Importance of control strategy for oxy-fuel burners in a steel reheat furnace

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First presented at AISTech 2013—Pittsburgh, Pennsylvania, USA—6 May 2013

Introduction

The steel industry has long been a willing partner in field trials of novel combustion technologies. It has willfully served as a medium to nurture innovation via adoption of new combustion inventions in its pursuit of energy efficiency and environmental stewardship. Combustion is an intriguing science that explores the conversion of chemical energy from fuels to useful heat utilized in an industrial process. This conversion can be accomplished in several different ways. Examples include – cold air-fuel combustion, preheated (recuperative or regenerative) air-fuel combustion, oxygen enriched air-fuel combustion and full oxy-fuel combustion. There is often much debate about which is the "best" among the above stated methodologies. The truth of the matter is that there is no way to "objectively" evaluate this in general terms. Every furnace/process is inherently different, comes with its own techno-economic constraints and needs varying solutions (sometimes a combination of the above) to "get it right".

The rolling mill management at ArcelorMittal Steelton (Steelton, PA) facility was investigating new combustion technologies to improve upon the performance of their recuperative air–fuel (older) batch steel reheat or "soaking pit" furnaces. The existing (older) burner technology and recuperative air pre-heaters were becoming inefficient and expensive to maintain. The preheat temperatures achieved were well below the designed capacity (i.e. 450 F vs. 700 F originally). Oxy-fuel combustion was considered as an effective alternative to achieve fuel efficiency and cycle times desired in the operation.

This paper discusses various aspects of oxy-fuel combustion such as heat transfer modes, energy efficiency and flame-furnace interaction. Further, it emphasizes the importance of having an appropriate control strategy to maximize the benefits that can be obtained from a combustion system. This ideology is illustrated using the findings from an installation of a "spacious" oxy-fuel combustion system in the ArcelorMittal Steelton batch reheat furnace (soaking pit).

Oxy-fuel combustion

The use of pure oxygen in the steel industry is commonplace. When used as an oxidizer in place of air, it has proven benefits such as improved energy efficiency, increased product throughput, reduced emissions, lower particulate carryover through the flue, etc. Simply put, use of oxygen in combustion eliminates the least efficient component in air-fuel combustion – nitrogen. It does not participate in combustion (is inert) and is transparent to radiation heat transfer. It does participate in convective heat transfer with the help of increased flue gas volumes flowing through the furnace; however, this benefit is usually accompanied by reduced residence times for effective completion of heat transfer. The concept of "available heat" (found in literature[1]) is often used to illustrate the enhanced efficiency of oxy-fuel over air-fuel combustion.

"Spacious" combustion

Oxy-fuel combustion is known for thermal radiation as the dominant mode of heat transfer. The typical explanation used in support of this claim is that higher flame temperatures in oxy-fuel combustion lead to enhanced heat transfer to the product (difference between temperatures to the power of four). It has been estimated in literature[1] that peak temperatures achieved in the flame can be as high as 5000 F. Unfortunately, this is often perceived as a potential to localized overheating, which is not factually correct. The peak flame temperatures calculated by the above method are considered under "adiabatic" conditions (temperature achieved when there is no heat loss to the environment). In reality however, the flame is constantly generating and transferring energy to surrounding heat sinks through its evolution in the furnace. Also, the flame temperatures achieved vary with location along the length of the flame/furnace, jet velocities, extent of mixing with furnace gases, heat transfer view factors, etc.

Radiation heat transfer can be limited by "view factors" (i.e. location of the heat absorbing sinks in the furnace relative to a radiation source, such as a flame). In steel reheating, for example, positioning the billets or blooms such that there are radiation shadowed zones can lead to uneven heating, conduction limited heat transfer and sometimes undesirable product quality. In such situations, having an effective "convective" component of heat transfer (in addition to radiation) can play a strong role. However, it is important to introduce this convective component without addition of more volumes in the furnace (e.g. nitrogen in air) as it can have an adverse effect on time available for heat transfer and increased energy carried out through the flue. This is where "spacious" combustion comes into play.

Spacious combustion is obtained with the help of plurality of high momentum flow jets introduced by Air Products' proprietary high shape factor nozzles that entrain surrounding flue gases (H_2O and CO_2) into the combustion space. This reduces the partial pressures of fuel and oxygen in the combustion space, resulting in uniformly distributed release of energy along the length of the furnace (see figure 1). Additionally, the flue gases entrained and accelerated within the combustion space generate a strong convective recirculation current in the furnace. Depending on the size of the furnace and energy density, a clever arrangement of several spacious combustion burners allows enhanced furnace convection (i.e. streamlined flow of flue gases with minimal choke or stagnations points) and synergistic radiative-convective heat transfer in the furnace.

Heat release profiles and interaction with furnace

More often than not, combustion in a furnace is approached like a "black box". Process flow sheet simulations focus on maximizing "energy-in minus energy-out," while the "devil" is in the details. Inadequate understanding or appreciation of combustion characteristics and their interaction with the furnace space can lead to selection and installation of unsuitable burner technologies, poor combustion control, uneven heating of furnace, unsatisfactory product quality or increased rejects, recurring furnace (and burner) maintenance, safety hazards and even disgruntled operators.

It is important to acknowledge the fact that every combustion system has a signature "heat release profile" and interacts uniquely with the furnace. For example, figure 1 shows the heat release profile for two different oxy-fuel burners developed at the Air Products Center of Excellence for Combustion. It can be seen that the heat release profile of a spacious combustion burner is uniform along the length of the furnace, whereas the other burner was developed specifically for rapid heat release in the furnace. Both of these burners, developed with different applications in mind, interact differently with the furnace and need to be controlled accordingly. Several other types of oxy-fuel burners with variety of signature heat release profiles have also been developed at the Combustion Center of Excellence at Air Products.

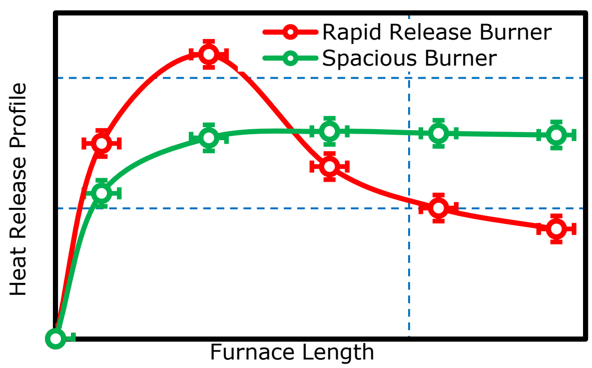

Figure 1: Heat release profiles for different types of Air Products oxy-fuel burners measured under controlled conditions in a test furnace

Discussion

Furnace setup

Air Products' Uniform Heating Oxy-fuel Burner, a spacious combustion oxy-fuel (natural gas) burner was installed in a batch steel reheat furnace (soaking pit) at the ArcelorMittal plant in Steelton, PA (see figure 2). The motivations for the oxy-fuel combustion trial were to achieve natural gas savings (reduce consumption by 45% or more), improved cycle times (reduce by 5% or more) and heating uniformity.

Typically 8–10 steel blooms averaging 8 tons each are charged into the soaking pit during each cycle. The blooms are loaded in a crisscross manner (see figure 2) resulting in several radiation-shadowed areas in the furnace, hence the motivation to use the "spacious" oxy-fuel combustion burner to enhance heat transfer. The burner was installed about 2/3rd of the height from the bottom of the furnace, while the flue located on the same side as the burner (i.e.

double pass configuration) was located about 1/3rd of the height from the bottom of the furnace. Two thermocouples (TC) were used in each soaking pit for – (1) firing rate control and (2) over temperature safety interlock. Both thermocouples were located on the opposing wall from that on which the burner was installed. A typical cycle would be as follows – (1) desired number of blooms are loaded, (2) temperature set point is input into the programmable logic controller (PLC) program that the control TC was to be maintained at, (3) set points are modified during the course of the cycle as required to accommodate needs or delays in downstream rolling operations, (4) operators inspect the blooms when temperature set points were reached and burner firing rates have leveled out at low firing rates for about 2-3 hours (soaking) and (5) blooms are drawn from the furnace if the operator deems them ready.

Figure 2: Photograph of a soaking pit furnace at ArcelorMittal's facility in Steelton, Pennsylvania

Preliminary results

Results from performance of the oxy-fuel pit and similar-sized air-fuel pit were compared after a few months of operation. Natural gas usage savings achieved were as high as 60% (well above the targeted 45%), however, the cycle times were initially slower by about 30%. This came as a surprise, as it was expected that the more efficient oxy-fuel burner would be able to heat the furnace faster. As stated earlier, the cycle times were based on operator's visual assessment of "readiness" of the steel to be drawn out of the furnace. If the blooms did not look ready, the operator would continue to keep the furnace in the soak mode for more hours before drawing them out for rolling.

Findings on deficiencies in control strategy

Though the preliminary results showed promising natural gas savings, the suboptimal performance on cycle time warranted further investigation into the potential causes. It was observed that while the rate of initial rise in temperature of the furnace was faster, the overall cycle time was slower. It is sometimes easy to focus on fringe benefits like "faster heating", while losing sight of the bigger picture. It was soon discovered that the control thermocouple (TC), located directly opposite the burner, was heating at a faster rate than the steel and achieved the temperature set point well before the steel did. In response, the PLC cut back the firing rate of the burner prematurely.

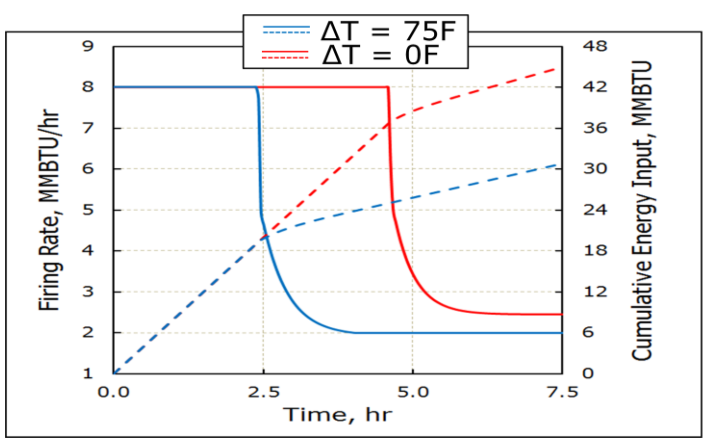

Figure 3: Illustration of firing rate and cumulative energy input into the furnace when the difference between control TC and steel temperature (ΔT) is (a) 0 °F (when control TC matches the steel temperature) and (b) 75 °F (when control TC measures higher than the steel temperature).

Development of effective location and control strategy

In order to improve upon the cycle time results, it was important to identify the best position to relocate the control TC while working with the physical constraints of the furnace. Of course, the best location would be on the steel surface (perhaps using an optical pyrometer) or better yet at the core of the bloom (but that was impractical). A control location optimizer program (CLOP) was developed at Air Products that uses a combination of computational fluid dynamic (CFD) tools, experimental data and reduced order modeling to identify the location in the furnace that best matches and correlates to the steel temperature. Figure 4 shows a snapshot of the CLOP output of ranking the location on the refractory wall that housed the control TC.

The CLOP results showed some obvious conclusions i.e. the lower you go in the furnace (where the steel is located), the better representation of the steel temperature you can get. However, every furnace has a limited number of "practical locations" of access and the CLOP helps identify the best among them. Based on this learning, the location of the control TC was moved from position "BEFORE" to position "AFTER" (shown in figure 4) at the soaking pit.

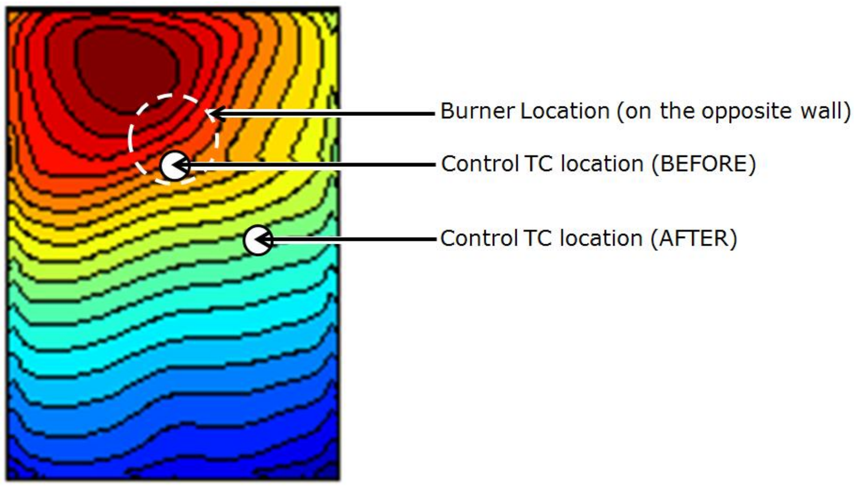

Figure 4: CLOP output ranking the locations for placement of control thermocouple for most effective control strategy. Red = worst location to Blue = best location.

Results after modification in control location

The results from the above modification showed immediate improvements in the performance of the soaking pit (summarized in Table 1). Percentage drop in the fuel usage is defined as the difference in fuel usage per ton–before (recuperative air fuel) and –after (oxy-fuel) relative to the fuel usage per ton–before. Not only did the cycle time of the oxy-fuel pit improve significantly, but also the fuel consumption improved. This might initially come as a surprise given that the burner stayed on high fire for longer using the new strategy, but the operators were able to draw the steel that was soaked much earlier. Caution needs to be maintained when using this strategy, as there is a potential to run the furnace at higher refractory temperatures using this approach. During the course of the current investigation, the "over temperature" thermocouple was well within the limit. So, in reality there was further room for improvement. Additional qualitative feedback was received from crane operators that the reheated steel blooms were "more uniform front-to-back and top-to-bottom" and "the amount of scale drop-off while unloading" was much lower, compared to other air-fuel pits. Unfortunately, these observations weren't quantitatively confirmed because of trial time constraints.

Table 1: Comparison of obtained benefits before and after improvement in control location

Description	Fuel Usage	Cycle Time	Observations
Oxy-fuel only	– 60 %	+ 30%	Reduced fuel usage but longer cycle time
Oxy-fuel + control location	– 68 %	– 8%	Faster cycle time and fuel usage is reduced further

Other heating strategies to consider

In addition to CLOP analysis, burner location strategies may also be considered to improve the overall performance of the furnace. Sizing and location of burners relative to physical dimensions of the furnace, sizes/shapes/position of products to be reheated (or melted), size/location of flue gas duct, can determine the effectiveness of energy transfer. For example, it can be seen from figure 4 that the location ranking plot is skewed to one side (to the left), which comes from the orientation of the top layer of the crisscrossed blooms (figure 2). Minimizing flow stagnation zones, reducing interaction between flames, convective fluid dynamic patterns, and other strategies play a key role in the uniform distribution of energy in the furnace and avoidance of issues like hot spots. Furnace manufacturers usually put emphasis on this when building a furnace for a given operation, however, these details may be easily overlooked while retrofitting or building additional energy capacity into an existing furnace with oxy-fuel conversions; sometimes resulting in suboptimal results.

Conclusions

A "spacious" oxy-fuel burner was trialed in a batch steel reheat (soaking pit) furnace at ArcelorMittal Steelton with motivation to reduce fuel consumption, reduce cycle time and achieve better heating uniformity compared to existing recuperative (700 F) air-fuel system. Preliminary results showed 60% fuel savings, however, the cycle times were initially slower by almost 30%. Further investigation showed a deficiency in the burner control strategy that was in place. A control location optimizer program (CLOP) was developed by Air Products to determine a better location for the control TC. Using the CLOP recommendations, the control TC was relocated to an alternative (practical) location. The cycle times improved significantly to 8% faster compared to the air-fuel system in place (i.e. 32% faster than oxy-fuel with old control strategy) and further improved upon the fuel savings to 68%. The above study showcases the importance of understanding the flame-furnace interaction and ensuring that an effective control strategy is in place to maximize the benefit from the heating process.

Acknowledgement

Just prior to the installation of the oxy-fuel system for evaluation of improvement of existing soaking pit furnaces, ArcelorMittal Steelton received confirmation to move forward on a capital project to construct a brand new continuous steel reheat furnace onsite in place of the existing soaking pit furnaces. So, improvement of the soaking pit furnaces was no longer a priority. We would like to acknowledge the commitment of the rolling mill management and operators for continuing with the installation of oxy-fuel burner technology and their willingness to co-author/share the learnings that we gathered during the trial, through this article.

References

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