Technical Report

Industrial experience with oxygen-fired glass furnaces[1]

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Among the leading industrial gases suppliers, Praxair has developed a leadership position in oxygen combustion technology and in on-site oxygen supply technology with its Vacuum Pressure Swing Adsorption process. A tailor-made solution with regard to oxygen burner technology and to oxygen supply method is provided to meet customer requirements.

The latest developments show a reduction in particulate emission of up to 30 % and in NO_x emission of up to 90 % compared to air/fuel-fired operations. These results are confirmed in industrial use.

Due to specific requirements in application technology, different burner concepts have been developed. These concepts can be classified in two groups: Conventional burners with direct oxygen-fuel mixing create high flame temperatures and NO_x formation; recirculating burners create low flame temperatures and NO_x formation due to controlled fluid dynamics to entrain furnace atmosphere into the main oxygen stream before the now diluted oxygen reacts with the fuel.

Industrielle Erfahrungen mit 100%-sauerstoffbefeuerten Glasöfen

Praxair nimmt als eines der größten Industriegase-Unternehmen weltweit eine führende Stellung in der Sauerstoff-Verbrennungstechnologie sowie in der Sauerstoff-Vor-Ort-Versorgungstechnologie mit dem nicht-kryogenen Vakuum-Druckwechsel-Adsorptionsverfahren ein. Entsprechend den jeweiligen Kundenanforderungen wird sowohl für die Sauerstoff-Brennertechnik als auch für die Sauerstoffversorgung eine maßgeschneiderte Lösung erarbeitet.

Mit den neuesten Entwicklungen ist es gelungen, die Staubemissionen um bis zu 30 % und die NO_x-Emissionen um bis zu 90 % gegenüber herkömmlichen fossilen Befeuerungssystemen zu senken. Diese Ergebnisse werden durch den industriellen Einsatz bestätigt.

Aus der anwendungsspezifischen Entwicklung heraus entstanden verschiedene Brennerkonzepte. Diese Brennerkonzepte lassen sich in zwei Gruppen einteilen, und zwar in konventionelle Brenner mit direkter Mischung von Sauerstoff und Brennstoff, verbunden mit hohen Flammentemperaturen und NO_x-Emissionen, sowie in Rezirkulationsbrenner, bei denen aufgrund der strömungstechnischen Eigenschaften die Ofengase in den Hauptsauerstoffstrom durch Rezirkulation eingemischt werden, bevor der dann verdünnte Sauerstoff mit dem Brennstoff reagiert; dies resultiert in niedrigen Flammentemperaturen und NO_x-Emissionen.

1. Oxygen burner technology

The development of Praxair's oxygen burner technology is application-related, i.e. tailor-made solutions are developed for each individual case.

New developments have allowed particulate emissions to be reduced by 25 to 70 % and NO_x emissions by up to 90 % compared to traditional air-firing systems. Industrial applications have already confirmed these results.

Various burner systems have emerged from this principle of applied development. Those burners in which the flame temperature, flame geometry and outlet velocity can be regulated over a broad range may be divided into:

a) Conventional mixing of fuel and oxygen (figure 1); high flame temperatures causing high NO_x formation.

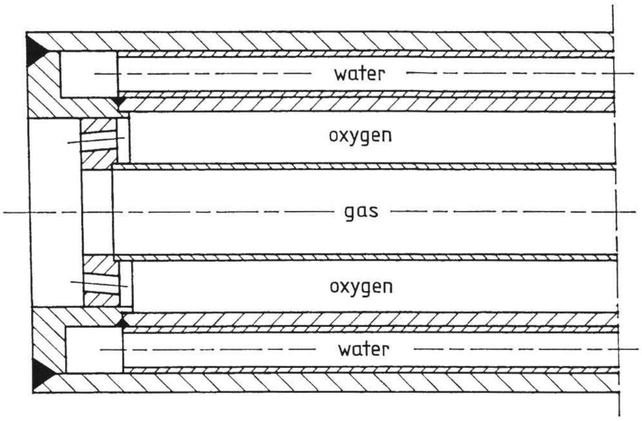

Figure 1. Schematic presentation of the conventional oxygen burner corresponding to Praxair burner types AB, J and E.

b) Recirculation oxygen burners: recirculation of furnace gases into the primary fuel-oxygen mixture leading to low flame temperatures and low NO_x formation (figures 2a and b).

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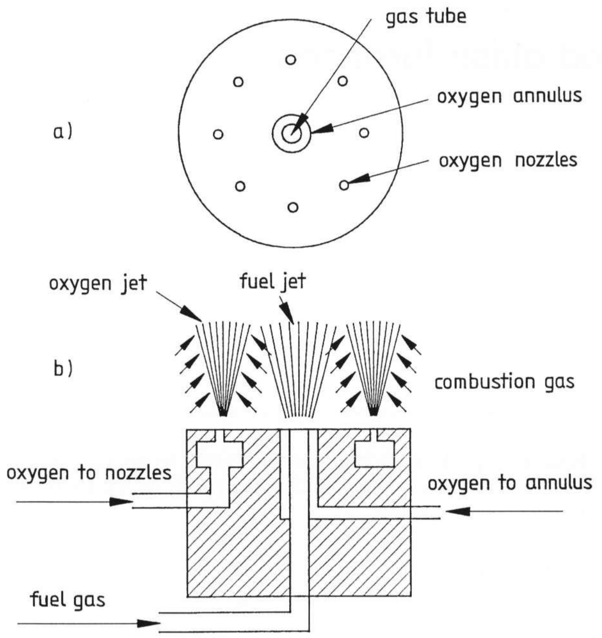


Figures 2a and b. Schematic presentation of the recirculation oxygen burner corresponding to Praxair burner types A and SJ [1]; a) top view, b) cross-section.

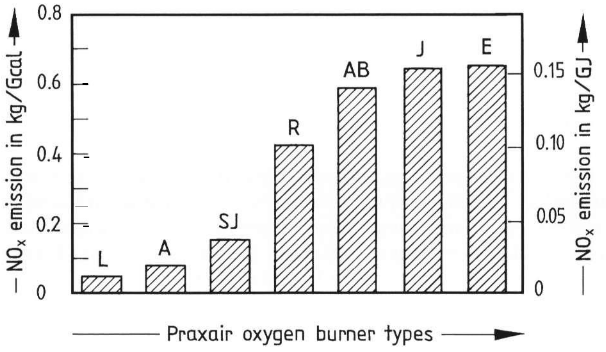


Figure 3. NO_x emissions determined by measurements in a test furnace with a simulated furnace atmosphere (7 % N_2, 2 % O_2, 1540 °C, wet). The letters L, A, SJ, R, AB, J and E stand for different Praxair burner types.

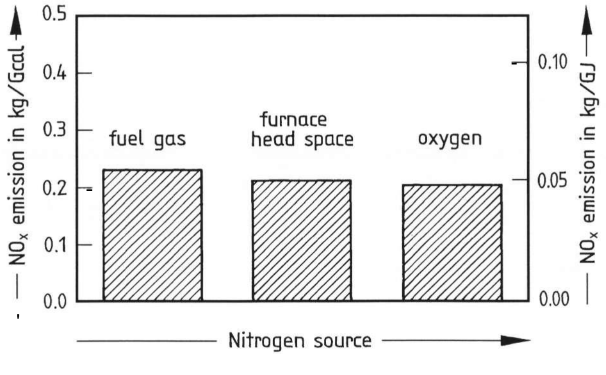


Figure 4. Specific NO_x emissions as a function of the nitrogen source for the Praxair burner type A. Furnace atmosphere: 7 % N_2, 2 % O_2, 1540 °C, wet.

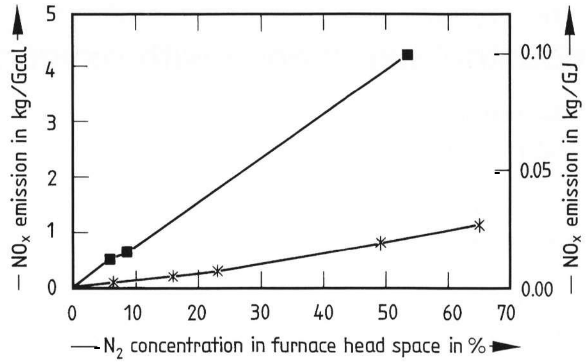


Figure 5. Comparison of the NO_x emissions of the conventional oxygen burner E (■) and the recirculation oxygen burner A (⋆) in wet furnace atmosphere.

Table 1. Praxair references for 100 % oxygen-fired glass furnaces

reference no.	production in t/d	glass type	oxygen use in t/d
1	310[2)]	flint glass	100 VPSA
2	310[2)]	flint glass	100
3	200	lead glass	50 VPSA
4	135	bottles	45 VPSA
5	115	glass wool	20
6	80	amber glass	32
7	28	glass wool	15
8	8	flint glass	7
9	8	flint glass	5

[2)] Praxair is the oxygen supplier and was involved in the design of the oxygen combustion system and the glass furnace.

Adjusting the flame temperature or the flame geometry allows to comply with either the demands of the process (i.e. type of raw material) and/or furnace parameters. For example, the entrainment of dust can be reduced at the charging side of the furnace by having lower combustion gas outlet velocities at the burner head.

2. Burner type and NO_x formation

Figure 3 illustrates NO_x measurements in a laboratory furnace with a simulated furnace atmosphere (7 % N_2, 2 % O_2 1540 °C). These are the conditions normally found in a 100 % oxygen-fired glass furnace, since nitrogen is also entering through the fuel and tramp air.

Figure 4 gives the specific NO_x emissions with reference to the nitrogen source. Fuel nitrogen in low-NO_x burners produces approximately 20 % more NO_x than the same nitrogen quantity from tramp air [2].

Figure 5 compares conventional burner NO_x emissions with those of a recirculation oxygen burner. The range of 0 to 10 % nitrogen is of particular interest for oxygen-fired glass furnaces.

3. 100 % oxygen-fired glass furnaces

So far 14 glass furnaces have been equipped with Praxair burner technology. Table 1 lists those designed for continuous operation. The rest was converted short-term for test purposes or for the period of regenerator repair.

Increased conversion to oxygen burners in the USA, Mexico and Brazil has taken place chiefly due to forthcoming legislation to reduce emissions (NO_x, particulates). Other advantages are to be found in increased melt rates as well as in energy and investment savings.

3.1. Energy requirement

Table 2 gives potential energy savings of various 100 % oxygen-fired furnace types. Optimum energy economy depends strongly on furnace construction. Compared to air burners, unit melters allow energy savings of up to 55 %, whereas up to 20 % is found in cross-fired furnaces.

Figure 6 illustrates the specific energy consumption in oxygen-fired glass furnaces with glass throughputs of 85 to 310 t/d. With reference to these measured values, theoretical calculations for glass furnaces using a batch with 60 % cullet indicate specific energy consumptions of 780 kcal/kg glass (≈ 3268 kJ/kg glass or 0.9 kWh/kg glass) to 840 kcal/kg glass (≈ 3596 kJ/kg glass or 0.97 kWh/kg glass). Both newly built furnaces were already conceived for 100 % oxygen firing. With a low cullet level, the first glass furnace requires 990 kcal/kg glass (≈ 4148 kJ/kg glass or 1.15 kWh/kg glass), the second 960 kcal/kg glass (≈ 4022 kJ/kg glass or 1.11 kWh/kg glass) with 11 % of the energy supplied by electrical boosting. An existing furnace converted to 100 % oxygen firing requires 1090 kcal/kg glass (≈ 4567 kJ/kg glass or 1.16 kWh/kg glass) including 4 % electrical energy.

Tables 3 and 4 refer to figures published for an end-fired regenerative U-shape flame melter (63 t/d) and a cross-fired furnace (300 t/d) [3 and 4].

3.2. Melting rate

Glass furnaces charged with batch material containing maximum 30 % cullet specifically designed for oxygen burners, can achieve glass melting rates of 4 t/(m^2 d) without additional electrical energy [5].

3.3. NO_x emissions

Figure 7 illustrates typical ranges of NO_x emissions for air burners and Praxair oxygen burners. The NO_x emissions for regenerative air-fired furnaces range from 1800 to 3600 g/t glass. Depending on the type of oxygen burner, nitrogen concentration in the combustion zone and the batch composition (i.e. with or without nitre), the NO_x emissions range between 90 and 1300 g/t glass.

Figure 8 corresponds to measurements in 100 % oxygen-fired glass furnaces (8 to 310 t glass/d). The indicated nitrogen concentration is a measure for the tightness of the glass furnace. The lowest NO_x emissions are achieved with a recirculation burner (80 to 420 g/t glass), with a nitre-free batch. The NO_x values 1000 and 1058 g/t glass were found at furnaces with conventional oxygen burners, whereas the value 1058 g/t glass was measured at Carr-Lowrey (table 3 and [3]), having nitre in the batch.

Table 2. Energy savings of various 100 % oxygen-fired glass furnaces

glass furnace type	throughtput in t/d	energy saving in %
recuperative (unit melter)	30	55
recuperative (U-furnace)	75	14
regenerative (cross-fired)	155	19

Table 3. Energy consumption and NO_x emissions (Carr Lowrey, Baltimore, MD (USA)). Glass with added nitre in a 63 t/d regenerative U-furnace

	air	oxygen
throughput in t/d	62.7	75.8
specific energy consumption in kcal/kg glass	1300	1080
furnace atmosphere (wet)		
N_2 in %	72	30
O_2 in %	5	1
NO_x emission in g/t glass	10800	1058

Table 4. Energy consumption and NO_x emissions (Gallo, Modesto CA (USA)) of a cross-fired furnace with a capacity of 300 t/d

	air	oxygen
throughput in t/d	303	305
specific energy consumption in kcal/kg glass	1195	1067
NO_x emission in g/t glass	2532	409

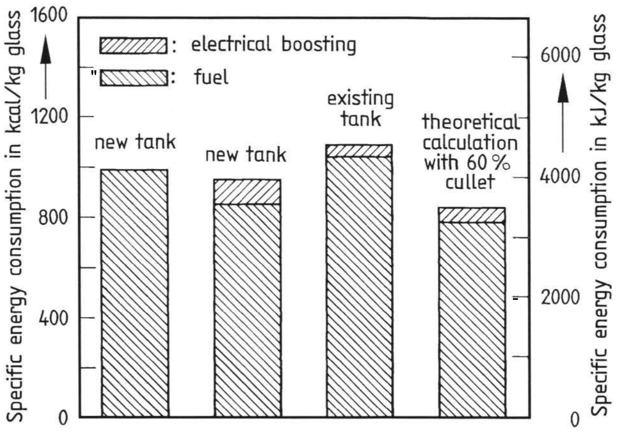


Figure 6. Specific energy consumptions of 100 % oxygen-fired glass furnaces.

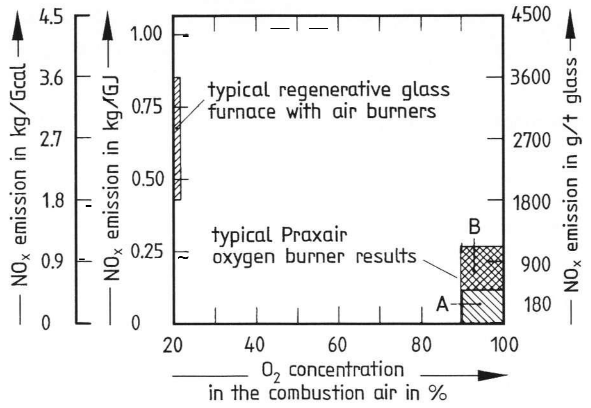


Figure 7. Comparison of measured NO_x emissions for air and oxygen burners. Area A: glass without nitre in the charge, area B: glass with nitre in the charge.

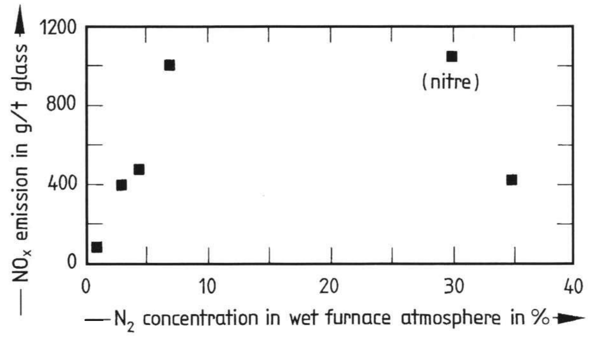
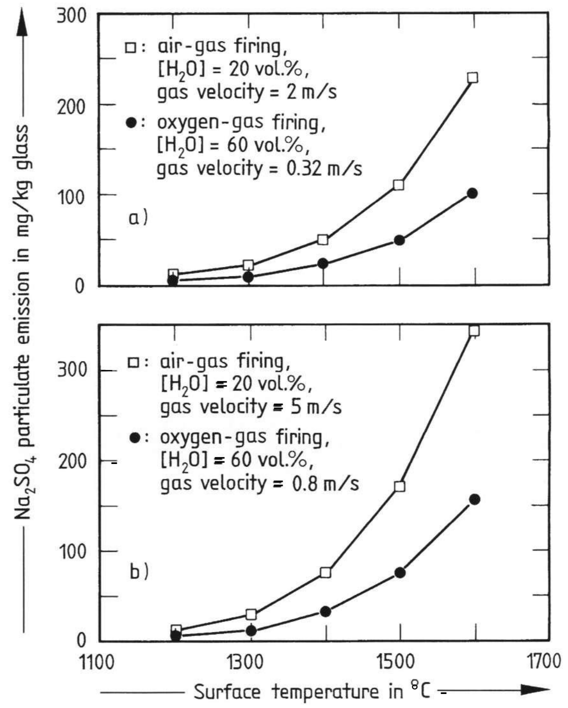


Figure 8. Measured NO_x emissions in 100 % oxygen-fired glass furnaces as a function of nitrogen concentration in wet furnace atmosphere.



Figures 9a and b. Comparison of particulate formation from NaOH vaporization only, a) for oxygen-gas firing and air-gas firing, b) for oxygen-gas firing, air-gas firing and higher gas (flame) velocities.

It is to be noted that given an energy requirement of 1000 kcal/kg glass (≈ 4190 kJ/kg glass), the NO_x values of 0.043 kg/GJ and 180 g/t glass correspond to a concentration of 627 mg/m^3, as per TA Luft conditions (dry flue gas, 8 % O_2). In absolute terms the NO_x emissions per ton of glass for the oxygen burner are thus considerably lower than in the air-firing systems.

3.4 Particulate emissions

Particulate emission measurements were made before and after conversion to 100 % oxygen-fired systems. Oxygen use led to a reduction in particulate emissions of 25 to 70 %. In these cases the resulting definitive particulate outputs were 430 to 650 mg/kg glass (soda-lime-silica batch). Since the particulate emissions were already considerably higher prior to conversion, only these typical values were obtained for well-established melting furnaces.

A theoretical study of this subject recently completed by Praxair (figures 9a and b, [6]) demonstrated the possibility of obtaining lower levels than in the past using oxygen burners. It is known that 80 to 90 % of particulates from soda-lime-silica glass melting occur due to NaOH volatilization and the ensuing reaction to Na_2SO_4 microparticulates.

Switching to oxygen firing produces higher vapour concentration in the furnace atmosphere, leading to an increased NaOH equilibrium vapour pressure. The considerably lower waste gas levels act to compensate.

A model calculation was elaborated based on the NaOH equilibrium vapour pressure curve and the convective mass transportation in the gaseous phase. Given a constant glass surface temperature and a constant combustion gas velocity over the glass surface, the calculation for conversion to oxygen burners shows a 50 % reduction of particulate mass concentration and a 50 % increase in particulate volume concentration. With respect to the soda-lime-silica batch, particulate emissions of not more thant 100 g/t glass should theoretically be attainable.

It is interesting to note that a higher velocity of the combustion gas and a higher glass surface temperature both lead to a significant increase in particulate emissions. Consequently, the combination of burner construction, design and adjustment would allow a substantial reduction in particulate emissions. Here too, as in the case of air burners, the requirement for a high melting rate must be set against low particulate emissions.

4. Means of oxygen supply

The most economical way of supplying oxygen generally depends on the rate of oxygen needed. If it is a small amount (e.g. in glassworks using auxiliary oxygen burners, but also in small specialty glass applications), then the liquid form is usually the low-cost alternative.

For requirements of more than 600 m^3 oxygen/h as per TA Luft conditions (dry flue gas, 8 % O_2), an on-site oxygen plant is more economical than a liquid supply. A very economical solution for on-site oxygen plants is the Vacuum Pressure Swing Adsorption unit (VPSA). In these VPSA plants zeolites separate the oxygen from nitrogen, water and carbon dioxide contained in the air. At present, Praxair uses oxygen VPSA plants in 3 glassworks to supply oxygen to 100 % oxygen-fired glassworks in the United States.

For those glassworks having several large oxygen-fired melting furnaces, an on-site cryoplant is the most cost-effective alternative.

5. Conclusions

Conversion of glass furnaces to 100 % oxygen-fired systems leads to energy savings and reduced NO_x emissions. At present, the furnaces already converted and originally designed for air burners have energy requirements of 800 kcal/kg glass ($\approx$ 3352 kJ/kg glass) at batch cullet levels of 60 %.

So far, specific NO_x emissions of 80 to 420 g/t glass have been achieved. Model calculations, based on measurements obtained in test furnaces and industrial glass furnaces, also indicate a possible NO_x emission of approximately 100 g/t glass, provided that these furnaces are well-sealed against tramp air, and equipped with low-NO_x burners.

In the case of 100 % oxygen-fired furnaces, the emission of particulates is reduced by 25 to 70 wt%. Model calculations of particulate formation conclude that particulate emissions in oxygen-fired glass furnaces may be reduced to less than 100 mg/kg glass.

6. References

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[3] Tuson, G.; Higdon, R.; Moore, R. D.: 100 % oxygen firing of regenerative melters. In: Wilcox, D. L. sr.; Bergeron, C. G. (eds.): Proc. 52nd Conference on Glass Problems, Urbana-Champaign, IL, 1991. Westerville, OH: Am. Ceram. Soc. 1992. p. 1–17. (Ceram. Eng. Sci. Proc. **13** (1992) no. 3–4.)

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[6] Beerkens, R.; Muijsenberg, H. P. H.: Sources of formation of particulates in soda-lime glass furnaces and model studies on volatilisation. TNO (TPD), Delft, study sponsored by Praxair Inc. Project no. 252.058, 1993.

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