Original Paper

Glass furnace technology for reduced emissions based on advanced control and monitoring

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This paper reports an advanced furnace viewing sensor for regenerative U-flamed glass furnaces, which is demonstrated in a 40 t/d pull furnace of tableware glass burning thick fuel oil. The system processes digitized images from the combustion chamber and uses information related to the geometric features of the flame for monitoring furnace performance. The procedure is shown to be able to reduce NO_x levels by up to 20 %, by means of adequate control of the fuel atomization air.

Glasschmelzofentechnologie zur Emissionsreduzierung mit hochentwickelter Steuerung und Kontrolle

Die vorliegende Arbeit beschreibt ein weiterentwickeltes Überwachungsgerät für regenerative U-Flammenwannen; das Gerät wird in einem schwerölbeheizten Ofen für Haushaltsglas mit einem Durchsatz von 40 t/d eingesetzt. Das System verarbeitet digitalisierte Bilder aus der Verbrennungskammer und verwendet mit den geometrischen Merkmalen der Flamme verbundene Informationen zur Kontrolle der Ofenleistung. Es wird gezeigt, daß das Verfahren durch entsprechende Regelung der Brennstoffzerstäubungsluft die NO_x-Emissionen um bis zu 20 % vermindern kann.

1. Introduction

The development and application of new and advanced sensors, together with the consequent processing of information in the hostile environment associated with industrial combustion chambers, is a crucial step towards optimized industrial competitiveness and environmental protection, as discussed for example in [1]. Although glass quality is of prime concern to glass makers, other constraints are nowadays challenging the glass industry in terms of the need for better energy efficiency and reduced pollutant emissions [2].

The protection of both the environment and natural resources has led to increasingly tighter legislation and, for example, NO_x emissions for most combustion systems have been limited to 500 mg NO_x/m^3 for reference flue gas O_2 concentrations of 8 %, at normal pressure and temperature reference conditions [3]. These conditions will be assumed throughout the text. This is to be contrasted with typical values measured in regenerative glass furnaces of 2000 to 3000 mg NO_x/m^3 (e.g. [4 to 6]), which stresses the need for new and more efficient technologies to prevent pollutant emissions.

Many attempts have been made so far aimed at reducing pollutant emissions by applying secondary measures [7], although the use of primary measures (e.g. [3 and 4]) is that which will lead to an environmentally sustainable development. Analysis has shown that current technologies are far from allowing to reduce the pollutant levels to the figures demanded, so that new developments are required, namely based on the use of high-performance sensors. The aim is to allow the characterization of the process which gives rise to the formation of pollutants, namely those associated with the combustion of liquid fuels.

The development of these sensors, together with their optimal use, should be analyzed in the overal context of manufacturing and engineering integration, which is an important objective of this paper. When sensors, control strategies and information management are conveniently integrated, then computer-based engineering technologies can be an economically effective strategy [8].

Combustion above molten glass in a tank is a highly complex aerothermochemical process, which depends upon the turbulent mixing of fuel and oxidizer and induces a large and fluctuating luminous flame, where chemical reactions occur with high heat release rates [5]. The spatial location and the shape of the flame in the furnace determine the heat transfer distribution to the walls and to the glass surface and, therefore, have a significant influence on the thermal efficiency of the furnace. In addition, the flame shape influences the strength of the heat convection currents in the glass melt which, in turn, directly influences the glass quality. Also, the shape of the flame is related to the firing conditions, which affect the pollutant emissions and the refractory and furnace lifetimes. Finally, the overall flame morphology has been related, at least empirically, to the temperature of the combustion gases, which also provides reliable information to evaluate the process of pollutant formation.

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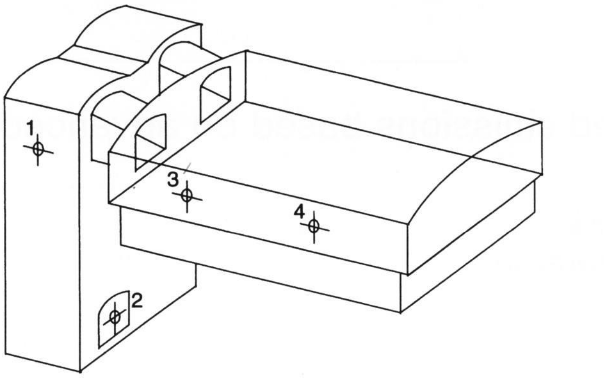


Figure 1. Schematic view of a glass furnace with identification of measuring ports.

Table 1. Furnace operating conditions

furnace pull in t/d	28
fuel flow rate in kg/h	340
air flow rate in kg/h	3450
temperature of crown thermocouple in °C	1515

Conventional sensors provide local information regarding the status of the furnace and do not allow the gathering of the data characteristic of the combustion processes. This paper contributes to filling this gap in the available technologies for monitoring and control in-furnace processes, and describes a new "on-line" flame viewing system able to be integrated in new furnace control strategies. The ultimate objective is to integrate an "on-line" flame characterization method based on advanced digital image analysis, with oxygen, temperature and pressure sensors and to act on the burner working parameters, as suggested in [1].

Section 2. describes the regenerative furnace used throughout this work, as well as the instrumentation. The flame viewing system is described and assessments of accuracy are presented. Section 3. presents sample results and the main findings are summarized in the last section.

2. Glass furnace and montioring procedure

2.1 Furnace configuration and operating conditions

The experiments were carried out in a regenerative, end-fired, thick oil fueled glass furnace. The furnace is dedicated to the production of soda–lime–silica tableware glass and comprises a total melting area of 25 m^2, in which the process of melting and fining of the glass takes place (figure 1). The rear wall of the furnace includes two inlet/outlet ports, through which the combustion air and waste gases flow according to the regenerative cycle. Two jet burners, spaced 0.5 m apart and inclined upward at 8°, are located below each port. The path of the flame and of the combustion gases forms a horseshoe (e.g. [9]), and the waste gases leave the furnace via the exhaust port. The furnace operates on a 25 min regenerative cycle, which is controlled by a gate valve installed between the inlet and outlet ducts.

The heavy fuel oil (with 85% C, 11% H, 3% S) is preheated up to 105 °C to allow atomization at a pressure of 0.2 MPa with the assistance of air at 0.25 MPa. The atomizing air is delivered to the burner through two concentric pipes and the related flow rates can be controlled by means of needle valves. The inner stream of swirling air breaks the fuel flow into droplets after passing through a swirl generator, thus defining the droplets diameter and, therefore, the flame length, while the outer stream of compressed air is only mixed at the end of the burner gun and, therefore, controls the aperture of the fuel spray.

Table 1 summarizes the furnace operating conditions used throughout this work, which are characterized by a slightly positive pressure of 2 to 3 mbar to avoid the suction of cold air into the combustion chamber and to decrease the migration of corrosive materials through the insulating layers of the furnace walls. Access to the combustion chamber is provided by two inspection ports on the right side of the combustion chamber. The regenerators are also equipped with two inspection ports at the upper and lower chamber, respectively, as defined in figure 1.

2.2 Measurement of NO$_x$ emissions

Major gas species concentrations were obtained with a suction probe, 3.5 m long, consisting of a sampling tube of 2 mm diameter mounted in a water-cooled jacket of 50 mm in diameter [5]. The probe was connected to dedicated gas analyzers through a water-cooled condenser, a diaphragm pump, a calcium chloride dryer and a cotton filter. Attention is focused here on the emission of nitrogen oxides, which were measured with a chemiluminescence analyzer.

The results were obtained by integrating sample records over a period of more than 1 min, which was set as a compromise between the long time scales typical of the flow and the required periodic cleaning of the probe. The gas sampling rate could be varied by means of a bypass valve between the outlet and inlet of the diaphragm pump, and the measured species were found to be independent of the suction velocity in the range 1 to 5 l/min. The results are expected to be close to density-weighted averages, within 10% of the maximum measured value [10].

2.3 Furnace viewing system and furnace monitoring

The furnace environment was analyzed making use of a conventional black and white CCD camera housed inside a water-cooled jacket with air purge and located at the front wall, in order to allow an upper view of the burners and the flame as described in figure 2. The output of the camera was digitally processed in a dedicated workstation in order to allow the on-line analysis of the flame geometry, as first realized by [11].

The ultimate objective is to improve the four main control system objectives, namely: a) glass quality control, through the analysis of the flame length, b) thermal efficiency maximization, through the detection of the flame shape, c) refractory and furnace life control, through analysis of flame shape and firing conditions; and d) pollutant emission and control, through the establishment of optimized firing conditions based on the flame shape analysis.

To achieve these objectives, it is clear that a flame classification methodology must be defined on the basis of the geometric parameters identified through the viewing system. This requires an initial off-line stage, during which the various flame classes are identified against nominal operating conditions. Only then, the on-line classification of flames can be realized to identify firing conditions, following the diagram of figure 3.

It is clear that the shape of the flame images depends upon the relative location of the collecting optics of the camera (figure 4), so that a calibrating grid is virtually generated in order to allow the evaluation of the flame length in furnace coordinates. The grid is computed assuming that the flame length corresponds to the maximum distance of the luminous flame to the burners, i.e. at their height.

The system includes the determination of the probability density function of the flame shape fluctuations inside the combustion chamber, which requires the use of edge and brightness detection procedures for flame identification, as exemplified in figures 5a to c. The procedure consists of identifying the pixels of the acquired images corresponding to the flame itself and those associated with the molten glass or corresponding to the furnace walls. This segmentation procedure was developed from the knowledge that thin image "objects" give rise to different average brightness distributions, with the flame being mainly formed by bright pixels, while the walls and molten glass are associated with dark pixels.

The data acquisition and processing system currently works at acquisition rates up to 0.5 Hz, which makes possible the calculation of the probability density function of the time-resolved flame position in the furnace. This probability density function is represented in figure 5c) in a grey scale where black means zero probability of flame existence.

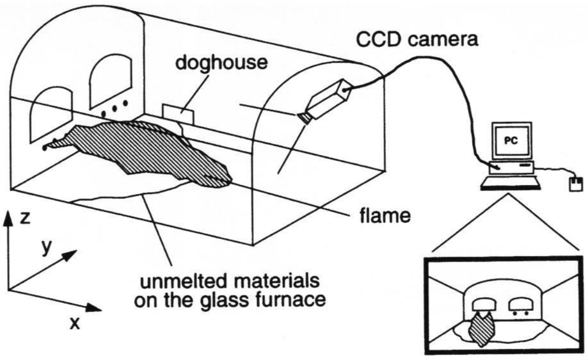


Figure 2. Schematic diagram of furnace viewing system.

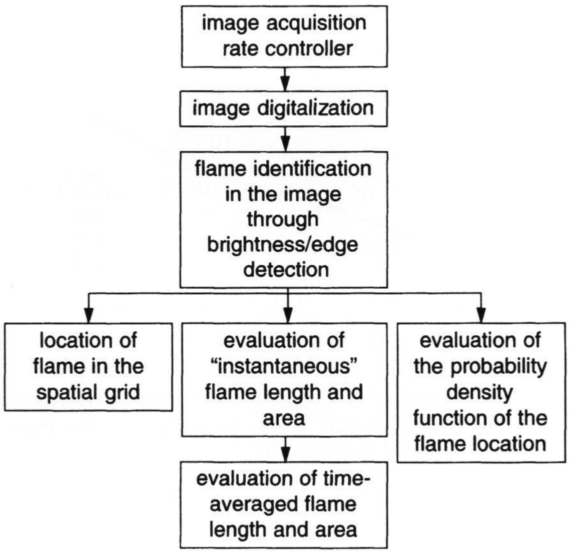


Figure 3.Block diagram of flame processing system.

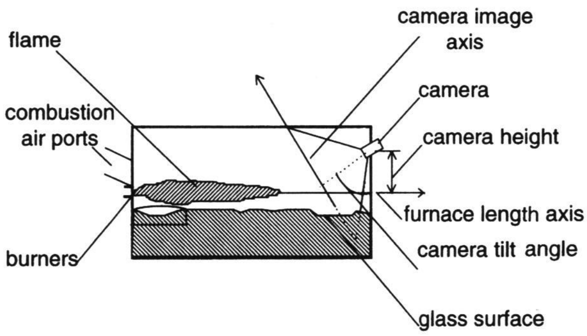
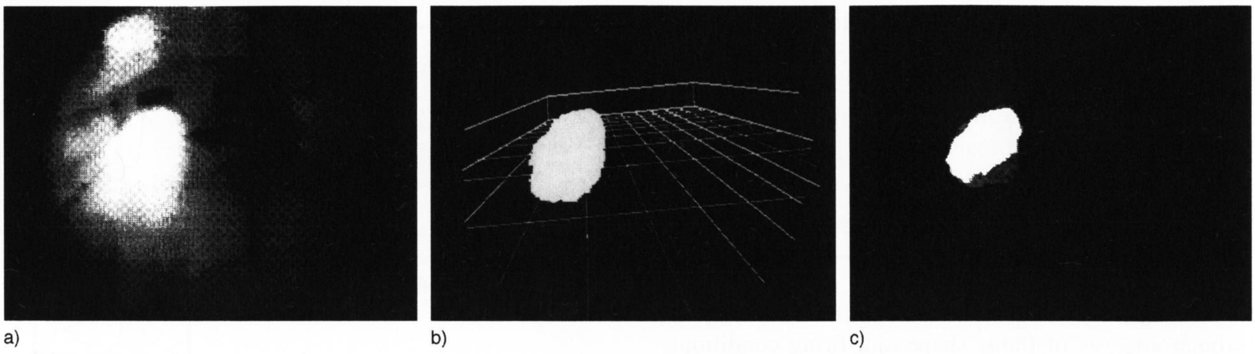


Figure 4. Schematic diagram of furnace viewing process.

The results of figures 5a to c show that the information obtained from the viewing system can be used to keep the flame geometry close to the optimum burning conditions. This can be achieved by continuously determining the geometry of the flame and acting in the values which control the atomizing air streams, as suggested in section 3. It should be noted that by conventional temperature measurements in the crown or at the exit of the furnace it is not possible to discriminate relevant fluctuations in flame shape that, as previously stated, have a determinant influence on furnace efficiency.



a) b) c)

Figures 5a to c. Typical procedures for flame image processing; a) digitized flame image, as acquired by the camera, b) time-resolved flame identification and analysis on the top of a virtually generated furnace grid, c) probability density function of flame shape fluctuations, over 10 min of operation of the furnace.

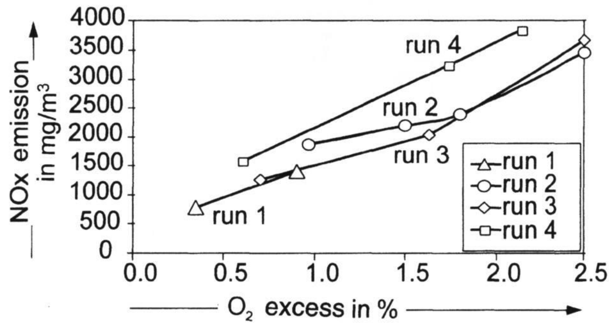


Figure 6. NO_x emission as a function of burner operating parameters and excess oxygen levels, measured at the upper chamber of the exhaust regenerator.

3. Results and discussion

The images obtained with the instrumentation developed throughout this work were compared with NO_x, O_2 and temperature measurements performed simultaneously in a working furnace; the results are discussed in the next paragraphs.

Figure 6 shows measured concentrations of oxides of nitrogen at the furnace outlet, as a function of the oxygen concentration (normalized to 8 % excess oxygen) for different burner operating conditions. These results confirm the expected trend of NO_x reduction as the excess air is decreased.

The experimental results analysis suggests that reductions in NO_x up to 20 % can be achieved by proper adjustment of the burner operating parameters. This conclusion results from the fact that the control of the needle valve in the atomization air line allowing the move from run no. 1 to run no. 2 (table 2) gives rise to a different flame geometry with an increase in the time-averaged length from 5.109 to 5.390 m, as shown in figure 7. This change in flame distribution affects the NO_x formation mechanisms, contributing to a decrease in NO_x emission from 2200 to 2000 mg/m³. On the other hand, changing from run no. 1 to run no. 3 leads to an increase in the mean flame length from 5.272 to 5.390 m, while the NO_x concentrations increase from 1500 to 2000 mg/m³.

It is clear that the mentioned figures relate to conventional burners, which are not optimized to reduce NO_x levels, but the implications of the results are important because they emphasize the advantage of using advanced sensing systems to increase furnace performance. The results allow to establish optimized criteria to control process variables making use of the information derived from the flame viewing system previously described, and figure 8 exemplifies a possible control scheme. As described in [1], it is obvious that the control objectives are strongly interrelated and, in consequence, multi-variable and multi-objective control strategies should be applied. In general, two categories of variables must be considered, namely: first, short-term control variables, including firing rate, air flow rate and batch feed rate; and second, long-term controlling parameters, such as batch preparation, fuel type and quality, and furnace condition. The former are subject to the low-level process control systems of the type described in figure 8, while the latter should be administered by supervisory control and based on knowledge [12].

In this context, the system of figure 8 will allow to integrate the control of the atomization air, making use of the information derived from the flame viewing system, with conventional control strategies derived from the crown temperature to control the air/fuel ratio.

From the experimental procedure it became clear that increasing one of the atomization air flows, while maintaining the other constant, systematic increases were obtained both on flame area and flame length. On the other hand, while increasing the axial atomization air flow leads to an increase in NO_x concentrations in waste gases at the exit of the combustion chamber, increasing the swirl levels decreases the NO_x emissions.

It should be noted that NO_x formation in the present furnace is mainly due to thermal mechanisms which occur in high-temperature reaction zones and depend on working parameters such as availability of combustion

Table 2. Furnace operating parameters

run no.	flame length in m	flame area in pixel	portion of swirl air in % (position of needle valve)	portion of axial air in % (position of needle valve)
1	5.272	5.939	40	20
2	5.313	6.309	40	40
3	5.390	8.549	40	60
4	5.109	7.336	20	60

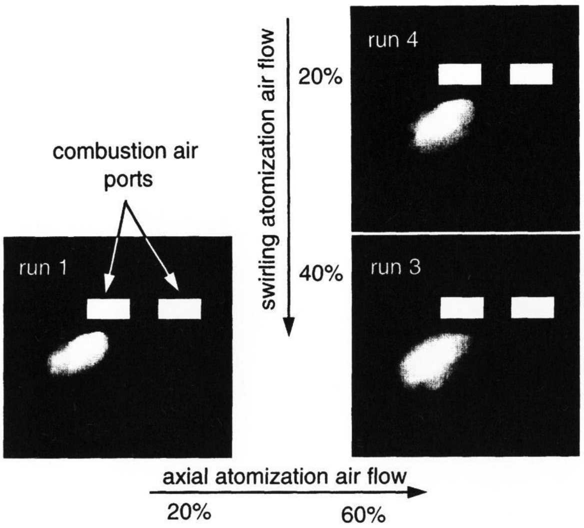


Figure 7. Typical flame images under different burner operating conditions obtained by changing the fuel atomization parameters.

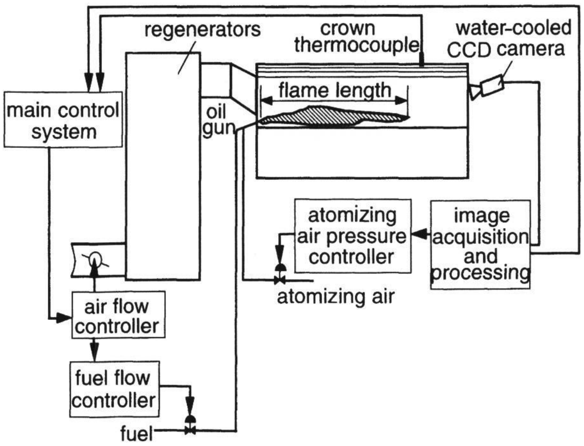


Figure 8. Integrated control system making use of a furnace viewing system.

air, local flame temperature, local excess air values, turbulent mixing and air-preheating temperature [13]. Consequently, NO_x emissions are indirectly related to the flame length, which is strongly influenced by the swirl and atomization conditions at the burner. For example, the observation that NO_x emissions decrease as the flame length is decreased, by increasing the swirl air flow, is explained through the enhancement of turbulent mixing which decreases the time scales associated with the combustion of reactants. The evidence is that the analysis of flame geometric parameters is suitable to optimize furnace control strategies.

4. Conclusions

The integration of an advanced optical sensor and monitoring scheme with current sensing and controlling technologies is described in this paper, based on results obtained in a process glass furnace with a nominal output of 40 t/d of tableware. The work involved the development of a furnace viewing system together with image processing algorithms which allowed the on-line characterization of the flame geometry.

The information derived from the system has been analyzed together with NO_x concentrations measured at the furnace outlet and has allowed to derive related reduction strategies by controlling the atomizing air. The results confirm the advantages of integrating advanced image processing technologies with conventional sensors to optimize the performance of industrial glass furnaces.

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5. References

[1] Farmer, D.; Heitor, M. V.; Sentieiro, J. et al.: New methodology for furnace monitoring, analysis, and control. Glass Ind. **73** (1992) no. 11, p. 10–16.

[2] Pilavachi, P. A.: Energy efficiency in process technology. Amsterdam: Elsevier, 1993.

[3] Flamme, M.; Haep, J.; Kremer, H.: NO_x reduction potential for glass melting furnaces. In: Proc. 3rd European Conference on Industrial Furnaces and Boilers, Lisbon (Portugal) 1995.

[4] Barklage-Hilgefort, H.; Sieger, W.: Primary measures for the NO_x reduction on glass melting furnaces. Glastech. Ber. **62** (1989) no. 5, p. 151–157.

[5] Cassiano, J.; Heitor, M. V.; Silva, T. F.: Combustion tests on an industrial glass-melting furnace. Fuel **73** (1994) no. 10, p. 1638–1642.

[6] Schmalhorst, E.; Ernas, T.: First practical experience with an SCR DeNOx facility in a container glassworks. Glastech. Ber. Glass Sci. Technol. **68** (1995) no. 5, p. 133–138.
[7] Kircher, U.: NO_x-Emissionen und Minderungsmaßnahmen in der Glasindustrie. Gas Wärme Int. **35** (1986) no. 4, p. 207–212.
[8] Heitor, M. V.: Advanced sensor systems for the application of CIME technologies in the process industry. A review. Ind. Metrol. **2** (1991) p. 1–31.
[9] Trier, W.: Glass furnaces. Design, construction and operation. Sheffield (UK): Soc. Glass Technol. 1987.
[10] Heitor, M. V.; Moreira, A. L. N.: Thermocouples and sample probes for combustion studies. Prog. Energy Combustion Sci. **19** (1993) p. 259–278.
[11] Victor, J.; Costeira, J. P.; Tomé, J. et al.: A computer vision system for the characterization and classification of physical phenomena inside glass furnaces. In: IEEE Industry Applications Soc., Annual Meeting, Dearborn, MI (USA) 1991.
[12] Lima, P.; Oliviera, P.; Ferreira, C. et al.: The architecture of a knowledge based controller for the operation of glass melting furnaces. In: Proc. Workshop on Computer Software Structures Integrating AI/KBS System in Process Control. Bergen (Norway) 1991.
[13] Puri, I.: Environmental implications on combustion processes. Chicago, IL (USA): CRC Press, 1993.

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