

Oxygen-staged combustion in oxy-fuel fired melting furnaces

After three decades of continuous industry growth, the benefits of oxy-fuel combustion for glass melting relative to air-fuel combustion are fairly well-known and include lower capital cost, higher fuel efficiency, reduced NO_x emissions and higher glass quality. Dr Mark D D'Agostini discusses added performance and emissions benefits that can be realised in oxy-fuel systems through the use of a technique known as oxygen staging.

Oxygen staging has evolved into a powerful tool for reducing NO_x emissions and increasing melting efficiency and product quality in oxy-fuel fired glass melting furnaces. 'Oxygen staging' is a means of delaying combustion by diversion of a portion of oxygen away from the flame. More specifically, it concerns near-flame staging in which the staged oxygen stream (or streams) maintains a proximity to the flame to ensure eventual co-mixing and complete combustion of the fuel with oxygen.

Figure 1 illustrates a flame with 'under-staged' oxygen, which underscores several key principles. The flame, being initially deprived of stoichiometric oxygen, generates soot and carbon monoxide (CO), the magnitude of which increases with the percentage of staged oxygen. The sooty region, in particular, comprises a cloud of microscopic carbonaceous particles

and can be quite opaque, thereby presenting an impediment to radiation heat transfer.

Conversely, due principally to the reaction of soot and staged oxygen, the underside of the flame is very luminous and transmits high rates of thermal radiation in the visible and near infrared regions of the electromagnetic spectrum. Since the radiation finds strong resistance in the adjacent soot cloud, the majority is directed downward to the glass surface. Melting efficiency is thereby increased relative to an unstaged flame. Moreover, as complete mixing of fuel and oxygen is delayed, the staged flame is longer than an unstaged one with the same fuel flow rate. This fact, combined with the enhanced visible and near-infrared radiation, ensures that peak flame temperatures are lower in the staged flame.

Results of computational fluid

dynamics (CFD) modeling of highly staged and unstaged oxy-fuel flames have shown that peak temperatures of the highly staged flame are lower by approximately 600°C. The substantially lower temperature in combination with the oxygen-starved condition of the staged flame leads to lower rates of NO_x generation.

Photographs of Air Products' Cleanfire HR₁ burner operating in both the non-staged and understaged modes effectively illustrate the differences in flame structure and radiant properties produced by under-flame staging with oxygen (see figure 2).

Oxygen staging and glass quality

Air Products' experience of replacing non-staged burners with understaged burners has verified that understaging the flame with oxygen increases glass bottom temperatures and this contributes to stronger convection currents in the glass melt and fewer glass defects. In one typical case of a funnel glass furnace converted from non-staged to understaged oxy-fuel burners, bottom glass temperatures increased by 10°C, while defects were reduced by nearly 50%⁽¹⁾. Furnace flue gas temperatures also decreased by 60°C, contributing to a reduction in specific fuel usage (energy input per unit output of glass) equal to nominally 9%.

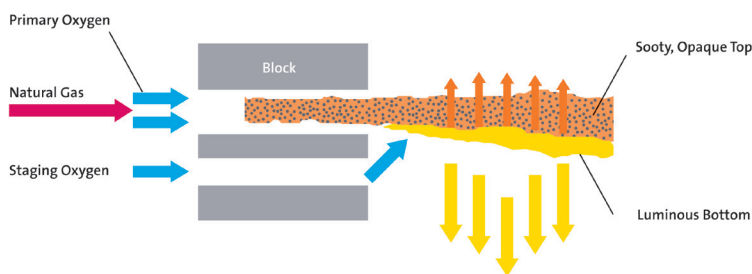


Figure 1: Illustration of directional flame radiation through oxygen staging.

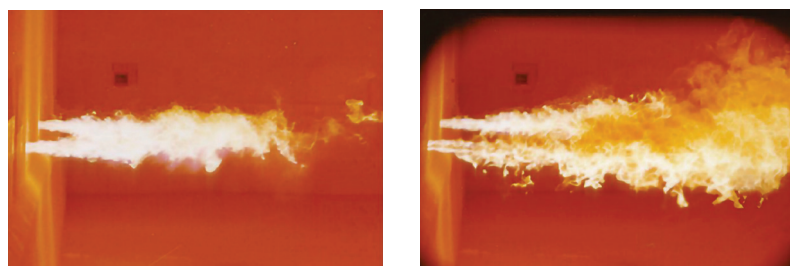


Figure 2: Cleanfire HR₁ burner without (left) and with (right) oxygen staging.



Figure 3: Cleanfire HR₁ burner with block (hot end view).



Figure 4: Cleanfire HR₁ burner with block (cold end view).

There is another aspect to the oxygen staging/glass quality story, with the connection between the two being glass surface foam. Foam forms within both the batch melting (primary foam) and fining (secondary foam) processes due to the evolution of gases from the glass. Secondary foam, which consists principally of sulphur dioxide, water vapour and oxygen, is particularly prone to aggregate in a stable layer of bubbles that, at times, can grow to several inches in thickness. The principal deleterious effects of surface foam are its impedence of heat transfer to the glass, consequent reflection of thermal energy to the crown and its corrosive properties with respect to furnace refractories. With respect to the lower rate of heat transfer to the glass, this lowers glass temperatures and weakens convection-driven secondary flows within the melt, interrupting the fining process and allowing more defects to persist through to the finished product.

Key factors influencing the rate of gas evolution and formation into foam include the batch composition, including the amount of sulphate added for fining, glass surface temperature and furnace gas atmosphere. Secondary foam, which is of principal concern to glass quality, generally occurs between 1400°C and 1500°C, with the volume of released fining gases and hence, the severity of the foaming problem increasing with temperature.

Concerning the gas atmosphere, it is known that a reducing environment

immediately above the glass surface can mitigate a foam problem through modification of foam properties. The mechanism through which this occurs is a reducing gas, such as carbon monoxide, in contact with the foam, which acts to lower surface tension gradients at the liquid interfaces of the foam bubbles, thereby promoting accelerated drainage of foam back to the melt⁽²⁾. This suggests the use of oxygen staging above the flame, ie creating a fuel-rich flame adjacent to the glass surface, as a means by which the combustion process can help to alleviate a foaming issue.

Oxy-fuel burner enables choice of under- and/or over-flame oxygen staging

Recognising the benefits of oxygen staging for higher melting efficiency and lower NO_x emissions, while also being aware of causes and cures of foaming, Air Products has developed a burner for oxy-fuel glass melting. The Cleanfire HR_x burner (patents pending) enables users to control both the magnitude and location of oxygen staging. The HR_x burner is equipped with three passages: A primary port that houses the burner fuel and oxygen nozzles; upper and lower oxygen ports for introducing staged oxygen; and two valves to control the direction and flow rate of oxygen among the three passages (see figures 3 and 4).

Compared to Air Products' HR_i

burner, where oxygen (under) staging is limited to 70% of the incoming oxygen, the HR_x burner is able to safely operate with oxygen staging in excess of 95%; early results have been impressive. In one container glass furnace, for example, where HR_x burners replaced HR_i burners, NO_x emissions and glass defects (seeds and blisters) were lowered by 40%, while specific fuel usage was reduced by over 3%. These beneficial effects were the result of proper application of the two HR_x burner design advancements. That is, the cause of lower NO_x emissions was the higher proportion of staged oxygen facilitated by the new burner, while the reduction in defects was due to the use of over-staged oxygen in the fining region that resulted in clearing of secondary foam (see figure 5; note the appearance of a mirrored surface with the HR_x burner). As for the reduced fuel consumption, this was enabled by both aforementioned factors.

It is clear the reduction of foam in the refining region not only reduced defects but also lowered the resistance of heat transfer to the glass, thereby contributing to the higher fuel efficiency. Furthermore, when applied to burners in the batch melting region, the increased understaging resulted in increased luminosity of the HR_x burner flames relative to those of the HR_i burners (see figure 6; note the variation in contrast between brightness of flame and breast wall for the two burners). This increased the rate of radiant heat transfer to the glass in that region of the furnace.

Summary

Benefits of oxygen staging in oxy-fuel fired glass melting furnaces have been mechanically explained, while a promising oxy-fuel burner technology that expands both oxygen staging functionality and the scope of benefits has been introduced. With this technology, glass producers can optimally adjust both the amount and location of oxygen staging relative to the flame in various regions of the melting furnace to enhance efficiency and glass quality, while reducing NO_x emissions. ●

**Cleanfire is a registered trademark of Air Products and Chemicals Inc and HR_x and HR_i are grade designations under that trademark covered by one or more patents and pending applications, including US 7390189 and US8512033.*

Reference:

1. J H Tyler et al, 'A Direct Comparison of Oxy-Fuel Burner Technology', presented at the 59th Glass Problems Conference, Columbus, Ohio, 27-28 October 1998.
2. P R Laimboeck, 'Foaming of Glass Melts', PhD dissertation, Technical University of Eindhoven, 1998, ISBN 90-386-0518-8.

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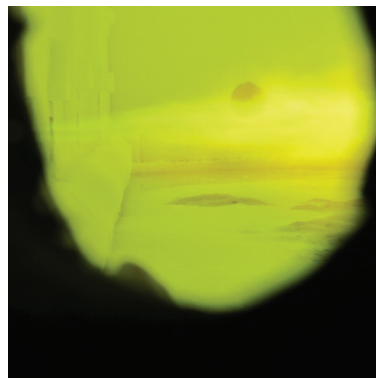
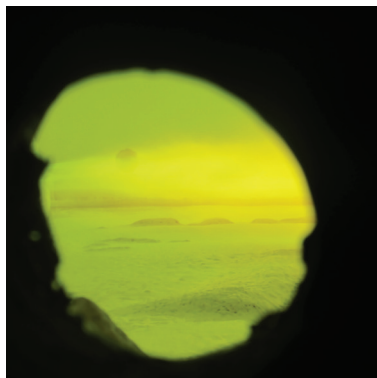


Figure 5: Glass melting furnace (left) with secondary foam in refining region and (right) with mirrored surface.

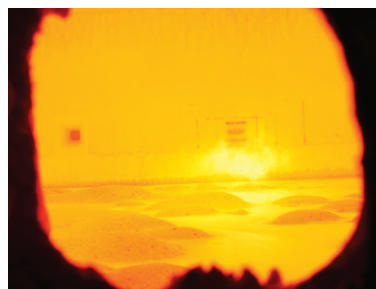


Figure 6: Cleanfire HR_i burner flame (left) and Cleanfire HR_x burner flame (right).