Transactions on Engineering Sciences vol 5, © 1994 WIT Press, www.witpress.com, ISSN 1743-3533

A computational approach to the combustion of pulverized Greek lignite in a power station combustor

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ABSTRACT

The paper describes the fundamentals of a developed numerical algorithm for calculating pulverized coal combustion in three-dimensional furnaces, and presents predictions of the main aerodynamic and combustion characteristics in a newly-constructed 300MW utility boiler of the Greek Public Power Corporation (P.P.C.), featuring tangential firing and operating on pulverized Greek lignite. The study explores numerically and points out the effects on the overall performance of the boiler of: a) increasing the size and b) reducing the moisture of the lignite particles fed into the boiler.

INTRODUCTION

The utilisation of coal as a source of energy is of major importance to the power industry. In Greece for example, 78% of the total electricity production stems from burning pulverized lignite, whereas only 13% of the energy demands come from oil and 7.5% from hydroelectric power stations ([1]). Despite this fact though, the development of thermal combustion chambers, fuelled with pulverized coal, has in the past -and for a long time- relied world-widely on empiricism and on laboratory-scale experiments, while there was an evident lack of complete and reliable computational procedures for their numerical study. Hence, during the last two decades, appropriate computer algorithms capable of predicting pulverized coal combustion have made their appearance in the technical literature; however, in their initial stage, these numerical methods were designed

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almost exclusively for 2-D, axisymmetric furnace geometries ([2],[3],[4],[5]). On the other hand, since most of the power generating industrial combustors are three-dimensional, there was a growing need for the development of robust computational methodologies for predicting the performance of such 3-D, physical-scale furnaces. So, recently, a number of computer codes capable of handling pulverized coal combustion in three-dimensional boiler geometries have been created by several researchers ([6],[7],[8],[9]), each one of which is based on different assumptions and mathematical submodels and has its own merits and disadvantages.

The purpose of the present paper is to present the fundamentals of a computer algorithm, which has been developed in the Lab. of Aerodynamics of the National Technical Univ. of Athens for calculating pulverized coal combustion in three-dimensional utility boilers and then to apply the developed numerical procedure to a large-scale utility boiler of the Greek Public Power Company, operating on Greek lignite, on the purpose to quantify the effects of changing the size and moisture content of lignite particles on the performance of the boiler.

THEORETICAL BACKGROUND

This section outlines the main features of the COCA-3 (acronym for COal Combustion Algorithm in 3 dimensions) computer code, which has been developed in the Lab. of Aerodynamics of N.T.U.A. and has been utilised for the numerical study presented herein.

The flow of the gaseous phase is described mathematically in the COCA-3 software by employing the three-dimensional, time-mean equations of transport for mass, momentum, gas species and enthalpy. The exact form of these equations has been given elsewhere ([10]) and will not be repeated here again. The turbulent viscosity and diffusivity are handled by the standard, two-equation "k-ε" turbulence model ([11]). All equations are coupled by the gas density, which is a function of enthalpy and gas molecular weight obtained from the combustion model. In all, there are eleven conservation equations of the gas phase to be solved. Their numerical solution is accomplished after discretization over control volumes, using the "hybrid differencing scheme"; the resulting finite-difference equations are then solved numerically by employing the SIMPLE algorithm along with a TDMA solver.

The solid phase (that is the lignite particles) is described using the Lagrangian approach; according to this

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approach, a representative number of discrete lignite particle groups is followed and their motion is calculated by integrating numerically the corresponding Lagrangian equations of particle motion in the three Cartesian directions ([10], [12]). The link between the gaseous and the particulate phases is achieved via appropriate source terms in the equations of the continuous phase, which represent the contribution of the solid particles to the gas-phase quantities (P.S.I.- Cell method, [13]; see also for details Anagnostopoulos & Bergeles [12]). In addition, the turbulent dispersion of lignite particles is simulated using the Stochastic Separated Flow (S.S.F.) model in the form proposed by Shuen et al. [14]. The release of lignite volatiles is modelled through a single-step devolatilisation scheme (Baum & Street [15]), whereas their combustion in the gas phase is simulated by employing the "eddy dissipation combustion model" of Magnussen and Hjertager [16]. The combustion of the remaining char is described mathematically via a chemical model which takes into account the simultaneous co-existence of the heterogeneous oxidation reaction of the coal and the film diffusion of oxygen into the pores of lignite particles ([17]). The empirical coefficients of the overall combustion model have been calibrated specifically for Greek lignite by Anagnostopoulos et al. [17] and so their values were taken according to the findings of that publication. Finally, the thermal radiation is computed via the approximate "non-equilibrium diffusion radiation model", discussed in detail by Rizvi [4].

The predictions of the coal combustion algorithm serve as input conditions for a developed NO production post-processor, which is based on De Soete's numerical model for calculating the quantity of NO formed during pulverized coal combustion from the fuel-bound nitrogen (Smith et al. [18], Hill et al. [19]).

THE NUMERICAL INVESTIGATION

Figure 1 shows a schematic of the plan view of the recently constructed Megalopolis boiler IV, which was simulated in the present study. This boiler belongs to the Public Power Corporation of Greece, it is wall-fired and its dimensions are: 15.25x17.25x56.42m. There are six sets of openings in the boiler; each set includes an upper and a lower burner and an opening for the drying pipes. At full load, one out of the six sets of burners usually remains closed (in this study burners No.5 were assumed out of operation). A nonuniform, three-dimensional Cartesian mesh (see Fig. 2) has been created for the

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numerical representation of the geometry of the boiler. More detailed description of Megalopolis boiler IV, along with information about its actual operational data and about other initial and boundary conditions employed in the computations can be found in Sargianos and Bergeles [10]. The computational experiments performed for this study include: a) Operation of the boiler under normal/standard conditions (exactly as those described in [10]) - "basecase run". b) Operation of the boiler with lignite particles of analogous distribution but of double Sauter mean diameter compared to the basecase run (S.M.D.=160μm). c) Operation of the boiler with pulverized lignite of half (10%) moisture content compared to the basecase run. Note that all the other operational conditions for cases (b) and (c) above were kept the same with case (a) so that the obtained predictions of all the cases investigated to be able to be compared with each other.

RESULTS AND DISCUSSION

Figure 3 shows calculated velocity vectors for the three examined cases on a vertical plane of the boiler passing through the back-positioned burners 4 and 6 (see Fig.1). It can be seen that there are no observable differences among the depicted flow fields of the three cases. This observation has been confirmed for other lateral and vertical cross sections of the boiler (not shown in this paper due to lack of space) as well. From the same figure it is observed that the highest velocities are localised in the position of the burners, whereas velocities of relatively high magnitude (but not as high as those appearing in the vicinity of the burners) exist in the upward-directed core of the flow, where obviously the main vortex of the flow field - due to tangential firing-is formed. Near the base of the boiler, one can discern a recirculation region resulting in secondary re-entrainment of the flow from the ash pit to the boiler, which mainly takes place close and parallel to the vertical walls of the furnace. Lower velocities are observed in the upper part of the boiler, where the flow has been oriented toward the exit (which is located at the upper right portion of the figures). At the upper left portion of the figures the location of the recirculation pipes, through which the flue gases are sucked in order to be used for preheating and drying of lignite, can also be seen.

Figure 4-A displays calculated average temperature profiles along the boiler's height for the three examined cases. The

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higher temperature levels predicted for the case with the reduced lignite moisture can be justified by the fact that when the moisture of a fossil fuel is reduced, then its calorific value is augmented, a fact which is obviously responsible for the observed trend. On the other hand, the lower temperatures predicted for the case with lignite particles of double Sauter mean diameter is an indication of incomplete combustion of these large particles; indeed, by refering to figure 5-A, it is seen that this case gives the lowest total fuel burnout, confirming the previous speculation. On the other hand, by inspecting figure 5-B, it is seen that the water vapour concentration along the boiler's height is smallest -as expected- for the case with fuel moisture 10%, whereas for the case with lignite particles of double Sauter mean diameter is higher in the bottom of the boiler and slightly lower at the upper part of it, compared to the basecase run; this is an indication that in this case most of the particles move and release their volatiles and moisture in the lower part of the furnace, whereas a smaller number of them arrive at large heights within the boiler. To this fact can be attributed the predicted higher NO concentrations of this case, compared to the basecase run, in a vertical slice containing the burners of the boiler (see Fig. 4-B); this fact affects the availability of oxygen in the upper part of the boiler, creating there an oxygen-lean region, because most of the available oxygen has been consumed earlier for the combustion of the large particles and their volatiles in the middle portion of the boiler. So, the predicted NO concentrations at large heights within the boiler are lower for the case with lignite particles of double diameter, since lower oxygen (which is necessary for the oxidation of fuel-bound nitrogen to NO) is available for them in this region. From figure 4-B, it is also observed that the case with lignite moisture 10% gives the highest predictions of NO concentrations, obviously due to the highest values of temperature obtained for this case (the NO formation mechanism is known to be very sensitive and to depend strongly on the temperature field).

Finally, by following and recording the trajectories of 11000 particles, it was found that while for the basecase run the number of lignite particles impinging on boiler's walls is negligible, for the case with lignite particles of double Sauter mean diameter this number mounts up to almost 28% of the totally injected through the burners particles; from these (see Fig. 6-A), the larger portion (57%) drops into the ash pit, whereas from figure 6-B it is seen that all the particles which fall

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into the hopper originate from lower burners. The rest 43% of the particles, which impinge on the vertical only walls of the boiler, originate practically from all the other open burners of the furnace with the exception that the contribution of the burners which are placed on the same vertical wall with the boiler's outlet (bur. 1 & 6) is very small (see Fig. 6-C). To the large number of lignite particles arriving at the boiler's base and vertical walls, without having been burned completely, may be attributed the observed in figures 4-A and 5-A trends of the examined case with the double particle size; this conclusion is in accordance with the observations of Luo et al. [9], too.

CONCLUSIONS

A parametric study of a newly-constructed 300MW utility boiler of the Greek Public Power Company, concerning its operation a) with lignite particles of double Sauter mean diameter (compared to the normal conditions) and b) with lignite of half moisture content (compared to the basecase) was carried out with the aid of the COCA-3 computer code, which has been developed entirely in the Lab. of Aerodynamics of N.T.U.A. for the simulation of pulverized coal combustion in three-dimensional combustors. The study has revealed that these changes in the operational conditions of the boiler do not affect the pattern of the flow field, but when the moisture contained in the fuel is reduced to half, then higher temperature as well as NO concentration levels are attained within the boiler. On the other hand, when the size of lignite particles is doubled (compared to the usual operational conditions of the boiler), this results in lower average temperatures and poorer fuel burnout, which are probably due to the impingement of lignite particles (because of their higher inertia) on the walls and the ash pit of the boiler, without having previously completed their burning.

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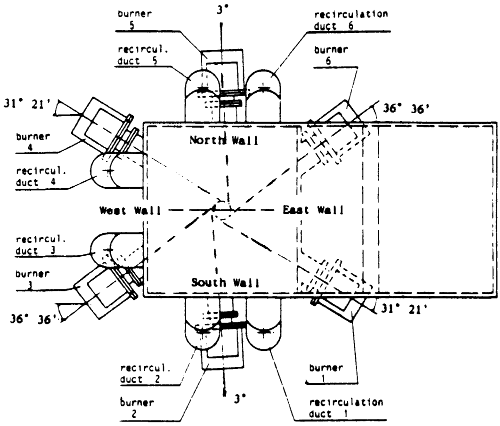

Fig.1: Plan view of Megalopolis Boiler IV.

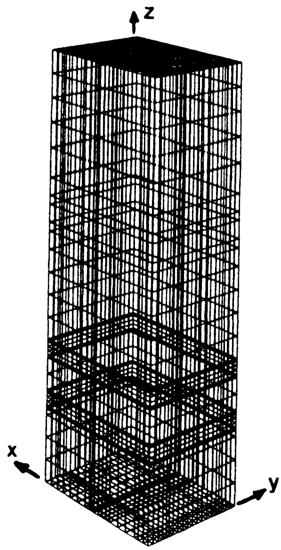

Fig.2: 3-D plot of the Cartesian mesh.

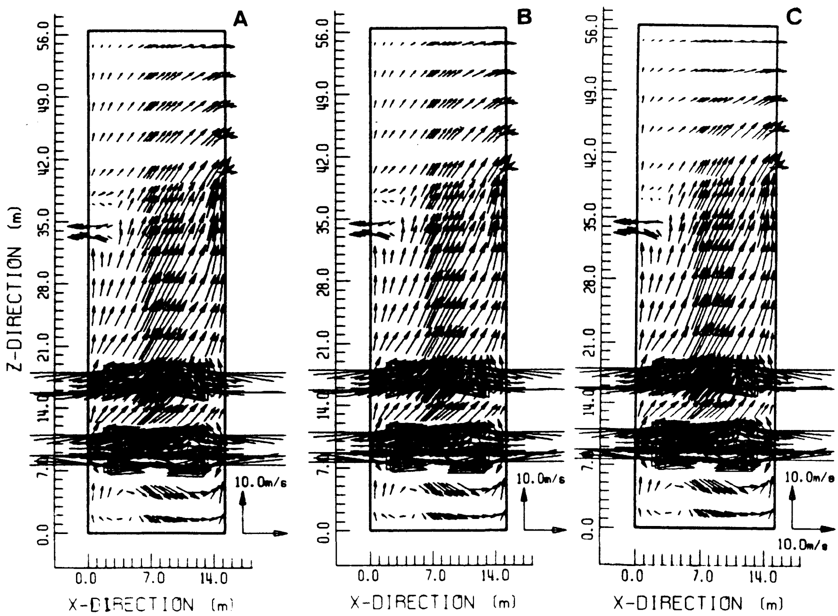

Fig.3: Predicted velocity vectors on a vertical "cut" of the boiler through burners 4 & 6 (y= 13.56m)
A: basecase run, B: particles of double diameter,
C: lignite with 10% moisture.

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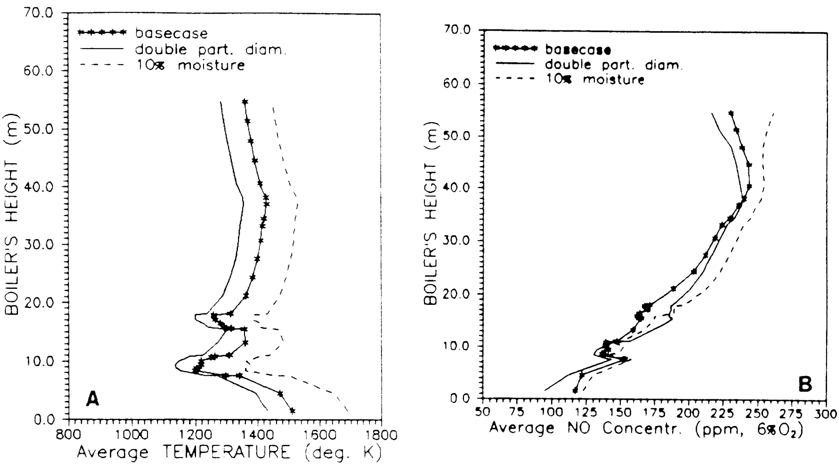

Fig.4: Predicted: (A) average temperature profiles and
(B) average NO concentrations
along the boiler's height (for the 3 cases examined).

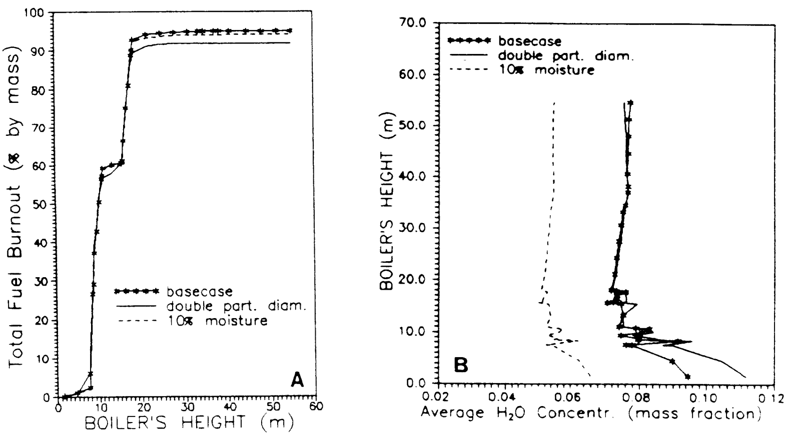

Fig.5: Predicted: (A) cumulative fuel burnout and
(B) average H_2O concentrations
along the boiler's height (for the 3 cases examined).

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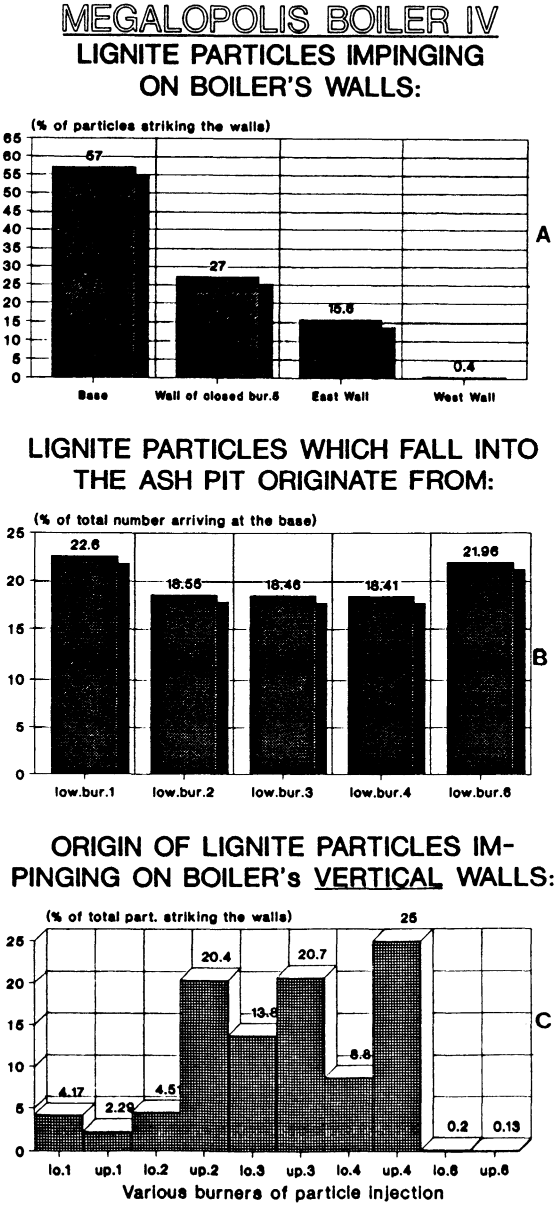

Fig.6: Statistics for lignite particles impinging on the walls of Megalopolis Boiler IV (case with particles of double diameter).