

CFD analysis of the combustion, gas flow, and heat exchange processes in a boiler of a thermal power plant

Maria L.S. Indrusiak, Cristiano V. da Silva, Arthur B. Beskow and José W. M. Kaehler

Research Group of Energy Production Systems, Catholic University of Rio Grande do Sul
Av. Ipiranga, n.6681, 90619-900, Porto Alegre – RS – Brasil

1 Introduction

The strategic role of energy and the current concern with greenhouse effects enhance the importance of the studies of complex physical and chemical processes occurring inside boilers of thermal power plants. Combustion comprises phenomena such as turbulence, radiative and convective heat transfer, particle transport and chemical reactions. The study of these coupled phenomena is a challenging issue. The state of the art in computational fluid dynamics and the availability of commercial codes encourage numeric studies of the combustion processes. In the present work a commercial software, CFX©Ansys Europe Ltd., has been used to study the coal combustion process in a 160 MW commercially operated thermal power plant, with the objective of simulate the operation conditions and identify inefficiency factors.

Coal reserves in Brazil, which are used mainly for electricity production, are enough to meet the next 200 years demand. Nonetheless, in order to face the competition from renewable, natural gas and nuclear energy sources, some main problems must be solved, as to reduce CO₂ emissions through increasing efficiency[1]. Also NO_x and SO_x emissions should be reduced to environmentally acceptable levels. At this way, an efficient operation of combustion chambers of these plants depends on the proper knowledge of the oxidation reactions and heat transfer from the combustion products to the chamber walls and heat exchangers, which requires a detailed analysis of the governing mechanisms.

2 Background

The set of equations solved by CFX are the mass, momentum, energy and chemical species conservation equations and the equations of state of real gas. An Eulerian description is adopted for the fluid phase and a Lagrangean tracking model for the coal particles. The κ - ω turbulence production–dissipation model is applied to solve the closure problem of the averaged Navier Stokes equations [2].

CFX calculates coal combustion by combining a particle transport calculation of the coal particles with a Arrhenius-Eddy Dissipation model to calculate the combustion of the volatile gases (assuming just methane and carbon monoxide as devolatilization products), also using two global steps to calculate the methane oxidation. The combustion of a coal particle is a two stage process: the coal devolatilization followed by the oxidation of the residual char to leave incombustible ash. Arrhenius equations are used to predict the devolatilization process and the Field model is used to predict the char oxidation. Devolatilization was usually modeled by two competing reactions in order to deal with the strong dependence on temperature and heating rate of the bituminous coal. The two equations have different rate parameters and volatile yields. The yield fractions for the lower temperature equation were obtained from proximate analysis and to the ones for the higher temperature equation were given the values suggested by Li et al. [3].

The model adopted for the char burn out computes the rate of the reaction taking into account the rate of diffusion of oxygen and its partial pressure at the particle surface [4]. Particle size plays an important role in that mechanism and was modeled by a Rosin-Rammler statistical distribution [5], with the parameters adjusted from pulverized coal analysis.

To predict the NO_x formation the Zeldovich model (thermal-NO) is used, along with the Fenimore model (prompt-NO). The Discrete Transfer Radiation Model is used to predict the radiation heat transfer of the gases to the walls. A gray gas model is adopted.

The heat transfer across boundaries and in heat exchangers is also considered. The combustion processes occurring in the boiler generate a huge amount of thermal energy which is transferred to the working fluid (water) in the heat exchangers by means of two basic mechanisms: convection and thermal radiation. In fact, heat transfer to the walls in a utility boiler is mainly due to radiation and the convective heat transfer has only a minor contribution [6]. Conversely, heat transfer in the tube banks, which were presented as porous media, was modeled by means of volumetric sink coefficients representing the total amount of thermal energy transferred to working fluid inside the tubes of each bank. The pressure losses due to the tube banks are also modeled assigning quadratic directional loss coefficients to the porous media, computed from the tube bank geometry data [7].

3 Geometry and Mesh Settings, Boundary Conditions and Convergence Criteria

The boiler under consideration is part of a pulverized coal thermal power plant. The combustion chamber modeled is rectangular in shape with four burners firing from each corner, producing a large vortex in the center of the chamber. The evaporation process occurs mainly in the tubes covering the boiler walls. In the upper middle of the boiler are the reheater, superheater and economizer tube banks. The entrance to the second stage was considered the outlet of the domain. The discretization of the 3D geometry was done using tetrahedral volumes. At the walls prismatic volumes were used in order to capture the boundary layer behavior. The mesh used has approximately 1.5×10^6 elements.

The convergence criterion adopted was the RMS of the residual values less than 1.5×10^{-6} .

The boundary conditions were obtained from the design data set and also from the operation data sheets. The operating conditions considered were the rated ones, for 160 MW. The following parameters were considered:

Inlet: The inlet conditions are those for air and coal flows entering the domain from the burner nozzles. Primary and secondary combustion air and pulverized coal mass flow rates and temperatures and also pulverized coal size probabilistic distribution parameters were set. To the raw coal was set the proximate analysis results.

Outlet: The outlet boundary is the flue gas passage to the second stage, where the mean static pressure was set.

Boiler walls: The boiler walls are covered with slanting tubes from the bottom until the beginning of the heat exchangers region; from there to the top the tubes are vertically positioned. Wall roughness, temperature and thermal radiation coefficients were set for that two wall regions.

4 Results

The temperature field is shown at Fig. 1-a (right) for a vertical plane diagonally positioned. The large amount of heat released by the devolatilization and oxidation of the volatiles is pointed out by the near red regions at the edge of the flames originated at each burner. Devolatilization is the first reaction of the combustion process and takes place where the air and coal mixture injected by the burners achieved the adequate temperature. The central vortex created by the tangential layout of the burners is visible at the center of the combustion chamber.

As the flow moves to the outlet the heat is exchanged with the walls and tube banks, creating the temperature gradient shown in the figure. The temperature and velocity fields are presented in a superimposed way at Fig. 1-g to 1-k for horizontal planes corresponding to the four burner levels and a level just upstream the burner region. The temperature color scale is the same for all the figures. At the lower burner levels the general temperature distribution show lower values than at the higher levels. At Fig. 1-g the temperature presents a trend to

equalization, due to both the absence of new inflows and the strong turbulence and vorticity of the flow. The velocity fields, represented by means of vectors, show that at the lower burner level the vortex region is narrow and increases in the upstream direction, due to the vortical moment imparted by the burners jets at each level. Figure 1-g shows the final aspect of the vortex which dominates the section, with a characteristic dimension of the same magnitude of the boiler wall horizontal length.

There is an intense formation of volatiles very near to the burner nozzles, denoting the action of the first reaction which is activated at relatively low temperatures. The oxidation of the resulting volatile yields is almost immediate, according to the set of equations which models the combustion process.

Figures 1-b to 1-f show the distribution of NO_x mass concentration along the boiler. The NO_x formation takes place mainly after the coal devolatilization and volatile oxidation, at the top edges of the air-fuel jets from each burner, where the higher temperatures were achieved. The major role of high temperature along with high oxygen concentration levels in NO_x formation is also emphasized by the expressive enlargement of NO_x production at the higher burner levels. An enhancement of the oxygen concentration is expected at these levels, where the inlet air jets are reinforced by the residual oxygen of the lower levels.

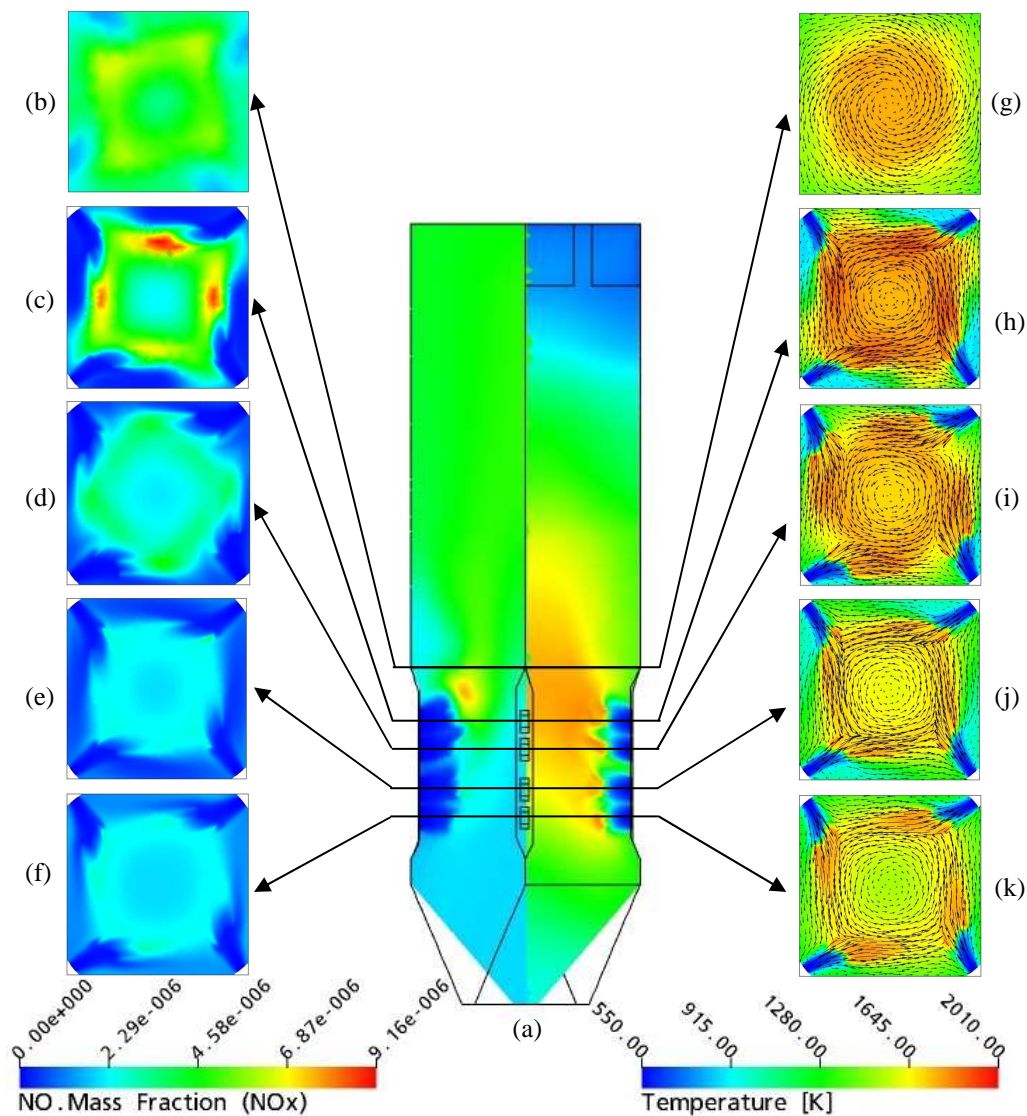


Figure 2: (a): NO_x mass fraction (left) and temperature (right) fields in the boiler. (b) to (f): NO_x mass fraction field in the boiler, at horizontal planes at positions indicated by the arrows. (g) to (k): Temperature field at the same horizontal planes. The superimposed vectors represent the velocity field in the planes.

The results obtained were analyzed and compared with known data of the boiler operation and with data from other studies concerning similar power plant units [ref!!](#). The main control parameters used to validate the results were the temperature and mass fractions of gases at the boiler outlet where there are regular measurements. The heat flux across the walls was also considered. Indeed, the heat transfer rate from the boiler to the working fluid at the heat exchangers was prescribed according to the operation data and the wall heat transfer rate was computed and compared with the operation data. Table 1 shows the main results. The consistency

Table 1

	Heat transfer rate [kW/m ²]	Outlet temp. [°C]	% O ₂	% CO ₂	CO [ppm]	NO _x [ppm]
Experimental data	204	414	6.5	13.2	58	168
Simulation data	136	567	4.4	20.8	0.7	8.53

6 Conclusions

The general description of the numeric model of a thermal power plant boiler using a commercial CFD code was presented in this article. The aim of the work is the use of the results to better understand the complex processes occurring within the boiler. Some results were presented and discussed. The temperature and velocity fields are in agreement with the expected behavior of a coal combustion chamber.

The code shows a good sensibility to variations in inlet and boundary conditions and this was explored in order to study the performance of the boiler at out of design and part-load operation conditions. Also the combustion, heat exchange processes and NO_x formation responses to other conditions at the burners, like the vertical tilt, were studied.

References

- [1] Williams, A., Pourkashanian, M., Jones, J. M. and Skorupska, N., 2000, "Combustion and Gasification of Coal", Taylor & Francis, New York.
- [2] CFX Solver Theory, 2004.
- [3] Li, Z. Q., Wei, Y. and Jin, Y., 2003, "Numerical simulation of pulverized coal combustion and NO formation", Chemical Engineering Science, v. 58, pp. 5161-5171.
- [4] Kanury, A. M., 1975, "Introduction to Combustion Phenomena", Gordon and Beach Science Publishers, New York.
- [5] Brown, W. K., 1995, "Derivation of the Weibull distribution based on physical principles and its connection to the Rosin-Rammler and lognormal distributions", Journal of Applied Physics, v. 78, n. 4, pp. 2758-2763.
- [6] Xu, M., Azevedo, J. L. T. and Carvalho, M. G., 2000, "Modelling of the combustion process and NO_x emission in a utility boiler", Fuel, vol. 79, pp. 1611-1619.
- [7] Knudsen, J. G., 1958, "Fluid Dynamics and Heat Transfer", Mc Graw Hill.