Ultra low nox oxy-combustion system for glass furnaces with adjustable flame length and heat transfer profile

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The performance of a combustion system in a glass furnace is mainly characterized by two relevant parameters:

- the control of temperature field which is essential for glass quality and process performance;
- pollutant emission levels (NO_x, dust…) which must respect more and more stringent regulations.

A new oxygen burner technology has been developed by AIR LIQUIDE in order to answer the double need of thermal profile optimization and minimization of NO_x emissions. This combustion system, relying on a large separation of the fuel and oxidant streams and on the adjustable distribution of the oxidant in three different streams, promotes a strong dilution of the fuel and oxidant jets with furnace gases.

The benefits provided by such a design were underscored with an oxygen–natural gas burner at a nominal firing rate of 2MW in an Air Liquide pilot furnace. The scale-up of this burner to a nominal firing rate of 5MW will particularly suit to large glass furnaces.

During these experiments, parametric measurements of furnace heat transfer profile, flue gas temperature and NO_x concentration were performed.

This burner demonstrated ultra low NO_x emissions: measured levels are 20 to 30 times as low as in standard oxy-burners for the same furnace temperature and O_2 percentage in dry flue gas.

It was also shown that by varying oxygen distribution between various streams, the furnace heat transfer profile along the flame axis could be adjusted to reduce the maximum crown temperature by 50°C and simultaneously increase the furnace back end temperature by 50°C. Thus, for a constant burner thermal input, the difference between the maximum crown and minimum back end temperatures could be varied from 190 to a minimum of 90°C. Variations in heat transfer profile showed a minimum impact on the ultra low-NO_x performance and the overall furnace heat transfer efficiency. When compared to standard burners with fixed characteristics, the ability to optimize flame properties and heat transfer profile in industrial furnaces is expected to translate into appreciable energy savings.

1. INTRODUCTION AND OBJECTIVES

The specifications of a new oxy-combustion system intended for Glass Industry were the following:

- Means to optimize the heat transfer profile for a given furnace geometry (in particular for large furnaces, with a transverse dimension of 9 to 12m);
- Significant reduction in NOx emissions compared to existing oxy-fuel burners.

The effect of some burner and furnace parameters on the heat transfer profile along the flame axis has already been put into evidence by Hottel and Sarofim [1967], Beér [1972 (b)], Michelfelder and Lowes [1974]. For furnaces with an axi-symmetrically positioned burner, the shape of the temperature profile along the furnace axis is affected by design variables such as the flame shape and momentum (that is to say the product of mass flow rate and velocity), the position and intensity of the furnace recirculation zone, the burner swirl level, and the fuel type. Because of the lack of quantitative design guidelines, a modeling study was conducted to identify the optimum range of flame length and momentum for a given furnace to achieve a uniform heat transfer profile (Finet [2000]). The results of this study were the following:

- A long, high momentum flame is recommended to maximize heat transfer away from the burner; moreover such operating conditions enable to reduce the maximum local flame temperature along the furnace axis, and the maximum furnace wall temperature;

- A short, low momentum flame is recommended to maximize heat transfer close to the burner.

Previous flame characteristics (long and high momentum on the one hand; short and low momentum on the other hand) cannot be reached with standard oxy-burners (for instance pipe-in-pipe burners) even with double impulse injections for oxidant. In these geometries where oxidant flow is located near fuel injection, increasing the flame momentum causes an acceleration of the mixture, a reduction in equivalent burner diameter and consequently a decrease of flame length. A possible solution to meet desired flame specifications is a double impulse system (see Fig.1) with a first oxidant flow located near the fuel injection (primary O_2) and a second one positioned at a larger distance (secondary O_2). Supposing the diameter of primary O_2 jet be more important than secondary O_2, changing the repartition between these two injections enables to modify flame momentum and length according to required characteristics. Indeed when increasing the oxidant repartition through the smaller and more distant injection (secondary O_2), flame momentum becomes higher and reactant jets entrain an important flow rate of combustion products: combustion is delayed and takes place over a longer and larger volume.

An other requirement for this new oxy-burner is a significant reduction in NO_x emissions compared with standard burner geometries. Some data used for such a development have been obtained during the OXYFLAM program [Lallemant, 2000]. This research project on oxygen – natural gas flames was performed from 1995 to 1998 with financing from a consortium of eight companies including AGA, Air Liquide, Gaz de France, Hoogovens., Linde, Nippon Sanso, Tokyo Gas and the IFRF. The main program objective was to generate a detailed set of experimental data to help in the design of oxygen burners and in the validation of computer codes for flame calculations.

A further analysis of these experimental results showed that the effects of the injection velocity and oxygen–natural gas jet separation on NOx emissions could be correlated by one simple parameter defined as ratio of the oxygen – natural gas distance over the oxygen nozzle diameter. Consequently NO_x emissions are primarily controlled by the degree of dilution of incoming reactants by combustion products from the colder, low O_2 containing furnace recirculation zone. Assuming free jet behavior, it is easily demonstrated from the Ricou-Spalding jet entrainment equation [Béer and Chigier, 1972] that the degree of dilution of the oxygen jet until the position of interaction between the two jets is proportional to the O_2/NG injectors distance over the oxygen jet diameter.

From the results of the studies presented above, the design guidelines of a low NO_x burner with adjustable heat transfer profile were defined as followed:

- The combustion system should feature means to change from a long, high momentum to a short, low momentum flame in order to modify the axial heat transfer distribution;
- The combustion system should favor the dilution of reactants by combustion products and promote low peak flame temperature.

The criteria above were met by 2MW burner prototype presented in the next paragraph.

2. EXPERIMENTAL SET-UP

Fig. 2 shows the relative position of the natural gas and oxygen injectors in 2MW burner prototype. For the experimental tests, a third criterion was added: flame stability. This explains the existence of an oxidant adjoining the natural gas injector in order to promote rapid mixing between the two streams. This flow (called in the following paragraphs "adjoining") guarantees a stable reaction zone immediately downstream of the natural gas injector, but its rate must remain low enough to avoid a high rate of thermal NO formation.

The ratio of the secondary oxidant – natural gas injector distance versus the secondary injector diameter is high enough to meet the criterion proposed by AIR LIQUIDE. Furthermore the secondary injector section should be small enough so that increasing the secondary oxidant ratio leads to an increase in total burner momentum. The primary oxidant injectors should also meet the jet dilution criterion and allow injection of at least 50% of the total oxidant rate.

It must be noted that compared to traditional burners based on a single ceramic block, this burner consists of two types of small ceramic blocks, one for the secondary oxygen lances, and one for the natural gas, adjoining and primary oxygen injectors. A ceramic block height of 100 mm is sufficient to accommodate injectors for burner firing rates up to 5.0 MW.

The experiments were performed in the AIR LIQUIDE CRCD pilot furnace (see Fig.3). This ceramic fiber lined furnace has a low thermal inertia and can operate at a wall temperature up to 1600°C. The combustion chamber is 6.0 m long, and has a rectangular cross-section of 1.5 by 2.0m. These internal dimensions are large enough to minimize flame confinement effects and allow investigating the interaction between the flame aerodynamics and the furnace recirculation zones. Based on constant velocity scaling rules, exact aerodynamic similarity is obtained between a 2.0MW flame in the CRCD furnace and a 5.0MW flame in a furnace with a length of 9.5m and a cross-section of 2.37 by 3.16m.

Heat extraction and furnace outlet temperature could be varied by insulating the sides of the water-cooled furnace floor, and by covering part of the water-cooled panels with a radiative screen consisting of silicon carbide panels. The furnace roof axial temperature profile was measured by 11 type S thermocouples. Average furnace temperature is calculated with data given by these 11 thermocouples. The heat extraction profile was obtained by calorimetric measurements over the 13 water-cooled floor panels. A set of analyzers and a suction pyrometer measured the flue gas composition (O_2, CO, CO_2, and NO_x) and temperature.

Video cameras were positioned in the furnace side, and above the furnace horizontal exhaust section. Image analysis was achieved: in particular fluctuation images were calculated in order to put into evidence luminosity fluctuation and quantify flame contour. In this case, fluctuation image was defined as the difference between current and average images.

An electric damper in the chimney duct allowed regulating the furnace pressure and minimizing air leakage into the furnace. Further details on this furnace and its diagnostics can be found in [Dugué, 1998]. The level of nitrogen concentration in the furnace dry flue gas was taken as the complement of the (CO_2+O_2) concentrations to 100%. Care was taken to record time-averaged data for stable input and output parameters. Experimental characterization of the burner prototype involved parametric measurements of furnace heat transfer profile, flue gas temperature and NOx concentration. A total of 365 firing modes were measured.

3. RESULTS

a. Influence of secondary oxygen ratio on flame structure and axial heat transfer profile

The influence of secondary oxygen ratio on flame structure is emphasized by Fig.4. Fluctuation images are shown according to face view for three various oxidant repartitions. In these three cases, adjoining oxygen flow rate remains constant and represents 15% of the total oxygen flow rate. The repartition between primary and secondary oxygen flows is the only modified parameter. Burner power is equal to 2MW and furnace temperature is about 1500°C. Fig.4 shows the effect of oxidant staging on flame width. For the lowest secondary oxidant flow rates, two separated flame contours may be distinguished. On the other hand for a secondary oxygen repartition equal to 80%, the two reactions zones are almost contiguous. In this configuration, flame volume becomes very large since 2MW flame is about 2m wide and 4.5m long.

Flame volume evolution as a function of secondary oxygen ratio has an influence on axial heat transfer. Fig.5 shows that low combustion staging (40% oxygen in secondary flow) enables to maximize heat transfer close to the burner whereas high staging (75% secondary oxygen) allows maximizing heat transfer away from the burner. In the latter case, thermal profile is much more homogeneous since the maximal difference on thermal flux is about 20kW. Consequently the design of this new burner answers one of the previously defined purposes: a large flexibility for the axial heat transfer distribution. It must be pointed out that the value of the secondary oxygen ratio yielding the highest heat extraction may be furnace dependent, and in particular dependant on the position of the flue gas duct compared to the burner position. It is expected that the ability to fine-tune the heat transfer profile along the flame axis should translate in improvement in product quality in many furnace types.

Flame volume evolution has also an effect on furnace local temperatures. Fig.6 displays the relation between the furnace front side, middle, back end and flue gas temperatures (see Fig.6 for the position of corresponding thermocouples) as a function of the secondary oxygen ratio. It shows that increasing the secondary oxygen ratio from 45 to 75% increases the furnace back-end temperature by 55°C, while decreasing the furnace front-end and maximum roof temperatures by 50°C. Fig.7 shows the correlation between burner total momentum and the difference between the maximum and back-end temperatures. On the one hand increasing the secondary oxygen ratio up to 45% (very low staging; flame structure similar to this observed in standard oxy-burners) causes a decrease of the total burner momentum and an elevation in the difference between the maximum minus back-end temperatures from 145 to 203°C. On the other hand increasing the secondary oxygen ratio from 45 to 75% leads to an increase of the total burner momentum and a reduction in the difference between the maximum minus back-end temperatures from 203 to 96°C. As observed from experience and internal studies, the increase in burner momentum has a beneficial impact on the furnace temperature uniformity.

b. NO_x emissions

i. Influence of secondary oxygen ratio

Fig. 8 shows the effect of secondary oxygen ratio on NO_x emissions as a function of the average furnace temperature. The furnace temperature was modified either by changing the heat extraction, or by changing the firing rate. For all data shown on Fig. 8, the nitrogen concentration in the dry flue gas was around 5.0%. The results show that for a secondary oxygen ratio of 75% and an adjoining oxygen ratio between 10 and 15%, the NO_x emissions range from 7 to 69 ppm for average furnace temperatures between 1210 and 1500°C. Because pure oxygen combustion leads to a dry flue gas volume reduction by a factor of about 9.5, the NOx emissions indicated above are equivalent to NOx concentrations of 0.7 to 7 ppm (1.5 to 15 mg/Nm3) in the combustion products from air combustion.

Throughout the experiments, it was noted that the combination of an adjoining oxygen ratio of 5% and secondary oxygen ratios above 70% led to large pressures fluctuations and increased air aspiration into the furnace. Under extreme conditions, a flame with 5% adjoining oxygen ratio and with 95% secondary oxygen ratio exhibited important changes in the flame reaction zone, with two main, luminous combustion zones located around the secondary oxygen jets. From the instantaneous furnace pressure data, the standard deviation of the pressure measurements was calculated. It showed that the furnace pressure standard deviation is about constant for a secondary staging ratio from 0 to 70%, and increases sharply in the range from 70 to 95%. This effect was observed experimentally from the increase in nitrogen content in the flue gas. Under very high secondary oxygen staging conditions, closing the chimney damper and increasing the mean furnace pressure to 2.5 mm H_20 could not prevent the increase in nitrogen concentration in the flue gas. Thus, although a high staging ratio is beneficial to minimize NO_x emissions, it appears preferable not to exceed a secondary oxygen ratio of 70% in order to keep pressure fluctuations and air aspiration to a minimum. The standard deviation of the instantaneous furnace pressure can be used as a useful indicator to optimize the burner oxygen distribution.

ii. Influence of Nitrogen concentration in flue gas

The influence of nitrogen concentration in flue gas on NO_x emissions was investigated for various average furnace temperatures and is displayed in Fig. 9. [Dugué, 1999] showed that the NO_x emissions are correlated to the nitrogen concentration in the flue gas whatever the source of nitrogen. Thus, for a same nitrogen concentration in the flue gas, premixing nitrogen in the fuel or oxygen supply line or aspirating air into the furnace leads to nearly identical NO_x emissions. In the present experiments, the nitrogen concentration was increased by opening the chimney damper, which reduced the furnace pressure and increased the air aspiration into the furnace. The furnace average temperature was maintained constant by increasing the firing rate to compensate the aspiration of cold air. The oxygen flow rate was also adjusted to maintain 3% O_2 in the dry flue gas.

Fig.9 displays NOx emissions results as a function of nitrogen concentration in dry flue gas and average furnace temperature. It must be noted that because the flue gas volume increases with the nitrogen concentration, NO_x concentration expressed as a volume concentration does not provide a true assessment of the absolute increase in NO_x as a function of nitrogen in the flue gas. For this purpose, it is preferable to recalculate the NO_x emissions as a mass per unit of fuel energy. It can be observed that the NO_x emissions of the diluted jet burner increase about linearly with the nitrogen concentration and exponentially with the average furnace temperature. It is significant that the NO_x emissions of this type of combustion system are controlled predominantly by the furnace temperature rather than by the theoretical adiabatic flame temperature. This is in agreement with the assertion that because of the high jet separation and injection velocities, the peak flame temperature is somewhat above the furnace temperature, but much below the theoretical adiabatic flame temperature obtained for undiluted reactants. Fig. 9 also shows that with 5% N_2 in the dry flue gas, the NO_x emissions range from 0.4 to 4.5 mg/MJ for average furnace temperatures from 1210 to 1500°C. It is interesting to compare these results with the emissions from air combustion. For example, the current NOx emission target of 500mg/Nm3 at 8% O2 for glass furnaces is, for air/natural gas combustion, equivalent to 140mg/MJ.

4. CONCLUSIONS

The performance of the AIR LIQUIDE Diluted Jet burner concept was characterized by parametric measurements of furnace heat transfer profile, flue gas temperature and NO_x concentration for a total of 365 firing modes. The recommended oxygen distribution of the Diluted Jet burner is the following:

- an adjoining oxygen ratio of 5 to 25%, in order to maintain a stable flame front and low furnace pressure fluctuations,
- a secondary oxygen ratio between 45 and 75%, depending on the required flame heat release and heat transfer profile, with the remaining oxygen flow introduced through the primary oxygen injectors.

It was shown that by varying the secondary oxygen ratio between 45 and 75%, the furnace heat transfer profile along the flame axis could be adjusted as to reduce the maximum crown temperature by 50°C and simultaneously increase the furnace back end temperature by 50°C. Thus, for a burner thermal input maintained constant, the difference between maximum crown and minimum back end temperature could be varied from 190°C to a minimum of 90°C. The variations in heat transfer profile showed a minimum impact on the ultra low-NO_x performance and the overall furnace heat transfer efficiency. When compared to standard burners with fixed characteristics, the ability to optimize the flame properties and heat transfer profile to each industrial furnace geometry is expected to have a positive impact on product quality, refractory wear, and fuel efficiency.

Under optimized conditions, this burner demonstrated NO_x emissions between 7 and 65 ppm, at 3% O_2 and 5% N_2 in dry flue gas (equivalent to 0.4 to 4.5 mg/MJ), for average furnace temperatures between 1220 and 1510°C, respectively. Because of the circa tenfold reduction in dry flue gas volume, these results are equivalent to emissions of 0.7 to 7 ppm NOx for air combustion. For an average furnace temperature of 1345°C and a nitrogen concentration of 55% in dry flue gas, the NOx emissions were 82 ppm, equivalent to 11.3 mg/MJ. For an average furnace temperature of 1495°C and a nitrogen concentration of 50% in dry flue gas, the NOx emissions would be about 400ppm. This ability to maintain ultra low NOx emissions, even under high nitrogen concentrations in the furnace gases, allows implementation of this technology in industrial furnaces fired with air and oxygen burners. Furthermore, as Diluted Jet burner consists of two types of small ceramic blocks (100mm high for burner firing rates up to 5.0 MW), this burner is very easy to implement in existing geometries.

Next perspectives for Diluted Jet concept are essentially about the fuel oil version. Fig. 10 shows a face view of live flame obtained during the first experiments. Heat transfer flexibility and low NOx emissions also tend to be the main characteristics of this fuel oil version.

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Beér J.M. and Chigier N.A., Combustion aerodynamics, Applied Science Publishers, 1972 (a)

J.M.Beér, *Recent advances in the Technology of furnace flames*, Journal of the Institute of Fuel, Vol 30, July 1972 (b)

Dugué J., *Comparison between high air preheat and pure oxygen combustion in pilot scale and industrial furnaces*, 13th IFRF Totem meeting – « High Temperature Combustion Research for Industry », Akersloot, The Netherlands, April 21-22, 1999

Dugué J., Von Drasek W., Samaniego J.M., Charon O., Oguro T.; Advanced combustion facilities and diagnostics, American/Japanese Flame Research Committees 1998, International Symposium Maui, Hawaii, October 11-15,

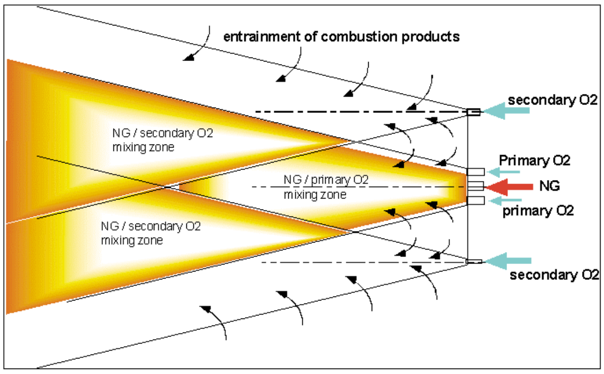
Finet, S., *Investigation on the influence of the burner momentum and flame length on furnace axial heat transfer profile*, AIR LIQUIDE Report, September 2000

Hottel H. C., Sarofim A. F., “Radiative transfer”, McGraw-Hill, New York, 1967

M. Katsuki and T. Hasegawa, *The science and technology of combustion in highly preheated air*, 27th Symposium (Int) on Combustion, pp 3135-3146, 1998

S. Michelfelder and T.M. Lowes, *Report on the Mathematical Modeling M-2 Trials*”, IFRF Doc. F36/a/4, August 1974

N. Lallemant, et al., *Flame Structure, Heat Transfer and Pollutant Emissions Characteristics of Oxy-Natural Gas Flames in the 0.7-1 MW Thermal Input Range*, Journal of the Institute of Energy, September 2000, vol. 73,pp. 169-182



5. Fig. 1: Jet Dilution concept
6. proposed by AIR LIQUIDE.

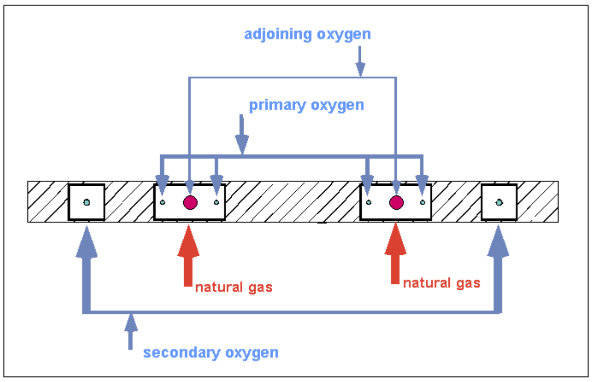


Fig. 2 : Prototype burner geometry

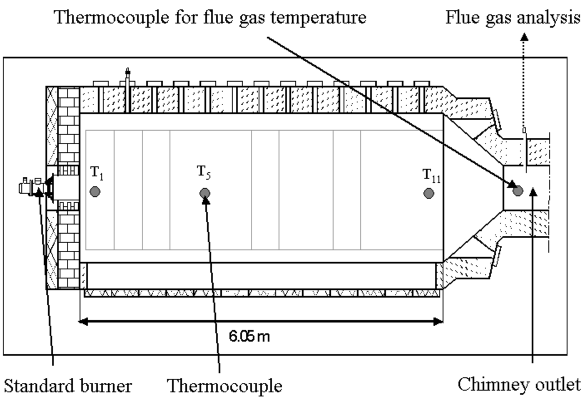
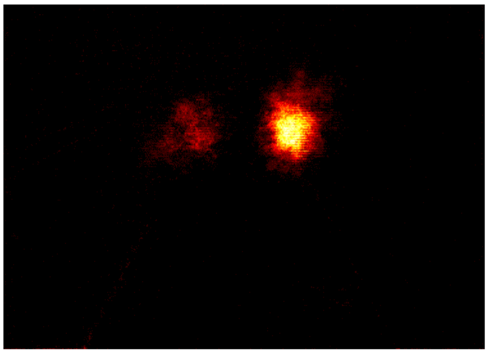
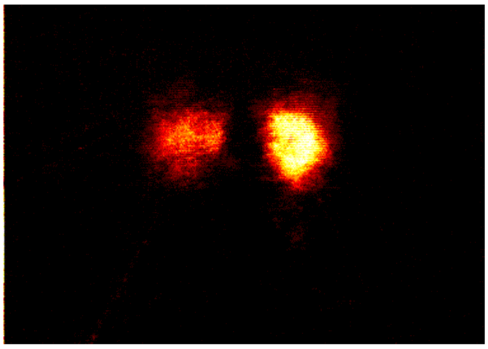


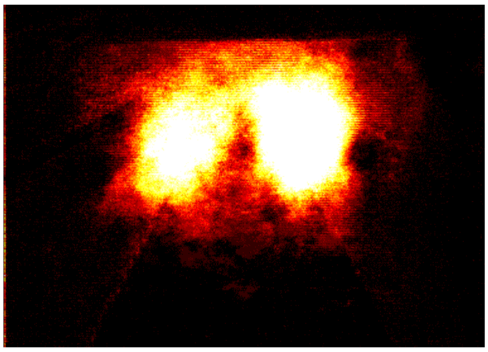
Fig.3 : AIR LIQUIDE CRCD pilot furnace.



a. Secondary oxygen ratio = 40%



b. Secondary oxygen ratio = 60%



c. Secondary oxygen ratio = 75%

Fig.4: Flame fluctuation (face view).
Power=2MW; Adjoining O_2 ratio = 15%

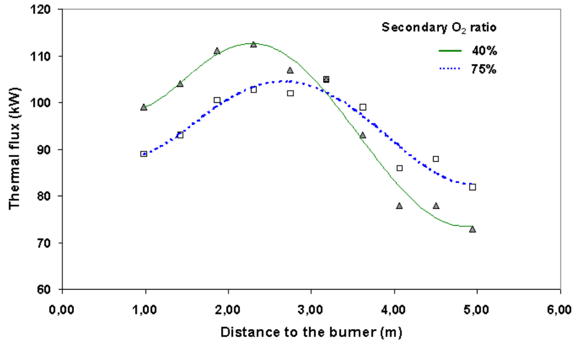


Fig. 5: Effect of secondary oxygen ratio on axial heat transfer.
Power=2MW; Adjoining O_2 ratio = 15%

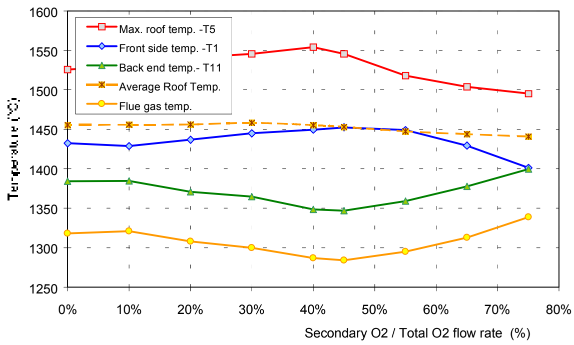


Fig. 6: Effect of Secondary O2 flow rate on furnace axial temperature

Power=2MW; Adjoining O_2 ratio = 15%

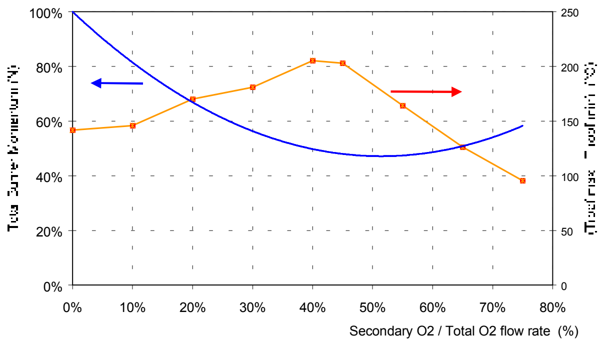


Fig.7: Relation between Secondary O_2 flow rate, total burner momentum and furnace axial temperature profile.

Power=2MW; Adjoining O_2 ratio = 15%

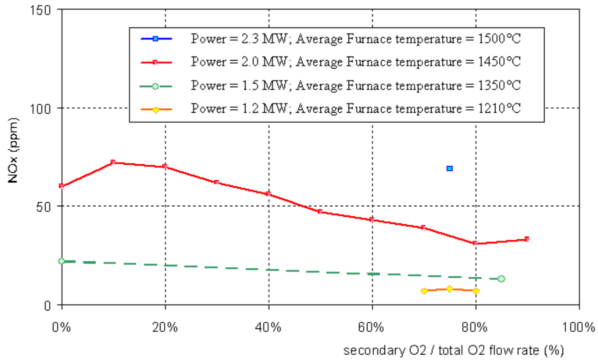


Fig.8: Influence of secondary oxygen repartition on NOx emissions

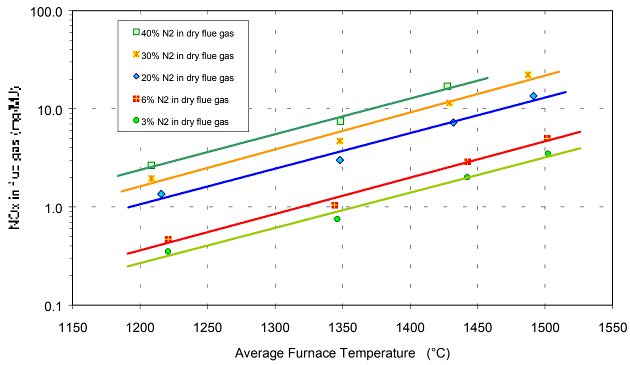


Fig. 9: Influence of Nitrogen content in flue gas and average furnace temperature on NOx emissions

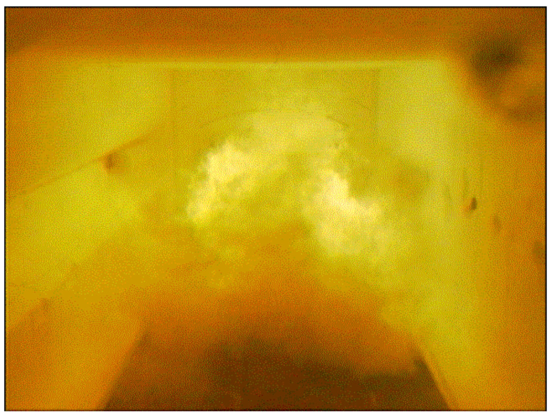


Fig.10: Flame live image (face view) of Dilution Jet Concept (fuel oil version).
Power=2MW; Secondary O_2 ratio = 75%