

Synchronized Oxy-fuel Boost Burners for Zero-Port Performance Optimization in Float Glass Melting Furnaces

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Abstract

Zero-port oxy-fuel boost burners have become widely accepted in float glass melting furnaces as a valuable means for increasing glass production and/or improving efficiency. However, boost burner effectiveness is often limited by flame interaction with the highly turbulent air-fuel flames. Moreover, both the strength and direction of these oxy-fuel flames versus air-fuel flame interactions are dramatically shifted following each regenerator reversal cycle. The result of these effects can include overheating of the charge wall and “snubbing” of the flame, causing concentrated heat release close to the breast wall and/or flame lofting toward the crown. By understanding the nature of these interactions, Air Products researchers have developed an advanced burner technology that is capable of automatically adjusting flame properties (particularly length, luminosity and momentum) with each regenerator reversal to avoid negative effects, while maximizing oxy-fuel performance benefits. This development combines Air Products Process Intelligence technology with the recently commercialized Cleanfire® HR_x™ burner. Both the methodology and beneficial results of field implementation of synchronized oxy-fuel boost burners are presented in this paper.

Introduction

Oxy-fuel boost burners have been employed in air-fired regenerative furnaces for a few decades and the benefits are well known [1,2]. The primary benefits include higher furnace efficiency and/or lower fuel consumption, higher productivity, improved glass quality, and lower NO_x [3]. While oxy-boosting has its benefits, there are also some challenges which include maintaining a consistent, highly luminous flame that can withstand the high levels of turbulence created inside air-fired regenerative glass furnaces. The oscillatory nature of the firing direction within a regenerative furnace creates changing air currents and turbulence patterns that can cause the boost burner flames to loft, deflect, and appear inconsistent. The inconsistent performance of the boost burner flames can result in overheating of the nearby charge wall. Also, premature flame shortening or “snubbing” can cause a concentrated heat release close to the breast wall and/or flame lofting toward the crown, releasing heat in the upper part of the furnace and away from the glass surface. This is especially true with staged oxy-fuel burners, where the mixing of oxygen and fuel is delayed by redirecting a portion of the oxygen above or below the flame in order to create a longer more luminous flame. Staged burners tend to lose flame momentum as staging levels increase, leading to increased susceptibility to lofting or snubbing due to turbulence. Many furnaces deal with the problem of boost burner flame turbulence by choosing flame stability over optimal heating, that is, they choose conservative burner settings (i.e. no staging) so the boost burner flames look acceptable during each reversal cycle. This leads to poor flame optimization and the benefits of oxy-boosting are greatly diminished.

To maximize the benefits of oxy-boosting and overcome the present challenges, Air Products developed a synchronized boosting system that is capable of automatically adjusting flame properties (particularly length, luminosity and momentum) with each regenerator reversal. The synchronized boosting system allows furnace engineers to customize each burner's settings for each firing direction and local atmosphere conditions. Such a system can ensure that each burner's flame quality is maximized to overcome the negative effects of turbulence generated by the regenerator reversal cycles. **Figure 1** depicts potential gas recirculation zones that can develop in the area between the Port 1 air-fired burners and the Port 0 oxy-fuel boost burners and negatively impact burner performance.

These recirculation zones can cause the boost burner flames to become entrained into the flow of the nearest air-fired burner (when firing on the same side), or it can alternately impede or deflect the flow of a boost burner firing in the opposing direction. This situation was modeled using Ansys Fluent computational fluid dynamic (CFD) simulation tools. In the simulation, a typical air-fired regenerative furnace size and geometry was replicated based on the production rate of 650 tons (U.S.) per day. **Figure 2** shows CFD modeling results that validate this observation.

Figure 1: A zone of recirculated gases can develop between the charge wall and the Port 1 air-fuel burners. This can cause the boost burner flames to deflect or be drawn into the nearby Port 1 air-fuel flame

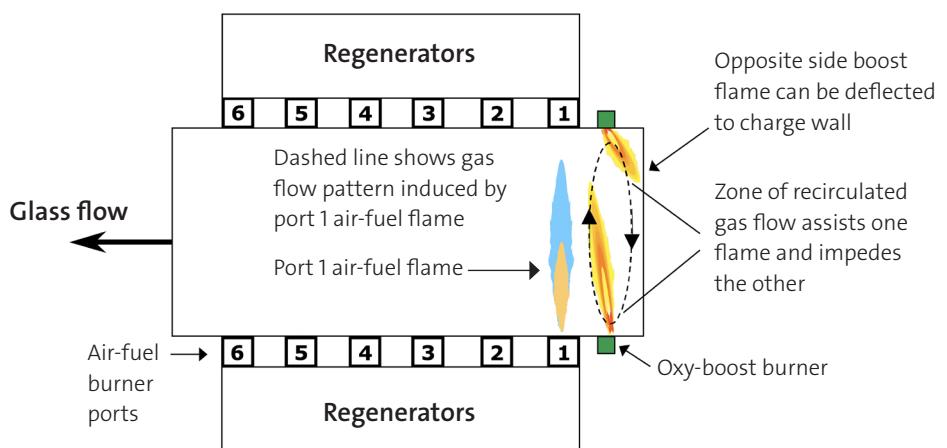
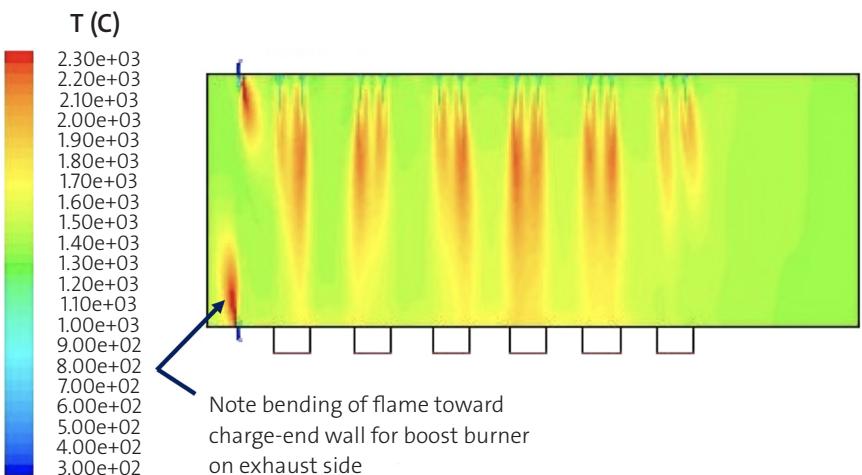


Figure 2: CFD modeling results showing the effect of recirculation patterns near the boost burners (far left side in the figure) that can cause the boost burner flames to deflect

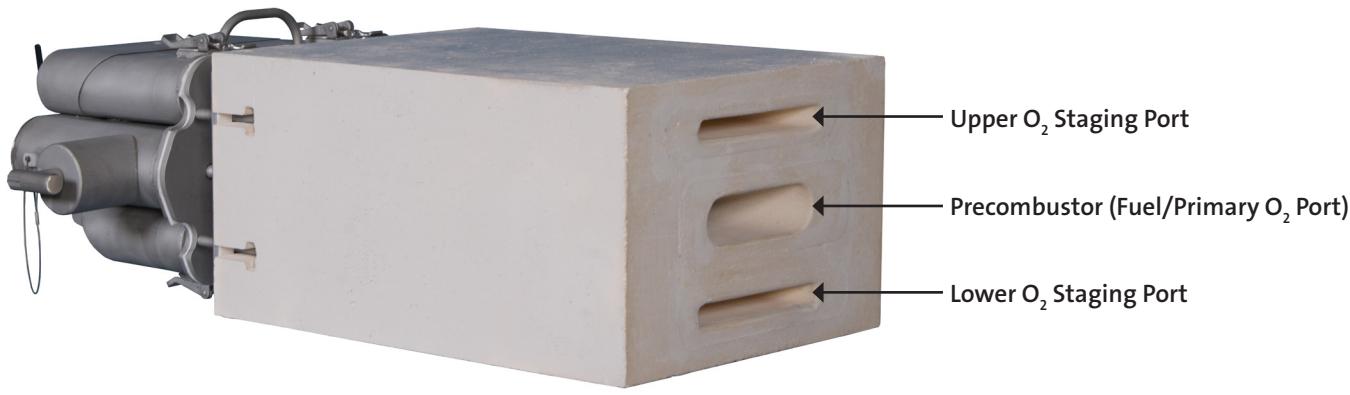


Air Products recently commercialized HR_x burner was used as the boost burner during the trial of the synchronized boosting system. The burner was designed to achieve a very high degree of staging (95%) with high momentum and luminosity and is a good fit for oxy-boosting applications [4]. The HR_x burner has a high level of adjustability, including two individual valves that control the direction and amount of staging oxygen. The HR_x burner replaced the Cleanfire® HR_i™ Advanced Boost burner in this project, therefore the results presented in this paper will show the effect of the transition from the HR_i Advanced Boost burner to the HR_x burner, with synchronized boosting. The impact of various furnace operational parameters will be discussed, including the effect on energy consumption, local furnace temperatures, and glass defects.

The Cleanfire® HR_x™ Burner

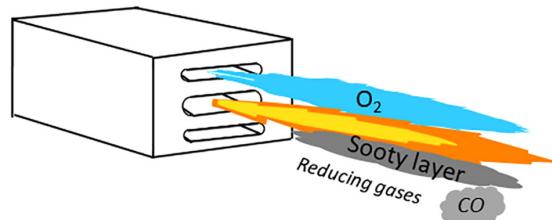
The Air Products Cleanfire® HR_x™ burner was a key component in the synchronized boosting system mainly because of its high degree of adjustability in controlling flame properties such as momentum and luminosity. The HR_x burner is a flat flame oxy-fuel burner designed for the glass industry that has several features which include increased flame radiation for high fuel efficiency, foam reduction capability for higher quality glass production, low NO_x emissions, and optional Instrumentation and sensors for remote performance monitoring. **Figure 3** shows a photo of the Cleanfire HR_x burner from burner block hot face.

Figure 3: Photo of Cleanfire® HR_x™ burner from the burner block hot face



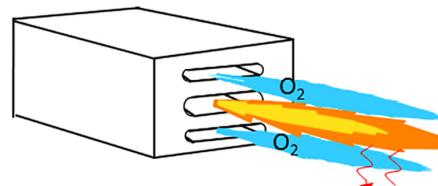
The HR_x burner block has three ports; a central precombustor port where the fuel and primary oxygen initiate combustion and the flame is rooted and stabilized, and upper and lower oxygen staging ports. The HR_x burner has unique oxygen staging capability where the staging oxygen can be directionally controlled and diverted through either the upper or lower (or split between both) staging ports that surround the primary precombustor. The modes of oxygen staging include Foam Control mode, Melt mode, and Split mode. Such directional control of staging oxygen provides several benefits including adjustment of flame length, momentum and luminosity. **Figure 4** depicts the various staging modes for the HR_x burner. Oxygen staging also prevents NO_x.

Figure 4: Various staging modes of the HR_x burner



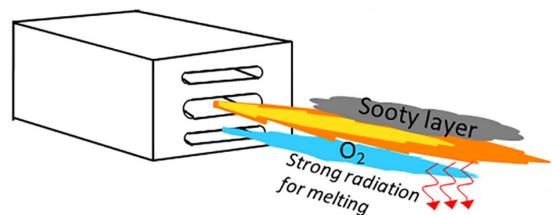
Foam Control Mode

- Staging O₂ on top of primary flame
- Produces long, staged flame with sooty underlayer, containing reducing gases (CO)
- Will reduce foam on surface of glass



Split Mode

- Staging O₂ on top and bottom of primary flame
- Produces shorter, stable flame with high radiance
- Good for boosting applications and/or locations with high turbulence (near flue)



Melt Mode

- Staging O₂ on bottom of primary flame, similar to traditional HR_x burner
- Produces long, flame with high radiance on underside for faster melting

formation by delaying mixing of oxygen and natural gas resulting in a lower initial flame temperature where most NO_x is produced. The HR_x burner is also equipped with a secondary valve, called the primary O₂ valve, that controls the amount of primary and staging oxygen that is distributed through the ports of the burner block. The primary oxygen valve essentially controls the amount of oxygen staging used, although the valve works in reverse of a typical staging valve.

Split Mode. In Split mode, an equal amount of oxygen is directed to both the upper and lower oxygen staging ports. This results in a shorter, brighter, and more stable flame. The Split mode can be especially useful in turbulent locations of oxy-fuel furnaces (i.e. near the flue) and for oxy-boosting applications.

Melt Mode. In Melt mode, oxygen is directed to the lower oxygen staging port of the burner block, which is below the primary flame. The flame will develop a bright bottom surface due to thermal radiation caused by the localized combustion of staging oxygen with the gases in the lower surface of the flame. The high radiation produced in Melt mode is directed downward towards the glass surface and has been shown to accelerate the melting process.

Foam Control Mode. In Foam Control mode, oxygen is directed to the upper oxygen staging port of the burner block which is above the primary flame. The resulting flame appears to have a sooty bottom edge that contains reducing gases made up of primarily carbon monoxide (in concentrations of several percent). The reducing atmosphere created by the flame extends out above the glass surface and acts to dissipate surface foam.

Primary Oxygen Valve. The HR_x burner includes an additional valve that controls the amount of primary oxygen that flows through the main burner nozzle with the natural gas. When the primary oxygen valve is 100% open, approximately 75% of the total incoming oxygen to the burner is passing through the primary nozzle. This condition enhances mixing between oxygen and natural gas in the main nozzle and generally creates a short, stable flame with high momentum. Additionally, with the primary valve 100% open, oxygen back pressure will decrease significantly, and the burner tip temperature will decrease due to the additional oxygen flow around the burner tip. In the opposite condition, where the primary valve is closed, there is approximately 5% of the incoming oxygen passing through the main nozzle with the remainder (95%) distributed to the upper, lower, or split staging ports, which is dependent on the selected staging mode, i.e. Foam Control, Melt, or Split mode, respectively. When the primary valve is closed, it is possible to achieve the maximum amount of oxygen staging and the flame length will become its maximum for the current firing rate. In addition, NO_x emissions will decrease, and flame luminosity will increase, due to the burning of intermediate soot that is formed.

Synchronized Boosting System

The synchronized boosting system was designed to allow for automatic adjustment of the boost burner flame properties, particularly length, luminosity and momentum in conjunction with each regenerator reversal cycle in air-fired side port furnaces. The system ensures that each of the oxy-fuel boost burners' flame quality is always maximized and mitigates the negative effects of turbulence due to the regenerator reversal cycles. Automatic control of the flame properties is achieved through pneumatic actuation of the staging mode and primary oxygen valves on the HR_x boost burners. A PLC-based control system works in conjunction with the plant DCS to change valve positions to preset locations with each regenerator reversal cycle. The optimum burner settings are determined through visual observation of the boost burner flames and optical temperature measurements of the charge end wall and breast walls near the boost burners. The synchronized boosting system allows furnace engineers to customize each burner's settings for each firing direction and local atmosphere conditions. Using both the flexibility of the HR_x boost burners and a system to switch burner settings with the reversal, we can optimize the boosting operation. The HR_x Synchronized Boosting system offers the potential to enhance the benefits of oxy-boosting, which include higher glass production and furnace bottom temperatures, lower glass defects, and greater fuel savings.

Results of Commercial Demonstration

A trial of the synchronized boosting system was conducted at a 650 ton per day air-fired regenerative side port float glass furnace. The furnace previously used HR_i Advanced Boost burners for a period of several years. In the trial, the HR_i burners were replaced with the HR_x burner including the synchronized boosting system. Results comparing the performance of the HR_i Advanced

Boost burners against the HR_x Synchronized Boosting system will be discussed in this section and include: energy consumption (MMBTU/ton), average bottom temperatures, average crown temperature, as well as the impact on glass defects. It should be noted that most of the results presented here were normalized to the HR_i Advanced Boost burner data as a baseline case to protect the confidentiality of the float glass plant's data. The furnace pull rate remained nearly constant throughout the trial period, but the cullet ratio changed slightly by about 2 percent. **Table 1** below shows the average cullet as a percentage of the batch material used for each case. The boost burner firing rates remained constant prior to and throughout the trial at 8.25 MMBTU/hr per burner. Also, the air-fired regenerative furnace in this trial was operating with the Glass Services Expert System (ES III) control system with all data sets presented here.

Table 1: Average cullet as a percentage of charged material for each of the boost burner cases evaluated in the trial

Burner Type:	HR _i Advanced Boost Burner	HR _x Burner with Synchronized Boost
Average Cullet (%):	18	20

Manual optimization of the flame properties was conducted prior to initiating the synchronized boosting system. Visual observations and optical temperature measurements using a 1-micron handheld pyrometer were used to help determine the optimal staging mode and primary oxygen valve settings for each burner and reversal firing cycle. **Table 2** below shows the optimal valve settings determined for the HR_x burners with the synchronized boosting system during the trial.

Table 2: Optimal staging mode and primary oxygen valve positions for the synchronized boost burners

Burner Position	Reversal Firing Cycle	Staging Mode	Primary Oxygen (% Open)
Left Burner	Left-to-Right	Melt Mode	0
	Right-to-Left	Split Mode	50
Right Burner	Left-to-Right	Melt Mode	100
	Right-to-Left	Split Mode	25

Impact on Oxy-fuel Flame Quality

An oxy-fuel burner's flame quality is generally assessed by evaluating the flame's stability and luminosity with respect to the batch material over which it is located. Since the air-fuel regenerative furnace inherently generates a high degree of turbulence, the oxy-fuel boost burner's performance is best when the

flame is located consistently over the batch material and the flame appears long and luminous to provide effective heat transfer to the batch. Many of the commercially available oxy-fuel boost burners have restricted flame adjustability and therefore there are less options with which to find optimal flame conditions. The HR_x burner is the perfect candidate for employing the automated synchronized boosting system because of the high degree of adjustability of the flame momentum and luminosity given its three staging modes (Foam Control, Split, and Melt modes) and high degree of oxygen staging. The flame quality was evaluated for the HRi Advanced Boost burner as compared to the HR_x burner with synchronized boosting throughout the course of the trial. **Figure 5** shows the right side oxy-fuel boost burners with opposed (left) side air-fuel burner firing. **Figure 5a** shows the HR_x burner where the flame quality was adversely affected by opposed firing air currents, and the flame was periodically pushed in the direction of the furnace charge end wall. **Figure 5b** shows the HR_x burner with synchronized boosting under the same circumstances, but here the flame properties were optimized to minimize the adverse effects of localized turbulence and increase flame stability and quality by automatically switching the burner valves to the appropriate settings. It should be noted that while this optimum setting for the HR_x burner improved the flame properties in this specific case of opposed firing, these optimum settings were not the same when the regenerator reversal changed to same-side firing. This is because the local air currents change dramatically with each reversal and affect the flame quality. Without automated synchronized boosting system in place, it is common practice to find the most conservative burner settings (minimal oxygen staging) where the flame properties are acceptable, but not optimal, for both regenerator cycles.

Figure 6 shows the typical flame quality of the left side oxy-fuel boost burners with opposed (right) side air-fuel burner firing. This is a side view of the flames from the location of the throat end (discharge end) left side port wall looking back at the charge wall. **Figure 6a** shows the HR_i Advanced Boost burner with minimal oxygen staging; **6b** shows the HR_x burner also with minimal oxygen staging; and **6c** shows the HR_x burner flame that is optimized using the synchronized boosting system. **Note:** the black dashed line was placed on each photo for reference and it represents the same position on the charge end wall in each photo. The HR_i Advanced Boost burner flame (**6a**) appears somewhat diffuse in appearance and this is partly due to the low amount of oxygen staging that was required for good stability under the opposed firing condition. The HR_x burner with minimal oxygen staging (**6b**) shows a slightly more luminous flame as compared to the HR_i burner. The oxygen staging was also limited for the HR_x burner under these conditions in order to maintain good flame stability during successive reversal cycles. The HR_x burner with synchronized boosting (**6c**) has optimized flame properties and appears long and luminous. This is because the synchronized boosting system allows for precise tuning of burner parameters to customize the flame properties based on the local atmospheric conditions.

Figure 5: Right side oxy-fuel boost burners with opposed (left) side air-fuel burner firing. Figure 5a shows the HR_x burner that is not optimized, where the flame can be periodically pushed in the direction of the furnace charge end wall. Figure 5b shows the HR_x burner with synchronized boosting where the flame properties were optimized and were automatically tuned to increase momentum and stability and minimize the effects of localized turbulence

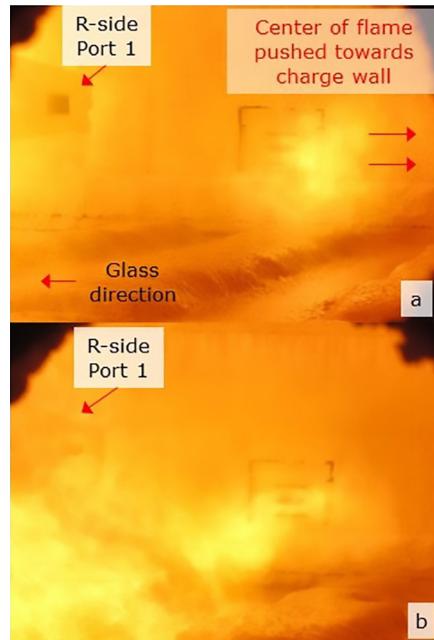
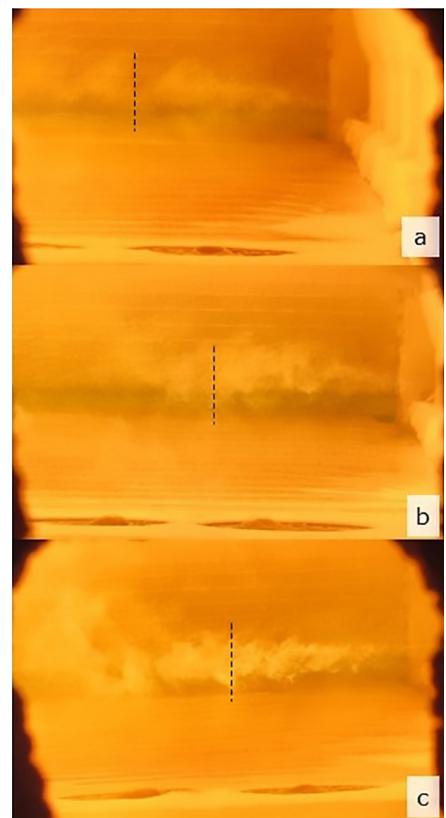


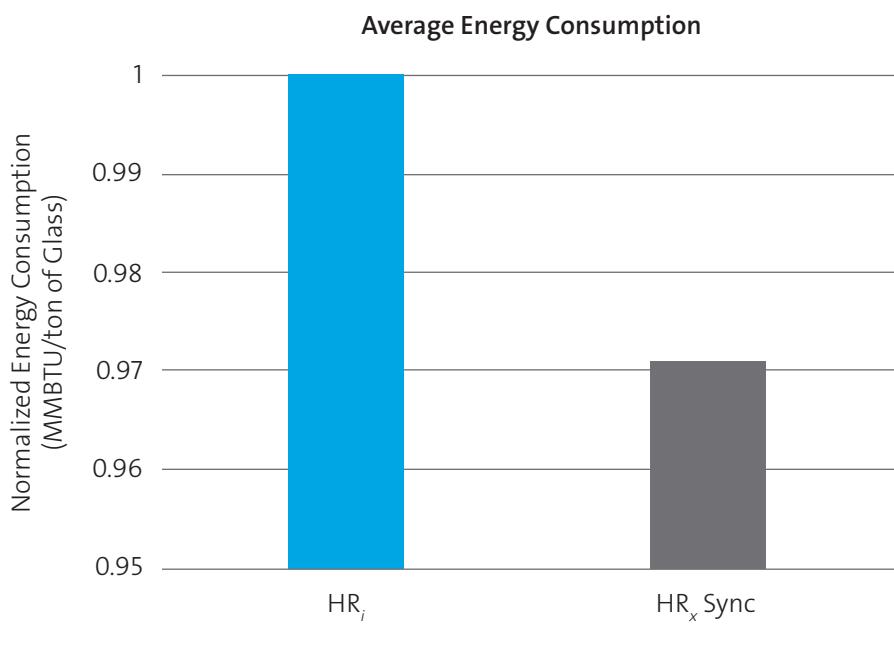
Figure 6: Left side oxy-fuel boost burners with opposed (right) side air-fuel burner firing. The view is from the throat (discharge) end wall looking back at the charge wall. Figure 6a shows the HR_x Advanced Boost burner with minimal O_2 staging (conservative burner settings); 6b shows the HR_x burner with minimal O_2 staging; and 6c shows the HR_x burner with synchronized boosting, with optimized flame properties. The black dashed line represents the same position on the charge end wall in each photo



Energy Consumption

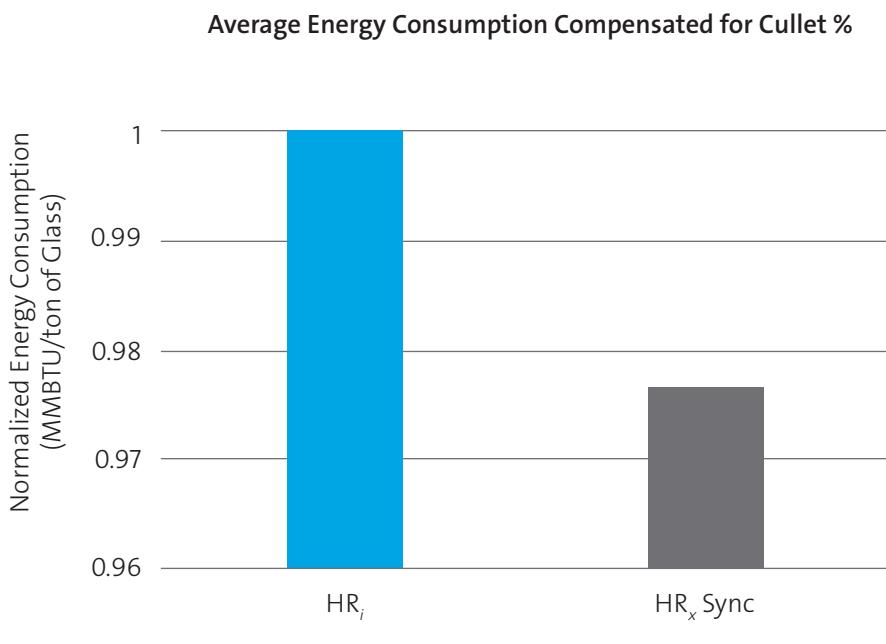
The furnace energy consumption was evaluated by multiplying the total natural gas consumption rate for the air-fired burners by the natural gas heating value. The result was then divided by the total tons of glass produced over the evaluation period, yielding the average energy consumption per ton (U.S.) of glass (unit shown: MMBTU/ton). The natural gas heating value varied over the course of the trial between 1035-1055 BTU/SCFH and this method of calculating energy consumption accounted for this variation. **Note:** energy consumption from electric boosting was not included because it is not used in this furnace. **Figure 7** shows the normalized average energy consumption for the HR_i Advanced Boost burner and HR_x burner with synchronized boosting. The data was normalized to the HR_i burner results for confidentiality. The energy consumption for the HR_x burner with synchronized boosting was lower by approximately 3%, as compared to the baseline HR_i Advanced Boost burner case.

Figure 7: Normalized average energy consumption (MMBTU/ton) per ton of glass produced for the HR_i Advanced Boost burner and the HR_x burner with synchronized boosting system



It was previously noted that the cullet ratio was slightly different for each case by approximately 2%. It is known that a higher cullet ratio can reduce the energy consumption requirement. Kovacec et al. [5] provided an estimate of approximately 2.9% reduction in energy consumption for each additional 10% of cullet added to the incoming raw materials. Therefore, a correction factor was applied to the data sets where 0.29% reduction in energy consumption was applied per 1% of added cullet in order to yield a more accurate estimate of the energy consumption during the trial. **Figure 8** shows the normalized energy consumption that is corrected for the change in cullet ratio for each case. The compensation for cullet resulted in a slight change in energy consumption, where the HR_x burner with synchronized boosting was approximately 2.3%.

Figure 8: The normalized average energy consumption (MMBTU/ton) per ton of glass produced, which is corrected for percent cullet, for the HR_i Advanced Boost burner and the HR_x burner with synchronized boosting cases. The applied correction considers changes to the energy consumption due to differences in the cullet ratio between each case

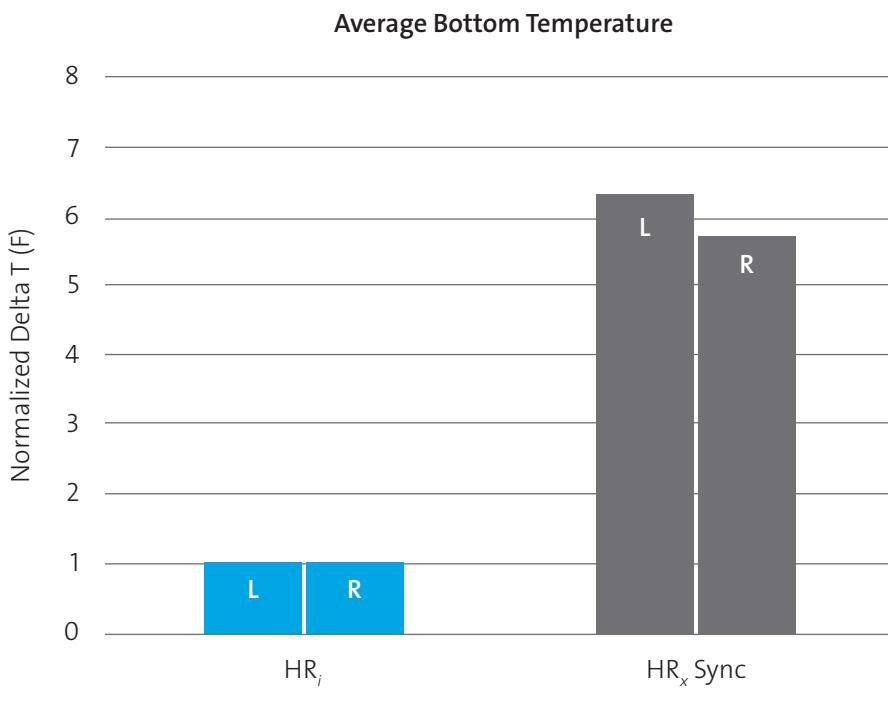


Impact on Glass Bottom Temperature

The glass bottom temperatures were recorded on the left and right side of the furnace with the nearest thermocouples located approximately 12 feet down tank of the boost burners towards the discharge end of the furnace.

Figure 9 shows the normalized temperature difference (Delta-T) of the average bottom temperatures for the HR_i Advanced Boost burner and HR_x burner with synchronized boosting. **Note:** the actual temperatures were not provided here due to confidentiality and instead the data was normalized to the HR_i Advanced Boost burner results. The average bottom temperatures increased between the HR_i burner and HR_x burner with synchronized boosting by approximately 6 degrees Fahrenheit. These results are favorable and show that the active tuning of the burner parameters using the synchronized boosting system can be effective in improving localized heat transfer from the oxy-fuel flames to the incoming batch material.

Figure 9: The average glass bottom temperature at the left and right side of the furnace located nearest to the charge end wall and approximately 12 feet down tank of the boost burners. The designation “L” and “R” in the figure denote the left and right thermocouples, respectively

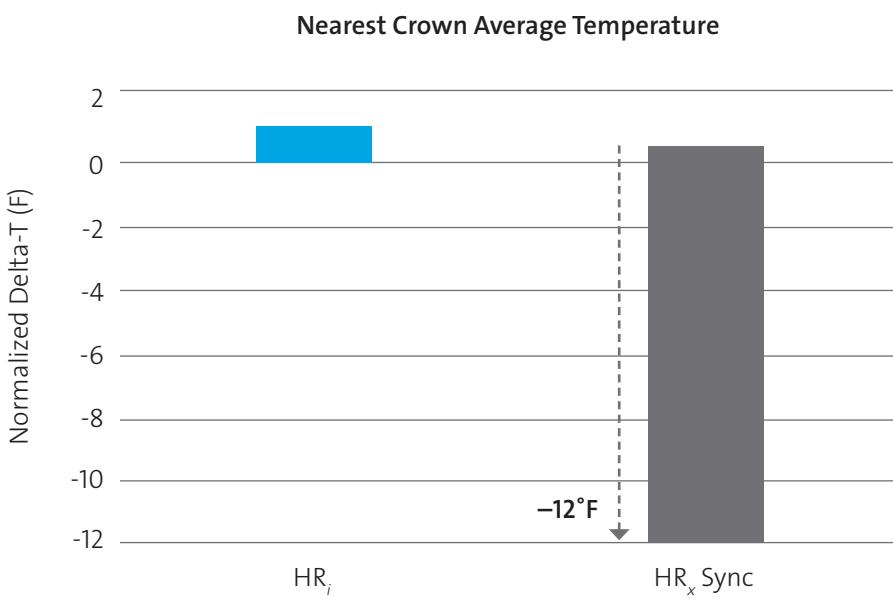


Impact on Furnace Crown Temperature

The nearest furnace crown thermocouple to the boost burners is located approximately 12 feet from the charge end wall, which is within approximately 4 feet of the burners, although centrally located in the crown between them.

Figure 10 shows the temperature difference of the local crown thermocouple between the HR_i Advanced Boost burner and the HR_x burner with synchronized boost, with temperatures normalized to the HR_i burner results. The HR_x burner with synchronized boosting shows an average temperature decrease of about 12°F as compared to the HR_i burner. This is partly due to the fact that the HR_x burner has higher flame momentum than the HR_i burner and can achieve a higher degree of staging. A higher degree of staging tends to lengthen the oxy-fuel flame, spreading the heat over a larger area. The HR_x burner's higher flame momentum also causes the flame direction to be focused straight over the glass surface preventing lofting and directing heat downward towards the glass instead of upwards towards the crown. But more importantly, these results highlight the effectiveness of the synchronized boost system where the HR_x burner flame properties are fully optimized to maximize flame luminosity and momentum thereby directing more heat transfer into the glass melt. In addition, lower crown temperatures are a desired result, as they help to maintain a longer furnace lifetime and reduce refractory-based glass defects.

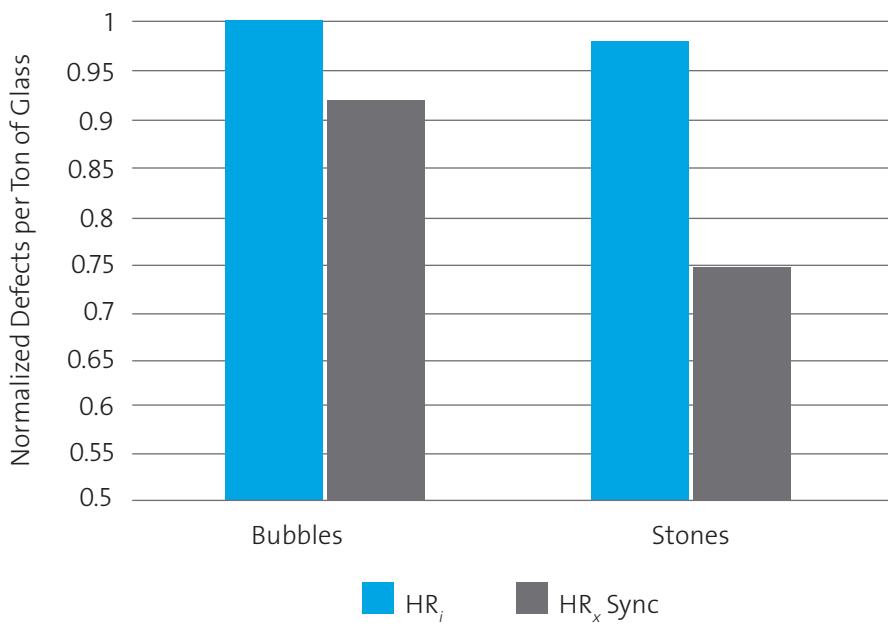
Figure 10: Temperature difference of the nearest crown thermocouple in proximity to the oxy-fuel boost burners for the HR_i Advanced Boost burner and HR_x burner with synchronized boosting cases. The data was normalized to the HR_i burner results and shows a decrease of approximately 12°F for the HR_x burner with synchronized boosting system



Impact on Glass Defects

Glass defect data for bubbles and stones was calculated on the basis of the average number of defects per ton of produced glass. The defect data was again normalized against the HR_i burner data, which is shown in **Figure 11** as having a value of 1, and therefore the HR_x burner with Synchronized boost results are shown as a fraction of the defects produced by the HR_i burner. The HR_x burner with synchronized boosting system results showed an 8% and 21% decrease in bubbles and stones, respectively. This result is favorable and logical because the glass bottom temperatures also increased when using the synchronized system. Increased bottom temperatures indicate a higher degree of heat transfer from the burners to the batch and more favorable heat recirculation and effective batch melting in the molten glass bath, which is the driver for lower defects.

Figure 11: Defects per ton of glass normalized to the HR_i , Advanced Boost burner case. The HR_x burner with synchronized boosting results are shown as a fraction of the defects produced by the HR_i burner. The synchronized boost system showed an 8% and 21% decrease in bubbles and stones, respectively



Summary and Conclusions

The Air Products HR_x Synchronized Boosting system was designed to overcome the high turbulence and changing air currents inherent with oxy-boosting inside air-fired regenerative side port furnaces. In essence, the system allows the boost burner flames to always be optimized for stability and luminosity. This is accomplished through automated valve switching at the burner, which overcomes the problems of high turbulence and changing air currents by customizing burner settings for optimal performance. The HR_x burner is a perfect fit for this system because it has the capability to fine tune the flame properties and quality via the staging mode and primary oxygen valves. The results of the trial showed that the synchronized boosting system is capable of generating more favorable furnace crown and bottom temperatures as well as significant improvements in glass quality, with a 2-3% reduction in energy consumption. Future work is underway to improve the system and methodology for optimization with the potential to gain even more benefits.

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