Optimization of Oxygen Steelmaking in Non-Conventional EAF Operations

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Keywords: Electric Arc Furnace, EAF, Hot Metal, Liquid Iron, DRI, HBI, Shaft Furnace, Oxygen Steelmaking, Sidewall Burners

INTRODUCTION

During the last several years, electric arc furnace steelmaking has been forced to adapt to new market conditions. China's fast economic growth has increased the worldwide demand for EAF raw materials and in particular for scrap. The high level of demand has driven scrap prices up to levels not seen in many years.

These high scrap prices have forced EAF steelmakers to adapt their operating process to lower qualities of scrap or to alternate iron bearing materials. In the US, EAF operations have adapted to using lower quality scrap while in China, where most high quality scrap is imported, the steel industry has been forced to charge molten pig iron (hot metal) to their EAFs if they are fortunate enough to have a captive source of liquid hot metal. In China, hot metal is cheaper and sometimes more readily available than scrap, therefore many mini-mills are constructing blast furnaces (typically < 1000 m^3) to reduce their requirements for scrap.. Therefore, it is common in China to find EAF operations that charge between 25% and 70% of their raw materials as hot metal. Since the EAF is not designed to accommodate such large quantities of liquid hot metal, the steelmaking process and the way oxygen and sidewall lancing burners are used, must be adapted to take advantage of the benefits that hot metal provide and to overcome the operating problems of using liquid iron.

Some steel mills have captive DRI facilities, which lower their reliance on the scrap market for raw materials. Furnaces charging large amounts of DRI also need to be operated differently from the traditional scrap based EAF. Furnaces charging more than 30% DRI are typically required to continuously charge DRI to prevent "clumping" of the DRI or HBI briquettes. The use of oxygen in these operations is significantly different than in the traditional EAF. Over-use of oxygen can drastically reduce the metallic yield of the process. Therefore, operating parameters must account for the chemical composition of the DRI raw material being used.

This paper will illustrate several optimization issues associated with "non-conventional" EAF operations. Industrial results of Air Liquide ACI technology will be presented for EAFs charging hot metal, large quantities of DRI and for shaft furnaces.

HOT METAL OPERATIONS

Practical Advantages and Disadvantages of Using Liquid Hot Metal in the EAF

Use of liquid hot metal in the EAF has several advantages and disadvantages. The most obvious advantage of pouring 1200°C (2200°F) to 1400°C (2552°F) hot metal into an EAF is the sensible heat associated with its use. Obviously, this drastically reduces the amount of electrical energy required for producing a heat of steel. Additionally, hot metal contains approximately 4.5% carbon and the additional chemical energy associated with the decarburization of a high carbon bath using oxygen provides further electrical energy savings.

The disadvantages of charging large quantities of hot metal are less obvious, but can be listed as follows:

- The quantity of oxygen required for refining and decarburization is much higher than for conventional operations due to the high concentration of carbon in the bath.
- Violent eruptions can occur during charging of hot metal into the furnace at the beginning of the heat because the high carbon hot metal is reacting with the highly oxidized slag.
- Electric furnaces are designed for scrap melting. They are typically not conducive to thorough bath mixing unless bottom stirring has been installed. As a result, large carbon concentration gradients can develop in the bath during refining. Any sudden mixing can cause carbon rich steel to interact with oxidized slag and/or lower carbon steel. This can cause violent reactions that can send metal and slag out of the furnace and onto the shop floor. Extreme reactions have been observed to send slag up through the electrode holes onto the current conducting arms.

Productivity Considerations. The productivity of an EAF using hot metal depends on the oxygen injection capacity of the lance and sidewall burners that are installed. A furnace that was initially designed to operate with 100 percent scrap will not likely be equipped to cope with the additional decarburization that will be required when large quantities of hot metal are added to the charge. Figure 1 illustrates the intuitive result that electrical power consumption reduces as the quantity of hot metal charged to the furnace increases. In a conventional furnace, this reduction in power consumption translates directly to a steady increase in furnace productivity. The actual performance of this furnace was better than theoretical calculations because the theoretical calculations assume a hot metal temperature of only 1200°C (2192°F) when the actual hot metal temperature was probably higher.

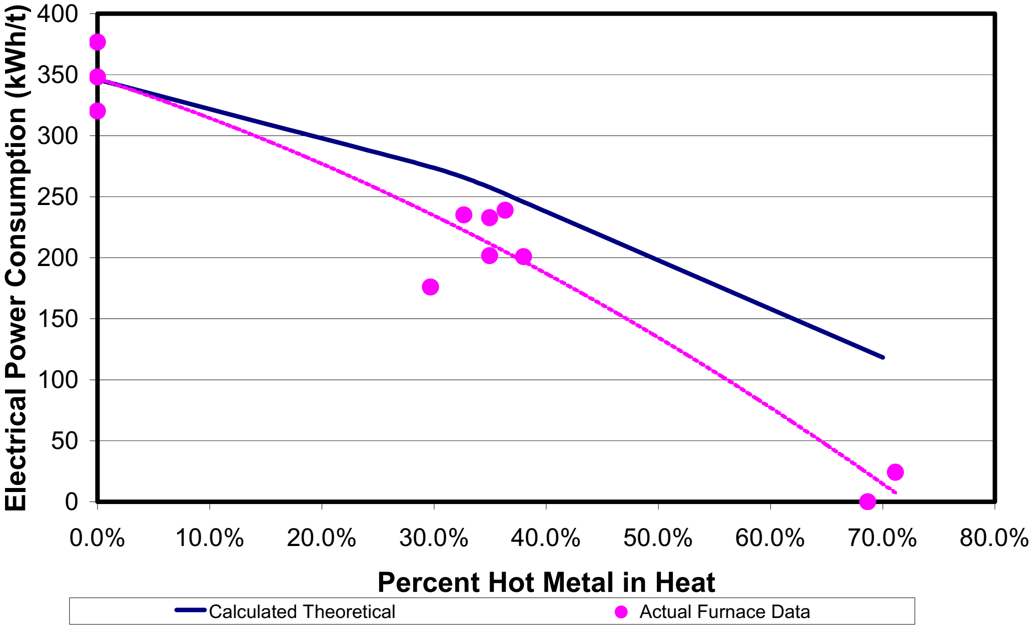


Figure 1: Electrical Power Consumption as a Function of Percent Hot Metal Charged

A furnace that begins charging large quantities of hot metal (when they previously charged only scrap) will see an initial increase in productivity as the quantity of hot metal increases in the charge. However, once the hot metal percentage increases beyond a certain level, the productivity begins to diminish because the rate-limiting step for EAF productivity becomes the capacity of the oxygen injections system. Figure 2 shows the effect on furnace productivity of increasing the proportion of hot metal in the charge. This furnace began to loose productivity after the proportion of hot metal increased beyond 40% of hot metal. In this furnace, when the percentage of hot metal in the charge increases beyond 40 %, the rate of oxygen input for decarburization becomes the rate limiting part of the process.

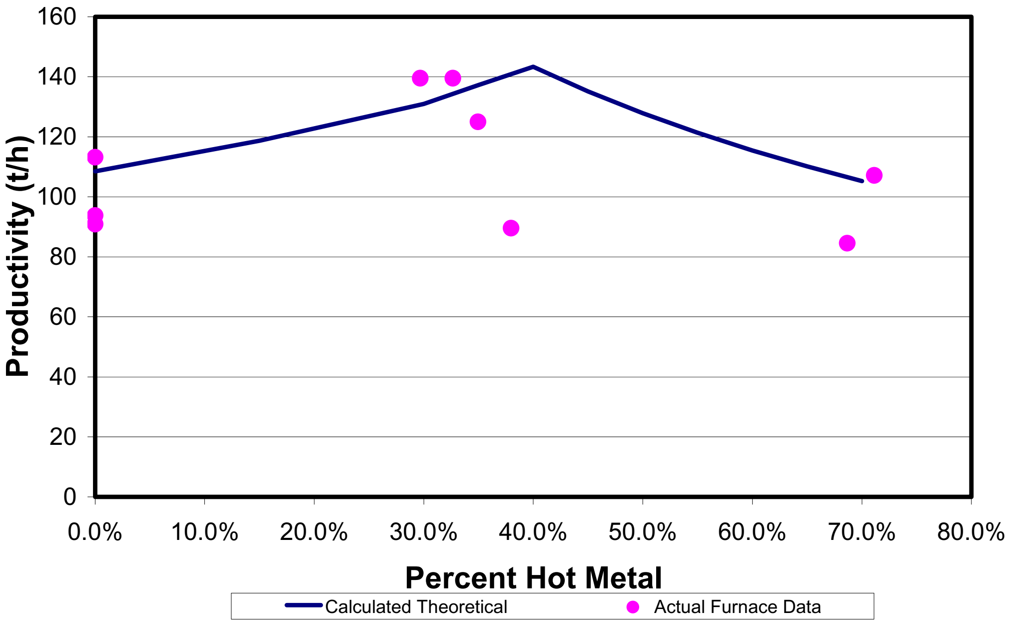


Figure 2: Furnace Productivity as a Function of Percent Hot Metal Charged

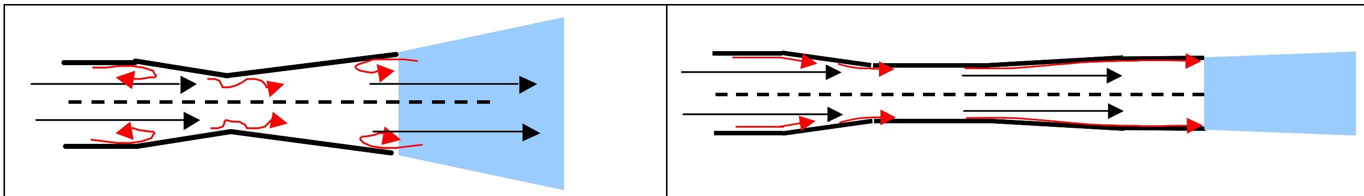
The furnace described in Figure 1 and Figure 2 installed the PyreJet™ burner system before it was anticipated that hot metal would be used as a charge material. The furnace was equipped with PyreJet™ sidewall lancing burners, each with the capability of delivering 2000 Nm3/h (1200 scfm) of supersonic oxygen to the bath. It was also equipped with two oxy-fuel PyrOx™ burners for melting scrap in the cold spots[1]. The PyreJet™ system (valve train and burners) was designed to accommodate up 20 percent Pig Iron to efficiently remove carbon from the bath while improving productivity and energy consumption. The operating results after PyreJet™ installation are shown in Table I[1].

Table I: Operational Improvement s at JianYin Xingcheng Special Steel Plant before and After Installation of PyreJet™ Burner System.

	Before PyreJet™	With PyreJet™	
	100 % scrap	100% scrap	20% hot metal charging
Scrap charged - excluding pig iron- (kg/t)	738.1	743.8	712.4
Electrical consumption (kwh/t billet)	346	324	285
Metallic Yield liquid/scrap)	91.5	91.5	92.1
Solid pig iron % in the scrap mix	32.5	29.4	15.0
Liquid hot metal poured in the furnace (%)	0%	2.6 %	19.4 %
Propane/Butane mix consumption, Nm^3/t		1.25	0.95
Oxygen consumption for EAF, Nm^3/t	46.8	51.9	46.9
Electrode consumption, kg/t	1.04	0.99	0.95
Carbon consumption, kg/t	7.6	6.4	5.4

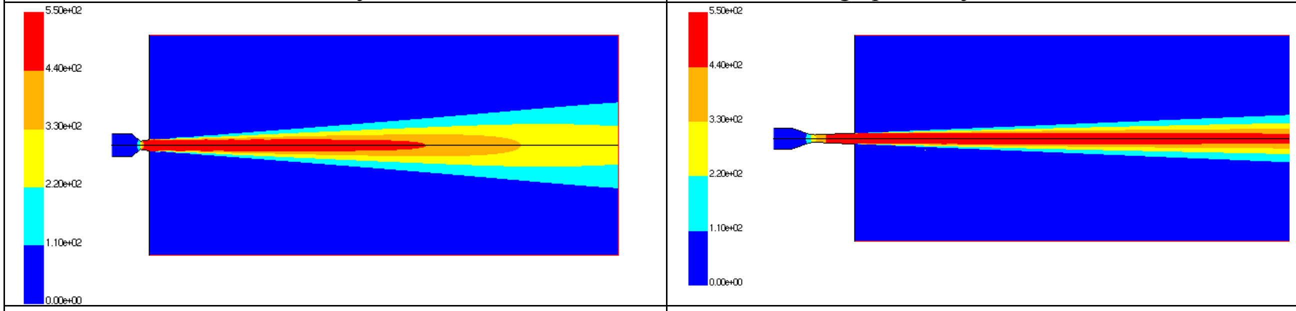
As the proportion of hot metal increased, it became necessary to begin using the door lance. The door lance has an oxygen injection capacity of 4000 Nm^3/h (2536 scfm). This increased the total oxygen injection capability to 10,000 Nm^3/h (6341 Nm^3/h). The data in Figure 2 represents the productivity of the furnace using 10,000 Nm^3/h oxygen injection capacity.

Operations Using More Than 35 % of Hot Metal. As can be seen in Figure 1 and Figure 2 the proportion of hot metal charged to this particular furnace reached 70%, with the majority of the heats using about 50 % hot metal. Due to the high local price of gaseous fuel and to the high level of hot metal, the plant decided to switch from PyreJet™ burners to ALARC-Jet™ injectors (supersonic injection without flame shroud). Figure 3 highlights the specific design of the ALARC-Jet™ injector.



Standard Supersonic tuyere.
Internal *turbulence* disturbs the jet

ALARC-JET supersonic tuyere
Advanced design protects jet from turbulence



Computer Modeling of Standard Tuyere:
The Jet is quickly expanding

Computer Modeling of ALARC-Jet tuyere
The Jet stays focused

Experimental Laser Visualization of non-adapted tuyere: the jet is quickly expanding

Experimental Laser visualization of **ALARC-Jet** in hot atmosphere : the supersonic jet stays focus.

Figure 3: Technical Description of the ALARC-Jet™ Sidewall Supersonic Oxygen Injector.

The ALARC-Jet™ injector has been specifically designed for EAF operations that do not need natural gas for preheating and melting scrap. In particular, the ALARC-Jet™ injector is best adapted for operations where high percentage of hot metal is charged, or where the furnace operates predominately under flat bath conditions (Shaft furnaces, conveyer charged preheated scrap, Continuous feeding of DRI). Its supersonic nozzle has been optimized to avoid entrainment of the ambient atmosphere surrounding the jet. This optimized nozzle, when used in a hot atmosphere (low density gases), can deliver a high quality, focused supersonic oxygen stream without the need for a protective flame envelope that is required by typical super-sonic nozzles.

The ALARC-Jet™ was installed on the furnace described above mostly to eliminate the need for gaseous fuel. The average operating performance with ALARC-Jet™ shortly after installation is compared to the operation with PyreJets™ in Table II. As can be seen, there is no apparent electrical energy penalty associated with its use in this furnace where flat bath conditions predominate. Table II shows that the energy consumption with ALARC-Jet™ is approximately the same as the operation with PyreJet™ when the electrical energy value is corrected for the proportion of hot metal charged to the furnace.

Table II: Comparison of Performance between ALARC-Jet™ and PyreJet™ for Operations using High Proportions of Hot Metal.

DC EBT Furnace	PyreJet	ALARC-Jet	ALARC-Jet Corrected to 23.3 %Hot Metal
1st Charge (tonnes)	61.8	61.7	61.7
Hot Metal (tonnes)	28.4	23.6	27.8
2nd Charge (tonnes)	31.0	34.0	29.8
Percent Hot Metal	23.3%	19.7%	23.3%
Electrical Energy (KWh/tonne)	261	269	260
O_2 via Door Lance (Nm^3/t)	24.5	25.6	-
O_2 via Injectors (Nm^3/t)	19.7	20.9	-
Power On Time (min)	33	33	32
Tap To Tap (min)	57	51	50

Carbon Injection

During the optimization of PyreJet™ and ALARC-Jet™ systems on several furnaces charging high proportions of hot metal, Air Liquide ACI has found that a good control of the carbon injection can be even more important for such operations than for normal scrap based operations. The importance of carbon injection in operations using high proportions of hot metal is both safety and process related. The following paragraphs explain why carbon injection is so important with high carbon bath system.

As mentioned above, one of the disadvantages of charging large proportions of hot metal to the EAF is the danger associated with relatively poor mixing conditions in the EAF. As refining proceeds, carbon concentration gradients develop in the bath with relatively low carbon concentration occurring in the bath in the vicinity of the points of oxygen injection. Slag in this vicinity contains relatively high concentrations of FeO. As a result, sudden mixing of the bath (caused by scrap cave-ins or tilting of the furnace) can cause high carbon steel to mix with areas of the bath that have a high oxygen potential. The resulting reaction is:

$$FeO_{(l)} \quad + \quad [C] \quad \Rightarrow \quad Fe_{(l)} \quad + \quad CO_{(g)} \tag{1}$$

The gas evolution from this reaction is very rapid, causing slag and sometimes steel to spray onto the slag floor and, in some extreme cases, to spray the electrode arms. The danger of this occurring is greater for furnaces that have a single location for oxygen injection. If for example, the only oxygen injection point is the door lance, the carbon concentration gradients in the bath will be much higher than for a furnace that uses three or more points of injection using sidewall-lancing burners.

To overcome this problem, it is important to control the oxygen potential of the slag in the vicinity of the of oxygen injection locations. Injecting carbon at those locations will reduce the quantities of FeO in the slag via the reaction:

$$FeO_{(l)} \quad + \quad C_{(s)} \quad \Rightarrow \quad Fe_{(l)} \quad + \quad CO_{(g)} \tag{2}$$

Carbon injection must begin at, or shortly after, the onset of supersonic oxygen injection into the bath and it must persist for essentially the entire duration of the refining process. To achieve control of the FeO in the slag, the carbon injection system must be controlled automatically and the system should have the ability to inject carbon at variable rates so that the ideal carbon injection rate can be sustained for the entire duration of melting and refining. The ideal carbon injection rate is determined mainly through mass balance calculation followed up by trials and adjustment to the carbon flow profile. All ACI PyreJet™ and ALARC-Jet™ systems on EAFs include controllable carbon injection in their scope of supply to include at least two points of carbon injection so that carbon is available at locations with high oxygen potential can develop.

Performance of PyreJet™ and ALARC-Jet™ on Furnaces Charging High Proportions of Hot Metal

The furnace performances for some of the Air Liquide ACI references charging hot metal into their furnace are listed in Table III. In every case, the power consumption and power on time have decreased. This is partly due to an increase in oxygen consumption, but it is also due to the fact that the PyreJet™ /ALARC-Jet™ systems were designed to deliver oxygen to the process at a rate that allows refining to be complete at the same time as the steel reaches tap temperature (decarburization rates measured up to 0.20%C/min.). In almost every case previously, the refining of the steel with oxygen was the rate-limiting step of the process. Additional carbon was required to balance the additional oxygen that was added to the furnace.

Table III: Performance improvement of PyreJet™ / ALARC-Jet™ systems on Furnaces Charging Hot Metal.

	Furnace 1		Furnace 2		Furnace 3		Furnace 4		Furnace 5	
	Immediately Before PJ	After PJ	Immediately Before PJ	After PJ	Immediately Before AJ	After AJ	Immediately Before PJ	After PJ	Immediately Before PJ	After PJ
Tap Size (tonnes)	50	75	125	125	40	40	105	105	95	95
Power Consumption (kWh/t)	363	293	346	285	280	143	349	288	294	238
Power On time (min)	51	39	54	45	70	36	38.4	32.5	31.2	24.5
Transformer Size (MVA)	45	65	90	90	15	15	100	100	70	70
Propane / Butane / Natural Gas (Nm3/t)	0	1.7	0	1.2	0	0	0	2.2	0	4
Oxygen (Nm3/t)	40	36.5	46.8	46.9	47	56	20	25.2	42	49
Hot Metal Charged (%)	0	13	0	20	30 - 50	50	20	20	32.7	40.2

OPERATIONS CHARGING HIGH PROPORTIONS OF DRI

Furnaces that charge DRI /HBI in small proportions can normally do so through the scrap bucket. However, once the proportion of DRI / HBI charged to an EAF increases beyond 20% to 25%, it must be continuously charged (normally through the roof) to prevent the agglomeration of the DRI / HBI particles. Furnace charging more than 60% DRI / HBI must maintain a large heel and continuously charge the DRI /HBI with the power on.

The properties of DRI are highly variable and the quality of DRI depends on economical considerations to determine what the final quality of the DRI product will be. The most important property is the percent of metallization of the DRI because this property reflects the amount of FeO remaining in the DRI product. Many DRI manufacturers try to produce DRI with enough carbon to reduce the FeO in the DRI. Table IV lists the typical properties of DRI that is typically available for use in steelmaking[2]. Since DRI is produced using iron ores (or iron ore concentrates) the gangue content is high compared to metallic charges to the EAF and these gangue materials require more charge lime than a typical scrap based operation to make a suitable slag. Table IV shows the typical V-Ratio of the gangue components in DRI Range between 0.06 and 0.6. Therefore, additional lime (compared to a normal scrap operation) must be added to flux these components to make a slag that has a Basicity (B_4) of 2.5 to 3.0.

The additional lime requires extra heat in the process to melt and produce the slag. Also, any FeO that is present in DRI must be reduced via reactions (1) or (2). These reactions both consume heat when they occur. Therefore, operations using DRI as a charge material require more energy (per tonne of steel) than do EAF operations using 100 percent metallic scrap charge. The properties of DRI also dictate how oxygen is used in the furnace.

Table IV: Range of Typical Properties for DRI / HBI

Property	Value
Total Iron	87 - 94
Metallic Iron	83 - 88
Metallization	91 - 95
FeO	6 - 11
Carbon	0 – 4.5
Phosphorous	0.01 – 0.080
Sulfur	0.003 – 0.15
Silica	1.0 – 4.5
Alumina	0.3 – 2.0
CaO	0.2 – 1.5
MgO	0.1 – 0.6
Basicity (B_4) = (CaO + MgO)/(SiO_2 +Al_2O_3)	0.06 – 0.6

Operators often complain about the lower yield associated with DRI usage because it is often used with few or no adjustments to the operating procedures. The high FeO content in DRI is the main reason for the lower yield because either two much oxygen is used in the process, or not enough carbon is injected to compensate for the oxygen.

The design and implementation of the ACI PyreJet™ system at OEMK in Russia considered all of these issues[3]. The furnace at OEMK has a capacity of 150 tonnes of liquid steel with a 90 MVA transformer. This operation uses more than 50 % DRI in its raw materials charge. The challenge was to increase the rate of melting of DRI by using PyreJet™ burners. Prior to the commencement of the project, the justification for installation of the PyreJet™ system was an electrical energy savings of 30 kWh/t. To achieve this goal, the oxygen consumption needed to be increased by 13 – 15 Nm^3/tonne (450 – 519 scf/t). Therefore, a significant amount of additional injection carbon would also be required to balance the extra oxygen. As mentioned above, this is particularly important when using high proportions of DRI. The results of this practice change using ACI PyreJet™ are shown in Table V[3]. The performance of the PyreJet™ system was better than expected due to the improvement in the quality of the foamy slag. The improved foamy slag resulted from injecting carbon at the location where the oxygen is injected into the bath (at each PyreJet™). This enabled electrical power input to increase, which helped reduce the energy losses from the process.

Table V: Results from PyreJet™ Installation in a Furnace Charging high Proportions of DRI.

Parameter	Before PyreJet (3 months)	After PyreJet	Delta (absolute)	Delta (%)
Electrical Energy Consumption (kWh/t)	610	553	-57	-9.3
Power on Time (min)	96	88	-8	-8.3
Oxygen Consumption (Nm^3/t)	14	27	+13	+92.9
Natural Gas Consumption (Nm^3/t)	0	2.7	+2.7	
Electrode Consumption (Nm^3/t)	2.4	2.3	+2.3	-4.2

SHAFT FURNACE OPERATIONS WITH LAUNDERED HOT METAL (EBT AREA)

The installation of PyreJet™ burners in a shaft furnace requires special considerations due to the charging method used. In particular, scrap is charged through a shaft (where scrap is preheated) into the furnace. Therefore, the scrap is concentrated on one side of the furnace. To be effective, sidewall burners must be concentrated at the side of the furnace where the scrap is located.

Figure 4 shows the layout for a recent PyreJet™ / PyrOx™ burner system in a shaft furnace (retrofit of existing sidewall lancing system). To promote efficient melting most of the burners are concentrated under the shaft (right side of Figure 4). Two PyreJet™ burners are located on the opposite side of the shaft to distribute the refining oxygen for uniform decarburization. In this particular furnace, hot metal is laundered into the furnace near the EBT area. The hot metal is poured into the furnace at a rate of about 2 tons/minute. The PyreJet™ burners were used in locations in the opposite side of the shaft to aid in fast decarburization of the hot metal poured in this area. However, this location is also suitable for ALARC-Jet™ sidewall supersonic injectors because there is no need for an oxy-fuel burner (no scrap) at that location. Table VI shows how using the principles described above has improved the performance of the shaft furnace operation with the PyreJet™ / PyrOx™ burner system versus existing sidewall lancing system.

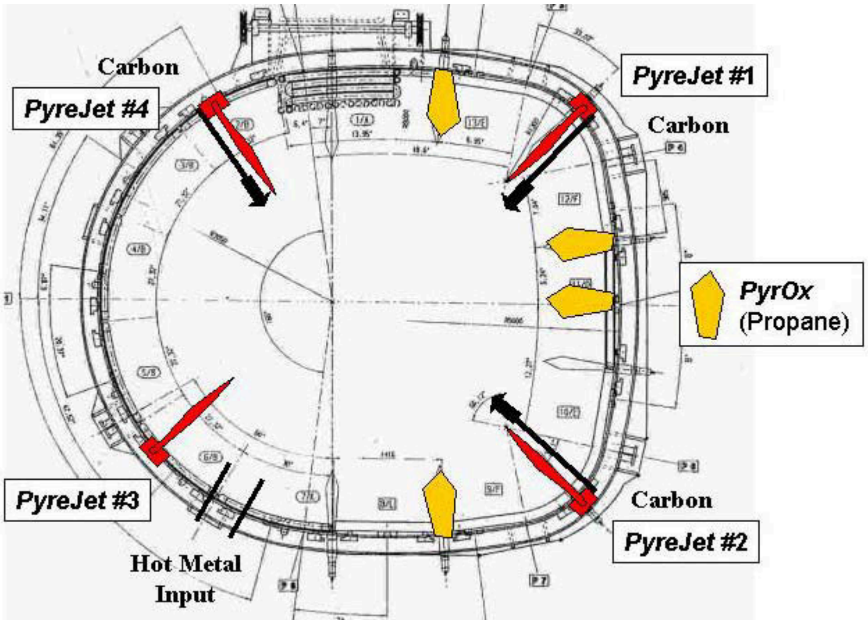


Figure 4: PyreJet™ and PyrOx™ Layout for a Typical Shaft Furnace

Table VI: Comparison of Shaft Furnace Operation before and after Installation of PyreJet™ / PyrOx™ System.

Shaft Furnace with Hot Metal Launder		ORIGINAL	ACI	DELTA
		existing sidewall lancing	PyreJet™ / PyrOx™	
Power ON time	(min)	24.3	23.0	-1.3
Tap to tap time	(min)	41.4	37.0	-4.4
Tapping weight	(t)	100.8	104.0	+3.1
Electrical Energy	(kWh/t)	213	190	-23.4
LPG	(Nm^3/t)	2.35	1.80	-0.55
Oxygen via Burners	(Nm^3/t)	41.8	34.7	-7.1

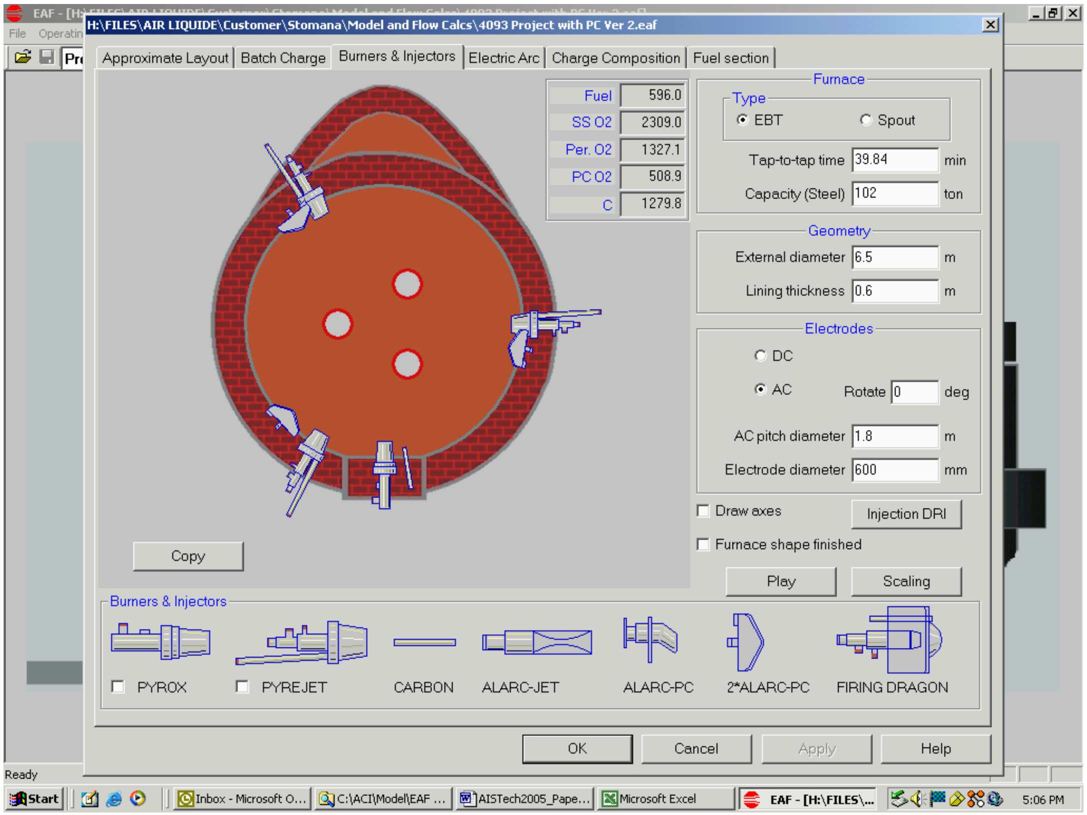
PYREJET™ AND ALARC-JET™ DESIGN CONSIDERATIONS FOR ALL EAF OPERATIONS

One of the most important aspects when designing a chemical energy system for an EAF is the good understanding of the present and future considerations of the customer. For example in China, the availability of hot metal varies dramatically on a daily and hourly basis. Additionally, melt shop managers are trying to increase the quantity of hot metal that they use to reduce their dependence on scrap supply. These often need solutions allowing for a high level of flexibility. Sometimes, ACI is required to propose systems and make performance guarantees on furnaces that are planning new equipment, for which there is no data for prior operation – for example, a new more powerful transformer. In these operations, the sidewall lancing burner system is a single component of a substantial furnace upgrade. In such situations, sophisticated methods for predicting the impact of a PyreJet™ system on the furnace operation are required. Modeling becomes also a vital tool for designing burner and injector systems.

Air Liquide ACI customizes its burner, injector and panel designs for each furnace operation based on the following data:

- Furnace size (tap tonnage)
- Furnace configuration (DC, AC, shaft furnace, EBT, Spout)
- Transformer size
- Current operating performance (kWh/t, power on time, oxygen, carbon, natural gas, electrode consumption, etc)
- Metallic yield.
- Raw materials quantity and quality
- Future considerations (in foreseeable future):
  - New equipment
  - Raw materials

ACI has developed an in-house EAF model that uses the existing EAF performance data to extrapolate the future process performance once the furnace is equipped with new equipment and starts using new raw materials. The model is first calibrated using any existing data that is available from a customer's operation. Based on this information, predictions can me made to determine the exact requirements that an ACI PyreJet™ system must have to meet the goals of the customer. Figure 5 shows one of the input screens for the ACI EAF Model and Figure 6 is an example output screen in the ACI EAF model.



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Fuel 596.0
SS O2 2309.0
Per. O2 1327.1
PC O2 508.9
C 1279.8

Furnace
Type: ● EBT ○ Spout
Tap-to-tap time 39.84 min
Capacity (Steel) 102 ton

Geometry
External diameter 6.5 m
Lining thickness 0.6 m

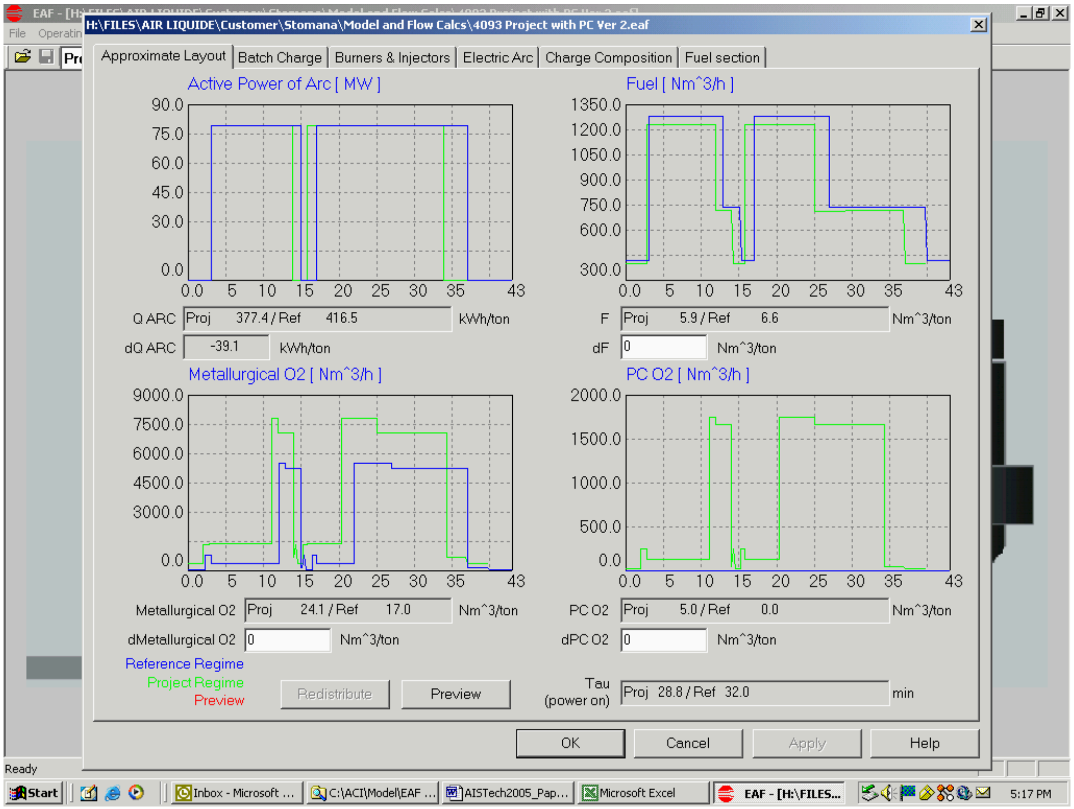
Electrodes
○ DC
● AC Rotate 0 deg
AC pitch diameter 1.8 m
Electrode diameter 600 mm

☐ Draw axes
☐ Furnace shape finished

Burners & Injectors
☐ PYROX
☐ PYREJET

Figure 5: Example Input Screen in the ACI EAF model

The model offers an important supplement to the technical know-how of the process engineers at ACI. It has assisted in the design and customization of many successful PyreJet™ and PyrOx™ installations worldwide. As raw material market conditions change around the world, EAF operators are being forced to dramatically adapt their processes to include different raw materials such as hot metal, DRI, pig iron, furnace dust, etc. In such an environment computer modeling tools will play an increasing role in designing new equipment for the evolving EAF.



Q ARC Proj 377.4 / Ref 416.5 kWh/ton
dQ ARC -39.1 kWh/ton
F Proj 5.9 / Ref 6.6 Nm^3/ton
dF 0 Nm^3/ton
Metallurgical O2 Proj 24.1 / Ref 17.0 Nm^3/ton
dMetallurgical O2 0 Nm^3/ton
PC O2 Proj 5.0 / Ref 0.0 Nm^3/ton
dPC O2 0 Nm^3/ton
Tau (power on) Proj 28.8 / Ref 32.0 min

Figure 6: Example Output Screen in the ACI EAF Model

This paper has highlighted technological solutions developed by Air Liquide ACI for several EAF operations that are considered non-conventional. Some of these non-conventional EAF processes are just in their first phase of evolution. As subsequent development phases are completed, Air Liquide ACI will adapt its technology to these new market conditions.

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