Combust. Sci. and Tech., 1997, Vol. 129, pp. 277–293
Reprints available directly from the publisher
Photocopying permitted by license only

Combustion Characteristics of a Front-Wall-Fired Pulverized-Coal 300 MW_e Utility Boiler

M. COSTA*, J. L. T. AZEVEDO and M. G. CARVALHO

Mechanical Engineering Department, Instituto Superior Técnico/Technical University of Lisbon, Av. Rovisco Pais, 1096 Lisboa Codex, Portugal

(Received 21 March 1997; In final form 26 June 1997)

This paper describes the results of an experimental study undertaken in an 300 MW_e, front-wall-fired, pulverized-coal, utility boiler. The data reported include local mean gas species concentrations of O_2, CO, CO_2, NO_x, and gas temperatures measured at several ports in the boiler including those in the burner region, and incident wall heat fluxes taken around the boiler periphery at 39 ports. The incident wall heat fluxes are reported for two boiler operating conditions. During the experimental work reported here, a considerable effort was made to assure minimum variations on boiler operating conditions and coal chemical and particle size characteristics so that the data presented are especially useful for 3-D mathematical model evaluation and development. The results reveal that: (i) the boundary air injected below the first row of burners leads to oxidizing conditions close to the back wall; (ii) local gas temperatures and CO concentrations in the boiler, near the burners, reached maximum values of about 1470°C and 1.6%, respectively; (iii) above the boiler nose the measured NO_x concentrations are reasonably uniform with averaged values of about 670 ppm; and (iv) wall radiant heat fluxes present maximum values at the side wall close to the intermediate row of burners.

Keywords: Utility boiler; pulverized-coal; combustion measurements; near burner region

INTRODUCTION

In a previous work (Costa *et al.*, 1996), we have reported combustion data for an industrial, glass-melting furnace, when we learned, in practice, that consistent full-scale data are notoriously difficult to obtain. Apart from the difficulties of measuring in industrial furnaces, it is extremely difficult to establish and

*Corresponding author. Fax: 351-1-8475545

maintain constant operating conditions over large periods of time. To minimize this problem a strong and effective cooperation between the experimental group and the boiler operators is essential. The present research group has maintained, for several years now, a solid collaboration with the people of a power plant located in Sines, about 140 km south of Lisbon on the Atlantic ocean coast, property of the Portuguese Electricity Company (EDP). The existing good relations with the operators of Sines power plant have encouraged the present authors to conduct the study reported here, whose objective was to extend the limited data base available for full-scale utility boilers firing pulverized-coal. Such combustion data are much needed for the development and evaluation of 3-D mathematical models.

The amount of pulverized-coal data available for full-scale utility boilers concern primarily gross flame properties such as radiative information and flue-gas analysis which does not give the detail required to interpret the more fundamental aspects of the combustion process. Examination of the literature reveals, however, the existence of a series of remarkable studies from Brigham Young University (BYU) in the USA (see Butler and Webb, 1991; Bonin and Queiroz, 1991, 1996; Butler *et al*., 1992; Queiroz *et al*., 1993 and Black and McQuay, 1996, among others) carried out on pulverized-coal, tangentially-fired boilers. Butler and Webb (1991) reported measurements of local mean temperatures and incident wall radiant heat fluxes for an 80 MW_e pulverized-coal, tangentially-fired boiler. These authors have paid special attention to the burner region. Simultaneously, Bonin and Queiroz (1991) reported the experimental results of a parametric study on the same boiler on local mean particle velocity, size and number density at three ports above the burner level. In this study, variable test parameters included furnace load, excess air and burner tilt. Recently, the BYU research team conducted a notable series of measurements on an 160 MW pulverized-coal, tangentially-fired boiler to investigate the effect of coal type, overfire air and burner tilt (see Black and McQuay, 1996). The data taken during the complete series of tests consisted of particle size, velocity and concentration, gas temperature and velocity, wall heat fluxes, solids composition, and species concentrations. Experimental data for full-scale utility boilers available from other sources have, in general, little detail and/or are limited to locations above the burners, see, for example, Boyd and Kent (1986), Fiveland and Latham (1993), Kakaras *et al.* (1995), Epple *et al.* (1995), Schnell *et al.* (1995), Dal Secco *et al.* (1995) and Magel *et al.* (1996), among others.

It is clear that little attention has been devoted to the burner region of full-scale utility boilers. This paper reports new combustion data obtained in an 300 MW_e, front-wall-fired, pulverized-coal, utility boiler using swirl burners. Measurements have been made of local mean gas species concentrations (O_2, CO, CO_2, NO_x), and gas temperatures measured at several ports in the boiler including those in the burner region, and incident wall heat fluxes taken around the boiler periphery at 39 ports. The incident wall heat fluxes are reported for two boiler operating conditions.

THE UTILITY BOILER

Sines power plant has four generating units, each rated at 300 MW_e and with a maximum continuous steam output of 950 ton/h at 535°C and 167 bar. After the high pressure turbine stage, steam is reheated at 43 bar to 535°C. For the purposes of the present work unit II was considered the more suitable one mainly because (i) EDP has recently conducted extensive global performance tests in the unit (ii) the present group (Azevedo *et al.*, 1996) has conducted detailed studies for the heat transfer in the convection section of the boiler and (iii) new burners are now being installed, which will allow us to conduct a new experimental comparative study in the future. The boiler of unit II was constructed by Mague/Foster Wheeler and is in operation since 1986.

Figure 1 presents a schematic view of the front-wall-fired, pulverized-coal boiler, showing the burners and the inspection ports where measurements have been performed during this study. With the exception of ports 8, 9 and 10, each port is represented here by a two-digit figure: the first identifies the level from the bottom to the top and the second the position in each level. The position in each level is numbered clockwise from 1 to 8 as indicated in the figure. The precise elevation of each level is given in Figure 1 with reference to the bottom of the boiler. The boiler is equipped with a large number of inspection ports each of about 75 mm in diameter. The inspection ports available at the front wall in level 6 are of difficult access. At the back wall, ports are only available at levels 1, 3 and 5 with limited access due to the convective path of the boiler. Above the boiler nose three ports are available at three different levels, numbered in Figure 1 from 8 to 10.

The boiler dimensions are approximately 43.5 m height, 15 m wide and 11.4 m deep. It is equipped with 20 swirl burners arranged in five rows of four burners installed on levels 1 to 5 (see Fig. 1). The distance between the burner centerlines is 2.6 m both in the vertical and horizontal directions. The distance from the side walls to the centerline of the burners closest to them is 3.6 m. At level 0, just below the first row of burners (level 1), the boiler has two holes for boundary air injection (see Fig. 1) each with an inner diameter of 0.95 m. The distance from the centerline of these holes to the side walls is 1.15 m. The

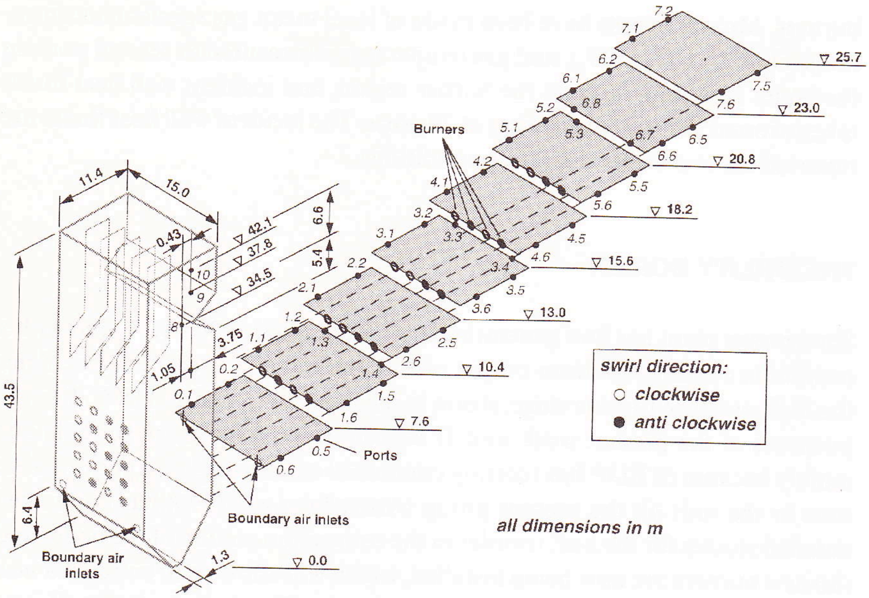

FIGURE 1 Schematic view of the boiler showing the burners and the inspection ports.

inspection ports used for measurements are located at a distance of 0.43 m from the boiler corner, with the exception of ports 7.2 and 7.5 whose distance is 0.63 m.

The coal is transported to five Foster Wheeler MBF pulverizers with gravimetric feeders to supply each burner row. The coal/primary air stream is introduced tangentially in an annulus between an inner sleeve (o.d. 0.273 m) and the secondary air inlet (i.d. 0.508 m). Inside the inner sleeve there are a propane igniter and an oil burner for start-up purposes. During normal operation core air is fed through the inner sleeve to prevent coal deposition. The secondary air is fed through a windbox after which it is forced through a set of adjustable vanes. The secondary air enters the boiler through two concentric annular inlets with external diameter of 0.74 and 0.99 m, respectively.

DATA ACQUISITION TECHNIQUES

Gas Species Concentration and Temperature

The sampling of gases for the measurement of local mean O_2, CO, CO_2 and NO_x concentrations was achieved using a 5 m long, water-cooled, stainless steel probe. It comprised a centrally located 3 mm i.d. tube through which quenched samples were evacuated, surrounded by two concentric tubes for probe cooling. The gas sample was drawn through the probe and part of the sampling system by an oil-free diaphragm pump. A condenser removed the main particulate burden and condensate. A filter and a 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 blowing back with high pressure air to maintain a constant suction flow rate. The analytical instrumentation included a magnetic pressure analyzer (Horiba Model CFA-321A) for O_2 measurements, and non dispersive infrared gas analyzers (Horiba Model CFA-311A) for CO, CO_2, and NO_x measurements. Zero and span calibrations with standard mixtures were performed before and after each measurement session. The maximum drift in the calibration was within $\pm 2\%$ of the full scale. The major sources of uncertainties in the concentration measurements were associated with the quenching of chemical reactions and aerodynamic disturbance of the flow. Quenching of the chemical reactions was rapidly achieved upon the samples being drawn into the central tube of the probe due to the high water cooling rate in its surrounding annulus – our best estimates indicated quenching rates of about 10^6 K/sec. No attempt was made to quantify the probe flow disturbances.

The literature, referred to in the introduction, reveals that for pulverized-coal fired utility boilers suction pyrometers had been preferred to fine wire thermocouples. This preference cannot be attributed to their superior performance but is probably due to the tendency of a thermocouple wire to break easily when exposed to hostile environments such as those encountered in furnaces. In addition, suction pyrometers cause greater aerodynamic and thermal disturbances to the flow field and present a tendency for probe blockages when sampling from the burner region as observed by, for example, Butler and Webb (1991). The fine wire thermocouple technique was preferred in the present study in view of the above considerations so that local mean gas temperature measurements were obtained using uncoated 300 μm diameter platinum/platinum: 13% rhodium thermocouples. The 300 μm diameter wires were located in a twin-bore alumina sheath with an external diameter of 4 mm and placed inside a 5 m water-cooled stainless steel probe. As radiation losses represent the major source of uncertainty in the mean temperature measurements an attempt has been made to quantify them in industrial environments in a recent study (Costa *et al.*, 1996). The calculation have indicated that in the regions of highest temperature the "true" temperature do not exceed the measured one by more than 8%. An additional source of uncertainty relates to the deposition of ash on the thermocouple wires. This results in an increase in radiation losses owing to the increase in surface area. The error due to ash deposition on the thermocouple wires was minimized during measurements by always moving the probe from the boiler walls towards the inner positions where the amount of char particles was higher. The condition of the thermocouple was frequently examined during measurements in these inner positions and, where necessary, the deposits were carefully removed or the thermocouple replaced.

Both probes were mounted on a traverse mechanism which allowed for movements along a line normal to the boiler walls through each inspection port up to 3 m from the wall. Great care was taken to avoid leakage of air into the boiler through the inspection ports, especially when probing from positions close to the side or back walls. No thermal distortion of the probes was observed and the positioning of them in the boiler was accurate to within ± 10 mm. The analog outputs of the analyzers and of the thermocouple were transmitted via A/D boards to a computer where the signals were processed and the mean values computed.

Incident Wall Heat Flux

The incident radiation fluxes at the boiler walls were measured using an asymptotic thin film, water-cooled, gas-purged radiometer (HY-CAL ENGINEERING). The radiometer has a 140° field of view and can measure total radiant fluxes up to 400 kW/m^2 in the wavelength range of 0.5 to 15 μm with a response time on the order of 180 milliseconds. The entire radiometer system was portable and easily handled by two workers. The radiometer was calibrated in a black-body furnace according to the procedure set out in Chedaille and Braud (1972). In this study, calibrations carried out before and after the experimental campaign showed differences of less than $\pm 3\%$ which gives an indication of the uncertainty of the measurements.

EXPERIMENTAL CONDITIONS AND DATA RELIABILITY

During the present study a mixture of two coals has been used: an American coal (Anker) and an Australian coal (Oak Bridge). The coal mixture properties and its size distribution for each row of burners are given in Tables I and II, respectively. Table III summarizes the boiler operating conditions for which the results reported herein were obtained. The values given in Table III are averaged over all the duration of the experimental campaign which has lasted

TABLE I Coal characteristics (courtesy of the Sines power plant)

Quantity	*Value*
Proximate Analysis (% as received):	
Moisture	6.77
Ash	13.36
Volatiles	28.85
Fixed Carbon	51.02
High Heating Value (MJ/kg)	27.65
Ultimate Analysis (% as received):	
Carbon	67.68
Hydrogen	4.4
Nitrogen	1.54
Sulfur	0.94
Oxygen	5.31

TABLE II Coal size distribution in the different burner rows* (courtesy of the Sines power plant)

Grind	*Row 1*	*Row 2*	*Row 3*	*Row 4*	*Row 5*
% under 16 μm	32.4	40.2	34.5	36.6	20.7
% under 30.8 μm	49.9	58.6	52.1	55.0	37.2
% under 79.3 μm	79.6	82.0	78.8	81.3	69.4
% under 106 μm	86.7	87.2	85.2	86.7	79.5
% under 204 μm	96.6	97.6	96.9	96.9	96.5
Sauter mean diameter (μm)	13.89	11.73	13.36	12.64	20.89

*Row 1 is the bottom row of the burners.

for about two weeks for runs 1 and 2. It will be noted in the following section that the data reported for run 2 includes incident wall heat fluxes only.

The operating conditions of run 1 are frequently used at Sines power plant in order to control NO_x formation/emissions from the present burner/boiler configuration. In a previous study the use of the upper row of burners (level 5) with overfire air (run 1) was investigated by EDP as a primary measure for NO_x reduction. The results were compared with model predictions (Coimbra *et al.*, 1994), showing that NO_x emissions could be reduced with this modification when compared with the case of all burners in operation (run 2).

It should be emphasized that during the experimental campaign, a very considerable effort was made by the people involved in the operation of the boiler in order to assure minimum variations on boiler operating conditions and coal chemical and particle size characteristics. The use of soot blowers in the furnace was avoided during the measurements. In support of our claim of

TABLE III Boiler operating conditions (courtesy of the Sines power plant)

Quantity	*Run 1*	*Run 2*
Net electrical generation (MW)	312	307
Steam pressure in the boiler drum (bar)	180	177
Coal feed rate, as received (ton/h)	103	105
row 1 to 3 (ton/h)	27*	22*
row 4 (ton/h)	22	17
row 5 (ton/h)	0	22
Primary air flow rate (ton/h)	288	334
row 1 to 3 (ton/h)	70*	65*
row 4 (ton/h)	78	70
row 5 (ton/h)	0	69
Secondary air flow rate (ton/h)	629	616
row 1 to 3 (ton/h)	142*	131*
row 4 (ton/h)	113	96
row 5 (ton/h)	90	127
Secondary air swirl number**, evaluated	0.6	0.6
Boundary air flow rate, evaluated (ton/h)	160	160
Primary air/fuel inlet temperature (°C)	64	64
Secondary air inlet temperature (°C)	360	360
Boundary air inlet temperature (°C)	360	360
O_2 in flue gases (dry volume %)	2.5	2.4
CO_2 in flue gases (dry volume %)	15.5	15.5
CO in flue gases (dry volume ppm)	15	8
NO_x in flue gases (dry volume ppm)	600	850
SO_2 in flue gases (mg/Nm^3)	2150	2030
Particle concentration (mg/Nm^3)	33	45
Carbon in ash (%)	3.2	2.5

*Per row; **Swirl number as defined in Beér and Chigier (1972); swirl direction in each burner is shown in Figure 1.

good repeatability, example profiles of O_2 and NO_x concentrations and temperature for run 1 are reported in Figure 2 for several ports along the boiler taken in different days. Excellent repeatability is demonstrated without which the usefulness of the data for evaluation and development of 3-D mathematical models would be questionable.

RESULTS AND DISCUSSION

Before examining the data in detail, some considerations concerning the nature of the flow in the present boiler configuration are required in order to

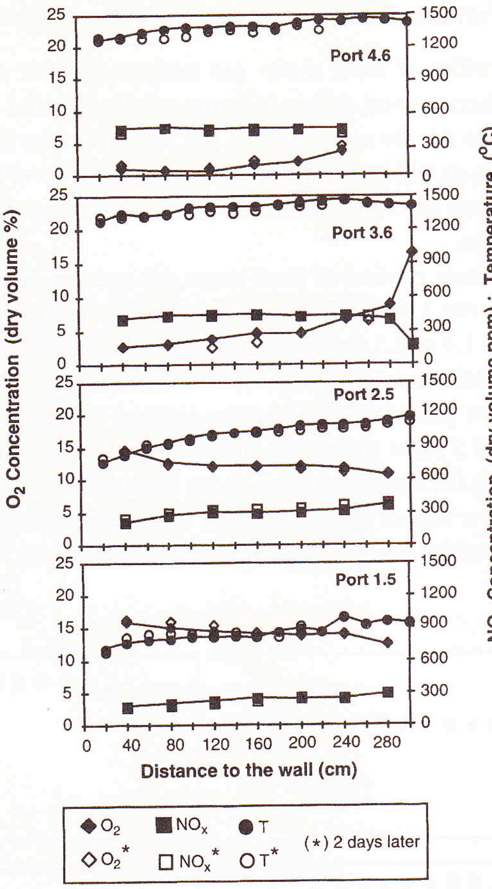

FIGURE 2 Profiles of local mean gas species concentration and gas temperature for run 1 through several ports taken on different days.

better understand the discussion of the results presented below. In what follows the principal qualitative features of the flow are based in a numerical study of the present research group for the same boiler and operating conditions, see Coimbra *et al.* (1994). In these calculations, however, the boundary air flow rate was neglected. The flow is mainly characterized by the deflection of the jets from the burners into two main parts close the back wall between levels 2 and 3. The flow deflected upwards presents high velocities near the boiler nose. At the ash pit region of the boiler a large recirculation zone is formed promoting an upward flow close to the front wall which is superimposed to the swirling motion created by the burners.

Combustion in-Furnace Data

Figure 3 shows profiles of local mean gas temperature for run 1 through symmetric ports where a good degree of symmetry is observed. This will have an obvious influence on the symmetry of the radiative flux incident on the corresponding walls, as will be shown below. Measurements of local mean gas species concentrations through symmetric ports were not performed during the present campaign.

Figures 4 and 5 show profiles of local mean gas species concentration and gas temperature for run 1 through several ports located at the side wall and at the back wall (ports 1.4 and 3.4), respectively. It will be noted in Figure 4 that measurements of local mean gas species concentrations through ports 5.5, 5.6, 7.5 and 7.6 were not performed during the present campaign. Viewed as a whole Figures 4 and 5 show the strong three-dimensional nature of the flow.

At port 0.6 (Fig. 4), the region between about 100 and 160 cm from the boiler side wall presents low temperatures and high O_2 concentrations which is due to the mixing effect of the boundary air injected at level 0 (see Fig. 1). Beyond

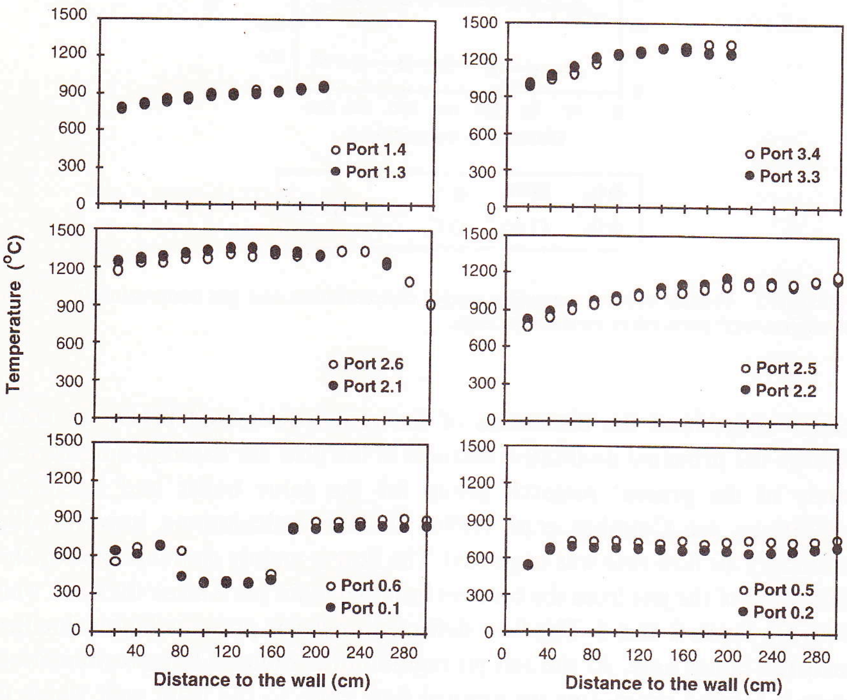

FIGURE 3 Profiles of local mean gas temperature for run 1 through symmetry ports.

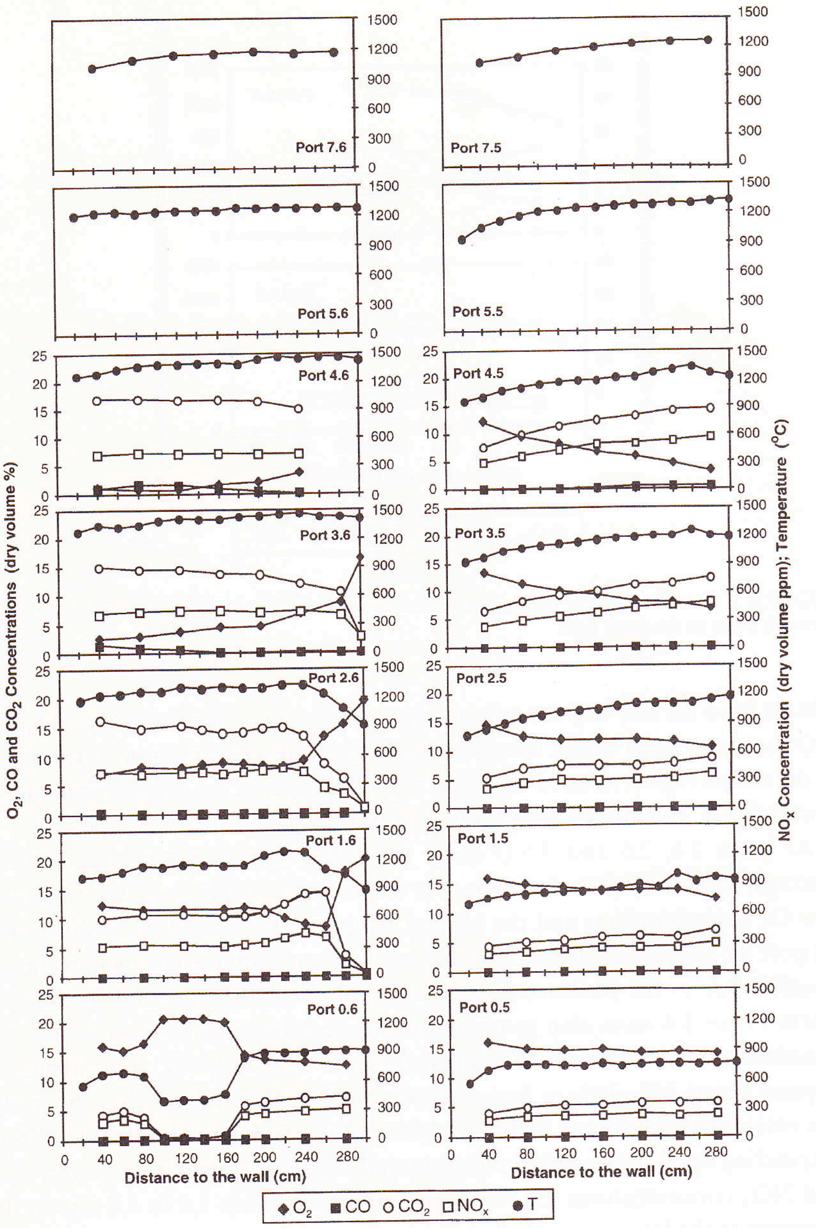

FIGURE 4 Profiles of local mean gas species concentration and gas temperature for run 1 through several ports at the side wall.

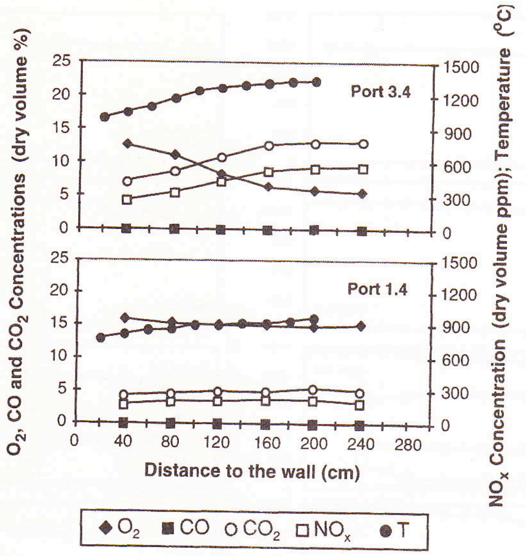

FIGURE 5 Profiles of local mean gas species concentration and gas temperature for run 1 through ports at the back wall.

180 cm from the side wall the reasonably uniform temperature and O_2, CO_2 and NO_x concentration values reveal the presence of the recirculation zone located at the ash pit region referred to above. The uniformity of the profiles observed at port 0.5 (Fig. 4) confirms the presence of this large recirculation zone.

At ports 1.6, 2.6 and 3.6 (Fig. 4), the flame boundaries are located, on average, at about 240 cm from the side wall as indicated by both the relatively low O_2 concentrations and the highest temperatures measured at this point. At port 4.6 reliable measurements beyond 240 cm from the side wall were not possible due to the presence of large amount of deposits around the burner. Ports 1.6 to 3.6 have also in common the simultaneous increase in the O_2 concentration and decrease in temperature and CO_2 and NO_x concentrations beyond about 240–260 cm from the side wall which indicates that the probe has entered inside of these highly complex flame jets. Up to about 200–240 cm (depending upon the port) from the side wall, the temperature and the O_2, CO_2 and NO_x concentrations are relatively uniform at ports 1.6 to 4.6 due to the presence of the large recirculation zone.

The O_2 concentrations gradually decrease along the boiler height from ports 1.6 to 4.6 (Fig. 4), which can be attributed to both the combustion progress and the diluting effect of the upward flow of reacted gases close to the front wall. Consistently, the measured gas temperatures and the CO_2 and NO_x

concentrations have a similar behavior with increasing values along the boiler height from ports 1.6 to 4.6. The highest temperatures are observed at ports 3.6 and 4.6 (around 1470°C), above which the gases are rapidly cooled and diluted by the introduction of air at level 5. At ports 3.6 and 4.6, the CO concentration are relatively high (maximum around 1.6%) which is the result of the low O_2 concentrations observed at these locations.

Ports 0.5 to 4.5 (Fig. 4), close to the back wall, reveal a gradual temperature increase and a reduction of the O_2 concentrations along the boiler height. The persistent relatively high O_2 concentrations observed at all of these ports suggests that the boundary air jets reach the back wall. It is also clear that the influence of the boundary air jets is gradually limited to smaller regions along the boiler height. In particular, at ports 3.5 and 4.5 the O_2 concentrations significantly decrease towards the inner positions probably due to the upward deflection of the flow close to the back wall which occurs between the second and third row of burners, as mentioned earlier.

The gas temperatures close to the back wall observed in Figure 4 are higher in the upper burner levels due to the occurrence of combustion close to the back wall. It is interesting to note that gas temperatures do not decrease significantly from levels 4 to 7 close to the back wall (ports 4.5 to 7.5) but close to the front wall (ports 4.6 to 7.6), the introduction of air in row 5 significantly decreases the gas temperatures from about 1450°C at port 4.6 down to about 1200°C at port 5.6.

The measured NO_x concentrations showed in Figure 4 follow, in general, the measured CO_2 concentrations throughout the boiler. Close to the back wall, from port 2.5 to 4.5, the NO_x concentrations increase due to char nitrogen conversion. Volatile combustion occurring closer to the burners could not be characterized in the present work. Nevertheless NO_x production at the flame edges can be observed at ports 1.6 and 2.6.

The profiles showed in Figure 5 for ports 1.4 and 3.4 transverse the boiler in the direction of the burners. At port 1.4 all profiles are relatively uniform throughout the region where measurements were made. The relatively low CO_2 NO_x concentrations and temperature and high O_2 concentrations result from both combustion being in its initial stages and the presence of the boundary air injected at level 0. At port 3.4, the relatively high O_2 concentrations and low temperatures close to the wall reveal, once again, the presence of boundary air. The decrease in O_2 concentration and increase in CO_2 and NO_x concentrations and temperature in the direction of the burners are due to the combined effects of combustion and mixing with the upward flow of hot reacted gases.

Figure 6 show the profiles of local mean gas species concentrations for run 1 for ports 8 to 10. The profiles reveal that the O_2 concentration increases

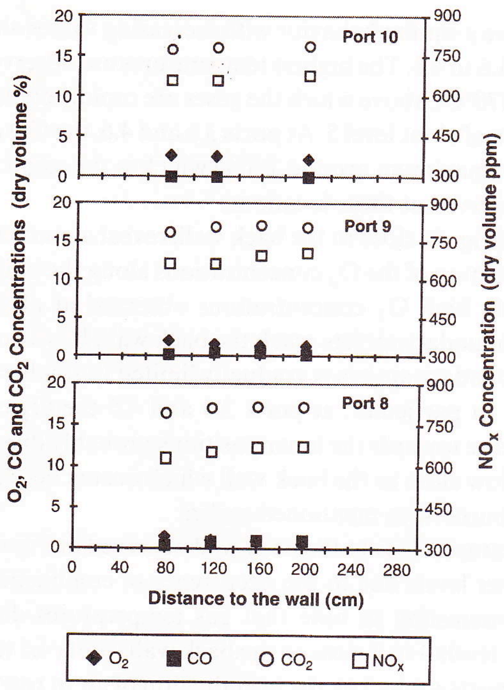

FIGURE 6 Profiles of local mean gas species concentration for run 1 through ports 8 to 10.

along the boiler height. At port 8, close to the boiler nose, the O_2 concentrations are very low with still significant CO concentrations. At ports 9 and 10 the measured gas species composition results from mixing with gases from the front wall region of the boiler, where overfire air is injected at level 5. At these ports the measured NO_x concentrations are reasonably uniform with averaged values close to the ones registered on-line by EDP at the economizer outlet (see Tab. III).

Incident Wall Heat Fluxes

The measured local incident wall heat fluxes for runs 1 and 2 are listed in Figure 7. In both cases the strong three-dimensional nature of the thermal radiation is clearly observed. In addition, the radiation heat transfer data for both runs reflect good symmetry with respect to opposite inspection ports at the same level. For run 1 the trends are somewhat similar to those of the temperature profiles but with the peaks in the burner levels being more accentuated due to the fourth power temperature dependency of radiation.

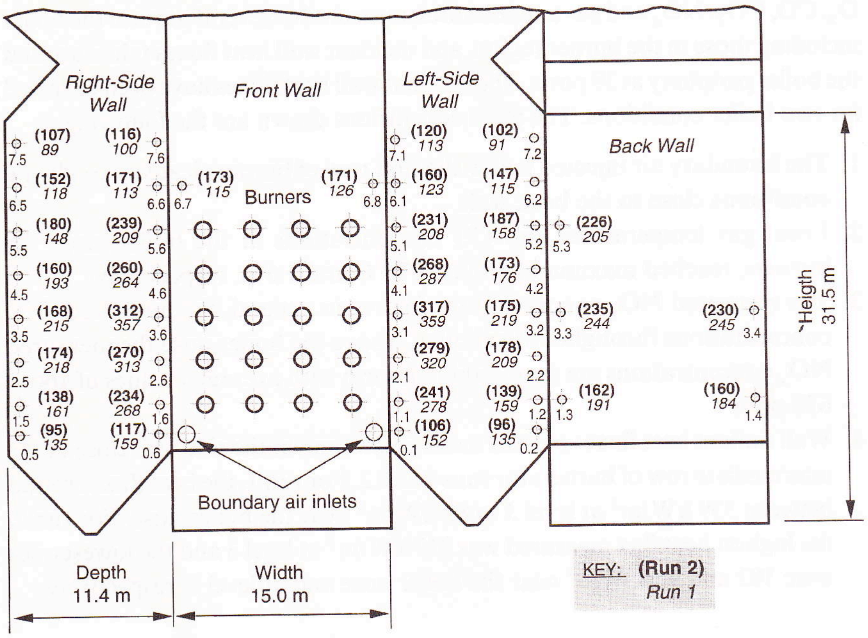

FIGURE 7 Measured incident wall heat fluxes (kW/m^2) for runs 1 and 2.

Ports located at level 4 present lower heat fluxes as compared with those at level 3, despite the similar measured temperatures in both levels. This can be attributed to the higher radiative heat losses to the upper furnace region at level 4–last row of burners in service in run 1.

Overall, the incident wall radiation flux data for run 2 show the same trend as run 1 but with a reduced magnitude except in levels 5 to 7. It is interesting to note that the higher values of the incident wall radiation fluxes were measured in leves 3 for both runs. The differences in the incident wall radiation fluxes for the two run are minimal at level 7. This is because the gas temperature profiles level out very rapidly due to mixing and the smoothing effect of thermal radiation resulting in very small differences between the gas temperatures of the runs at level 7.

CONCLUDING REMARKS

Measurements have been obtained in an 300 MW$_e$, front-wall-fired, pulverized-coal, utility boiler. The results include local mean gas species concentrations of

O_2, CO, CO_2, NO_x and gas temperatures, measured at several ports in the boiler including those in the burner region, and incident wall heat fluxes taken around the boiler periphery at 39 ports. The incident wall heat fluxes have been collected for two boiler conditions. The main conclusions drawn are the following:

1. The boundary air injected below the first row of burners leads to oxidizing conditions close to the back wall.
2. Local gas temperatures and CO concentrations in the boiler, near the burners, reached maxima of about 1470°C and 1.6%, respectively.
3. The measured NO_x concentrations follow, in general, the measured CO_2 concentrations throughout the boiler. Above the boiler nose the measured NO_x concentrations are reasonably uniform with averaged values of about 670 ppm.
4. Wall radiant heat fluxes present maximum values at the side wall close to the intermediate row of burners for runs 1 and 2. For run 1, the heat fluxes varied between 359 kW/m^2 at level 3 to 89 kW/m^2 near the boiler nose. For run 2, the highest heat flux measured was 317 kW/m^2 at level 3 and the lowest ones were 102 and 95 kW/m^2 near the boiler nose and at level 0, respectively.

Acknowledgements

Financial support for this work was provided by the JOULE III programme of the European Commission under the contract N° JOF3-CT95-0005 and is acknowledged with gratitude. The authors would like to thank the personnel of the Sines power plant for their valuable assistance during all the stages of the experiments, particularly, Mr. Luís Matos. The authors wish also to thank undergraduate student Paulo Silva and technicians Manuel Pratas and Rui Martins who assisted them in conducting the work presented here. Thanks are also due to Jorge Coelho for his cooperation during the preparation of the figures.

References

Azevedo, J. L. T., Carnall, F. and Carvalho, M. G. (1996) Heat Transfer Assessment of a Boiler Convective Section. In *New Developments in Heat Exchangers*, eds. Afgan, N., Carvalho, M. G., Bar-Cohen, A., Butterworth, D. and Roetzel, W. Gordon and Breach Publishers.

Beér, J. M. and Chigier, N. A. (1972) *Combustion Aerodynamics*. Applied Science Publishers, London.

Black, D. L. and McQuay, M. Q. (1996) Particle Size and Velocity Measurements in the Radiant Section of an Industrial-Scale, Coal-Fired Boiler: the Effect of Coal Type. In *Combustion and Fire*, HTD-Vol. **328**, pp. 19–27, eds. McQuay, M. Q. *et al.*, The American Society of Mechanical Engineers, New York.

Bonin, M. P. and Queiroz, M. (1991) Local Particle Velocity, Size and Concentration Measurements in an Industrial Scale Pulverised Coal Fired Boiler. *Combustion and Flame*, **85**, 121–133.

Bonin, M. P. and Queiroz, M. (1996) A Parametric Evaluation of Particle-Phase Dynamics in an Industrial Pulverized-Coal-Fired Boiler. *Fuel*, **75**, 195–206.

Boyd, R. K. and Kent, J. H. (1986) Three-Dimensional Furnace Computer Modelling. *Proceedings of the 21st International Symposium on Combustion*, 265–274.

Butler, B. W. and Webb, B. W. (1991) Local Temperature and Wall Radiant Heat Flux Measurements in an Industrial Scale Coal Fired Boiler. *Fuel*, **70**, 1457–1464.

Butler, B. W., Wilson, T. and Webb, B. W. (1992) Measurement of Time-Resolved Local Particle Cloud Temperature in a Full-Scale Utility Boiler. *Proceedings of the 24th International Symposium on Combustion*, 1333–1339.

Chedaille, J. and Braud, Y. (1972) *Measurements in Flames*, eds. Beér, J. M. and Thring, M. W. Edward Arnold Ltd., London.

Costa, M., Mourão, M., Baltasar, J. and Carvalho, M. G. (1996) Combustion Measurements in an Industrial Glass-Melting Furnace. *Journal of the Institute of Energy*, **69**, 80–86.

Coimbra, C. F. M., Azevedo, J. L. T. and Carvalho, M. G. (1994) 3-D Numerical Model for Predicting NO_x Emissions from an Industrial Pulverised Coal Combustor. *Fuel*, **73**, 1128–1134.

Dal Secco, S., Méchitoua, N. and Simonin, O. (1995) Three Dimensional Modelling of Coal Combustion and NO_x Formation in a 250 MW Coal Fired Furnace. *Proceedings of the Third International Conference on Combustion Technologies for a Clean Environment*, Paper 31.2, Lisbon, Portugal, July.

Epple, B., Schneider, R., Schnell, U. and Hein, K. R. G. (1995) Computerized Analysis of Low-NO_x Coal-Fired Utility Boilers. *Combustion Science and Technology*, **108**, 383–401.

Fiveland, W. A. and Latham, C. E. (1993) Use of Numerical Modeling in the Design of a Low-NO_x Burner for Utility Boilers. *Combustion Science and Technology*, **93**, 53–72.

Kakaras, E., Ntouros, Z., Founti, M. and Papageorgiou, N. (1995) Influence of the Quality of Greek Brown Coals on NO_x-SO_2 Emissions from Thermal Power Stations. In *Combustion Technologies for a Clean Environment*, eds. Carvalho, M. G., Loockwood, F. C., Fiveland, W. A. and Papadopoulos, C. Gordon and Breach Publishers.

Magel, H. C., Schneider, R., Risio, B., Schnell, U. and Hein, K. R. G. (1996) Numerical Simulation of Utility Boilers with Advanced Combustion Technologies. Presented at the *Eighth International Symposium on Transport Phenomena in Combustion* (ISTP-VIII), San Francisco, U.S.A, July 16–20, 1995. In *Transport Phenomena in Combustion*, Vol. 2, pp. 1118–1129, ed. Chan, S. H. Taylor and Francis.

Queiroz, M., Bonin, M. P., Shirolkar, J. S. and Dawson, R. W. (1993) Experimentally Determined Particle Number Density Statistics in an Industrial-Scale, Pulverized-Coal-Fired Boiler. *Energy and Fuel*, **7**, 842–851.

Schnell, U., Schneider, R., Magel, H. C., Risio, B., Lepper, J. and Hein, J. R. G. (1995). Numerical Simulation of Advanced Coal-Fired Combustion Systems with In-Furnace NO_x Control Technologies. *Proceedings of the Third International Conference on Combustion Technologies for a Clean Environment*, Paper 31.1, Lisbon, Portugal, July 3–6.