International Journal of Thermodynamics (IJoT)
ISSN 1301-9724 / e-ISSN 2146-1511
www.ijoticat.com

Vol. 16 (No. 2), pp. 55-61, 2013
doi: 10.5541/ijot.448

Flameless Oxidation as a Means to Reduce NO_x Emissions in Glass Melting Furnaces*

J. Leicher[1] **A. Giese**

Gas- und Wärme-Institut Essen e.V., Germany
[1]leicher@gwi-essen.de

Abstract

In the glass industry, very high process temperatures are required in order to melt the raw materials. These temperature levels are usually achieved by burning natural gas with strongly pre-heated air. However, this creates ideal conditions for a strong formation of nitrous oxides (NO_x), a pollutant whose emissions are strictly regulated. The industry is therefore very much interested in technologies to suppress the production of NO_x within the furnace itself. One possible approach is the so-called flameless oxidation, a novel combustion regime which is characterized by very homogeneous temperature distributions and low NO_x production. While this form of combustion is firmly established in the steel industry, the glass industry has been reluctant to change its production methods as the glass melt is very sensitive to changes in the furnace conditions.

Gas- und Wärme-Institut Essen e.V. (GWI), in cooperation with its partners, investigated how to best introduce flameless oxidation into glass melting furnaces. Using both simulation and experimental techniques, a GlasFLOX burner was developed and then examined with regards to its NO_x reduction performance. In a second step, the retrofitting of an operating furnace was carried out, based on a strategy determined by extensive CFD simulations.

After five years of operation, the operators of the retrofitted plant report unchanged product quality, while NO_X emissions have been reduced by about 50 %.

Keywords: *Glass melting furnace; flameless oxidation;* NO_X *emissions.*

1. Introduction

The melting of glass on an industrial scale is a very energy-intensive process which, depending on the glass quality being manufactured, can easily require process temperatures of more than 1600°C. In glass melting furnaces these very high temperature levels are usually achieved by means of intensive pre-heating of the combustion air, either recuperatively (maximum air pre-heat temperatures around 800°C) or regeneratively (maximum air pre-heat temperature 1400°C).

However, high temperatures, combined with a near-stoichiometric operation of the burners and long residence times due to the size of the furnaces and generally low flow velocities, generally lead to a significant formation of nitrous oxides (NO_x). As the emission of these pollutants is strictly regulated by emission laws, the glass industry is very interested in techniques to reduce NO_X emissions without resorting to costly secondary flue gas treatment. Instead, techniques are preferred which reduce NO_x formation in the furnace itself, of course without reducing the glass quality.

One such potential primary technique to reduce NO_X emissions is the so-called flameless oxidation (FLOX) technology, which is already well-established in the steel industry. Other common names for this technology are mild or colorless combustion. This technology, first developed in the 1980s (Wünning, 1996), uses high momentum jets of fuel and air to entrain large amounts of hot, but chemically inert flue gas and mix it with fuel and combustion air. In this manner, the shape of the reaction zone is changed: instead of an almost two-dimensional reaction front, a three-dimensional reaction volume is created in which the reactants are significantly diluted by the hot exhaust gas. The consequence of this change in the form of the reaction zone is that a much more homogeneous temperature distribution is obtained, without the temperature peaks usually found in conventional diffusion flames. As thermal NO_x formation is highly dependent on local temperature, this much more homogeneous temperature distribution drastically reduces NO_x emissions. Figure 1 shows a comparison between the standard and the FLOX modes of combustion while Figure 2 shows flame images both in the visible and UV spectrum (using an OH chemoluminiscence method) of standard diffusion flames and FLOX combustion.

The name "Flameless Oxidation" derives from the fact that due to the dilution of the reaction zone, there is no visible flame while operating in FLOX mode, as can be seen on the lower left hand side of Figure 2. Nevertheless, complete consumption of the fuel gas is achieved, which can be shown by CO measurements in the exhaust gas. The different shapes of the reaction zones can be visualized by the OH^* chemoluminiscence images as shown on the right hand side of Figure 2. While the standard combustion shows a zone of intense combustion near the burner outlet, the reaction zone in the flameless mode is lifted off the burner throat and shows a more even OH distribution.

While the intense mixing of the reactants with hot but chemically inert exhaust gas lifts local temperatures above the self-ignition limits, the local oxygen concentrations are reduced (cf. Figure 3), leading to a unique form of combustion characterized by very homogeneous temperature and heat flux distributions, stable combustion behaviour and very low NO_x emissions. Also, noise emissions are low compared to conventional burners.

---

*This paper is an updated version of a paper published in the ECOS'11 proceedings. It is printed here with permission of the authors and organizers.

**Corresponding Author

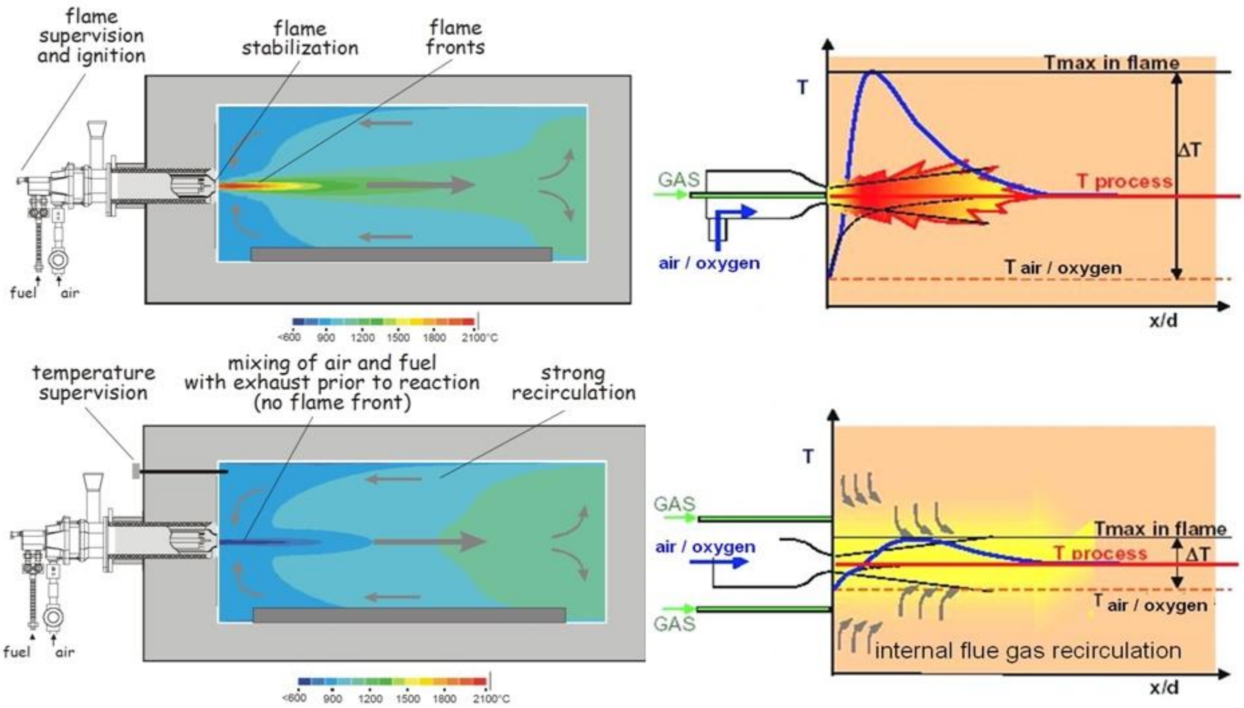

Figure 1. Overview of standard combustion (top) and flameless oxidation (bottom). On the right hand side, the respective temperature evolutions are shown (Wünning, 2003) (figure is in color in the on-line version of the paper).

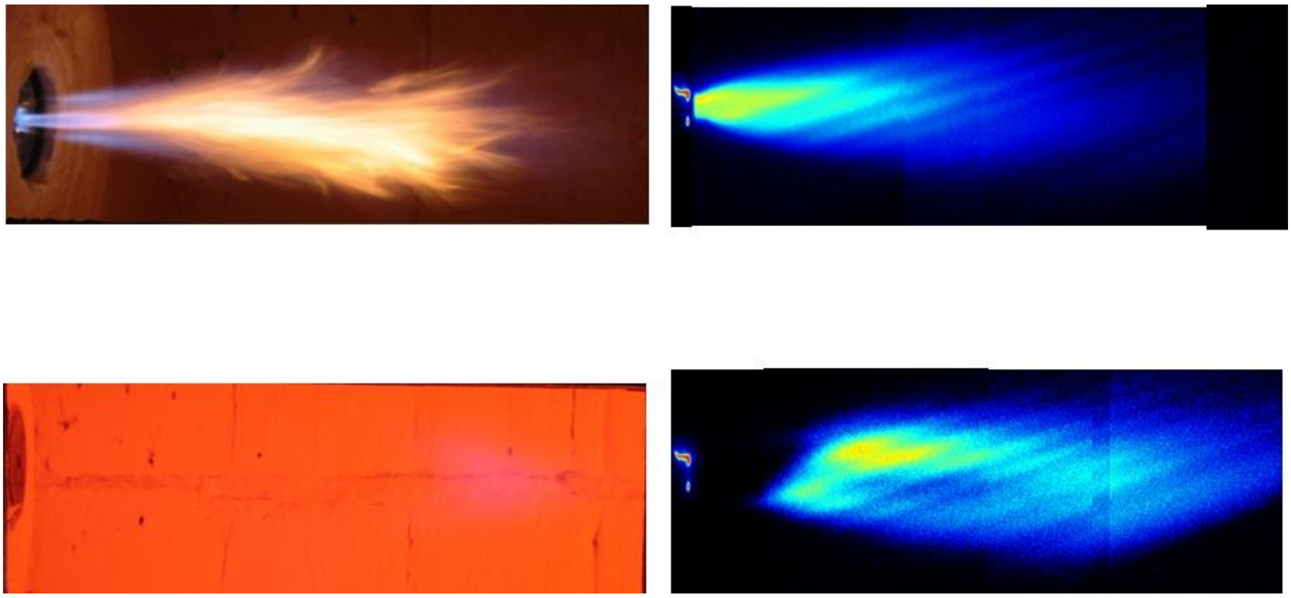

Figure 2. Comparison of standard (top) and FLOX (bottom) combustion modes in the visible and the UV spectrum (figure is in color in the on-line version of the paper).

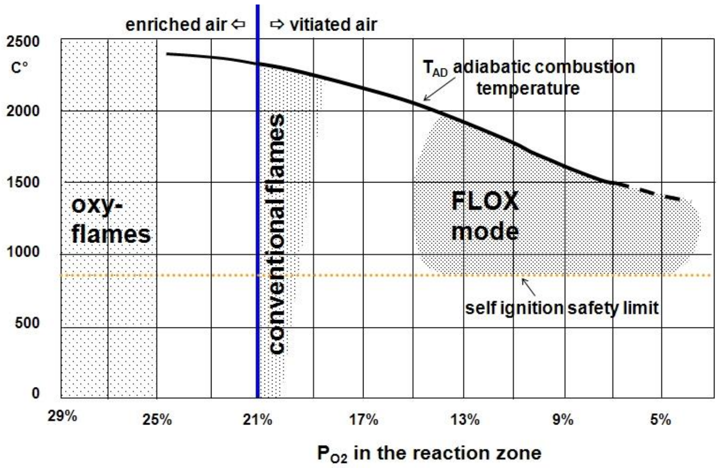

Figure 3. FLOX mode as a function of the partial pressure of O_2 (Milani, 2000).

FLOX combustion mode has successfully established itself as a method to reduce of NO_x in many high temperature applications. The glass industry, however, has been hesitant to adopt this burner technology as flames in glass melting furnaces are traditionally highly luminous while the reaction zones in FLOX combustion are almost entirely invisible. However, results from a previous research project called EURONITE (Flamme et al, 2000) were promising enough that a glass manufacturer (OSRAM GmbH) and a burner manufacturer (Hotwork International) could be convinced to join GWI in a research project called GlasFLOX which investigated the applicability of FLOX technology for glass melting furnaces.

2. Burner Design, CFD Study and Test Rig Experiments

One of the defining characteristics of flameless oxidation burners is the very high momentum of the fuel jets and combustion air. It is therefore obvious that FLOX burners can only be applied to glass furnaces with recuperative air preheating because only in this configuration the required high velocities jets for the combustion air can be achieved. A schematic of such a recuperative glass melting furnace is shown in Figure 4.

The primary objectives of the GlasFLOX project were to design a FLOX burner for operation in glass melting furnaces which would produce less than 500 mg/(N m^3) NO_x and at the same time show good behaviour at partial loads. Of course, maintaining the quality of the glass was of paramount importance.

In a first step, a 500 kW FLOX burner for application in glass melting furnaces was designed. CFD simulations were carried out to find an optimum geometry for the burner which was then manufactured and extensively tested at one of GWI's semi-industrial test rigs in order to validate that the targeted NO_x emission levels were achieved. Figure 5 shows a comparison between the original (HWI) and the newly designed GlasFLOX burner systems. In the lower half of the figure, the CFD-calculated velocity distributions can be seen. As intended, the reduced section area of the nozzle leads to much higher air velocities which impart a very high momentum to the gas/air jet. While the higher velocities cause higher pressure drops in the burner, these were found to be within acceptable limits.

Numerical simulations of the original and the GlasFLOX burners in a combustion test rig showed that lower maximum temperatures were achieved in the case of the flameless oxidation burner while the temperatures of the flue gas remained almost the same (cf. Figure 6). The difference in maximum temperatures amounted to about 200K. These CFD simulations also show the different size and shape of the reaction zones when comparing a conventional reference burner to a flameless oxidation system.

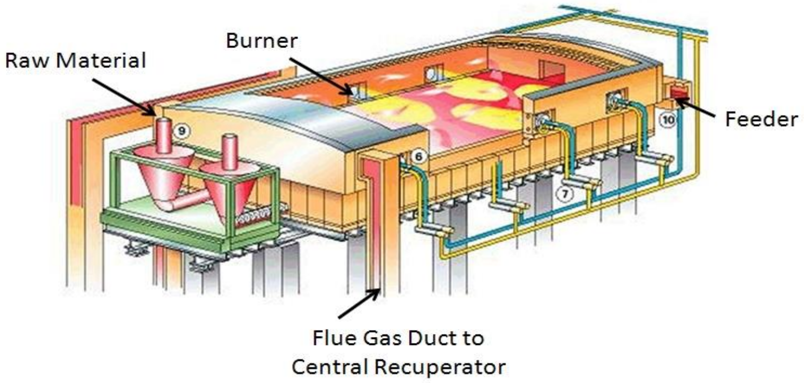

Figure 4. Schematic of a recuperative glass melting furnace (figure is in color in the on-line version of the paper).

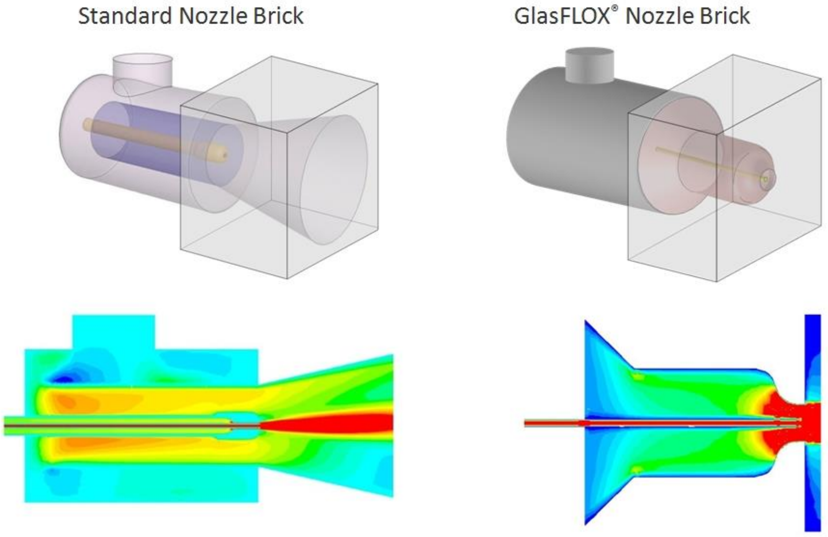

Figure 5. Comparison of the standard nozzle brick and the newly designed GlasFLOX brick with simulated velocity distributions (figure is in color in the on-line version of the paper).

All CFD studies mentioned in this paper were carried out using ANSYS FLUENT (Version 6.3). The standard k-ε-model was used to describe the influence of turbulent fluctuations on the averaged flow properties while combustion and its interaction with the turbulent flow field were handled using the eddy-dissipation model in combination with a common 2-step methane reaction mechanism (Jones & Lindstedt, 1988). The discrete-ordinates model was used to describe radiative heat transport in the furnace.

These findings were validated by measurements. The experimental investigations of both the original and new burner system in GWI's test rig prove that the GlasFLOX system was able to comply with the target emission values for NO_x (cf. Figure 7), which was already significantly below the legal emission limits of 800 mg/Nm^3.

Due to these very promising results, the retrofit of an existing glass melting furnace with the new GlasFLOX burners was planned.

3. Conversion of a Glass Melting Furnace and Testing under Real-Life Conditions

The glass melting furnace which was to be retrofitted with GlasFLOX burners is a side-fired furnace with ten burner positions which are connected to a central recuperator to recover waste heat from the exhaust gas in order to preheat the combustion air. A sketch of the plant is shown in Figure 8.

The process operators did not want prolonged downtimes of the plant and hence loss of production, which is why the retrofit campaign was planned in advance aided by CFD simulations of the furnace. Several configurations were simulated and evaluated.

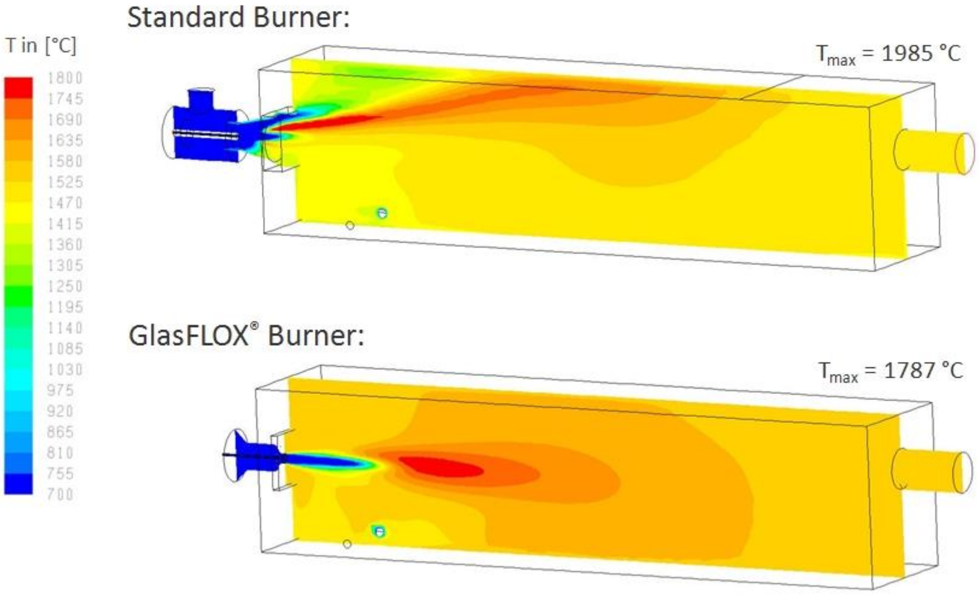

Figure 6: Comparison of the simulated temperature distribution for the two burners in GWI's test rig. (figure is in color in the on-line version of the paper).

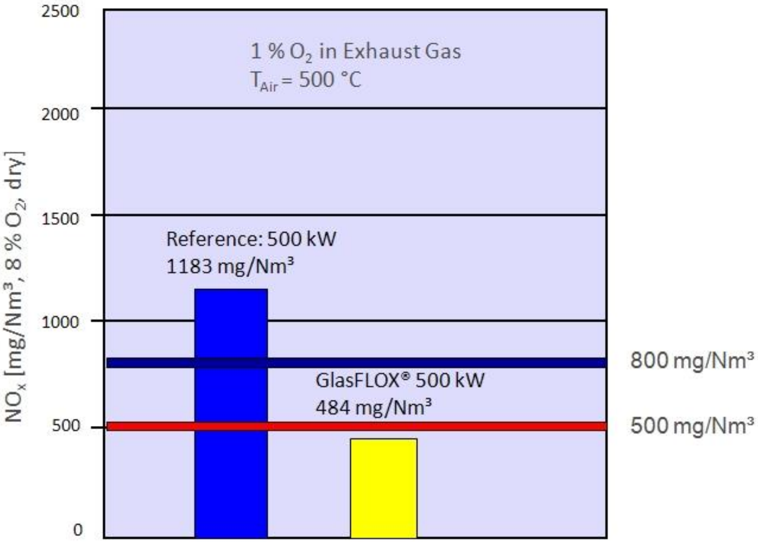

Figure 7. Measured NO_x emissions of the original (HWI) burner and the new GlasFLOX burner (figure is in color in the on-line version of the paper).

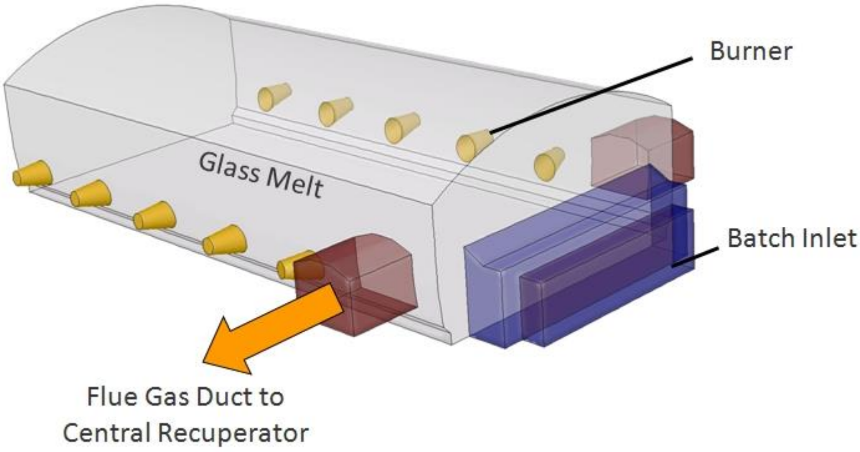

Figure 8. Schematic of a glass melting furnace (figure is in color in the on-line version of the paper).

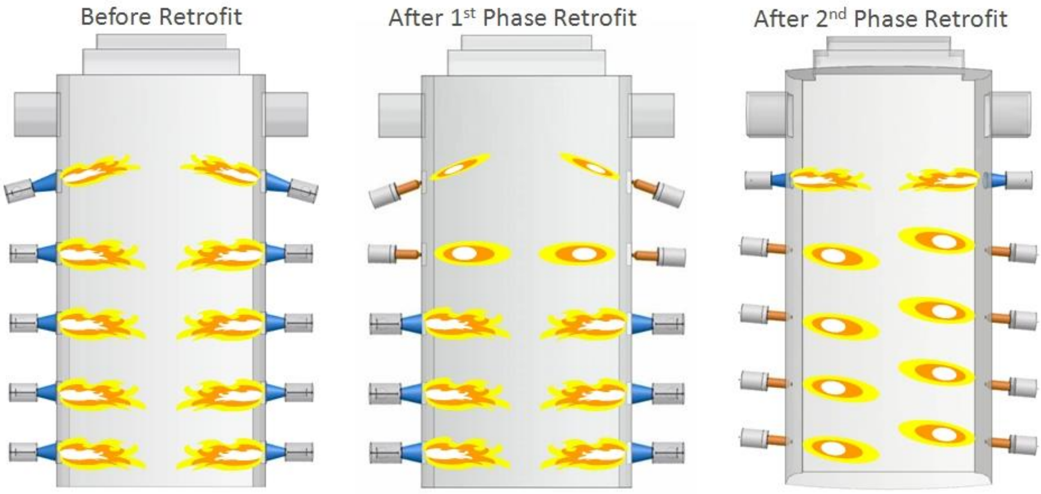

Figure 9. Burner configurations for the various retrofit phases (figure is in color in the on-line version of the paper).

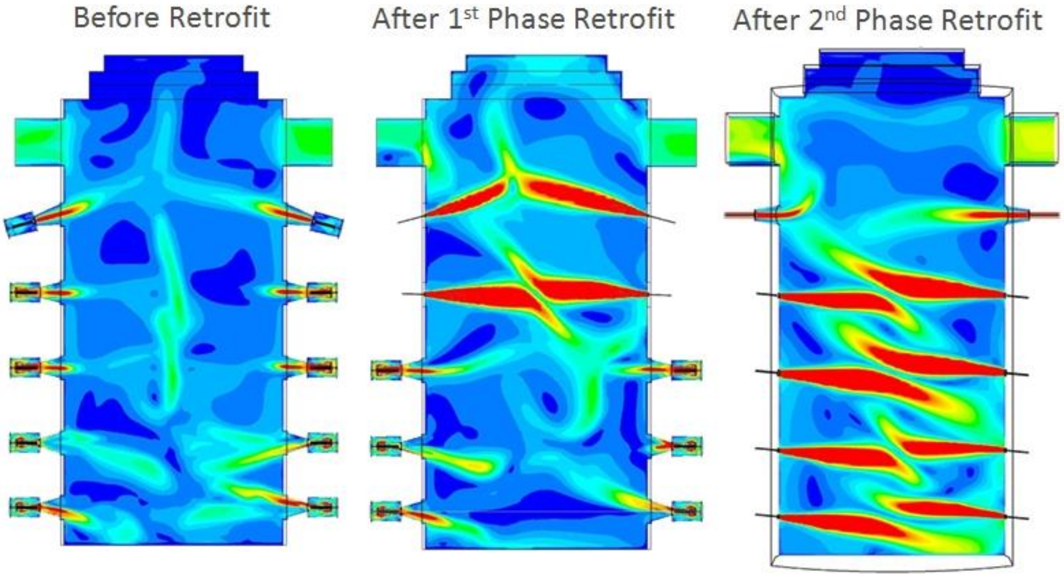

Figure 10. Simulated velocity distributions near the glass bath for the various retrofit phases (figure is in color in the on-line version of the paper).

In a first step, only four of the ten existing burners were substituted with GlasFLOX burners, those close to the batch inlet (cf. Figures 9 and 10, center images). However, simulations showed that this configuration led to increased gas velocities near the batch and the flue gas ducts. High velocities in this area are not desirable as this may lead to carry-over from the dust-laden batch material into the recuperator which may cause increased wear and tear or even damage of the recuperator.

Therefore, a second configuration was investigated in which all but the two burners closest to the batch inlet were swapped with GlasFLOX burners (cf. Figure 9, right hand image). In this way, low velocities close to batch inlet and flue gas ducts can be maintained, minimizing the risk of dust carry over into the recuperator. Figure 8 shows the various steps of the retrofit, while Figure 9 shows the calculated velocity distributions immediately above the glass melt for the various configurations (Giese et al., 2008; Scherello et al., 2007).

Also, several different alignments and configurations of the burners were simulated numerically in order to avoid collisions of the jets which might cause increased turbulence and hence disturbance of the glass bath and potential dust-ups. This was not a problem before as the burner exit velocities of the original burners were relatively low, but became important when using the flameless oxidation burners with their much higher jet momentum. It was found that a burner orientation of 5 degrees off the burner axis was well-suited to avoid these issues (see Figure 11).

In the next phase, the conversion of the furnace was carried out based on the strategy determined by the CFD simulations. Eight standard burners were replaced with GlasFLOX burners with the two burners closest to the batch inlet remaining untouched in order to maintain low gas velocities near the batch. After the retrofit, pollution emission measurements were performed in order to evaluate the impact of the new burner system on NO_X emissions. Comparisons with NO_x emission measurements taken prior to the retrofit showed a reduction of about 45% while maintaining constant fuel consumption and, most importantly, glass quality. Also, condensation in the flue gas ducts was found to be reduced by about 30%.

Due to the increased combustion stability inherent in the FLOX technology, it was even possible to reduce the excess air ratio, thus reducing fuel consumption.

After five years in operation, the plant operators are very pleased with the new burner system. NO_x emissions remain low, and there is hardly any corrosion to be found at neither the burner tips nor the nozzle bricks. The burners themselves require less maintenance than the original equipment. While there were some reservations in the beginning to the use of high momentum burners in a glass furnace due to the fear of increased dust-ups, this was found not to be the case. In fact, the amount of dust in the flue gas decreased slightly.

4. Conclusion

In the course of a research project carried out by the Gas-und Wärme-Institut in cooperation with several industrial partners, namely OSRAM GmbH and Hotwork International AG, introduced the flameless oxidation technique into the glass industry. In the beginning, this combustion concept which has already been successfully implemented in various high temperature manufacturing processes, was regarded with some scepticism due to the lack of a visible flame and the requirement for high velocity gas flows in a glass melting furnace. However, using both experimental and numerical techniques on a lab-scale, it could be shown that this combustion concept can be successfully adapted for use in glass melting furnaces.

The subsequent conversion of the furnace to flameless oxidation operation was prepared beforehand by extensive use of CFD simulations in order to minimize the downtime of the plant. The retrofitted furnace has been operating for about five years now, with an excellent operational track record. NO_x emissions are about 45% lower than before the conversion, while maintaining the same glass quality as before. It is also possible to reduce the excess air ratio in the furnace since FLOX combustion is much more stable than conventional combustion systems. Thus, fuel consumption can be reduced slightly.

5. Acknowledgment

The authors wish to thank all the participants of the GlasFLOX project and gratefully acknowledge the funding by the German Federal Ministry of Economy and Technology (BMWi).

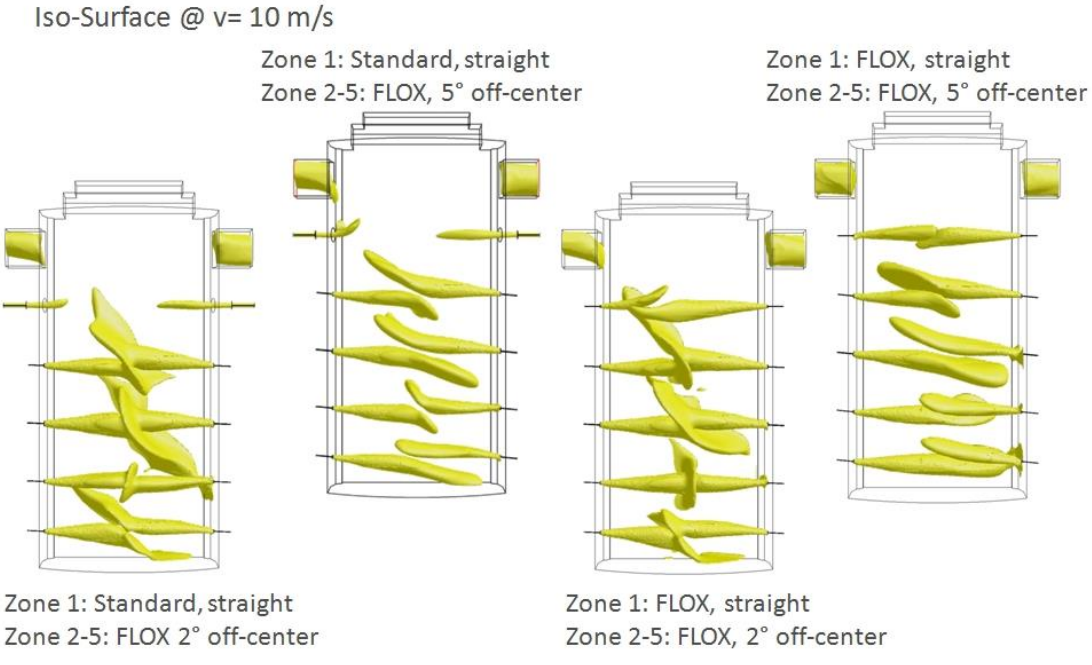

Figure 11: Velocity iso-surfaces for various burner configurations.

Figure 12. View into the GlasFLOX glass melting furnace (figure is in color in the on-line version of the paper).

References:

Flamme, M., Kösters, M., Scherello, A., Kremer, H. & Boß, M. (2000). *Experimental Study of Heat Transfer Intensification in Glass Melting Furnaces*. Final report of task 2.2 of the EURONITE project (JOE3CT970083). Gas- und Wärme-Institut Essen e.V., Germany.

Giese, A., Konold, U., al-Halbouni, A. Görner, K., Schwarz, G., & Köster, B. (2008). *Application of Flameless Oxidation in Glass Melting Furnaces*, 7th International Symposium on High Temperature Air Combustion and Gasification, Phuket, Thailand.

Jones, W.P., Lindstedt, R.P. (1988). *Global reaction mechanisms for hydrocarbon combustion*, Comb. & Flame. *73*(3), 233-249.

Milani, A. (2000). *"Mild Combustion" techniques applied to regenerative firing in industrial furnaces*, 2nd International Seminar on High Temperature Combustion, Stockholm, Sweden.

Scherello, A.; Konold, U., & Görner, K. (2007). *Anwendung der flammenlosen Oxidation für Glasschmelzwannen mit rekuperativer Luftvorwärmung – GlasFLOX®*, 23. Deutscher Flammentag, 12.-13. September 2007, Berlin, Germany, VDI-Bericht 1988.

Wünning, J. G. (1996). *Flammlose Oxidation von Brennstoff*. PhD Thesis. RWTH Aachen, Germany.

Wünning, J. G. (2003). *FLOX-Flameless Combustion*. Thermprocess Symposium. Düsseldorf, Germany.