# Application of Oxygen-Enriched Combustion in an Industrial Reheating Furnace Using CFD


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An important part of the hot rolling process is the reheating of steel products to target temperature using the combustion of natural gas in a furnace. To increase energy efficiency of this reheating process, oxygen enrichment can be used with high entrainment of reaction product gases to distribute the combustion reaction area. The modeling of various configurations was undertaken using computational fluid dynamics to use oxygen enrichment or oxy-fuel in order to avoid changes in the furnace zone temperatures while reducing fuel usage. Effects on the combustion, temperature distribution, species and heat transfer to the steel product are under study.


An important part of the hot rolling process is the reheating of steel products to target temperature using the combustion of natural gas in a furnace. The reheat furnace is the most energy-intensive part of the hot rolling mill; it commonly comes second only to the energy required by the blast furnace in the entire steelmaking process.[1] Methods of reducing fuel and energy usage for industrial furnaces relate back to the combustion process.[2,3] Increasing the combustion air temperature using recuperative or regenerative processes on the flue gas is one commonly implemented method. Control of the combustion itself is also important; while stoichiometric mixing is the theoretical ideal, turbulent mixing and dilution requires some excess air, commonly assumed as 10% by industrial rules of thumb.[4,5] Improvement of mixing could reduce the necessary excess air and improve fuel economy. Oxygen enrichment of the combustion air beyond 21 vol.% oxygen is also used to improve mixing. In this scenario, the molar fraction of oxygen is increased, replacing nitrogen in the combustion air. Out of the three, the least implemented in steelmaking is the use of oxygen enrichment.

Oxygen enrichment can be used with high entrainment of reaction product gases to distribute the combustion reaction area. This entrainment of furnace gases slows the reaction, which lowers the overall temperature and spreads the high-temperature area throughout the zone for a more uniform heating to the product. Higher temperatures may yield higher heating rates, but they will also lead to the generation of larger amounts of nitrous oxides and may cause damage to the internal structures of the furnace. Natural gas is largely used inside reheat furnaces, which can be simplified to the reaction of methane with air:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \quad \text{(Eq. 1)}$$

Here, nitrogen does not contribute anything to the reaction besides being a diluent. Nitrogen reduces the possibility of oxygen meeting methane and requires energy to be brought from its original temperature to the temperature of the combustion products.[6] As such, any reduction in nitrogen content via oxygen enrichment can increase the flame and gas temperatures within the furnace through basic thermodynamic principles. This is usually

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accompanied by a reduction in the firing rate of the furnace and an overall fuel savings.

There are many studies on reheating furnaces focused on modeling the combustion between air and a fuel, usually natural gas or coke oven gas. However, there are fewer studies regarding oxygen enrichment, which can be implemented in many ways. Bisio et al. reviewed the benefits of oxygen enrichment through an exergy analysis and found that there is clear potential for fuel reduction based on the increase in flue temperature and in oxygen enrichment level.[7] They also discussed the economic benefits in relation to oxygen enrichment, such as replacing natural gas with blast furnace or coke oven gas or by increasing the productivity of the furnace. As such, the implementation of oxygen enrichment has been of interest for many researchers. Atreya summarized a report put together for the U.S. Department of Energy (DOE) on pre-heated combustion air systems with oxygen enrichment.[8] The higher-temperature flames brought about using oxygen enrichment of the oxidant also increases the NOx thermal generation rate. One objective of this study was to implement oxygen-enriched combustion without this increase in NOx formed and with a simultaneous reduction in fuel usage. They attempted this by using various configurations of the oxidant and fuel inlets and differing momentum ratios of the two in order to force entrainment of the furnace gases into the jets before they could meet and fully react. This delayed reaction and elongated reaction zone resulted in homogeneous combustion. The entrainment of furnace gases and the high momentum resulted in efficient mixing and increased the residence time of the NOx formed, allowing it to "reburn." Lowe et al. also investigated the benefits of "oxy-firing" on carbon capture; removing the nitrogen results in less overall flow leaving the furnace with a much different composition.[9] This composition is largely water vapor, which can be condensed to quickly recover the carbon dioxide in the product gases. Iron oxidation under air-fired combustion and oxygen-enriched combustion was experimentally studied by Sobotka et al.[10] The increase in temperature was also found to increase the predicted scale formation, especially for 100% oxy-fuel combustion. Applying these principles within an industrial environment can prove difficult due to the competing effects in beneficial and detrimental phenomena. To further investigate the implementation of oxygen enrichment, computational fluid dynamics (CFD) was utilized by various researchers.

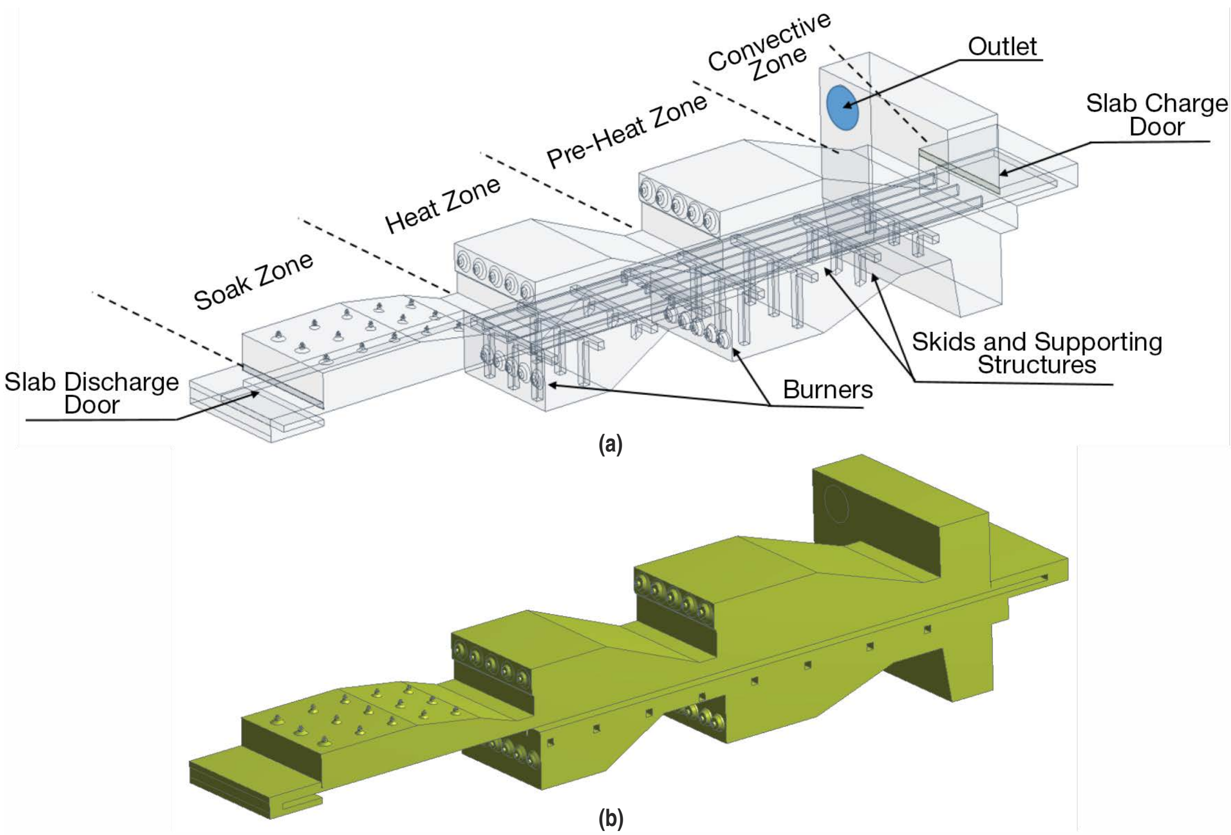
Karimi and Saidi modeled oxygen enrichment within a 2D pusher-type reheating furnace in 2010.[11] They found that the furnace efficiency and production increased with the use of oxygen-enriched combustion while reducing energy consumption per ton of steel and NOx production rates. This was mainly attributed to the higher flame temperature and corresponding increase in the heat flux to the steel product along with the reduced nitrogen in the product gases. A recommendation of oxygen-enriched combustion levels between 21 and 45 vol.% was given by the authors. Alvarez studied the differences in NOx generation in oxy-coal combustion in an entrained flow reactor simulation with air and $O_2/CO_2$ environments.[12] Increasing the level of oxygen enrichment was found to consistently predict more NOx formation than found in scenarios with 21% $O_2$ by volume. Recently, Mayr et al. investigated the performance increase of using oxy-fuel burners for a pusher-type furnace in 2017.[13] Using oxy-fuel burners instead of air-fuel burners resulted in a productivity increase of 13% and a simultaneous increase in efficiency from 62.9% to 65%.

The entire reheating furnace process is quite complex. Implementing operational changes can be costly due to the downtime required and the time to run any necessary experiments. For example, it can be laborious and expensive to add thermocouples into a slab to study the temperature evolution of slab as they traverse the furnace. As such, many researchers have turned to computational methods to study the reheating furnace and the benefits of various operational changes. While many of the computational methods are simplified models based on empirical work, when adequately validated, these methods can still give an accurate view of the reheating furnace process. For the purposes of this paper, the numerical modeling of various burner configurations was undertaken using CFD to use oxygen enrichment or oxy-fuel to maintain a given slab heating rate while reducing fuel usage. Medium oxygen enrichment (46 vol.% $O_2$) and oxy-fuel (100 vol.% $O_2$) were applied to the preheating zone, which has the highest fuel usage of the three zones.

## CFD Methodology and Modeling

**Models —** The governing equations determine the solution of the simulation through the solution of the conservation equations for momentum, mass and energy, along with scalar transport equations. ANSYS Fluent © 18.2 and 19.2 were used to solve the numerical equations. The overall solver is the pressure-based coupled solver (PBCS), and all equations are solved using second-order schemes except for the discrete ordinates model. In addition to the PBCS, the pseudo-transient method was utilized. Both solver settings have been found to be more efficient than the alternative.[14] The realizable k-ε model was used to solve for turbulence. Radiation was calculated using the discrete ordinates model; the weighted sum of gray gases model was applied to the furnace gas absorption

Figure 1



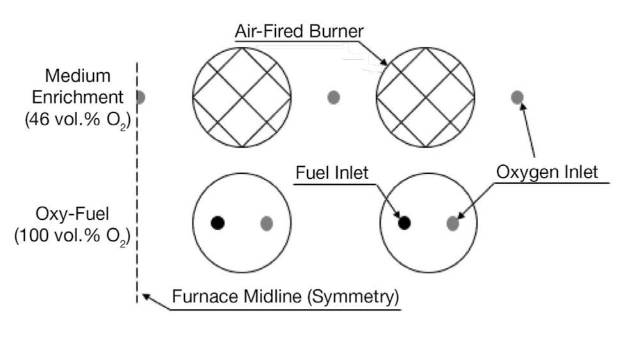

*Domain of the full furnace model with transparency (a) and without (b).*

coefficient. For combustion, non-pre-mixed combustion models were used. For the base case, the steady flamelet model was used with thermodynamics and chemical kinetics from the San Diego Mechanism.[15] For oxygen enrichment cases, the equilibrium model was utilized to use a three-stream approach with the thermodynamics, again, from the San Diego Mechanism. This was necessary as the oxygen enrichment is only applied to the pre-heating zone, requiring inlets for air, oxygen and the natural gas. Previous study of the differences in these modeling approaches has found the largest difference lie almost entirely within the flame envelopes.[16]

Geometry — The domain of the current simulation setup was halved to exploit a symmetry boundary condition. This choice required a uniform lineup of the slabs within the furnace. The furnace of study in this work is the ArcelorMittal Burns Harbor (now Cleveland-Cliffs – Burns Harbor) pusher-type furnace #1. Mesh density was much higher in crucial regions related to areas of mixing and combustion, especially near the burners. The slab domain is a rectangular prism and is also halved to match the full furnace domain. Fig. 1 shows the domain of the full furnace. The full furnace is 112 feet long, 24 feet tall and 34 feet wide. The slab domain is modeled after an industrial slab of average dimensions (318 inches x 55 inches x 9.9 inches). It is halved along the largest dimension.

In the full furnace, there is the pre-heat, heat and soak zones. Of the three, only the soak zone does not have bottom burners, but instead a hearth that the slabs are pushed along. As this is a pusher-type furnace, the slabs rest on water-cooled skids. Skids affect the slab heating via radiative shielding,[4] so they were modeled as wall boundaries on the bottom of the slabs. Supporting structures were also cut from the domain to model any potential flow obstruction. In this way, the radiative shielding and the flow changes caused by the skid and structural supporting skids were modeled without modeling the conduction or convective heat transfer, which accounts for very little of the skid impact. The outlets consist of the main furnace outlet and the furnace charge and discharge doors, which are modeled as slightly open. The main furnace outlet is above and to either side of the furnace charge door, thus encouraging the flow to travel in the opposite direction to the slabs.

## Figure 2




*Burner configurations used for oxygen enrichment conditions.*

For oxygen enrichment cases, the burner configuration must be changed to promote entrainment of furnace gases and increase the momentum of the incoming flow. As nitrogen constitutes the bulk of the mass flow coming into the air-fired burners, reducing the nitrogen leads to a somewhat dramatic decrease in the momentum of said flow. This reduces the flame shape and leads to elevated temperatures not found in normal air-fired combustion operation. Low levels of oxygen enrichment (>30 vol.% $O_2$) may not need a change in the burner, but higher levels up to oxy-fuel will benefit from a different burner configuration. Fig. 2 shows the burner configurations for each level of oxygen enrichment in the study as recommended by industrial guidance from Praxair Inc.;[17] these are applied to both the top and bottom of the pre-heating zone. Fig. 2 is truncated and does not show all of the burners in the zone. For medium oxygen enrichment, the air-fired burners (obfuscated here) are still in use with oxygen ports between each burner and between the furnace sidewalls and the burners closest to them. For oxy-fuel, the face of the burner is replaced by two inlet ports for fuel and oxygen. These ports are separated by 5 inches and the fuel port is closest to the furnace midline on all the burner faces.

For the oxygen in both the medium-oxygen enrichment and oxy-fuel cases, the flow needed to be at sonic conditions at the inlet port.[17] As such, the size of the inlet ports was dependent on the total flow of oxygen into the zone, which changes with the firing rate drawbacks. For the fuel ports in the oxy-fuel case, the velocity was set to be a constant 550 feet/second, which also influenced the final area of the fuel port.[17]

## Boundary Conditions

**Base Case:** Boundary conditions were largely provided by collaborators at the plant. Conditions were monitored throughout a given day and key boundary conditions were tracked. A slab with thermocouples drilled into it was also run through under these conditions. As such, validation has been done based on time-averaged conditions in previous published works.[18]

Fuel and air conditions are shown in Table 1. Only the pre-heat and heat zones have a top and a bottom section of burners. The soak zone is primarily composed of small burners (soak small) with a row of larger burners (soak large) near the discharge of the furnace. There is a secondary and a primary air due to the staged combustion instigated by the burner setup. The secondary air is 80% of the total air. Of note is that the air temperature is elevated due to recuperative technology already in use at this facility. These values are averaged over hours of tracked data provided by industry and input uniformly for each burner. These conditions are for the total of all burners in each zone; as such, each burner will get the same fraction of this total.

The fuel in question is natural gas with a methane content of 95.98 vol.% along with 2.26 vol.% ethane and other trace species such as nitrogen, carbon dioxide and propane. Only those species with more than 0.1 vol.% are input into the model.

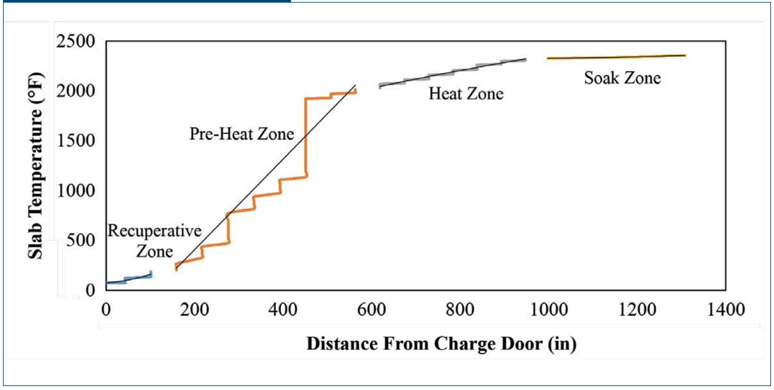
The temperature profile assigned as the boundary condition on the slab walls was derived as a piecewise function from the slab thermocouple temperatures recorded. This temperature evolution and the breakdown of the function per zone is shown in Fig. 3. In this graph, a "recuperative" zone is labeled. This zone, also called the non-firing zone, shows a slight increase in slab temperature due to convective heat transfer from high temperatures gases produced from the subsequent firing zones. This area is near the main outlet of the furnace, so all gas flow passes over these relatively cold slabs. These temperatures only vary in the direction of slab travel and are thus uniform in the axial direction. This is untrue for further slab temperature profiles provided via the iterative methodology described previously.

## Table 1

*Fuel and Air Inlet Conditions*

| Zone | Fuel ($ft^3$/sec) | Primary air ($ft^3$/sec) | Secondary air ($ft^3$/sec) | Air temperature (°F) | Fuel temperature (°F) |
|---|---|---|---|---|---|
| Pre-heat top | 34.8 | 83.5 | 333.9 | 811.3 | 80.0 |
| Pre-heat bottom | 27.9 | 67.9 | 271.8 | | |
| Heat top | 14.7 | 32.9 | 131.4 | | |
| Heat bottom | 10.3 | 23.0 | 92.1 | | |
| Soak small | 9.5 | 115.6 | N/A | | |
| Soak large | 4.6 | 51.5 | N/A | | |

Figure 3




*Slab temperature throughout the furnace from thermocouple measurements.*

Furnace and skid walls are modeled as adiabatic. The emissivity of the slabs is assumed to be a constant 0.75.

**Oxygen Enrichment Cases:** The oxygen enrichment in this study is only applied in the pre-heating zone. Scale formation is typically quite small in the pre-heating zone, so the higher concentrations of oxidizing species in this zone caused by higher levels of oxygen enrichment are less of a concern. This zone also uses the most fuel, so a reduction in fuel usage realized in this zone would be the most beneficial out of the three zones in the furnace. Finally, the flow from the soak and heating zones will further dilute the unique atmosphere found in the pre-heating zone due to the application of oxygen enrichment.

Another benefit of oxygen enrichment is also directly due to the reduction of nitrogen. Energy that would have gone to heat the relatively inert nitrogen up to the temperature of the product gases is now able to continue to heat said product gases. In terms of adiabatic flame temperature, much higher flame temperatures can be reached. With the higher flame temperatures and higher concentrations of radiating species, the radiation heat transfer is highly enhanced. The largest issue for oxygen enrichment is then directly related to this higher flame temperature. The higher the temperatures rises, the more NOx will be formed. To avoid NOx formation while still utilizing the benefits of oxygen enrichment, the reaction must be delayed. A delayed reaction will release less heat in one area at a given time. Usually this delayed reaction is accomplished through higher-momentum jets to promote the entrainment of furnace gases as previously described. Alternatively, staged combustion is also possible, where the oxidant is fed to the fuel in stages.

After discussion with industrial collaborators from Praxair, the case parameters were developed as shown in Table 2.[17] Case 1 refers to the baseline air-fired combustion case, and cases 2 and 3 are for medium oxygen enrichment and oxy-fuel cases respectively. Cases 2 and 3 have the same firing rate as case 1 (0% firing rate drawback). The oxygen-to-fuel ratio was kept the same for all cases to keep excess oxygen the same as well as to reduce the number of changing variables. The velocities shown for oxygen give the oxygen jet the sonic condition at the room temperature condition at which it enters the furnace.

As a firing rates are kept the same for the oxygen-enriched cases, it was expected that the slab heating rate for the pre-heating zone would increase. As this study is focused on fuel savings, this increase would necessitate further cases with firing rate drawbacks to match the baseline heating condition. As such, additional oxygen enrichment cases are described as needed in the results section under the respective "Firing Rate Drawback" section headers for both oxygen enrichment levels. However, the circular ports described by Fig. 2 are replaced by ports in a triangular formation equidistant from one another. The area is determined by the flowrate given by the drawback along with the velocity found in Table 2. For the oxy-fuel case, these ports — a trio for both the fuel and oxygen incoming flows — are offset from the burner face normal direction into the furnace by 13° away from each other. This gives the oxygen and fuel jets incoming into the furnace for the firing rate drawback of the oxy-fuel case an angle of 26° between them. This added distance also helps to delay the reaction and promote a more homogenous combustion.

## Results

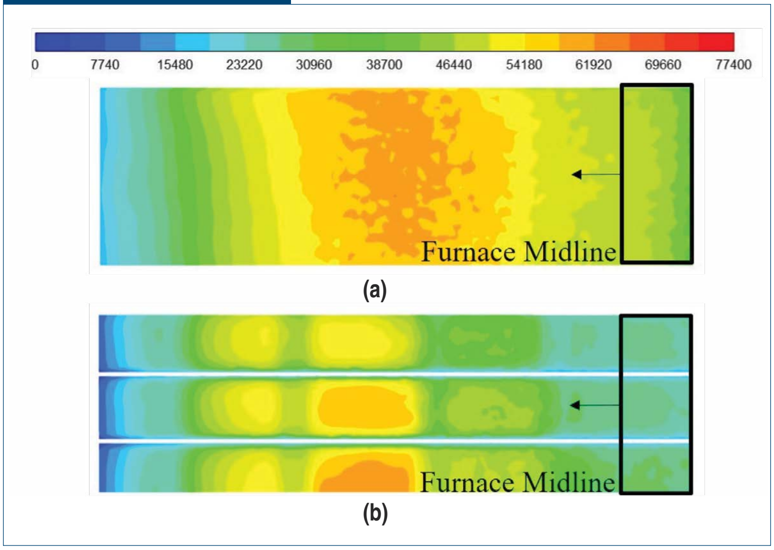
**Base Case —** As the main concern is matching the heating of the slab, a small analysis of the base case heating is required. This heating is based on the prescribed temperature profile of the slabs and can be

Table 2

*Oxygen, Air and Fuel Conditions for Oxygen Enrichment Cases*

| Case | Oxygen content (%) | Oxygen/fuel ratio | Velocity (ft/s) Primary air | Secondary air | $O_2$ | Fuel |
|---|---|---|---|---|---|---|
| 1 | 21 | | 430 | 270 | — | 120 |
| 2 | 46 | 2.51 | 130 | 80 | 1,080 | 120 |
| 3 | 100 | | — | — | 1,080 | 550 |

## Figure 4




*Heat flux into the slabs in the pre-heat zone top (a) and bottom (b) for the base case [Units: Btu/h-ft$^2$].*

seen in terms of heat flux in Fig. 4. The color bar has a high maximum heat flux compared to the colors shown as this color bar is shared throughout the paper by all heat flux figures. As such, the highest heat flux of all cases is utilized. The half-slab shown moves from right to left on the page. The largest heating is roughly in the middle of the zone for both the top and bottom; the largest overall heat flux is found on the bottom. The lowest heat flux is at the end of the zone where the furnace roof comes down and cuts off the steel product from view of the flames in the pre-heat zone.

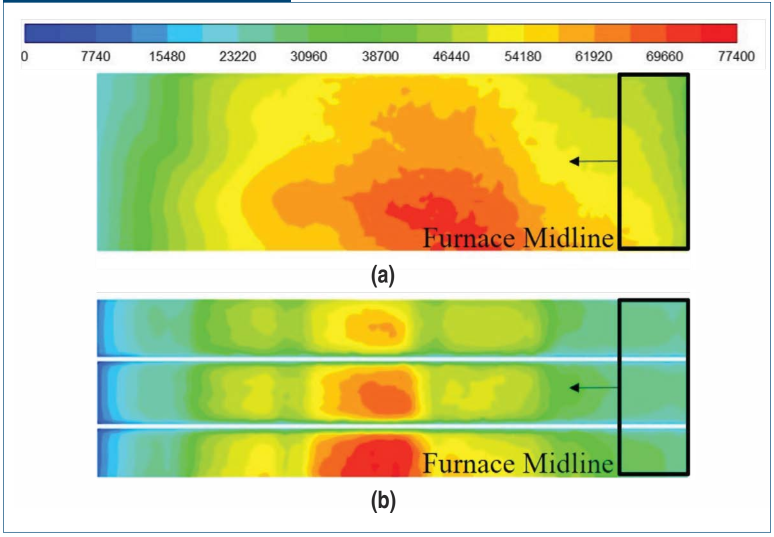
The total energy into the slab top and bottom is 71.5 MMBtu per hour. Of this, 61% is through the top of the slab. 91% of this energy is from radiation, with the remaining 9% from convection.

**Medium Oxygen Enrichment —** The 46 vol.% oxygen content for the combustion oxidant injected leads to a lower nitrogen injection and higher flame temperature. Considering most heat is transferred through radiation, which is influenced by flame temperature, injecting same amount of fuel will cause overheat.

Needing to match the heating of the base case, an iterative trial-and-error method was attempted. The first case run was a firing rate drawback of around 40%. This entailed using 60% of the oxidant and of the fuel as used in the base case. The areas of the oxygen ports were varied to maintain sonic conditions. The lowest heat flux into the slab is still at the end of the pre-heating zone to the left of the page, and the trend of heating near the middle of the pre-heating zone is same with base case. The largest heating on the top of the slab near the core of the slab, and the same is true of the bottom of the slab.

Heat into the slab from the 40% lead to a third case that was roughly between the previous cases. This final case entailed the implementation of a 25% firing rate drawback. The heat flux into the slab for this case is shown in Fig. 5. The trends of the heating to be hotter toward the core of the slab are consistent with previous medium oxygen enrichment cases, but the overall heating is much closer to that found in the base case. Total energy input was 78.2 MMBtu per hour, which is slightly more than that found in the base case (~110%), which shows that there may still be a need to decrease the pre-heating zone firing rate slightly. Of this heating, 59% was through the top, and radiation accounted for around 91% of the energy coming into the slab.

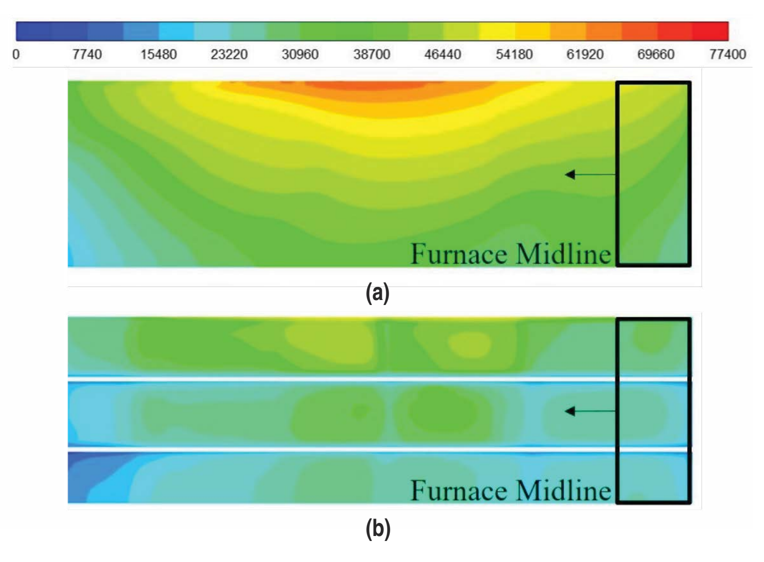
## Figure 5




*Heat flux into the slabs in the pre-heat zone top (a) and bottom (b) for the medium oxygen enrichment case with a 25% firing rate drawback [Units: Btu/h-ft$^2$].*

**Oxy-Fuel —** For the oxy-fuel cases, the burner configuration was very different from that of the baseline case, and the only nitrogen in the zone is from flow incoming from spatially subsequent zones (heating and soaking). As such, the heat flux can be very high in certain areas. And, the oxy-fuel cases have very

Figure 6




*Heat flux into the slabs in the pre-heat zone top (a) and bottom (b) for the oxy-fuel case with a 50% firing rate drawback [Units: Btu/h-ft$^2$].*

high-momentum jets coming from the burner face. This increased velocity increases the convection near the slab. The overall rise in temperature due to hotter flames also enhances convection, though to a lesser degree than it enhances radiation. This leads to an overall larger heat flux into the slab relative to the base case.

To this end, the firing rate needs to be reduced and a fuel savings is expected to be realized. From literature, an optimistic possibility of a 50% firing rate drawback (with an associated 50% fuel savings) was found for industrial furnace operation.[19] Applying this firing rate drawback (see Fig. 6) shows that this assessment may have been a little too idealistic. Fig. 6 shows low heat flux into both the top and bottom of the slab. Interestingly, the highest heat fluxes here are found at the edges of the slab. This is caused by the incoming flow from subsequent zones pushing the top and bottom flames in the pre-heat zones to the sides from large recirculation zones that are found in the base case.[16] Regardless, the energy into the slab for this case was found to be around 65.3 MBtu per hour, which is 92% of the energy input of the baseline case. Radiation accounted for around 93% of this energy input. As this energy input is lower than the baseline, a more modest reduction of around 40–45% is expected to obtain a heating profile closer to that of the baseline case.

## Conclusions

The quality of a steel product relies heavily upon many different conditions and processes in the overall steelmaking and finishing process. Within the reheating furnace, the rate and intensity of slab heating needs to be fast enough for the sake of productivity and efficiency in reaching the target dropout temperature, but slow enough so as to avoid overheating the steel or propagating cracks. In the effort of utilizing a fuel savings from oxygen enrichment, medium oxygen enrichment and oxy-fuel conditions were applied to the pre-heating zone.

Without drawing back the firing rate, the heating in this zone increases with increasing oxygen enrichment, which shows a large potential for fuel savings, among other benefits of oxygen enrichment. For medium oxygen enrichment, a firing rate drawback of 25% was found to give around 110% of the total energy input of the base case. For oxy-fuel case, an optimistic attempt to reduce fuel usage with a 50% firing rate drawback, however, was found to yield an energy input of 92% that of the base case. Further estimates place more likely firing rate drawbacks for the medium oxygen enrichment and oxy-fuel cases to be closer to 33% and 45% respectively.

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## References

1. S.H. Han, S.W. Baek and M.Y. Kim, "Transient Radiative Heating Characteristics of Slab in a Walking Beam Type Reheating Furnace," *International Journal of Heat and Mass Transfer,* Vol. 52, No. 3–4, January 2009, pp. 1005–1011.
2. P. Mullinger and B. Jenkins, *Industrial and Process Furnaces: Principles, Design and Operation,* Elsevier via Butterworth-Heinemann, Hungary, 2008.
3. S.R. Turns, *An Introduction to Combustion: Concepts and Applications,* 3rd ed., McGraw-Hill, 2012.

4. Z. Li, P.V. Barr and J.K. Brimacombe, "Computer Simulation of the Slab Reheating Furnace," *Canadian Metallurgical Quarterly,* Vol. 27, No. 3, 1988, pp. 187–196.
5. J.M. Casal, J. Porteiro, J.L. Miguez and A. Vazquez, "New Methodology for CFD Three-Dimensional Simulation of a Walking Beam Type Reheating Furnace in Steady State," *Applied Thermal Engineering,* Vol. 86, April 2015, pp. 69–80.
6. C.E. Baukal Jr., *Oxygen-Enhanced Combustion, 2nd ed.,* CRC Press, 2013.
7. G. Bisio, A. Bosio and G. Rubatto, "Thermodynamics Applied to Oxygen Enrichment of Combustion Air," *Energy Conversion and Management,* Vol. 43, December 2002, pp. 2589–2600.
8. A. Atreya, "Highly Pre-Heated Combustion Air System With/Without Oxygen Enrichment for Metal Processing Furnaces," Final Progress Report For DE-FC36-02ID14348, February 2007.
9. C. Lowe, N. Brancaccio, J. Jamaluddin, J.A. Erazo Jr. and C.E. Baukal Jr., "Technology Assessment of Oxy-Firing of Process Heater Burners," *Energy Procedia,* Vol. 37, 2013, pp. 7793–7801.
10. C. Sobotka, H. Antrekowitsch and H. Schnideritsch, "The Influence of Oxygen-Enriched Burner Systems on the Scale Formation of Steel Alloys During Heating Processes," *AISTech 2014 Conference Proceedings,* 2014.
11. H.J. Karimi and M.H. Saidi, "Heat Transfer and Energy Analysis of a Pusher Type Reheating Furnace Using Oxygen Enhanced Air for Combustion," *Journal of Iron and Steel Research International,* Vol. 17, No. 4, April 2010, pp. 12–17.
12. L. Alvarez, C. Yin, J. Riaza, C. Pevida, J.J. Pis and F. Rubiera, "Oxy-Coal Combustion in an Entrained Flow Reactor: Application of Specific Char and Volatile Combustion And Radiation Models For Oxy-Firing Conditions," *Energy,* Vol. 62, December 2013, pp. 255–268.
13. B. Mayr, R. Prieler, M. Demuth, L. Moderer and C. Hochenauer, "CFD Modeling and Performance Increase of a Pusher Type Reheating Furnace Using Oxy-Fuel Burners," *Energy Procedia,* Vol. 120, August 2017, pp. 462–468.
14. M. Keating, "Accelerating CFD Solutions," ANSYS: Tips and Tricks, Vol. 5, No. 1, 2011, pp. 48–49.
15. "Chemical-Kinetic Mechanisms for Combustion Applications," Mechanical and Aerospace Engineering (Combustion Research), University of California at San Diego.
16. B. Worl, "Numerical Investigation of Combustion and Oxidation in a Steel Reheat Furnace," master's thesis, Purdue University Northwest, December 2019.
17. Personal Communications with Kelly Tian, Praxair Inc., 2019.
18. X. Liu, G. Tang, A. Silaen, J. Cox, K. Johnson and C. Zhou, "Investigation of Operational Effects on Slab Heating Characteristics in a Pusher-Type Reheat Furnace With Continuous Slab Motion," *ASME 2017 Heat Transfer Summer Conference,* Bellevue, Wash., USA, July 2017.
19. S. Gangoli, B. Kenworthy, G. Buragino, R. Hewertson, A. Sane and J. Mocsari, "Oxy-Fuel Technologies and Strategies for Secondary Aluminum Melting Operations," *Light Metal Age,* August 2017, pp. 22–27. ✦


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