CONVENTIONAL AND OXY FUEL COMBUSTION IN A GLASS FURNACE INSTALLATION

Th. Panidis\textsuperscript{1}, K. K. Perrakis\textsuperscript{1}, P. Koutmos\textsuperscript{1}, S. Orfanos\textsuperscript{2} and D. D. Papailiou\textsuperscript{1}

\textsuperscript{1}Laboratory of Applied Thermodynamics, Mechanical Engineering and Aeronautics Department, University of Patras, GR 265 00 Patras-Rio, Greece,

\textsuperscript{2}Yula Glassworks S.A., 5 Orizomilon Str., GR 122 44 Egaleo, Greece

ABSTRACT

A continuing study to improve the performance and environmental impact (especially NO\textsubscript{x} emissions) of industrial glass furnaces is presented in this work. The methodologies include the use of oxy-fuel burners and alternative combustion schemes. The investigation is based on experimental measurements on experimental and full scale glass furnaces as well as the use of computational tools capable to predict the chemical, flow and heat transfer processes in the furnace.

1 INTRODUCTION

The efficient use of energy in high energy consuming combusting systems and the corresponding environmental impact have become of major importance to science and technology for several years now. In a market which every day becomes more open and globalized and facing environmental and pollution legislation with hard to reach standards, the only way to remain competitive is to possess up to date technology and know how. One of the main concerns in high energy consuming combustion systems, such as glass furnaces, is the control of the NO\textsubscript{x} emissions, which are toxic gases that adversely affect the eyes and lungs, contribute to acid rain and global warming and are precursors to ground level ozone formation and photochemical fog [1]. The oxidation state and high temperature flames within a glass furnace promote the evolution of high concentration of nitrogen oxides [2] and conventional air-fuel combusting systems are unable to meet the environmental standards. Considerable effort has been devoted lately in the research and development of alternative techniques aiming at the reduction of NO\textsubscript{x} formation, including the investigation of different combustion schemes, such as modifications to the combustion and furnace geometry or the use of improved oxidiser and fuel placement.

Although the basics of furnace design are well known, individual companies, supported by experience, have their own additional know-how that influences their design philosophy. During the years of operation Yula Glassworks S.A. has developed own expertise in the design and construction of glass furnaces following the trends in this field internationally and adopting techniques and improvements that fitted the production philosophy. Yula glassworks located in between urban area in Attici face considerable legislative restrictions concerning the environmental and pollution impact of operation besides space limitations. In order to cope with the competition in the open market, optimisation of the efficiency of processes and equipment is very important for the status of the company. This is the reason for example that Yula is between the first high energy consuming industries in Greece, which have switched to natural gas fuel. In order to keep this edge Yula has started since several years a collaboration

E-mail: panidis@mech.upatras.gr
with Laboratory of Applied Thermodynamics (LAT), University of Patras which has considerable expertise in experimental and numerical investigation of combustion systems, ranging from basic research and modelling to contributions to equipment and process design and evaluation. The aim of this collaboration is to investigate alternative techniques which will improve the efficiency and reduce the environmental impact of the current generation of Yula's glass furnaces and influence the design of the next generation. The investigation relies on experiments revealing the trends of the modifications in a scaled down glass furnace located in the Yula glassworks as well as on the monitoring of the thermochemical parameters in a production furnace. In order to keep the cost of the investigation reasonable a numerical code had to be developed to support the extensive evaluation of the range of possible variations in the design and the operating parameters of the burner-glass furnace system. This code has to be capable to predict the chemical, flow and heat transfer processes in order to be used as a tool for the efficient design of industrial equipment.

2 EXPERIMENTAL INVESTIGATION

The experimental part of this work is based on detailed measurements on experimental furnaces as well as on global performance measurements on industrial furnaces in order to test and evaluate combustion performance as related to the NOₓ emissions when oxy-fuel combustion is used under conditions approaching real production conditions. Moreover these experimental results are also to be used for the evaluation of the computer code used to improve burner and furnace design.

2.1 Experimental Apparatus

An experimental glass furnace (1.9x1.7x1.5 m³, 8 tons, fig. 1), was constructed in the earlier stages of this investigation at Yula glassworks. The combustion chamber was 1.6 m long and 1 m wide. The height of the vault varied from 0.45 m at the sides to 0.60 m at the centre. The oxy-fuel burner installed in the furnace was stainless-steel made, feeding fuel through a central opening and oxygen/air through eight orifices located around it. The fuel used was LPG (85% Butane-15% propane) with a lower heating value of 28456 Kcal/Kg. The excess combustion oxygen used was 4-7 % measured at the stack. For each set of conditions a period of 5-8 hours was needed to reach steady state.

Inlet conditions (pressure and temperature) and flow rates were constantly controlled for both oxidiser and fuel supplies. Furthermore the oxygen concentration in the oxidiser was measured. Leak and flame detectors driving solenoid valves were used to ensure safe operation of the furnace.

High temperature thermocouples (0.5 mm Pt/Pt-Ro 13% wire in a double ceramic protection sheath) manufactured at Yula Glassworks were used to monitor the temperature in the furnace [3], [4]. Two rows of three thermocouples were used to simultaneous measure the temperatures at three cross sections located 10, 65 and 120 cm from the inlet wall. The measuring locations on the horizontal plane at the burner's level (20cm from the glass surface) were at distances 0, 7, 14, 21 and 28 cm from the side wall. On the central vertical plane

![Figure 1. Cross Section of the experimental glass furnace](image-url)
measurements were performed at 0, 7, 14 and 21 cm from the top. Furnace wall and melting glass temperatures were measured with an optical pyrometer. The flue gas temperature was measured with a K thermocouple positioned in the chimney. NO and NO$_2$ concentration in the flue gasses was measured at the stack with a gas analyser. The output of instruments was stored for processing in a computer through an A/D data acquisition board (NI), using suitably developed software (based on NI Labview IV).

Currently this furnace is under reconstruction. It is going to work with natural gas and it has been redesigned to improve operating conditions and facilitate modifications for the investigation of alternative combustion schemes.

### 2.2 Temperature measurements

Measurements were conducted under several inlet conditions. More specifically the oxygen purity and the fuel flow rate combinations shown in table 1 were used. Characteristic surface plots of temperature distribution measured in three furnace cross sections, at distances $z=15$, $65$ and $115$ cm from the inlet wall, are presented in figure 2. High temperature gradients are observed around the flame and near the walls while in the intermediate space these are suppressed (isothermal space), probably implying the presence of nonburned/nonmixed air/oxygen lances around the flame (mainly in the top).

<table>
<thead>
<tr>
<th>Table 1. Measured combinations (x)</th>
</tr>
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<tbody>
<tr>
<td>$O_2$</td>
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<tr>
<td>------</td>
</tr>
<tr>
<td>O2 %</td>
</tr>
<tr>
<td>21</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>60</td>
</tr>
</tbody>
</table>

$(V_{fuel}=12$ Nm$^3$/h, 21% $O_2)$

$(V_{fuel}=12$ Nm$^3$/h, 40% $O_2)$

**Figure 2.** Temperature distribution (°C) in furnace cross sections
The high temperature gas stream developed downstream the flame preserves to the end of the furnace. As expected the flame temperature rises with increasing O₂ purity (fig. 3), (due to less heat absorbed by the diminishing N₂ - less thermal load), approaching for purity above 40-50% to a plateau level specified by the fuel consumption and thermal load. It seems that further increase in O₂ purity would only slightly increase the flame temperature for each fuel flow rate (V_fuel). The thermal gain is obvious, since for the same V_fuel hotter flames are developed and accordingly higher wall, glass, and flue gas temperatures have been measured.

2.3 NOₓ production

The NOₓ production as a function of the O₂ purity is shown in figure 4 in mgr per Kcal of heat released (calculations based on fuel flow rate and lower heating value). Since NOₓ emissions increase with flame temperature, [2], the observed initial increase with O₂ purity is due to the corresponding increase of the temperature in the furnace. As the temperature reaches the plateau level the NOₓ production shows a trend to diminish for higher O₂ purity towards complete elimination probably expected to be attained for 100% O₂. This trend is more obvious for high fuel supplies due to the fact that plateau temperature is attained for lower O₂ purity.

The NOₓ production in Kgr NOₓ per tone of glass produced (calculations based on glasswork’s data) for the worst experimental case (fuel flux 12m³/h, maximum temperature developed ~1700 °C for oxygen purity 40-50%) is less than 50% of the mean emission levels in conventional furnaces (3.5-5.5 Kgr NOₓ per tone of glass) with simultaneous considerable energy savings due to the higher heat amounts transferred to the glass and furnace walls.

3 THE NUMERICAL CODE

The code is a 3D, finite volume scheme for steady state or transient, multicomponent,
chemically reacting flows. The main transport equations incorporated in the code are summarized in table 2 [5, 6, 7]. A k-ε and a RNG k-ε turbulence model have been implemented to account for turbulence effects. Chemistry routines allow the use of reaction models incorporating chemical reactions which are considered to be in equilibrium as well as reactions progressing kinetically [8]. Radiative heat transfer is taken into account using the discrete ordinates method [9, 10, 11]. The code has already been use with reasonable success for predictions on an industrial, regenerative, horseshoe flow type furnace used for the production of glass containers in Yula glassworks [12].

### Table 3
Composition of TEFA 1

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<table>
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<tr>
<th></th>
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</thead>
<tbody>
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<tr>
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</tr>
<tr>
<td>O₂</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>He</td>
<td>0.0157</td>
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</tr>
</tbody>
</table>

3.1 **Predictions of the combustion in an experimental glass furnace.**

The code is currently used to improve the design of the experimental furnace. The basic concept is the same with the original furnace. Particular attention in this model was directed at simulating as accurately as possible certain important aspects of the fuel/air injection systems and geometrical details of the actual furnace configuration such as: location and distribution of the burner, flue gases passages etc. In order to prescribe the inlet and outlet boundaries with sufficient accuracy without overburdening the computations a structured grid with 23x15

**Figure 5.** Velocity vectors in the furnace

**Figure 6.** Isotherms in the furnace
nodes on the inlet-outlet wall and 20 nodes along the furnace length was used. Pure methane was used as fuel for the calculations since Yula has recently switched to natural gas TEFA 1 whose main content is methane (see table 3). The volumetric fuel flow rate for the calculations was 40 Nm$^3$/hr and the air/fuel ratio was 11.5.

Certain assumptions were adopted in order to reduce the processors time for these preliminary runs. For this reason steady state operation was considered and turbulence was accounted with a k-$\varepsilon$ model. Chemistry was kept at a minimum using a global CH$_4$ mechanism. A one step global mechanism is currently developed for the estimation of thermal NO$_x$ emission for these reduced chemistry runs [13].

With these settings the code converged to the solution after 1000 iterations, taking less than 20 min CPU time on a Pentium II-300 computer. In figures 5 and 6 the predicted velocity vectors and temperature distributions are presented in several cross sections of the furnace. Maximum temperature attained at the centre of the flames is 2300 K and the flue gases leave the furnace at 1500 K, values which are compatible with previous on site measurements. The predictions of velocities and temperatures in the flame area are compatible with the observations.

4 CONCLUSIONS

The general conclusions from the present work are summarised as follows.

- The measured flame temperature and the corresponding temperature of the furnace (glass, walls) increases (as expected) with O$_2$ purity for the same fuel supply, with obvious advantages in fuel consumption for glass melting.
- As already stated the optimum operational conditions depend on the flame’s temperature and the corresponding N$_2$, O$_2$ concentrations. Consideration of the experimental results leads to the conclusions that increase of temperature almost ceases at O$_2$ concentration over 50-60%, while by increasing O$_2$ purity above this percentage results to NO$_x$ decrease with its obvious elimination in the limiting case of N$_2$ absence.
- The NO$_x$ production for the worst experimental case is less than 50% of the mean emission levels in conventional furnaces. Further decrease can be achieved through burner and combustion process redesign, to improve the heat transfer from the flame and keep its temperature as low as possible. Unfortunately the high flame temperatures developed near the furnace walls (due to its relative small size), did not allow tests for higher fuel supplies and O$_2$ purity, in order to prevent a temperature increase over the thermal strength limit of the walls material. Further experimental effort to higher O$_2$ purity, and fuel flow rates must be carried out to confirm and extent the results found.
- Besides giving valuable fundamental information the existing experimental facilities and the information derived offer an important data base for the validation of numerical codes to be used for the study and efficient design of industrial furnaces. In this project there is direct interaction between experiments and calculations. The code is validated and improved based on the experimental evidence and it is further used to predict optimum configuration for the experimental as well as the full scale furnace.

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REFERENCES