Optimization of EAF Operations Through Offgas System Analysis

Jeremy Jones[1]
Paykan Safe[2]
Brian Wiggins[2]

[1]Nupro Corporation, Grand Island N.Y.
716-773-8726
716-773-8735 Fax

[2]Gas Cleaning Technologies, Irving, Texas
972-717-5175
972-717-4310 Fax

Key Words: EAF, Energy, Environment, Offgas Systems, Optimization, Steelmaking

INTRODUCTION

When reviewing EAF operations, one finds that energy consumption can vary greatly between one operation to another. The design of electric arc furnaces has changed considerably in the past decade. Emphasis has been placed on making furnaces larger, increasing power input rates to the furnace and increasing the speed of furnace movements in order to minimize power off time in furnace operations. Many modern flat products minimills are now striving to achieve tap-to-tap times of 45 minutes or less. With advances in technology it is now possible to make heats in less than one hour with electrical energy consumption in the range of 350 - 400 kWh/ton in conventional furnaces. Some hybrid furnace designs achieve even lower energy consumption in the range of 200 to 250 kWh/ton. The electric furnace has evolved into a fast and low cost melter of scrap where the major criterion is higher productivity in order to reduce fixed costs. Innovations that have helped to achieve the higher production rates include:

- Oxy-fuel burners
- Oxygen lancing / carbon/lime injection /foamy slag practice
- Post-combustion in the EAF freeboard
- Improvements to furnace electrical supply
- Innovative process technologies (scrap preheat, continuous charging etc.) to name just a few.

At the same time, increased power input to the EAF has resulted in large, costly offgas system requirements. Gas collection and cleaning equipment can account for up to 25 % of the capital cost for a new meltshop facility. This is a growing concern as this equipment does not contribute to meltshop productivity and hence profitability. Offgas systems are designed for peak operating conditions that may exist only 10 to 20 % of the operating cycle. Optimization of operating cycles with a view to reducing the magnitude of peak conditions within the system could result in lower cost facilities that are better utilized.

In recent years, much more attention has been paid to the function and operation of the EAF offgas system. It has been realised that the offgas system is really just an extension of the operations in the EAF. Through analysis of the offgas system requirements and operation, it is possible to “tune” the operations in the EAF. At the most fundamental level of analysis, it is possible to develop heat and mass balances for various portions of the EAF tap-to-tap cycle. As opposed to the typical analysis that looks at the total mass and energy balance over a whole heat, the analysis of various segments of the operating cycle helps to identify energy efficiency at various stages of the operation. This will allow the operator to truly optimize EAF operations.

The following paper looks at both overall and piece-wise heat and mass balances for various EAF operations. This analysis will demonstrate that opportunities exist for lowering EAF energy requirements by reducing energy input during certain portions of the cycle when energy transfer to the steel is inefficient. This will help to reduce operating costs as well as improving the overall operation of the EAF and the offgas system. Improved understanding of EAF operations will in turn result in less expensive, better-utilized, offgas systems.

ENERGY INPUTS TO THE EAF

Many forms of energy input are now used in the EAF. In the past the bulk of the energy input to the EAF was electric. Oxygen was used only for refining the steel and supplied less than 20 % of the total energy requirement. The use of auxiliary energy in the EAF is one of the biggest issues for EAF operations today. The correct sizing of primary and secondary energy inputs to the EAF is necessary to provide operating flexibility and to allow for variation in furnace feedstocks. This paper attempts to review energy requirements in modern EAF steelmaking and shows the various options available to steelmakers to ensure low cost production of quality steel.

Electrical Energy

The International Iron and Steel Institute (IISI), classifies EAFs based on the power supplied per ton of furnace capacity. For most modern operations, the design would allow for at least 500 kVA per ton of capacity. The IISI report on electric furnaces " The Electric Furnace - 1990" indicates that most new installations allow for 900 - 1000 kVA per ton of furnace capacity. Most furnaces operate at a maximum power factor of about 0.85. Thus the above transformer ratings would correspond to a maximum power input of about 0.75 to 0.85 MW per ton of furnace capacity.

EAF operations are also using much larger power supplies in an attempt to maximize total power input to the furnace. Most modern operations are sized to have in excess of 0.9 MVA/ton/hour of melting capacity. Transformer sizes in excess of 120 MVA are now common. In the case of DC furnaces, electrode size limitations are being overcome by using multiple electrodes. At Preussage Stahl AG, the strategy is to have a power rating of 0.90 MW per metric tonne of furnace capacity which will allow for melting of a 100 tonne heat in 50 minutes. At the same time, advances in AC technology (notably the use of high impedance transformers, series reactors or saturateable reactors) have allowed AC furnaces to achieve gains similar to those experienced with DC operations.

Oxygen Use In The EAF

Much of the productivity gain achieved over the past 10 - 15 years was related to oxygen use in the furnace. Exothermic reactions were used to replace a substantial portion of the energy input in the EAF. Whereas oxygen utilization of 300 scf/ton was considered the norm just 10 years ago, some operations now use as much as 1300 scf/ton for lancing operations. With post-combustion, total oxygen rates as high as 2500 scf/ton have been implemented in the EAF. It is now common for between 30 and 40 % of the total energy input to the EAF, to come from oxy-fuel burners and oxygen lancing. Oxygen utilisation has grown with the use of alternate iron sources in the EAF, many of which contain elevated carbon contents (1 to 3 %). In some cases, electrical energy now accounts for less than 50 % of the total power input for steelmaking.

Over the past 10 years, a large percentage of North American operations have looked to the use of increased oxygen levels in their furnaces in order to increase productivity and decrease electrical energy consumption. High levels of oxygen input are standard on most new EAF installations. Increased use is being made of bottom and side-wall injectors. These allow for better distribution of both oxygen and carbon within the EAF leading to better control of slag foaming and higher energy efficiency.

Oxy-Fuel Burner Application In The EAF

Oxy-fuel burners are now almost standard equipment on electric arc furnaces in many parts of the world. The first use of burners was for melting the scrap at the slag door where arc heating was fairly inefficient. As furnace power was increased, burners were installed to help melt at the cold spots common to UHP operation. This resulted in more uniform melting and decreased the melting time necessary to reach a flat bath. It was quickly realized that productivity increases could be achieved by installing more burner power. Typical productivity increases reported in the literature have been in the range of 5 - 20 %. In recent years oxy-fuel burners have been of greater interest due to the increase in the cost of electrodes and electricity. Thus natural gas potentially provides a cheaper source of energy for melting. The primary function of burners in a high powered EAF is to ensure even scrap melting thus decreasing the potential of scrap cave-ins and broken electrodes.

Steelmaking Energy Requirements

To melt steel scrap, it takes a theoretical minimum of 300 kWh/ton. To provide superheat above the melting point of 2768 F requires additional energy and for typical tap temperature requirements, the total theoretical energy required usually lies in the range of 350 to 370 kWh/ton. However, EAF steelmaking is only 55 to 65 % efficient and as a result the total equivalent energy input is usually in the range of 560 to 680 kWh/ton for most modern operations. This energy can be supplied from a number of sources including electricity, oxy-fuel burners and chemical bath reactions as shown in the following section. The distribution selection will be highly dependent on local material and consumable costs and tends to be unique to the specific meltshop operation.

Several factors are immediately apparent from these balances:

1. Much more chemical energy is being used in the EAF and corresponding to this, electrical power consumption has been reduced.
2. Furnace efficiency has improved with UHP operation as indicated by the greater percentage of energy input retained in the steel.
3. Losses to cooling water are higher in UHP operation due to the greater use of water-cooled panels.
4. Miscellaneous losses such as electrical inefficiencies were much greater for older low powered operations.
5. Energy loss to the furnace offgas is much greater in UHP furnace operation due to greater rates of power input and shorter tap-to-tap times.

Of course the above figures are highly dependent on the individual operation and can vary considerably from one facility to another. Factors such as raw material composition, power input rates and operating practices (e.g. post-combustion, scrap preheating) can greatly alter the above balance. In operations utilizing a large amount of charge carbon or high carbon feed materials, up to 60 % of the energy contained in the offgas may be calorific due to large quantities of un-combusted carbon monoxide and Hydrogen. Recovery of all of this energy in the EAF could decrease energy input by 8 to 10 %, though in reality, most attempts at recovering this energy have resulted in energy savings of 2 – 3 %. Thus it is important to consider such factors when evaluating the energy balance for a given furnace operation.

REVIEW OF EAF HEAT BALANCES

Many EAF operations have recently developed heat balances for their furnaces. These balances are based on the total energy inputs and outputs to the furnace over the whole tap-to-tap cycle. Several such balances are shown in Figures 1 a to d.

Analysis of such balances indicates that there are wide variations in energy requirements and in the efficiency of energy transfer in the EAF. The form of energy inputs vary widely and these will tend to have an effect on energy losses from the process. Electrical energy input varies from 340 – 500 kWh per ton for the cases considered for this paper. The combustion of organic compounds associated with the scrap typically accounts for 40 – 80 kWh/ton. Electrode consumption accounts for 15 – 25 kWh per ton of the total energy input. The largest variations are for energy input related to oxygen injection and the amount of burner power input used. Oxygen/carbon reactions typically account for 100 – 250 kWh per ton of energy input. Burners account for an energy input of 25 – 80 kWh per ton. In the case of these latter two types of energy input, large gas volumes are generated and these will tend to remove energy from the EAF in the offgas stream. In the case of oxygen carbon reactions, CO is generated which if not burned in the EAF will contribute to much higher total offgas heat-load.

For the most part, the energy retained in the steel is approximately 350 – 380 kWh per ton, dependent on tap temperature. Energy retained in the slag varies from 30 – 50 kWh per ton and is dependent both on steel tap temperature and the amount of slag generated per ton of steel. Thus these energy requirements are pretty much set by steelmaking requirements.

The other energy outputs include losses to water cooled components at 60 – 100 kWh per ton, miscellaneous and electrical losses at 20 – 80 kWh per ton and losses to the offgas at 140 – 180 kWh per ton. All of these losses are related to the manner in which the furnace is operated and the efficiency of energy transfer to the steel in the furnace.

Electrical and miscellaneous losses are related to equipment properties and the number of furnace back-charges respectively. Thus miscellaneous losses can be reduced by using denser scrap or by reviewing charge bucket practices to reduce the number of back-charges.

Losses to the water cooled furnace components are a function of the rate of energy input and the efficiency of this energy transfer to the steel. Thus for a furnace with high power input rates, every effort must be made to ensure that high energy transfer efficiencies are achieved.

Losses to the furnace offgases are a major concern for two reasons. Firstly, these represent lost energy from the process, which could otherwise be put to use in scrap melting operations. Secondly, High offgas heatloads require more costly offgas system components to cool these gases before they are cleaned in the baghouse. Losses to the offgas system arise from two sources – calorific heat and sensible heat. Sensible heat is the heat contained in the gases leaving the EAF based on gas temperatures. Thus if hot gases are unable to transfer heat to the scrap and the steel, the sensible heat load in the gases leaving the EAF will increase. Calorific heat is potential energy based on the ability of the furnace offgases to oxidize further resulting in a release of energy. Typically the gases which have high calorific heat content include hydrogen and carbon monoxide. However, vaporized or partially combusted organic compounds sometimes leave the furnace in the offgas and these too can contain a significant amount of calorific energy.

It becomes apparent that the key to minimizing offgas heat-load is to ensure that high energy transfer efficiencies are achieved for any forms of energy input which result in additional offgas generation in the furnace. One attempt at ensuring better energy transfer efficiency has been to use offgas to heat scrap either external to the EAF or as part of an integrated furnace scrap pre-heat operation. This is not always a feasible solution for existing furnace operations and as a result a better method for monitoring energy efficiency in the EAF is required. If better heat transfer efficiency can be achieved in the EAF, less heat will be lost to the offgas. As a result, offgas system requirements will be reduced. Typical requirements are discussed in the following section.

TYPICAL DESIGN PARAMETERS FOR EAF OFFGAS SYSTEMS

A typical single furnace melt shop fume control system consists of a primary off-gas evacuation system and a secondary fume collection system. The primary off-gas system handles the fumes generated in the furnace during the melting practice, and the secondary fume collection system captures the charging, tapping and fugitive emissions from the furnace.

Primary Off-Gas Handling System

A typical 120-150 ton furnace production rate can be between 150 to 170 TPH. The primary off-gas design parameters can be as follows:

- Off-gas volume 30,000 – 40,000 scfm
- Off-gas temperature 3000 - 3500 F
- Carbon monoxide level 10 - 30 %
- Hydrogen level 5 - 15 %
- Total heat content 3 – 5 Mbtu/min
- Chemical heat fraction 50%

The primary gas cleaning system will need to condition and clean the gas effectively during all phases of the melting practice. A typical gas handling system consists of the following gas cooling components:

- Water-cooled duct to cool the process gas to about 1200 F,
- Addition gas cooling is provided either by evaporative coolers or various type of heat exchangers to cool the gas to about 600 F,
- Dilution air-cooling provided through the canopy hood system to cool the gas to the baghouse operating temperature of about 250 -275 F.

Secondary Fume Control System

The secondary gas collection system consists of a canopy hood above the furnace to handle the charging plume as well as the furnace fugitive emissions during the melting practice. The furnace primary gas collection system is not meant to over-draft the furnace to avoid occasional puffing from the furnace openings. Over-drafting the furnace would result in high electrode consumption and excessive heat loss from the furnace through the off-gas volume. Therefore, the canopy hood is meant to capture the fugitive emissions from the furnace during the upset conditions. The melt shop layout should consider the impact of cross-draft on the plume rising velocities to effectively capture the furnace fugitive emissions.

The charging exhaust rate requirements for a 120 –150 ton furnace is about a 1,000,000 CFM depending on the melt shop lay out and the canopy hood configuration. Typically, the charging exhaust rate sets the capacity of the EAF fume control system.

For a typical operation that produces 1.2 to 1.4 million TPY, the fume control system capacity is around 1.3 million CFM. Typical design parameters that are used to quickly size an EAF operation fume control system is 1 CFM : 1 TPY (overall system) or 300,000 acf/ton for the primary gas handling system.

ENERGY EFFICIENCY IN THE EAF

The EAF energy balance alone, does not however, tell the whole story. While it is important how much total energy goes into the EAF, it is just as important that whatever energy is provided is also used efficiently. As the efficiency of energy transfer varies widely in various furnace operations, it is important to review these efficiencies in the context of overall process efficiency.

Electrical Efficiency - Foamy Slag Practice

At the start of meltdown, a fairly short arc is used so that the arc does not radiate back onto the furnace roof causing damage. Electrical efficiency during scrap meltdown is fairly high (typically 88-92 %) because the scrap shields the arc. As the scrap melts into the bath, the arc tends to radiate more and more energy to the furnace shell and roof. As a result, many operations in the past, reduced the power factor at flat bath to give a shorter arc which would not radiate as much energy to the furnace shell.

Over the past decade, many operations have adopted "foamy slag practice". Foamy slag was initially associated with DRI melting operations where FeO and carbon from the DRI would react in the bath to produce CO which would "foam'" the slag. At the start of meltdown the radiation from the arc to the sidewalls is negligible because the electrodes are surrounded by the scrap. As melting proceeds the efficiency of heat transfer to the scrap and bath drops off and more heat is radiated from the arc to the sidewalls. By covering the arc in a layer of slag, the arc is shielded and more energy is transferred to the bath. Oxygen is injected with coal to foam up the slag by producing CO gas in the slag. In some cases only carbon is injected and the carbon reacts with FeO in the slag to produce CO gas. When foamed, the slag cover increases from 4 inches thick to 12 inches. In some cases the slag is foamed to such an extent that it comes out of the electrode ports. Claims for the increase in energy transfer efficiency, range from an efficiency of 60 - 90 % with slag foaming compared to 40 % without. It has been reported that at least 0.3% carbon should be removed from the bath using oxygen in order to achieve a good foamy slag practice.

Lime is the most common flux used in modern EAF operations. Most EAFs use basic refractories and the steelmaker must maintain a basic slag in the furnace in order to minimize refractory consumption. Slag basicity has also been shown to have a major affect on slag foaming capabilities. Thus lime tends to be added both in the charge and also via injection directly into the furnace. Lime addition practices can vary greatly due to variances in scrap composition. As elements in the bath are oxidized (e.g. P, Al, Si, Mn) they contribute acidic components to the slag. Thus basic slag components must be added to offset these acidic contributions. If silica levels in the slag are allowed to get too high, significant refractory erosion will result. In addition, FeO levels in the slag will increase because FeO has greater solubility in higher silica slags. This can lead to higher yield losses in the EAF. High FeO levels can also make it difficult to achieve good slag foaming.

Traditionally, carbon was injected via a secondary lance through the slag door or via a combined lance for carbon and oxygen. This provided carbon close to the point where the bulk of the FeO was being generated but additional FeO that was generated from other sources (burners, FeO occurring in the scrap etc.), would only be reduced when carbon circulated in the bath. In some AC operations, it is difficult to generate sufficient slag foaming to bury all three electrodes with carbon injection at a single point. Many EAF operations are now injecting carbon at several points within the furnace. In some cases, oxygen is injected at several points as well.

The effectiveness of slag foaming is dependent on several process parameters including slag basicity, FeO content slag temperature and availability of carbon to react with oxygen and FeO. Typical carbon injection rates for slag foaming are 5 - 10 pounds per ton liquid steel for low to medium powered furnaces. Higher powered furnaces and DC furnaces will tend to use 10 - 20 pounds of carbon per ton liquid steel. This is due to the fact that the arc length is much greater for these furnaces than for low powered AC operations and therefore greater slag cover is required to bury the arc. If a deep foamy slag is achieved it is possible to increase the arc voltage considerably. This allows a greater rate of power input. Slag foaming is usually carried out once a flat bath is achieved. However, with hot heel operations it is possible to start slag foaming much sooner.

As slag foams, it typically flows out of the furnace through the slag door. If slag foaming is started too early, there may be insufficient slag cover at the end of refining to bury the arc. Some operations inject additional flux into the furnace during refining to ensure that this does not occur. In addition, slag can become so hot towards the end of refining that it becomes too fluid and can no longer sustain foaming. High FeO content in the slag at the end of refining can also be a problem when tapping at very low carbon content. Sometimes un-calcined dolomitic stone or limestone is added in order to chill the slag and adjust the slag chemistry. An added benefit is that the stone calcines and produces CO_2 that also aids slag foaming.

Figures 2 and 3 demonstrate the benefits of achieving good slag foaming both in terms of stability of power supply and for minimization of heat losses to the furnace shell. Signs that good slag foaming is being achieved include, reduced maintenance on furnace panels, reduced delta wear, reduced electrode consumption, lower nitrogen levels in the steel at tap and reduced power consumption.

Oxy-Fuel Burner Efficiency In The EAF

Oxy-fuel burners are now almost standard equipment on electric arc furnaces in many parts of the world. The first use of burners was for melting the scrap at the slag door where arc heating was fairly inefficient. As furnace power was increased, burners were installed to help melt at the cold spots common to UHP operation. This resulted in more uniform melting and decreased the melting time necessary to reach a flat bath. It was quickly realized that productivity increases could be achieved by installing more burner power on under powered furnaces. On most modern UHP furnaces, the primary function of oxy-fuel burners is to provide heat to cold spots to ensure even scrap melting and thus reduce the possibility of scrap cave-ins.

Typically burners are employed in one of three modes. Most modern furnaces use a slag door burner and sidewall burners. Some operations have roof burners. In the past, slag door burners were generally used for small to medium sized furnaces where a single burner could reach all of the cold spots. Door burners had the advantage that they could be removed when not in use. On large UHP furnaces, a burner lance is used to clear the slag door area of scrap so that scrap cutting operations can commence early in the heat. It is important that the scrap be heated sufficiently so that it can be cut using the supersonic oxygen lance. Large furnaces typically use between 3 and 6 sidewall mounted burners for cold spot penetration. For EBT furnaces, the sump area at the front of the furnace can be a considerable cold spot. If un-melted scrap builds up in this area, it can interfere with tapping operations. Many operations are now installing burner injectors in the sump area to eliminate this cold spot.

Oxy-fuel burners aid in scrap melting by transferring heat to the scrap. This heat transfer takes place via three modes:

Forced convection from the combustion products to the scrap
Radiation from the combustion products to the scrap

Conduction from carbon or metal oxidation and from scrap to other scrap

Primarily heat transfer is via the first two modes except when the burners are run with excess oxygen. Heat transfer by convection and radiation is highly dependent on the temperature difference between the scrap and the flame and on the surface area of the scrap exposed for heat transfer. As a result oxy-fuel burners are most efficient at the start of a melt-in period when the scrap is cold. As melting proceeds the efficiency will drop off as the scrap surface in contact with the flame decreases and due to the fact that the scrap temperature also increases. It is generally recommended that burners be discontinued after 50 % of the meltdown period is completed so that reasonable efficiencies are achieved. An added complication is that once the scrap heats up it is possible for iron to react with the water formed by combustion to produce iron oxide and hydrogen. This results in yield loss and the hydrogen must be combusted downstream in the offgas system. Usually the point at which burner use should be discontinued is marked by a rise in offgas temperature (indicating that more heat is being retained in the offgas). In some operations the temperature of the furnace side panels adjacent to the burner is used to track burner efficiency. Once the efficiency drops below a set-point the burners are shut off. Many burners are now mounted in copper blocks in order that they can be fired at higher rates without causing damage to the furnace shell. Copper has a much higher heat transfer coefficient than steel and thus the water-cooled copper blocks can tolerate much higher heat loads.

Heat transfer by conduction occurs when excess oxygen reacts with material in the charge. This will result in lower yield if the material burned is iron or alloys and as a result is not generally recommended. However in the period immediately following charging when volatile and combustible materials in the scrap "flash off", additional oxygen in the furnace is beneficial as it allows this material to be burned inside the furnace and thus results in heat transfer back to the scrap. This is also beneficial for the operation of the offgas system because the offgas system does not have to handle this heat downstream.

Typical industry practice indicates that 0.133 MW of burner rating should be supplied per ton of furnace capacity. Other references recommend a minimum of 32 kWh/ton of burner power to eliminate cold spots in a UHP furnace and 50 – 100 kWh/ton of burner power for low powered furnaces.

Heat transfer efficiencies reported in the literature vary greatly in the range of 50 - 75 %. Burner efficiency as a function of operating time based on actual furnace offgas measurements has been determined. A typical efficiency curve is shown in Figure 4. These trials show that burner efficiency drops off rapidly after 40 - 50 % of the melting time. By 60 % into the melting time burner efficiency has dropped off to below 30 %. It is apparent that a cumulative efficiency of 50 - 60 % is achieved over the first half of the meltdown period and drops off rapidly afterwards. As a result, typical operating practice for a 3 bucket charge is to run the burners for 2/3 of first meltdown, 1/2 of second meltdown and 1/3 of third meltdown. For operations with only one backcharge, burners are typically run for 50 % of each meltdown phase.

Many burner systems are now equipped with the ability to inject oxygen into the furnace. Typically burners will cycle between "burner mode" and "oxygen injection mode" throughout the meltdown cycle. In some cases this will result in instantaneous oxygen injection rates to the EAF in excess of 6000 cfm. This will result in rapid scrap meltdown but if sufficient carbon is not provided to recover the iron units, high yield loss will result. High FeO levels in the slag at meltdown may also impede slag foaming and result in excessive refractory wear.

Similar conditions can arise during refining if burners are used to provide supersonic oxygen injection to the bath. Most burners must be mounted high in the side-wall in order to minimize damage and plugging caused by slag and metal splashing. Typically, the furnace water-cooled shell extends 8 to 12 inches beyond the refractory furnace bottom. As a result, burners must be installed so that the flame does not impinge on the refractory because this would cause accelerated refractory erosion. Thus the lower in the furnace shell that the burner is installed, the shallower the angle of impingement on the bath must be in order to clear the refractory. The more shallow this angle is, the more difficult it becomes to achieve good bath penetration. Injectors installed higher in the furnace shell can achieve a better penetration angle but the gas momentum is much lower at the bath surface due to the greater distance that the gas jet must travel. The result is, that the slag will tend to become highly oxidized in the vicinity of the oxygen injector. Additional carbon should be injected in order to balance FeO generation and to ensure that good slag foaming is achieved.

The amount of power input to the furnace has a small effect on the increase in heatload and offgas volume. The major factor is the rate at which the power is put into the furnace. Thus for a low powered furnace(high tap-to-tap time), the total burner input to the EAF may be in the range of 80 - 100 kWh/Ton but the net effect on the offgas evacuation requirements may not change much because the burners are run for a long period of time. Likewise for a high powered furnace, due to the short tap-to-tap time the burner input rate may be quite high even though the burners supply only 30 kWh/Ton to the furnace.

Oxygen Efficiency In The EAF

- Over the past 20 years oxygen lancing has become an integral part of EAF melting operations. It has been recognized in the past that productivity improvements in the open hearth furnace and in the BOF were possible through the use of oxygen to supply fuel for exothermic reactions. Whereas previously oxygen was used primarily only for decarburization in the EAF at levels of 96 - 250 scf per ton in modern operations anywhere from 10 - 30 % of the total energy input is supplied via exothermic bath reactions. For a typical UHP furnace oxygen consumption is in the range of 640 - 960 scf/ton. Oxygen utilization in the EAF is much higher in Japan and in Europe where electricity costs are higher. Oxygen injection can provide a substantial power input - a lance rate of 2000 scfm is equivalent to a power input of 12 MW based on the theoretical reaction heat from combustion of carbon to CO and associated bath reactions.

Oxygen injection can be applied in two ways. Early in the heat, oxygen can be injected to cut the scrap, thus speeding up the meltdown process. Once a sufficient liquid pool is formed, oxygen is injected into the liquid steel where it reacts with carbon, silicon, aluminum and manganese.

Scrap cutting operations - are usually commenced once the scrap has been heated enough so that the oxygen jet will ignite when it impinges on the scrap. Many operations start scrap cutting oxygen too early and as a result, the oxygen is not used efficiently. As discussed previously, many burners are now equipped to alternate between a scrap heating mode and an oxygen injection mode. If scrap is not sufficiently melted back, prior to starting scrap cutting, the oxygen jet can deflect back on the furnace side-wall causing damage. If the stream of oxygen penetrates well into the scrap, any heat generated through the oxidation of Fe to FeO will be radiated to the surrounding scrap and heat transfer efficiency will be close to 100 %. If the oxygen cannot penetrate the scrap, heat will be radiated back to the furnace side-wall and much lower net heat transfer efficiency will result. If only part of the oxygen reacts with iron, the remainder will remove some heat as it leaves the furnace again reducing the net heat transfer. In actuality, all of these mechanisms occur resulting in varying degrees of efficiency in scrap cutting operations. When the furnace freeboard begins to open up, heat may also be radiated to the furnace roof resulting in damage to the delta. Therefore, scrap cutting operations should not proceed much more than 50 % - 60 % into meltdown operations. Additional carbon must be supplied to ensure that FeO generated during scrap cutting operations is recovered during refining.

Oxygen injection - Oxygen lances can be of two forms. Water-cooled lances are generally used for decarburization though in some cases they are now use for scrap cutting as well. The conventional water-cooled lance was mounted on the furnace platform and penetrated into the side of the furnace through a cut-out in the water-cooled panel. Water-cooled lances are not intended to penetrate the steel bath though they sometimes penetrate into the slag layer. Consumable lances are designed to penetrate into the bath or the slag layer. They consist of consumable pipe which is adjusted as it burns away to give sufficient working length. The first consumable lances were operated manually through the slag door. Badische Stahl Engineering developed a robotic manipulator to automate the process. This manipulator is used to control two lances automatically. Various other manipulators have been developed recently and now have the capability to inject carbon and lime for slag foaming simultaneously with oxygen lancing. One major disadvantage of lancing through the slag door is that it can increase air infiltration into the furnace by 100 - 200 %. This not only has a negative impact on furnace productivity but also increases offgas system evacuation requirements substantially. As a result, not all of the fume is captured and a significant amount escapes from the furnace to the shop. This can be even an more significant problem if substantial quantities of CO escape to the shop because this gas cools rapidly and as a result not all of the CO burns to CO_2. Thus background levels of CO in the work environment may become an issue.

To reduce the amount of air infiltration to the EAF, some operations insert the lance through the furnace side-wall.

Energy savings due to oxygen lancing arise from both exothermic reactions (oxidation of carbon and iron) and due to stirring of the bath with leads to temperature and composition homogeneity of the bath. The product of scrap cutting is liquid iron and iron oxide. Thus most of the heat is retained in the bath. The theoretical energy input for oxygen reactions in the bath is as follows:

$Fe + 0.5\ O_2 \rightarrow FeO$ heat input = 0.17 kWh/scf O_2

$C + 0.5\ O_2 \rightarrow CO$ heat input = 0.08 kWh/scf O_2

Thus it is apparent that much more energy is available if iron is "burned" to produce FeO. Naturally though, this will impact negatively on productivity. Studies have shown that the optimum use of oxygen for conventional lancing operations is in the range of 1000 - 1250 scf/ton. Above this level yield losses are excessive and it is no longer economical to add oxygen. Typical operating results have given energy replacement values for oxygen in the range of 0.056 - 0.125 kWh/scf oxygen, with an average of 0.1 kWh/scf oxygen. These values show that it is likely that both carbon and iron are reacting. In addition some studies have shown that the oxygen yield (i.e. the amount reacting with carbon) is in the range of 70 - 80 %. This would support the theory that both carbon and iron are reacting. During "scrap cutting" operations the oxygen reacts primarily with the iron. Later when a molten pool has formed the FeO is reduced out of the slag by carbon in the bath. Thus the net effect is to produce CO gas from the oxygen that is lanced.

Based on the information cited in the preceding section, it can be expected that for every scf of oxygen lanced, 0.75 scf will react with carbon to produce 1.5 scf of CO (based on the average energy replacement value of 0.1 kWh/scf oxygen). If in addition the stirring effect of the lancing brings bath carbon or injected carbon into contact with FeO in the slag, an even greater quantity of CO may result. That this occurs is supported by offgas chemical analysis data that indicates a decarburization efficiency of greater than 100 %. Thus during the decarburization period up to 2.5 scf of CO may result for every scf of oxygen injected. Typical oxygen lance rates are in the range of 1000 - 3500 scfm per lance and are usually limited by the ability of the fourth hole system to evacuate the furnace fume. Recommended lance rates for various furnace sizes indicate a rate of approximately 25-30 scfm/ tonne of furnace capacity. In some newer processes where feed materials are very high in carbon content, an oxygen lance rate equivalent to 0.1 % decarburization per minute is required. In such cases, the lance rate may be between 6000 and 10,000 scfm which is similar to BOF lance rates.

For bath carbon levels above 0.3 %, essentially all of the oxygen reacts to produce CO. Though FeO is produced locally at the point of injection, the FeO circulates within the furnace an reacts with carbon to form CO. Below 0.3 % carbon the efficiency of oxygen reacting to form CO drops off and more and more FeO is generated in the slag. For tap carbon levels below 0.1 % C, FeO levels in the slag can be quite high and represent an unavoidable yield loss. Increased carbon injection becomes necessary to control slag FeO levels and prevent excessive refractory erosion.

The efficiency of heat transfer from oxidation reactions is extremely high due to the fact that the reactions are taking place in the bath. The only energy removed is the sensible heat in the CO leaving the bath. However, good bath penetration is necessary to ensure that the reactions are taking place in the steel. Bath penetration is a function of the angle of gas impingement on the bath surface.

If the angle is too shallow, the oxygen will push back the slag cover, exposing the bath to oxidation and allowing more nitrogen into the steel. Slag splashing can cause damage to the furnace shell and may increase electrode wear. If the oxygen reacts on the steel surface, a large amount of the heat generated will radiate to the furnace shell and roof because the slag cover has been pushed back. This will result in low heat transfer efficiency to the steel as well as increased furnace wear and potentially higher heat loads to the offgas.

Too steep an injection angle can cause steel and slag to slop back onto the lance tip which ultimately will cause lance failure. Though the instantaneous heat transfer efficiency is not effected, the loss of oxygen lance operation will affect steelmaking efficiency once the lance fails.

The major drawback to high oxygen lance rates is the effect on fume system control. Offgas volumes are greatly increased and the amount of CO generated is much greater. This must be taken into account when contemplating increased oxygen use. The following factors can also have an effect on lancing operations:

- The use of oxygen lancing throughout the heat can be achieved in operations using a hot heel in the furnace. Oxygen is lanced at a lower rate throughout the heat to foam the slag. This gives better shielding of the arc leading to better electrical efficiency. It also gives lower, more continuous flowrates of CO to the offgas system leading to lower peak offgas rates. Thus it reduces the extraction requirement of the offgas system.

- High generation rates of CO may necessitate a post-combustion chamber in the DES system. If substantial amounts of CO are not captured by the DES system, ambient levels in the work environment may not be acceptable. Typically up to 10 % of the CO unburned in the furnace reports to the secondary fume capture system during meltdown.

- Operating with the slag door open increases the overall offgas evacuation requirements substantially. If possible oxygen lances should penetrate the furnace higher up in the shell. Another factor to consider is that the increased amount of nitrogen in the furnace will likely lead to increased NO_x. Potentially the use of a furnace enclosure might become attractive for operations using high lance rates.

CO Post-Combustion

Generically, post-combustion refers to the burning of any partially combusted compounds. In EAF operations both CO and H_2 are present. A high degree of CO post-combustion corresponds to high H_2 post-combustion. CO gas is produced in large quantities in the EAF both from oxygen lancing and slag foaming activities. Since it is not possible for CO to burn to CO_2 in the bath, CO will be the predominant gas in the freeboard during these operations. Large amounts of CO and H_2 are generated at the start of meltdown as oil, grease and other combustible materials evolve from the surface of the scrap. If there is sufficient oxygen present, these compounds will burn to completion. In most cases there is insufficient oxygen for complete combustion and high levels of CO result.

The heat of combustion of CO to CO_2 is three times greater than the heat of combustion of C to CO. Thus this represents a very large potential energy source for the EAF. If the CO is burned in the furnace it is possible to recover heat within the steelmaking process, thus reducing the heatload that the offgas system must handle. Studies at IRSID have shown that the potential energy saving is significant and could be a much as 80 kWh/tonne. Tests conducted at Vallourec by Air Liquide showed that the offgas from the furnace could contain considerable amounts of non-combusted CO and that these occurred when there was insufficient oxygen present in the furnace freeboard.

Post-Combustion In Electric Arc Furnaces

Several trials have been run using PC in the EAF. In some of the current processes, oxygen is injected into the furnace above the slag to post-combust CO. Some processes involve injection of oxygen into the slag to post-combust the CO before it enters the furnace freeboard. Most of these trials were inspired by an offgas analysis which showed large quantities of CO leaving the EAF. Combustion products directly contact the cold scrap. PC can also be carried out low in the furnace or in the slag itself. Heat transfer is accomplished via the circulation of slag and metal droplets within the slag. PC oxygen is introduced at very low velocities into the slag. Some other systems have incorporated bottom blown oxygen (via tuyeres in the furnace hearth) along with injection of oxygen low in the furnace. It is claimed that PC low in the furnace can give efficiencies averaging 4.5 kWh/ Nm^3 oxygen whereas PC high in the furnace gives only 3 kWh/ Nm^3 oxygen. The theoretical limit for PC of CO at bath temperatures (1600 C) is 5.8 kWh/Nm^3 of oxygen. Post-combustion in the slag typically aims at combustion of 20-30 % of the CO generated. Post-combustion in the free-board aims at 80 % combustion of the CO. Introduction of PC oxygen through burners was only 60 % efficient.

For PC oxygen levels greater than 15 Nm^3/tonne yield losses were excessive. In addition other methods of introducing the oxygen were attempted. Oxygen introduced through the delta increased productivity but increased electrode consumption by a factor of three.

The usefulness of the heat generated by post-combustion will be highly dependent on the effective heat transfer to the steel scrap and the bath. Trials at BSW using ALARC PC show that the increased heat load to the water cooled furnace panels was 6 - 7 kWh/tonne. Oxyfuel burner use can lead to yield losses and increased electrode consumption as some combustion products react with iron to form FeO. Trials run on the preheating of scrap with oxy-fuel burners showed that above scrap temperatures of 1400 F, 2-3 % yield loss occurred. If additional carbon is not supplied a yield loss will occur. This is likely to be the case for PC. An iron yield loss of 1 % equates to a power input of 13.2 kWh/tonne. This can have a significant effect on the overall PC heat balance resulting in a fictitiously high HTE for PC.

As Fe is oxidized to FeO, a protective layer can form on the scrap. Once the FeO layer is formed, oxygen must diffuse through the layer in order to react with the iron underneath. This will help to protect the scrap from further oxidation if this layer does not peel off exposing the iron. At temperatures above 2400 F the FeO will tend to melt and this protective layer will no longer exist.

The concept of the energy profile for the EAF

It is important that operators are made aware of heat transfer limitations for auxiliary energy inputs. For example, operation of individual burners above the 4 – 5 MW range, usually results in conditions where any additional energy input is difficult to transfer to the scrap. Elevated offgas temperature and damage to the furnace shell usually result. Oxygen injection rates through a single port nozzle are limited to the 2500 – 3000 scf range for injection at a single location. Higher injection rates at a single point typically result in localized depletion of bath carbon and higher slag FeO levels. In some cases slag foaming is adversely affected.

Thus if higher oxygen injection rates are desired, the use of multiple injection locations becomes imperative.

Other process parameters can also be used as an indication of whether auxiliary energy sources are being applied correctly. The following serve as examples:

- Higher than normal nitrogen levels in the steel may be a sign of poorer scrap quality or may be related to the angle of oxygen impingement on the bath surface.
- Accelerated roof delta wear may be an indication of increased arc flare (poor slag foaming) or improper use of burners (high fire with little or no scrap present)
- Excessive slag line wear may be caused by insufficient flux additions but if this is localized in the area of oxygen injection, it may indicate excessive slag FeO levels which must be remedied through additional carbon injection at this point.
- The taper angle of the electrode is an indication of arc stability and gives an indication of how good slag foaming operations are and also an indication of electrical efficiency.
- High temperature alarms on roof and side-wall panels. In some cases these alarms are the result of inadequate water flow to the panel but many times these are an indication that burner flame is blowing back onto the furnace shell or that excessive arc flare is occurring in the furnace.
- High yield losses may indicate that insufficient carbon is being added to the furnace. In addition, it may indicate that oxy-fuel burners being operated in scrap cutting mode are injecting oxygen at too high a rate. In this case panel over-temp alarms are also likely.
- Local slag over oxidation may result from poor bath penetration when using burner-injectors for bath decarburization.

These are but a few examples of using process parameters to gain a better understanding of furnace operations. As EAF facilities strive to optimize furnace operations, more and more data is being logged and analyzed. It is important to keep in mind however, that the EAF operator requires simple straightforward tools that allow him to see process trends.

The advent of several EAF post-combustion technologies has lead to much greater interest in offgas system chemical analysis. Many systems were developed for offgas analysis both as a tuning aid for use when initially setting up the post-combustion system and as a tool for controlling injection levels of post-combustion oxygen. Unfortunately, present analysis methods make it difficult to analyze the offgas and report the results in "real time" which is required if the analysis system is truly intended to provide process control feedback. However, several operations have successfully used such gas analysis systems to obtain better information about their EAF operations. The major draw-backs to such systems is that they are expensive and are difficult to maintain. As a result, many operators are seeking a simpler, less expensive method for providing feedback to their EAF operations.

One such system can be developed at a minimum cost to the EAF facility. Through continuous offgas flow and temperature measurement, it is possible for the EAF operator to track such things as:

- Variations in oil and grease content of the scrap
- Poor oxy-fuel burner heat transfer efficiency
- Variations in offgas heat-load throughout the whole tap-to-tap cycle
- Trouble-shoot offgas system damper operations
- Slag foaming efficiency

Through the use of simple process monitoring tools, it is possible to develop thermal profiles for the EAF for the entire tap-to-tap cycle. Once typical profiles have been developed, the operator can use these for comparison with the actual profile for a given heat. In this way, the operator is given the tools to trouble-shoot furnace operations and make adjustments to optimize the steelmaking process.

FUTURE CONSIDERATIONS FOR EAF STEELMAKING

It is important that we recognize that the EAF is a dynamic operation with variations in feed composition from heat to heat. It has also been shown that the efficiency of energy transfer to the scrap also varies considerably over the course of a heat. As a result, it is useful to look at the concept of an EAF thermal profile – essentially, an energy input profile across a heat. Through the monitoring of offgas flow and temperature, we can imply what the energy transfer efficiency is across the entire heat. If this is tied in with monitoring of the cooling water temperature rise, it is possible to track energy efficiency in a simple but meaningful manner.

Poor control of the carbon/oxygen balance in the EAF can lead to high yield losses and higher operating costs. Optimization of energy efficiency in the EAF is not only a cost issue. If low energy efficiency is achieved, more energy must be used in the EAF. A large portion of the energy losses will leave the furnace in the offgas. This will impact on the capability of the offgas system to handle higher heat loads and provide an acceptable working environment in the meltshop.

Without doubt, current trends in EAF design indicate that high levels of both electrical and chemical energy are likely to be employed in future furnace designs. As so many have pointed out, we are headed towards the oxy-electric furnace. The degree to which one form of energy is used over another will be dependent on the cost and availability of the various energy forms. Raw materials and their cost will also affect the choice of energy source.

The use of alternate iron sources containing high levels of carbon will necessitate the use of high oxygen blowing rates which equate in turn to high levels of chemical energy use. A word of caution is in order though for such operations, as some thought must enter into how to maximize energy recovery from the offgases generated. In addition, high levels of materials such as cold pig iron can sometimes lead to extended tap-to-tap times which will reduce furnace productivity. If hot metal is used, some method must be provided to recover energy from the offgases. Materials which are also high in silicon will provide additional energy to the bath but at the cost of additional flux requirements and greater slag quantities generated.

The furnace operator is the most capable person for optimizing furnace operations because he is exposed to the furnace everyday. Just as an experienced operator can identify mechanical and electrical equipment problems merely through the sound of the furnace or through visual observation, an operator can also be trained to observe process parameters and to use these observations to optimize furnace operations. Energy efficiency will have an effect on product quality, operating cost, productivity and offgas system operations. It is important therefore that we supply the furnace operator with the tools necessary to fulfill and exceed management requirements for the future.

REFERENCES

E.H.McIntyre, E.R.Landry, “Electric Arc Furnace Efficiency”, CMP Report No. 92-10, December 1992, pp 3-8 to 3-9.