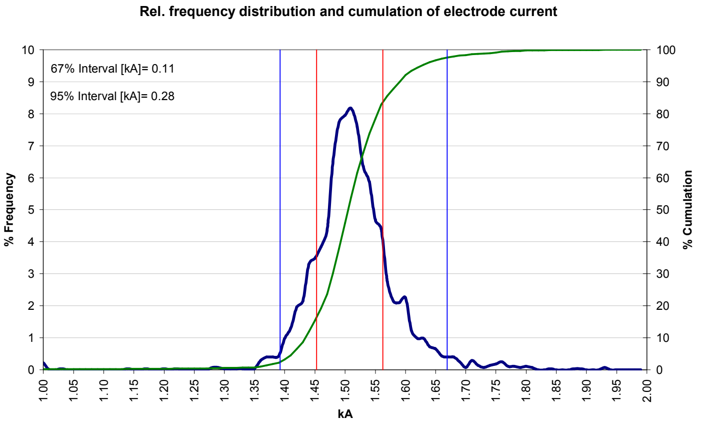


Figure 13: Optimized regulation with lower amount of fluctuations

Foamy slag operation

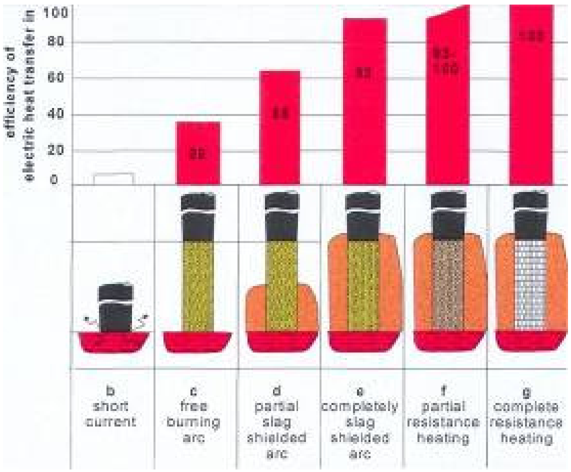


Figure 14: Efficiency of arc as function of the coverage /7/

Besides the high yield of oxygen for the metallurgical reactions slag foaming is the main important process step during refining. The foaming slag practice is presently the only way to transfer high electrical power into the furnace without destroying the refractory in the hot spots. Additionally the yield of the arcs is depending on the coverage of the arcs.

Figure 14 indicates the arc efficiency on flat bath. From a 100% yield of electricity with resistance heating the energy is lost to the atmosphere and bricks through radiation down to 36% if the arc is burning totally free. This can also be found easily in practice by measuring the heating velocity of steel in the refining phase. The foaming behavior is depending on the slag composition and on the injection technology. In **Figure 15** the slag behavior for foaming is shown. From the left figure it can be said that:

1. Acidic slag has the highest foaming index, the so called homogeneous foaming.
2. Slags with a low content of iron oxide below 10% form more stable foam than highly oxidized slags (over 40% FeO = non-foaming slags)
3. At low iron oxide contents slag basicity influences strongly the foaming index. With fixed FeO-content, at higher basicity the foaming index decreases. With a high FeO-content basicity plays no role

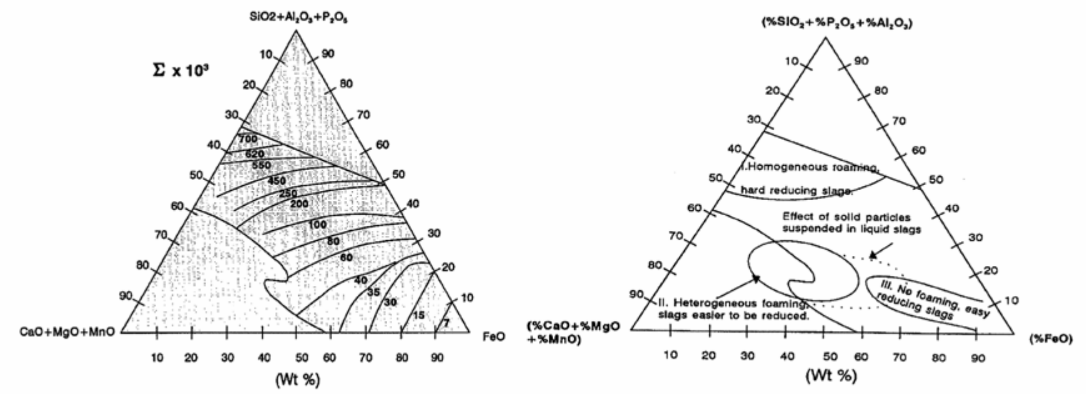


Figure 15: Slag foaming: Isostability curves (left) and chemical composition with foaming behavior (right figure) /8/

On the right side of **Figure 15** the areas for slag foaming are shown. The aim is to reach the zone of heterogeneous foaming and easy reducing slag. Heterogeneous foaming means that solid particles are present due to over saturation and stabilize the foaming formation. With the correct slag composition the injection technology is the second step. Necessary for foaming is the production of CO-bubbles. This can be done by reactions at the slag-metal-interface (reduction of FeO with C from steel), gas-metal-interface (burning of carbon in steel), carbon-slag-interface (reduction of FeO with carbon in slag), slag-gas (reduction of FeO by CO), or carbon-gas (reduction of CO_2 by C in slag) /8/. The burning of carbon from steel is done by oxygen injection through pipe or injectors. The other reactions in the slag are promoted by carbon injection in the slag.

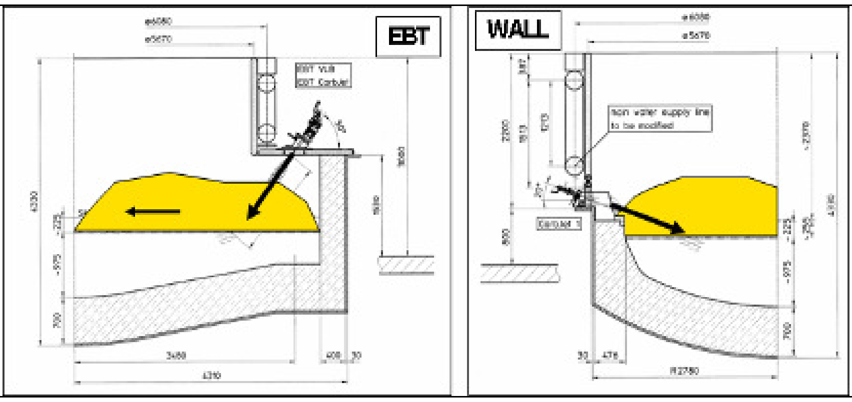


Figure 16: Carbon injection through EBT panel or side wall

With BSE tools the carbon injection is done through CarbJets in the sidewall or in the EBT platform. The aim of these injectors is to avoid losses of carbon in the off gas. With the CarbJet in the sidewall the injector is working in the slag and enriching the slag by carbon. In the EBT the foamy slag cannot leave the furnace directly and the foaming slag is moving towards the center of the furnace to cover the arc.

The lime injection from the sidewall is performed in the same manner as carbon in the hot spots of the electrodes (LimeJets). By this injection the slag composition can be changed e.g. for dephosphorization.

SIMULATION OF BURNER AND INJECTION MODE OF BSE-VLB

Furnace basics are the fundamentals of this simulation to optimize injection either in burner or in lancing (= oxygen injection) mode. The simulation shows the VLB-operation calculated with the CFD (Computational fluid dynamics) technique.

Meltdown of scrap

The demand of the operation is a homogeneous und symmetric melt down of the scrap in the furnace. Due to the electrical cold spots in the furnace during scrap operation the burner usage shall give the needed energy in areas not reached by the arc: Three cold spots can be found in an AC-furnace, in a DC-furnace the arc from the single electrode is concentrated on one hot spot in the furnace. In the optimum way the electrical and chemical energy is melting down the scrap simultaneously for the next charging or refining i.e. the thermal symmetry is reached.

Objectives of the burner usage are the following:
1. Heating up of cold scrap and a large furnace volume
2. Melting down the scrap also in lower parts of the furnace
3. Free oxygen for cutting scrap after it has reached reaction temperature with oxygen

Name	Main Oxygen [Nm3/h]	Secondary Oxygen [Nm3/h]	Gas [Nm3/h]
Burner 1	350	300	300
Burner 2	100	550	300
Burner 3	550	100	300
Burner + Lancing	1000	200	200

Table 2: Flows of oxygen and gas for simulated flame styles in melting

With a short burner flame the area in front of the burner gets heated up but the areas at a larger distance are not heated well. Therefore the flame shapes of the VLB can be changed to avoid the small cavity melting but to follow the scrap from panel to lower regions in the furnace without a cold area behind the VLBs. The flame shapes of the VLB can be changed flexibly for a fast meltdown.

In the following simulation results different flame types are shown:

1. Burner flame with constant energy (3 MW) but with variable flows in main and secondary oxygen
2. Increased main oxygen flow for cutting scrap in lower parts of the furnace

The flows of the flame types are shown in **Table 2**.

In the burner mode the gas and oxygen flows are mostly stoichiometric i.e. the gas is burned with the oxygen after the following equation. In **Burner 2** and **Burner 3** mode the total flow is also kept stoichiometric but the oxygen flow is distributed differently. In **Figure 17** the heat distribution in the furnace is shown from the simulation for the different burner modes.

In the **Burner 1** case the heat from the 3 MW burner with main oxygen = 350 Nm^3/h and secondary oxygen = 300 Nm^3/h are shown. It is visible that the area to be heated up is very large and a large volume of the furnace with scrap can be heated up. This flame is necessary in the beginning of the process if the furnace is full of cold scrap and the total cold spot area needs heating. In this case the heat is also transferred to the panels to avoid cold spots behind the VLBs.

Also in this stage the velocity of the gas streams is kept small to keep the heat in the area where it is needed: Close to the wall and keeping a large volume. As can be seen just a short distance can be found with high velocity, after approx. 55 cm the velocity has fallen below 250 m/s. Due to this low velocity the heat is kept in a small volume around the burner and the scrap is heated up. In a theoretical distance of 1,4 m from the nozzle the velocity is close to zero.

During meltdown cold scrap is located directly in front of the burners. Due to the construction of the copper box the flame starts directly at the wall; no cold spot can be found behind the burners. With a soft flame and mainly undirected and slow oxygen from the secondary and main oxygen the cold scrap can be preheated and this flame can easily penetrate the hollow spaces between the scrap to heat up by radiation.

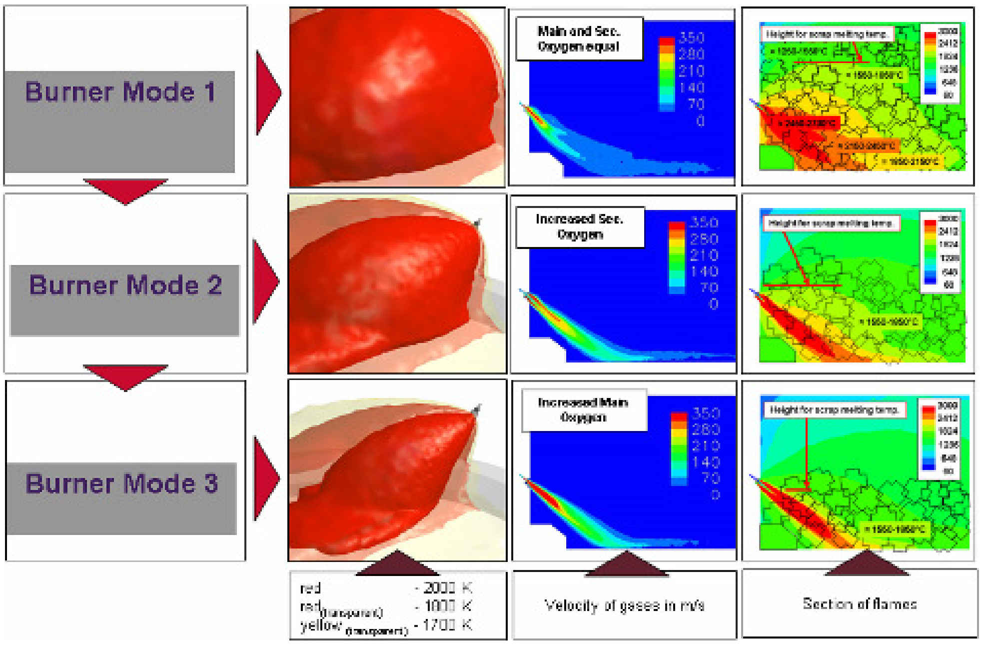


Figure 17: Simulation for different burner modes of the VLB

With ongoing melting time the flame shape is changed automatically: The oxygen from the undirected secondary nozzle is increased while the main oxygen from the Laval nozzle is decreased in stoichiometric order. This means that the flame velocity is increased and the flame gets faster. The aim is to transfer the heat from the VLBs in lower zones of the furnace below the scrap to reach a high efficiency. The temperature for scrap melting is no longer needed in higher areas but has to be shifted lower to avoid temperature losses by off gas.
The effect on the temperature distribution is shown in the **Burner 2** row in **Figure 17**. As can be seen in this result the scrap melting temperature is lowered in the furnace shell i.e. with the higher velocity of the secondary oxygen the heat is more concentrated in the lower areas and can follow the scrap melting. This flame type is used in the medium melting down phase.
In this **Burner 2** operation the velocity is increased with the secondary oxygen to get deeper into the scrap after building the cavity in upper areas. The stream is kept longer on high velocity, the velocity of 250 m/s is reached at a distance of approx. 1,1 m from the burner nozzle.
In the last stage of pure burner usage the flows are changed again for increasing the flow by the main oxygen (**Burner 3 Mode**). Although even with 3 MW the flame gets more concentrated by higher temperatures in lower zones of the furnace. Again the volume of steel melting temperatures gets lowered for keeping the high yield of the chemical energy. The temperature distribution shows a small diameter down to the steel surface with over 2000°C in the middle. The area of melting scrap (> 1550°C) is also in a small volume reaching easily the bath surface.
The velocity of the gases shows approx. 350 m/s from the nozzle which is kept a long distance. In this last period of pure burner flame the heat is transferred from the burner down to the scrap and bath surface.

Between melting and refining

With increasing heat in the furnace and lower melted scrap the temperature for the reaction with oxygen is reached. In this case the oxygen from the main nozzle is increased over the stoichiometric value to have free oxygen for scrap cutting also in lower parts of the furnace. The lancing velocity is not reached in this case but the accelerated oxygen stream combined with the burner power leads to refining. This flame type is called **Burner + Lancing-Flame**. In this example a 2 MW **Burner + Lancing-Flames** is used: The flame power is set to 2 MW but the main oxygen is regulated to 1000 Nm^3/h.
In the slag the following reactions are taken into account:

$$C \quad + \tfrac{1}{2}\, O2 = CO$$
$$CO + 0{,}5\ O_2 = CO_2$$

In the simulation (**Figure 18)** it is found that the heat produced from the burner gets lower and the hot area from 1550-1850°C is reduced back to a small tip. The main aim of this flame is to bring free oxygen in lower parts of the furnace to cut hot scrap and start the refining phase.

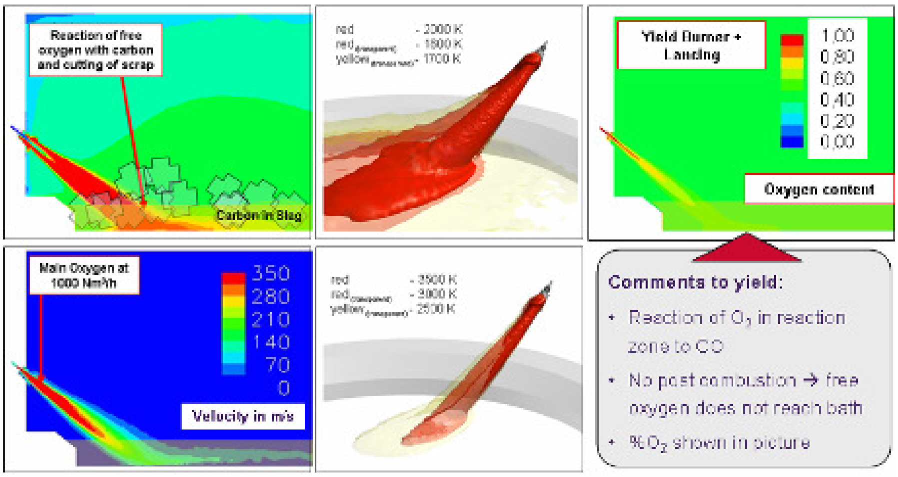


Figure 18: Simulation of the "Burner + lancing" mode

The velocity of the oxygen above 230 m/s (= 0,7 Mach, 25°C) reaches a length of 1,6 m from the panel. In the figure it is visible that a reaction is taking place in the slag area on the steel surface i.e. the free oxygen is reacting with carbon to form CO and CO_2. With remaining hot scrap in the furnace the steel is cut easily and the foaming can be started. This way of operation leads to the refining stage in flat bath. From the temperature distribution it is visible that at the surface the temperature is raising up to 2000 K, in a small spot also 3500 K through the reactions is reached.

The yield of the oxygen is simulated by taking just the reaction to carbon monoxide into consideration to avoid the oxidization of the CO with free O_2 which is not reaching the reaction zone. The atmosphere above the reaction zone gets enriched with oxygen which is not reacting to CO. In this calculation approx. 50% of the total lancing oxygen is not burned with gas.

Refining - Simulation

After finishing the melt down phase the refining mode is started on flat bath. In the simulation an oxygen flow of 1800 Nm^3/h is used for main oxygen. With the VLBs flows between 1300 and 2700 Nm^3/h are possible, in this case a standard flow was used. The aim is a fast decarburization and heating up to tapping temperatures with the input of chemical energy. In the simulation the Lancing-Mode is simulated i.e. the injection of oxygen in a coherent jet with a shrouding flame in the steel bath.

The VLB lancing stream was simulated under furnace conditions. The carbon in the slag reacts with the oxygen which can reach this area and react to CO to detect the yield of oxygen. As can be seen in **Figure 19** on the top right side the atmosphere around the oxygen stream is filled with oxygen which is not reacting i.e. not reaching the carbon in the slag. The total enrichment can be found to be 10-15% of the total oxygen i.e. 85-90% of the oxygen can reach the reaction zone and react with carbon. In this calculation the combustion of gas to CO_2 is neglected for shrouding, i.e. the gas is just reacting to CO with oxygen.

As can be seen a in the upper part in **Figure 19** a strong reaction is taking place from the carbon combustion in the reaction zone and the heat is heating up the bath. The temperature directly at the burner tip is coming from the combustion of gas and oxygen for shrouding. The figure on the right side on top shows a zone of over 3000-3500 K due to the burning of carbon to CO and CO_2.

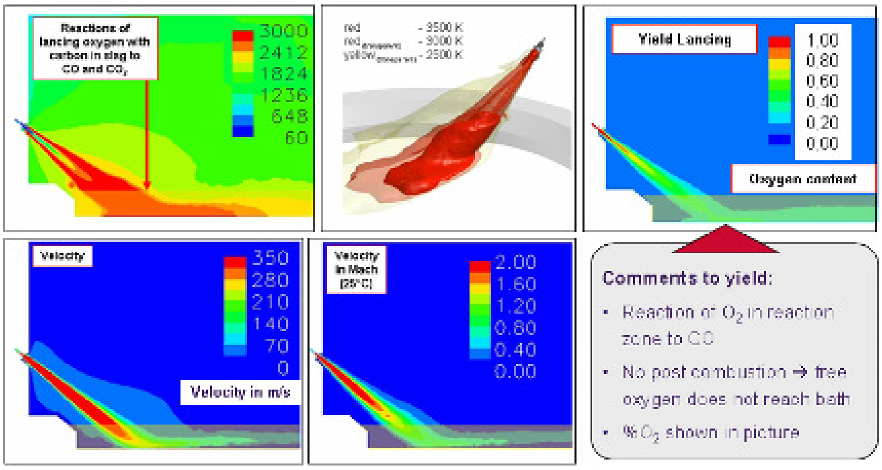


Figure 19: Simulation of the "Lancing" mode

The velocities are shown in the lower part of the figure. As indicated the velocities on the right side are shown in Mach scale, on the left side in m/s-scale. It can be seen that the stream is running with over 350 m/s in the reaction area. At the bottom (steel bath) the velocity is decreased because the steel bath is simulated as a solid surface. Around the stream just a velocity between 0-70 m/s can be found i.e. the stream is very compact. The simulation shows for refining a high percentage of oxygen reaching the reaction zone and creating the chemical energy with carbon. For the determination of the yield in reality experiments have been made.

Refining – Measurement

The yield of the injection can just be measured by the carbon content which is controllable online. The alloy oxidization cannot be measured although approx. just 30% of the oxygen is used for alloy combustion (Fe, Si, Mn) and just 70% for carbon combustion. In these tests the total oxygen input was compared to the carbon oxidization, the only measurable parameter.

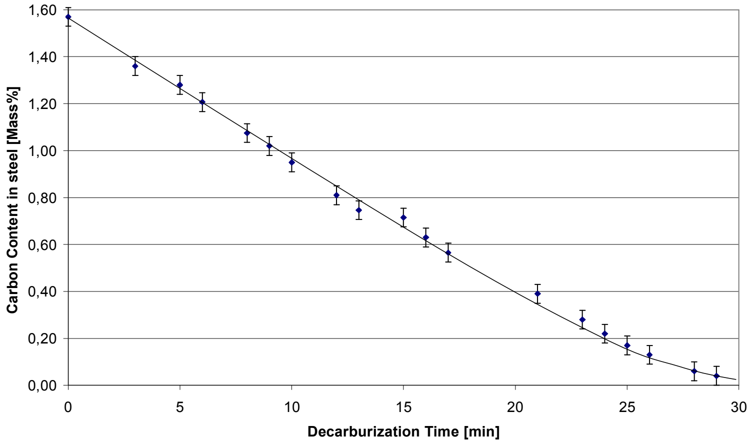


Figure 20: Carbon content of steel bath as function of injection time

In **Figure 20** the carbon content of the heats from both furnaces is shown as a function of the blowing time. In average a decarburization speed of 6,5 points/min was reached down to 0,2% C: As can be seen a constant decarburization speed in the range of 1,6%C down to 0,2%C was detected. The heats were tapped at the scrap-hot metal-furnace with a carbon amount of 0,5-0,6%C for railway steel grades. Below 0,2%C the decarburization speed decreases due to a lower percentage of carbon in the bath and the measurable yield of the VLB is also decreasing. For the decarburization the following amount of oxygen is needed with the assumption that pure CO is produced in the steel bath:

In this case the partial burning of C to CO was assumed to be the main reaction to get the minimum yield of the oxygen. Therefore the yield for the pure carbon burning without Fe, Si and Mn can be calculated to

$$\textbf{Yield}_{\text{O2 lancing, C combustion}} = \textbf{74\%}$$

The highest decarburization speed was found to be 8,11 points/min i.e. a decarburization yield of 92% from the pure lancing oxygen without shrouding oxygen was reached. In the range below 0,2% carbon the yield of oxygen decreases down to 40% and below 0,1% down to 20% due to the low percentage of carbon; more iron is burned.

CUSTOMER INSTALLATIONS AND RESULTS

With the BSE injection technology an optimization of the furnace operation from the chemical point of view is possible due to the high yield of material use and the large flexibility of operation. A total number of 187 Lance Manipulators are working around the world, additionally 19 LM2s (=lance manipulator with temperature-sampling auto-unit) have been installed. The sidewall injection allows the automatic operation including free programming of the operation and totally free adjustment of main oxygen, secondary oxygen and gas.
Since 1999 a total number of 40 VLB systems have been installed worldwide. The highly efficient chemical energy input, the custom build up of every system to fit the customer's needs combined with modern and reliable technique gave operational benefits to steel producers.

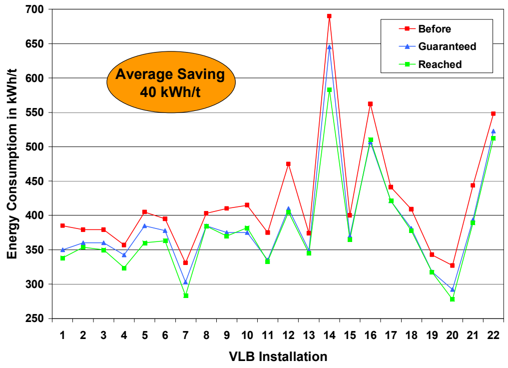


Figure 21: kWh-reduction with VLB installations

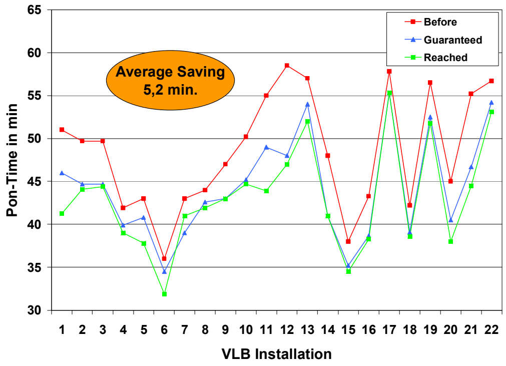
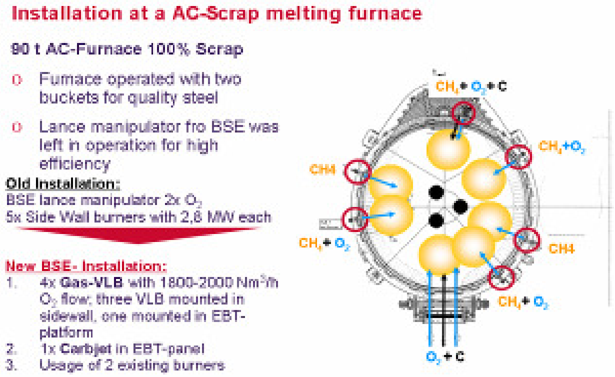


Figure 22: Power-on-time reduction with VLB installations

In **Figure 21** and **Figure 22** the kWh- and PON-time reduction is given for installation after 2004 up to 2006. It can be seen that an average kWh-reduction of 40 kWh/t$_{liq}$ and a PON-time reduction of 5,2 min were reached. In this figure all different raw material inputs are put together, in the next chapter some installations and results are shown where the efficiency of the chemical energy input was increased.

1st example: 90t scrap melting furnace with new chemical energy tools:

This furnace is operated with a scrap preheating system and was equipped with 5 burners and a BSE lance manipulator. For increased energy efficiency 4 VLBs were installed in the sidewall to work in combination with the LM.


Installation at a AC-Scrap melting furnace

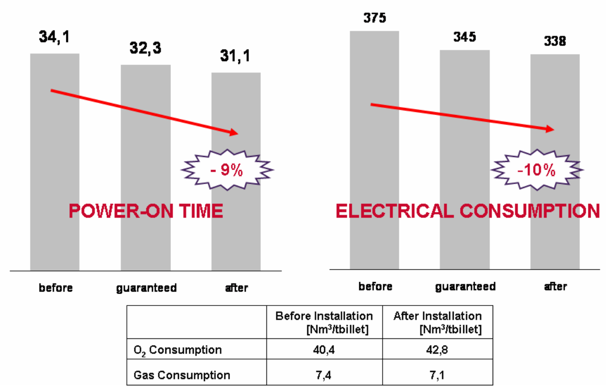
90 t AC-Furnace 100% Scrap

- Furnace operated with two buckets for quality steel
- Lance manipulator fro BSE was left in operation for high efficiency

Old Installation:
BSE lance manipulator 2x O$_2$
5x Side Wall burners with 2,8 MW each

New BSE- Installation:
1. 4x Gas-VLB with 1800-2000 Nm^3/h O$_2$ flow; three VLB mounted in sidewall, one mounted in EBT-platform
2. 1x Carbjet in EBT-panel
3. Usage of 2 existing burners

Figure 23: Installation at 90 t AC furnace



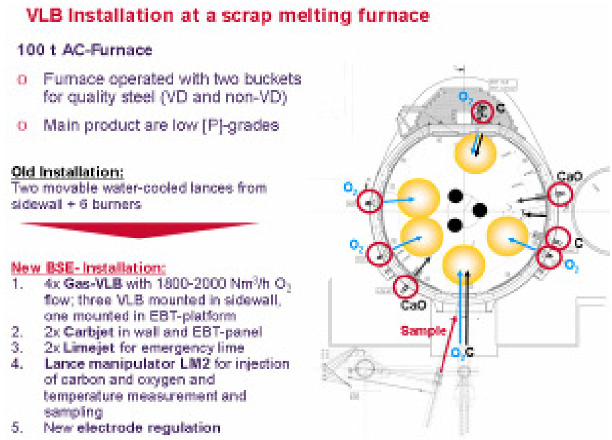
	Before Installation [Nm^3/tbillet]	After Installation [Nm^3/tbillet]
O$_2$ Consumption	40,4	42,8
Gas Consumption	7,4	7,1

Figure 24: Results of the installation

The installation is shown in **Figure 23**, the results of the installation are given in **Figure 24**. As can be seen the PON-time and the electrical power consumption were reduced by 37 kWh/t with an increase of oxygen by 2,4 Nm^3/t and decreased gas consumption of 0,3 Nm^3/t. This result means that the new injection technology works more efficiently i.e. more energy is produced in the furnace.

2nd example: 100t AC Furnace with new chemical energy tools and new regulation

The installation at this furnace included LM.2, VLB and electrode regulation results are shown in **Figure 25** and **Figure 26**. In this case the furnace operation was optimized by changing the scrap layering, changing the transformer tap operation and the chemical energy tools. The combination of all three made a difference of 19% reduced PON-time and 12% reduced power consumption with the same input of oxygen and gas. In this case the scrap layering was changed so that the melting down behavior was improved. With the higher power input the losses during the PON-period were lowered and with the LM in front of the door and sidewall also the foamy slag was improved. Additionally the lime consumption was reduced due to the injection of emergency lime just if Phosphorous was high.


VLB Installation at a scrap melting furnace

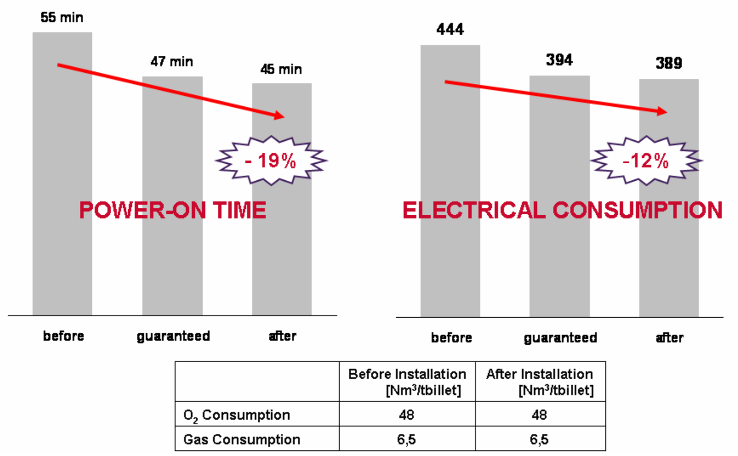
100 t AC-Furnace

- Furnace operated with two buckets for quality steel (VD and non-VD)
- Main product are low [P]-grades

Old Installation:
Two movable water-cooled lances from sidewall + 6 burners

New BSE- Installation:
1. 4x Gas-VLB with 1800-2000 Nm^3/h O$_2$ flow; three VLB mounted in sidewall, one mounted in EBT-platform
2. 2x Carbjet in wall and EBT-panel
3. 2x Limejet for emergency lime
4. Lance manipulator LM2 for injection of carbon and oxygen and temperature measurement and sampling
5. New electrode regulation

Figure 25: Installation at 100 t AC furnace



	Before Installation [Nm^3/tbillet]	After Installation [Nm^3/tbillet]
O$_2$ Consumption	48	48
Gas Consumption	6,5	6,5

Figure 26: Results of the installation

RESULTS FROM ELECTRICAL OPTIMIZATION FOR DECREASED PON-TIMES

The arc furnace process can only be efficient if the electrode regulating system is working effectively. An effective regulating system allows the best electrical energy transfer from the arc to the charge, thus the electrical energy utilization is maximal and the energy wastage is minimal respectively.

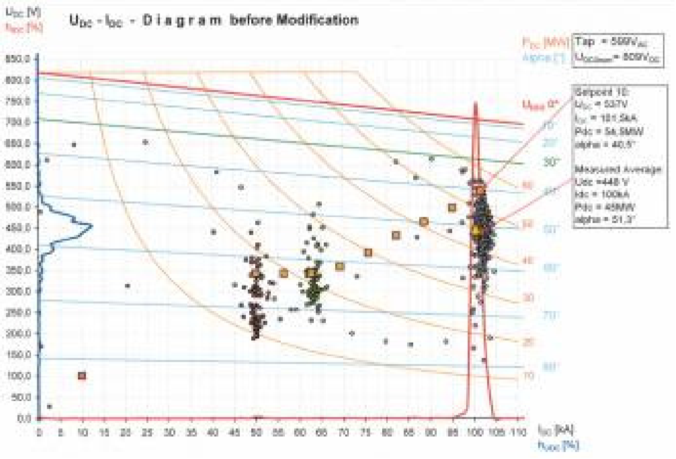


Figure 27: Operation before the optimization

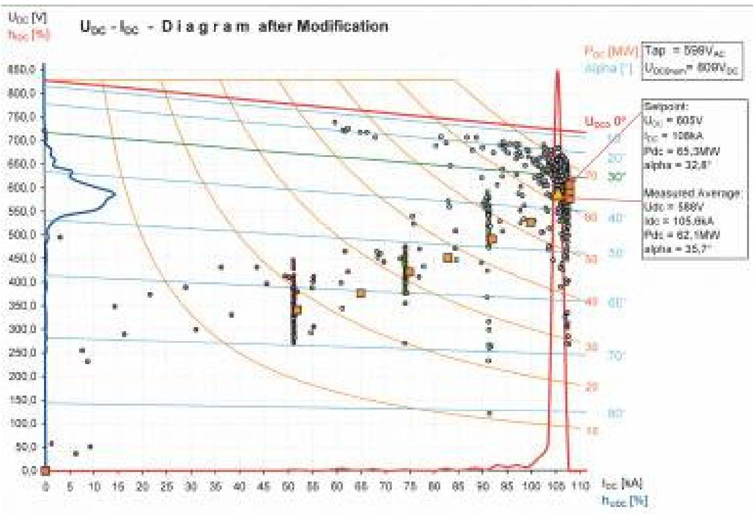


Figure 28: Operation after the optimization

Experience shows that the regulation systems of many DC arc furnaces are not optimally adjusted. The potential for improvements is large. As an example the results of the adjustment and tuning of a DC arc furnace regulating system shall be presented.

DC arc furnaces have two regulation loops, one for the voltage and one for the current. Both influence each other and must interact optimally. AC arc furnaces have one degree of freedom less, there only the current is variable as the voltage is set by the transformer tap. A precondition for regulator tuning is of course the correct function of the electrode mast hydraulic system and the mast movements (roller guides). If the mechanical part is not functioning optimally, then no good results can be expected by regulator tuning.

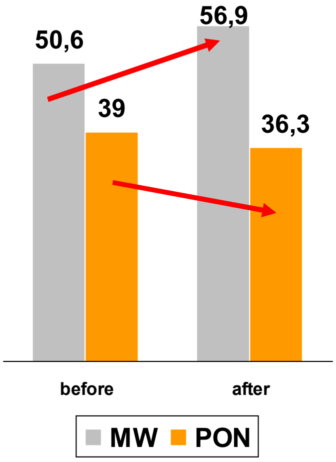


Figure 29: Results of the DC optimization

The regulator optimization concentrates on the following main parameters:

- Gain of the voltage and current PI regulator (Kp values)
- Integration time of the voltage and current PI regulator (Ti values)
- Output signal of voltage regulator for up -and down-speed of electrode
- Certain limits and adaptive parameters

During an optimization campaign the following results could be achieved on a 86 t / 90 MVA EAF by tuning the regulation system and the power program (**Figure 27** to **Figure 29**):

- Less setpoint deviation, less fluctuation
- Use of higher DC voltage setpoints feasible
- Increase in active power: ≈ +6MW (50,6 to 56,9 MW)
- Decrease in power on time: ≈ -3min (39 to 36,3 min)

SUMMARY

Losses of the efficiency taking place in the furnace due to the non optimized electrical and chemical energy input play a major role in the decrease of PON-times and increasing productivity. Different influences can be found on the total energy consumption but the main intention is to increase productivity under the given circumstances.

The homogenization and acceleration of the melt down are the main tasks to be taken by burners with the additional input of energy in cold spots of the furnace. In refining the chemical energy from metallurgical reactions and the foamy slag for increasing the arc efficiency is the challenge. The electrical power input efficiency depends on the performance of the electrode regulation system in connection with the hydraulic and mechanical system of the furnace and on the foamy slag conditions. Experience shows that large potentials for improvements can be found for optimization of the electrical power input and the foamy slag.

BSE supplies the steel industry with highly efficient tools for chemical energy input and with optimization expertise for reaching the goal of operational excellence.

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