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Combustion measurements in an industrial glass-melting furnace

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This paper describes the results of an experimental study undertaken in an industrial regenerative 'horseshoe'-flow-type oil-fired furnace for the production of glass containers. The data reported include in-flame gas species concentrations of O_2, CO, CO_2 and NO_x, and gas temperatures, for one of the furnace operating conditions. The results reveal: a) in-flame peak temperatures of about 1690 °C; b) exhaust-gas temperatures of about 1520 °C; and c) exhaust levels of CO at 0.1%vol and NO_2 at 580 ppm. The data presented are especially useful for evaluation and development of 3-D mathematical models.

1 Introduction

The increased interest in mathematical modelling by manufacturers of full-scale combustion equipment as a means of determining design improvements cannot be overemphasised. Mathematical models demand reliable and detailed data for their validation. Unfortunately, at present there are relatively little data from full-scale plants, and to a large extent this is because of difficulties in controlling and measuring such flames. This is especially the case in the glass industry. As a consequence, validation of mathematical-modelling proposals against full-scale data is virtually impossible for glass-melting furnaces. For some years one of the present group's main areas of research has been the modelling of industrial glass furnaces[1]. The group has long suffered an insufficiency of good full-scale data, and the main objective of the present work is to help redress the problem.

This paper reports new combustion data obtained in an industrial glass-melting furnace, the property of the Santos Barosa Company, which is in Marinha Grande, Portugal. Measurements have been made for in-flame mean gas species concentrations of O_2, CO, CO_2 and NO_x, and mean gas temperature. These data supplement the limited amount from the other related study, notably Cassiano *et al*[2], who reported results for a regenerative 'horseshoe'-flow-type oil-fired furnace similar to that used in the present study. Data from other sources for furnaces of this type are scarce. Barklage-Hilgefort & Sieger[3] have studied the effectiveness of flue-gas recirculation and air-staging in controlling NO_x emissions. That study took place in an industrial glass-melting furnace but it involved only flue-gas measurements. Nakamura *et al*[4] have also investigated NO_x-reduction methods, and have released detailed in-flame data—but for a scaled-down compartment of a full-scale glass-melting furnace.

The remainder of this paper is in five sections: describing the industrial glass-melting furnace and instrumentation; presenting the experimental conditions, results and related discussions; and summarising the most important conclusions.

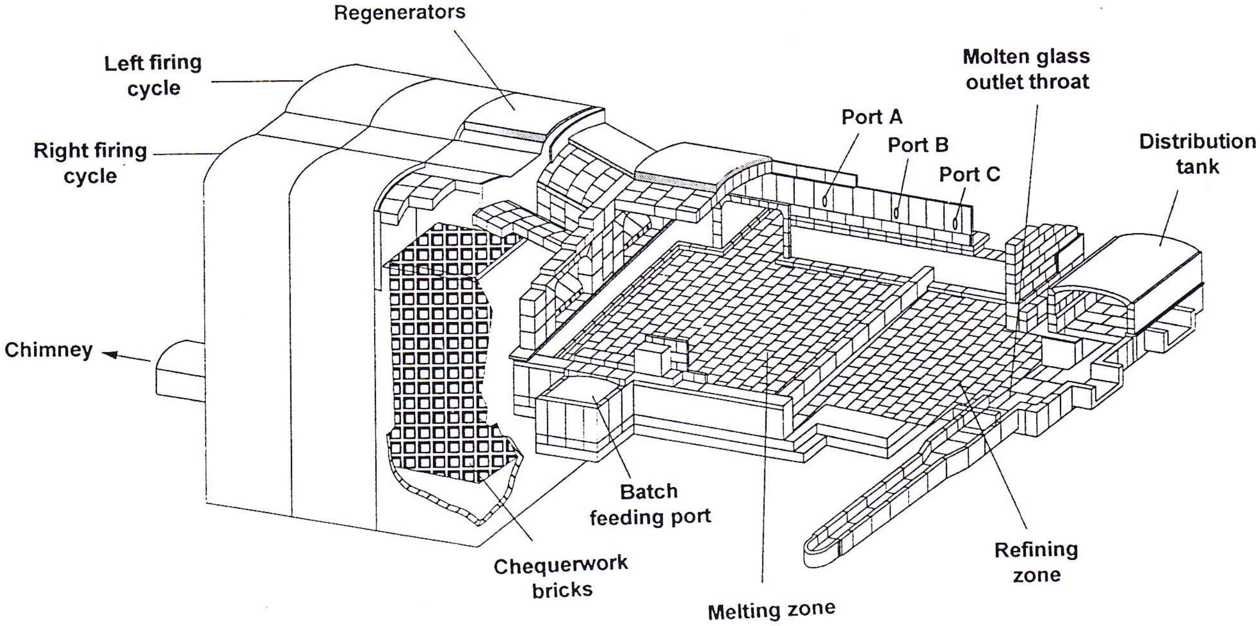

Fig.1 Schematic view of furnace.

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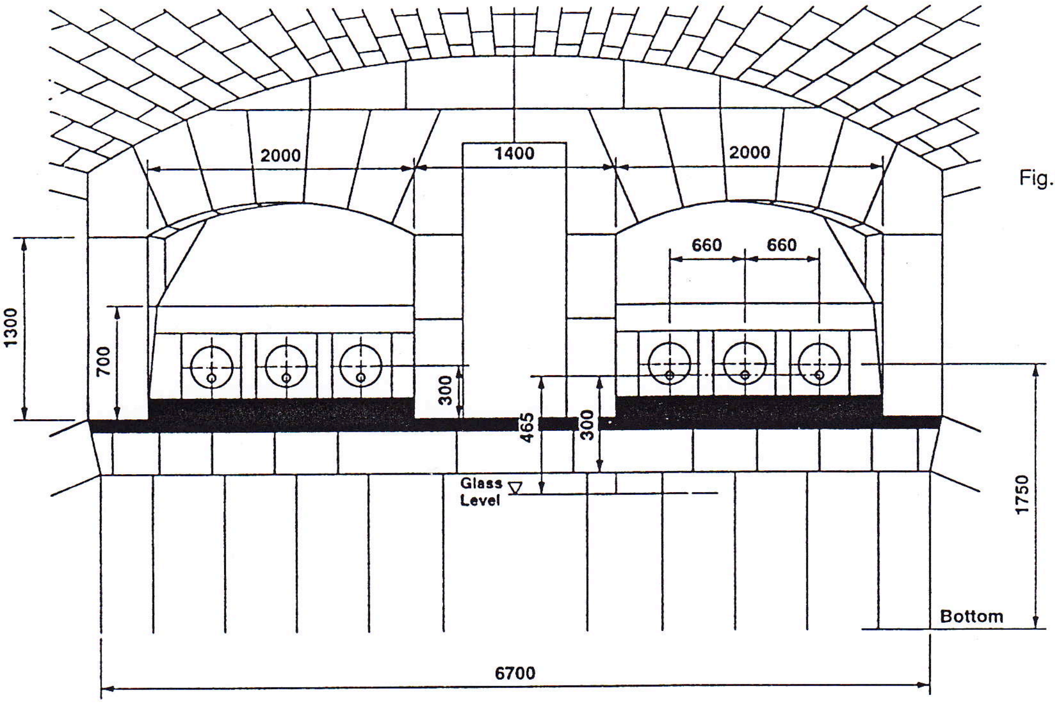


Fig.2 The rear wall arrangement.

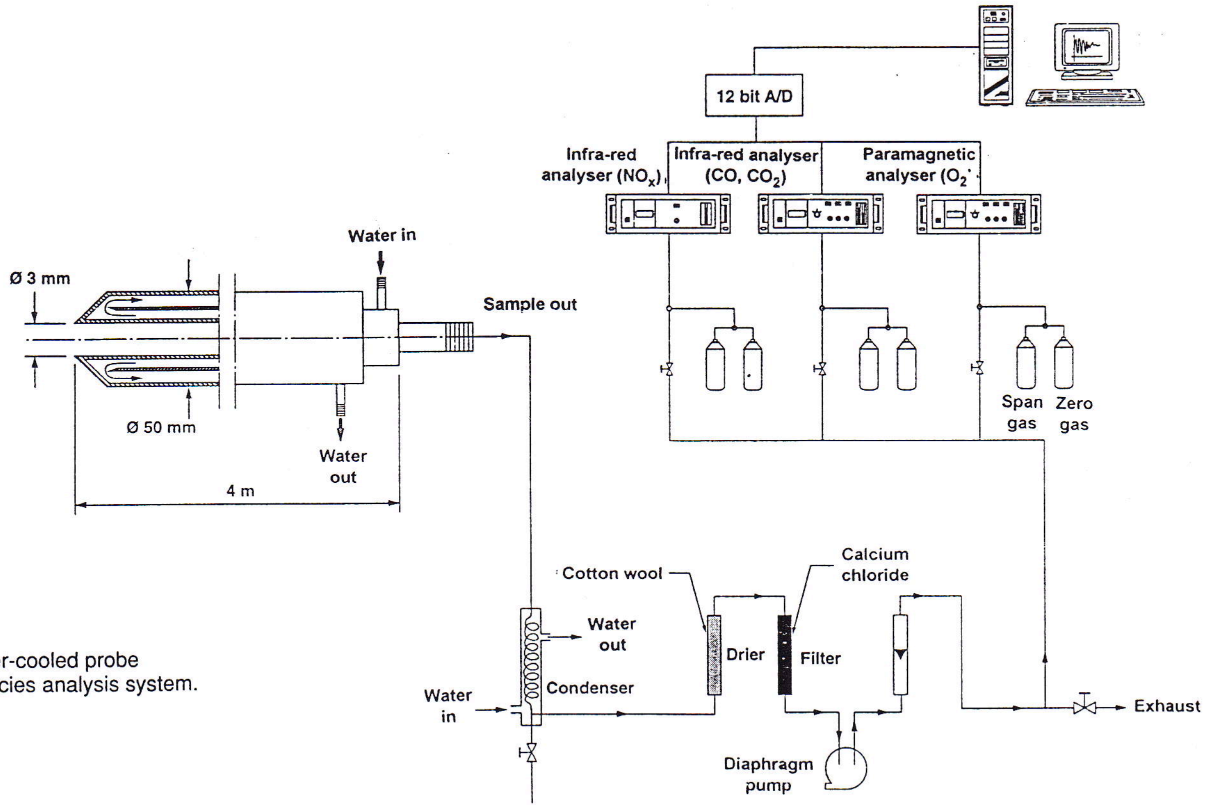


Fig.3 The water-cooled probe and the gas-species analysis system.

2 The industrial glass-melting furnace

Fig.1 is a schematic view of the glass furnace used in the present work; it is a regenerative 'horseshoe'-flow-type furnace firing heavy fuel oil. The combustion chamber is above the tank in which the melting and refining of the glass take place; the melting area is 48 m^2, and the refining area is 24 m^2. Fig.2 illustrates the arrangement of the two combustion-air/combustion-products ports and of the two burners located at the rear wall of the combustion chamber; all the relevant dimensions are shown in mm. Each burner comprises three air-assisted nozzles, inclined upwards at an angle of 9 °.

The combustion air, which is preheated in the regenerators, enters the furnace through the port above the burner at a downward angle of 14°; the flame forms a loop within the combustion chamber, and exits through the partner port. The furnace is fired from each port alternately, to enhance the uniformity of heat-transfer to the glass surfaces, and to allow regeneration; the regenerators are switched every 20 minutes. In the combustion chamber are three square inspection ports (135 × 135 mm) for probing and viewing, as shown in Fig.1. In Trier[5] can be found a detailed description of a furnace of this type, and its operation.

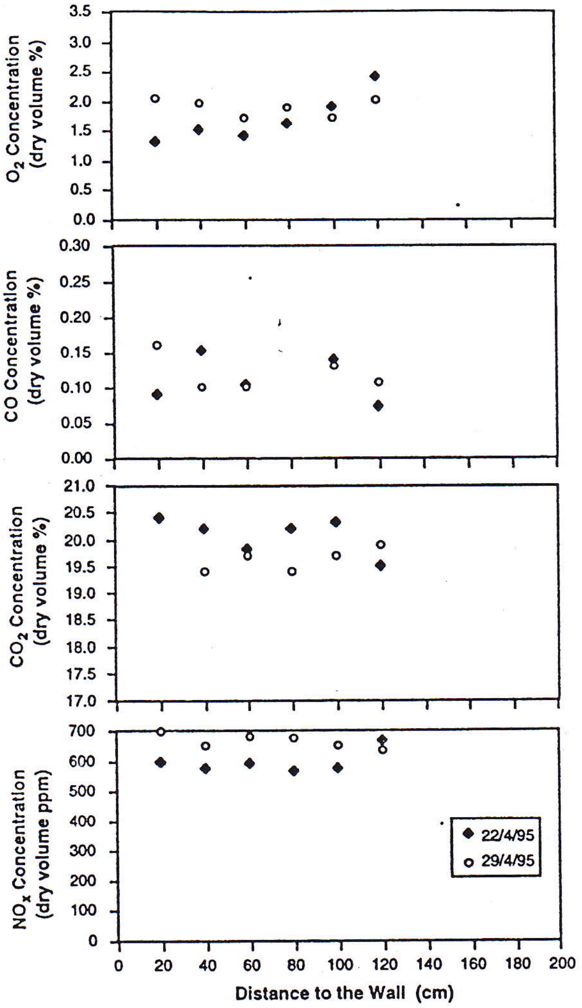


Fig.4 Measured gas-species profiles along port A, taken on two separate days.

3 Measuring techniques and experimental uncertainties

The sampling of gases for the measurement of O_2, CO, CO_2 and NO_x was achieved by means of a water-cooled stainless-steel probe, whose design and dimensions are shown in Fig.3. It comprised a central tube of 3 mm i/d through which quenched samples were evacuated; this was surrounded by two concentric tubes for cooling.

Fig.3 also shows a schematic of the gas-analysis system. The sample was drawn through the probe and part of the system by a 100% oil-free diaphragm pump, and a condenser removed the main particulate burden and condensate. A filter and drier removed any residual moisture and particles, so that a constant supply of clean, dry combustion gases was delivered to each instrument through a manifold to give species concentrations on a dry basis. The probe was cleaned frequently by being blown back with high-pressure air to maintain a constant suction flow rate. The analytical instrumentation included a magnetic pressure analyser (Horiba Model CFA-321A) for O_2 measurements, and non-dispersive infra-red gas analysers (Horiba Model CFA-311A) for measurements of CO, CO_2 and NO_x. Zero and span calibrations with standard mixtures were performed before and after each measurement session.

The major sources of uncertainties in the concentration measurements were associated with the quenching of chemical reactions, sample handling and analysis, and aerodynamic disturbance of the flow. Fast quenching of the chemical reactions was achieved, and our best estimates indicated that uncertainty due to the solubility of CO_2, UHC and NO_2 in water was negligible. The error due to the dissolution was estimated by operating the sampling

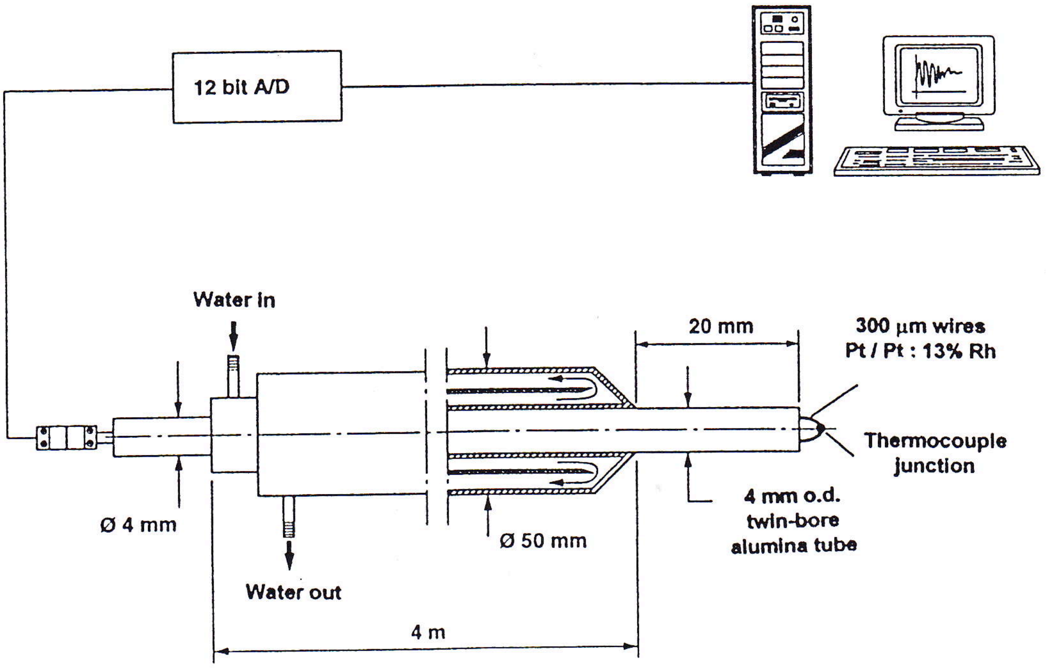


Fig.5 The temperature-measurement system.

system with the probe supplied with samples of standard mixtures with compositions similar to those in the flames studied. No attempt was made to quantify the probe flow disturbances. The repeatability of the data was checked regularly during each experimental session, and on separate days. Fig.4 shows data obtained on separate days. A reasonable agreement is demonstrated, without which the usefulness of the data for the validation of mathematical models would be questionable.

Measurements of gas temperature were obtained by means of uncoated Pt/Pt13%Rh thermocouples of 300 μm wire diameter. The wires ran in a twin-bore alumina sheath with an external diameter of 4 mm, placed inside a stainless-steel water-cooled probe (Fig.5). As radiation losses represent the major source of uncertainty in the measurements of mean temperature, an attempt was made to quantify them on the basis of a theoretical expression developed by De[6]. The equation requires that temperatures be measured with three thermocouples of the same material but of different diameters (in the present work 40, 80 and 300 μm). The calculation indicates that in the regions of highest temperature the 'true' temperature exceeds the measured one by about 10%. As in the species measurements, the repeatability of the data was also evaluated for the temperature measurements. Fig.6 shows a typical result where acceptable repeatability is demonstrated.

Both probes were mounted on a traverse mechanism that allowed for movements along a line normal to the furnace wall through each inspection port, up to 2 m from the wall. The positioning of the probes in the furnace was accurate to ±10 mm. The analogue outputs of the analysers and of the thermocouple were transmitted via A/D boards to a computer where the signals were processed and the mean values were computed.

4 Experimental conditions

A No.6 heavy fuel oil was used during the present measurements. Its main properties, in %wt, were: 88.4 carbon, 9.3 hydrogen, 2.0 sulphur, <0.2 nitrogen, 0.04 ash; the HCV was 43.96 MJ kg^{-1}. Table 1 summarises the furnace operating conditions for which the results reported herewith were obtained. The values are averaged over the one-month duration of the experimental programme.

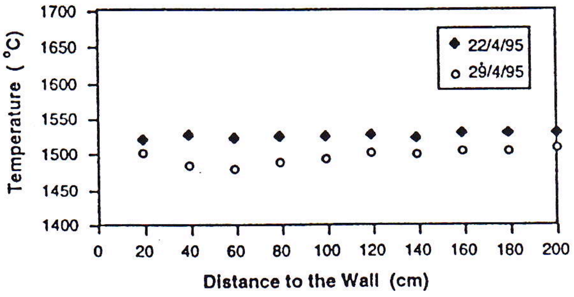


Fig.6 Measured gas-temperature profiles along port A, taken on two separate days.

Table 1 Furnace operating conditions

Colour of glass	Amber
Output, t day^{-1}	166.3
Specific melting rate, t m^{-2} day^{-1}	2.3
Specific energy consumption, GJ t^{-1}	4.9
Fuel: flow rate, kg h^{-1}	827.4
preheated temperature, °C	113
pressure, bar	2.8
Atomising air: flow rate, kg h^{-1}	1059
preheated temperature,°C	50
pressure, bar	2.4
Air: flow rate, kg h^{-1}	10 592
preheated temperature, °C	1400
Air:fuel ratio	14
Crown temperature T_1, °C	1531
Crown temperature T_2, °C	1502
Crown temperature T_3, °C	1395
Bottom temperature T_4, °C	1249

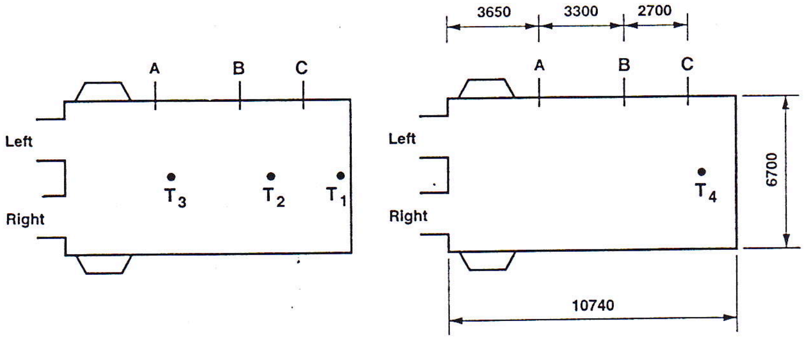
Fig.7 shows the location of the thermocouples at the crown and bottom of the furnace. Note that after the reversal of the regenerators a period of about 2 minutes was allowed for the furnace to reach steady-state conditions, after which data-collection began.

5 Results and discussion

As mentioned earlier, the measurements reported in this section were made along ports A, B and C (Fig.7). Note that ports A and B are in the melting zone whereas port C is in the refining zone. Figs.8 to 12 show the profiles of O_2, CO, CO_2 and NO_x concentrations and of gas temperatures, respectively, for the flame studied obtained at the three inspection ports available. The meaning of *left* and *right* in these figures can be discerned from Fig.7: the *left* profiles correspond to the visible flame zone, and the *right* profiles correspond to the exhaust zone.

At port A the data for the left-hand firing cycle reveal an inner region, 100-200 cm, of intense combustion—as indicated by the low O_2 concentrations and relatively high CO and CO_2 concentrations. The high CO concentrations (>6%vol) in the region between 140 and 200 cm indicate an intermediate stage in the reaction, because of insufficient mixing within the fuel jet. The temperature peak of about 1690 °C, at 120 cm, indicates the location of the flame boundary where mixing is intense as the result of strong shear between the fuel spray and the combustion air. Note that the temperature profile at this port is similar to that of NO_x concentration, which suggests that NO_x is formed mainly via the thermal mechanism, as expected at these high temperatures.

Further downstream, at ports B and C, for the left-hand firing cycle the O_2, CO_2 and NO_x concentrations and the temperature profiles flatten progressively, and the CO concentration diminishes as the result of conversion to CO_2. The conversion of CO to CO_2 appears to be slow, given the significant distance between ports; specifically, the CO concentration falls from a maximum value of 7.7%vol at port A to a maximum of 2.3 at port B, with both of these maxima located at a distance of 180 cm from the chamber wall. At port C the CO concentration still presents a maximum of about 1%vol located at a distance of 140 cm from the wall.



a) Crown

b) Bottom

Fig.7 The glass furnace, showing the measuring ports and the location of thermocouples.

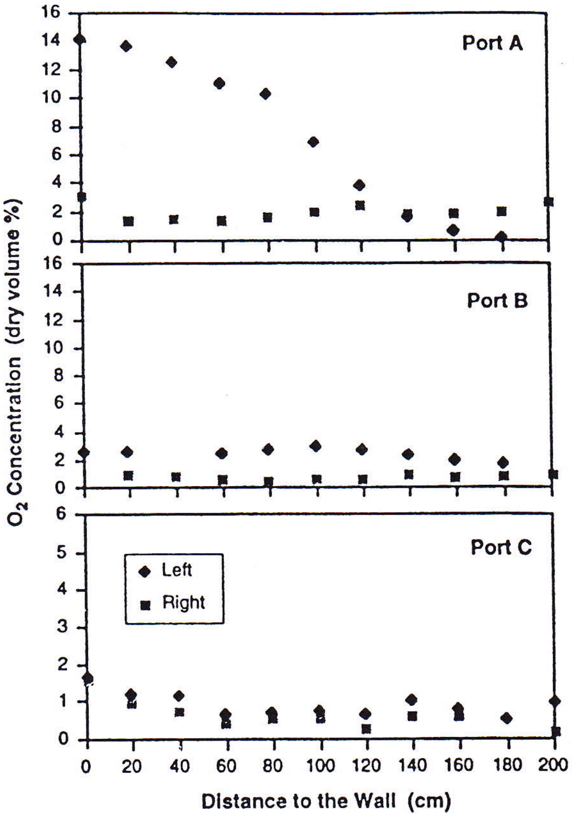


Fig.8 Measured O_2 concentration profiles along ports A, B and C.

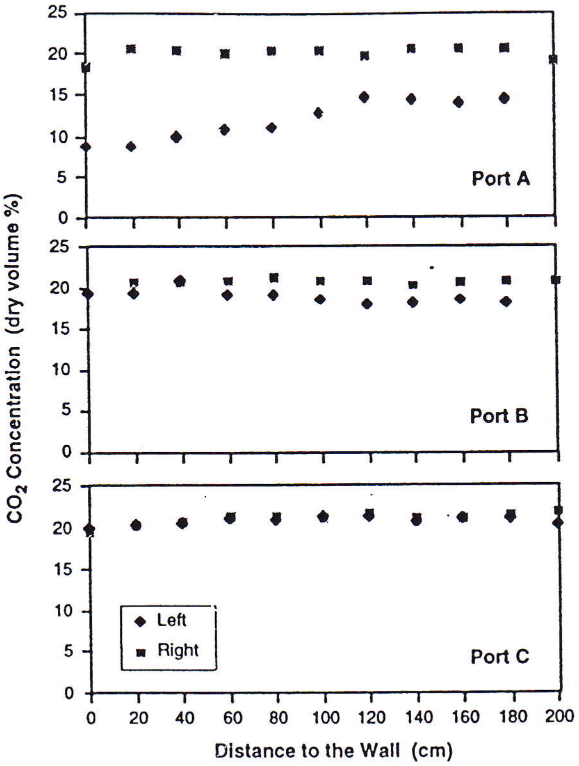


Fig.9 Measured CO_2 concentration profiles along ports A, B and C.

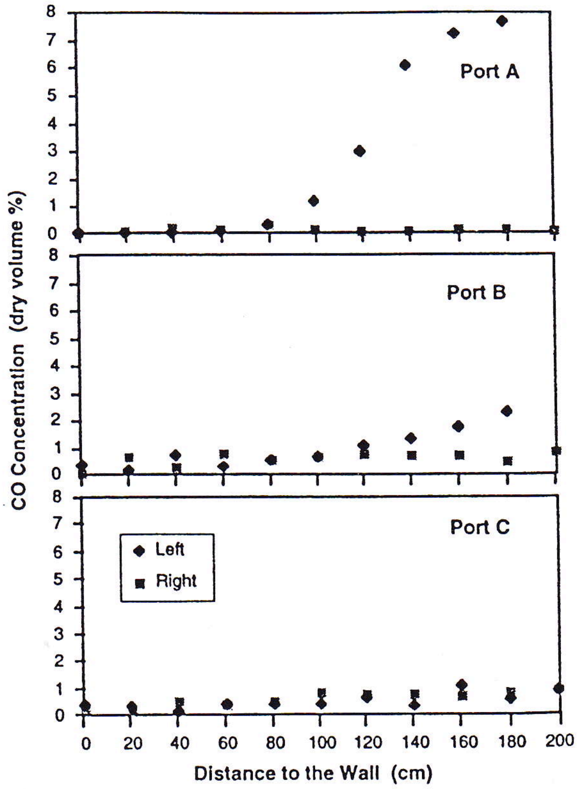


Fig.10 Measured CO concentration profiles along ports A, B and C.

Table 2 Comparison of present results and those of Cassiano *et al*[2]

Measured amount	Cassiano	Present work
Maximum flame temperature, °C	1660	1690
Temperature of exhaust gas, °C	1540	1520
Maximum concentration of CO, %vol	5	7.7
Concentration of exhaust CO, %vol	0.5	0.1
Concentration of exhaust NO_x, %vol	4000	580

In the refining zone, at port C, all the data profiles for the right-hand firing cycle, particularly those of temperature, are similar to those for the left-hand firing cycle (as it should be), revealing the good performance of the present furnace. Moving towards the chamber exit from port C to port A, the data for the right-hand firing cycle show: a) a rise in the O_2 concentration from 0.5 to about 1.8%vol because of the mixing with gases from the inner regions of the flow; b) a fall in the CO concentrations because of the oxidation to CO_2; c) a marginal rise in the NO_x concentration, which indicates formation of thermal NO_x yet in the exhaust region as the result of the persisting high temperatures. Near the exit of the combustion chamber, at port A, the levels of CO and NO_x are about 0.1%vol and 580 ppm respectively.

Finally, Table 2 presents a comparison between the present significant results and those of Cassiano *et al*[2]. Note that the data from the two studies are significantly consistent, with the exception of the NO_x exhaust levels. The in-flame measurements of Cassiano *et al* appear to indicate either some limitations in fuel breakdown or lack of correct mixing of the combustion gases in the furnace. Undoubtedly, these are the reasons for the higher CO exhaust levels observed in that work. But these reasons may also play a role in the higher NO_x emissions that the same workers have reported. In any case, the absence of information on, for example, fuel-nitrogen content, fuel atomisation and mixing efficiency prevents the interpretation of this discrepancy, which could not be traced to failings in the present measurements.

6 Conclusions

Measurements have been obtained in an industrial glass-melting furnace. The results include in-flame gas species concentrations of O_2, CO, CO_2 and NO_x, and gas temperatures for one furnace operating condition. The main conclusions are:

1 The CO and NO_x exhaust levels were 0.1% vol and 580 ppm, respectively; the temperature of the exhaust gases was approximately 1520 °C.

2 Overall, the in-flame temperature profiles revealed a remarkable uniformity, especially in the refining zone; this is evidence of the high performance of the present glass-melting furnace.

3 The data presented are of special importance to the critical evaluation and development of 3-D mathematical models, because of their detail and of the care exercised to ensure reliability.

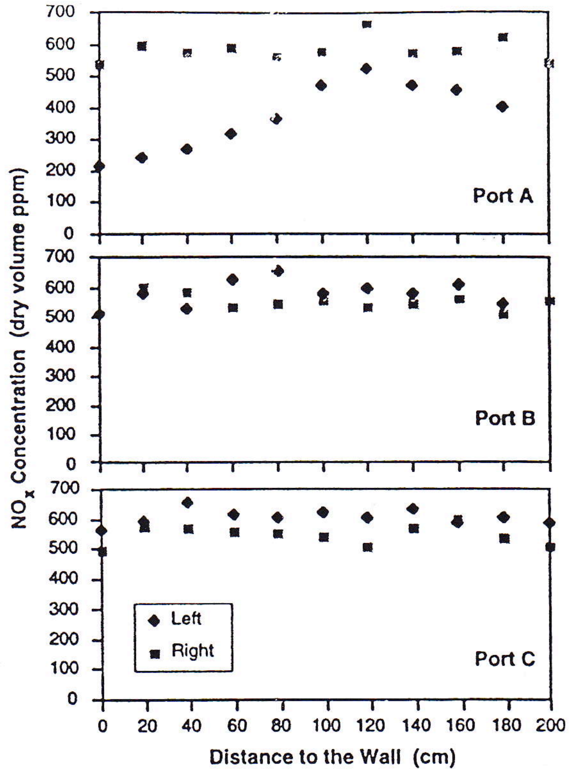


Fig.11 Measured NO_x concentration profiles along ports A, B and C.

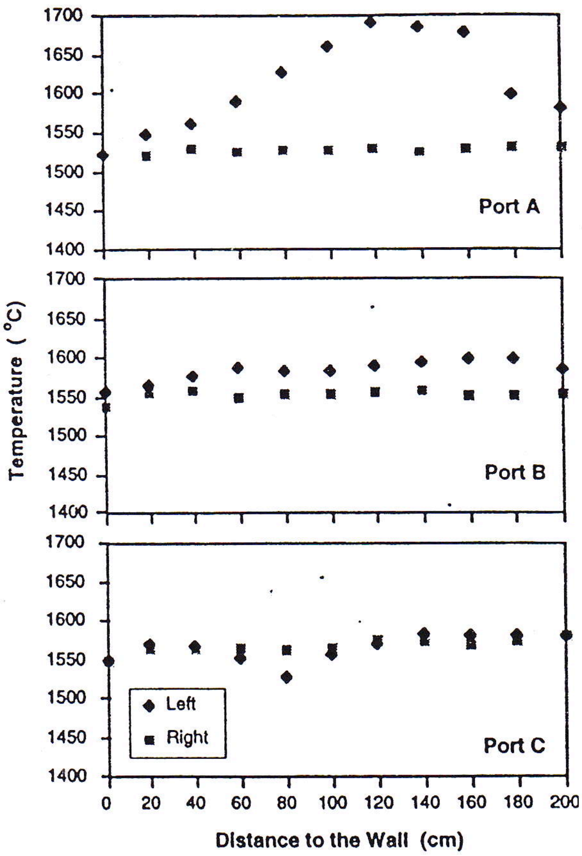


Fig.12 Measured gas-temperature profiles along ports A, B and C.

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8 References

1 CARVALHO M G, SEMIÃO V S and COELHO P J. Modelling and optimization of the NO formation in an industrial glass furnace. *Trans ASME J Eng for Industry*, 1992, **114**, pp 514-523.

2 CASSIANO J, HEITOR M V and SILVA T F. Combustion tests of an industrial glass-melting furnace. *Fuel*, 1994, **73**, pp 1638-1642.

3 BARKLAGE-HILGEFORT H and SIEGER W. Primary measures for the NO_x reduction on glass melting furnaces. *Glasstech Ber*, 1989, **62**, pp 151-157.

4 NAKAMURA T, SMART J P and VAN DE KAMP W L. The effects of fuel air mixing on NO_x reduction and heat transfer in high temperature, gas fired, glass melting furnaces. Institute of Energy 1st Int Conf on Combustion and Emissions Control, Cardiff, September 1993.

5 TRIER W. Glass Furnaces—Design, Construction and Operation. (English trans.) Society of Glass Technology, Sheffield, 1987.

6 DE D S. Measurement of flame temperature with a multi-element thermocouple. *J Inst Energy*, 1981, **54**, pp 113-116.

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