CFD ANALYSIS OF THE PULVERIZED COAL COMBUSTION IN A BOILER USING DIFFERENT BRAZILIAN MANUFACTURED COALS: CE 3100 AND CE 4500

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ABSTRACT

At the present work the commercial software CFD code CFX © Ansys Europe Ltd. has been used to study a behavior of pulverized coal - PC - combustion process in a 160 MWe thermal power plant installed at the southern region of Brazil with the objective of simulating the boiler operation conditions using two different kinds of benefited Brazilian coal - the CE3100 and the CE4500. It was expected that this study can be identify some possible operation problems, as time of the fuel into the combustion chamber, unburned fuel in ash, and try to obtain data about the pollutants formations, like CO and NOx, behind temperature and concentrations fields for each benefited coal used, indicating the best option of the benefited coal to be used. The results show that the coal with less quantities of ash is the most appropriated to burn into this boiler, indicating that a previews treatment on the Brazilian coal actually used at this boiler should be better at energetic view point.

Keywords: Computational fluid dynamic, thermal power plant, Brazilian coal combustion

1. INTRODUCTION

In many parts of the world's coal is an important source of energy, mainly in the production of electricity. It is known that the probable reserves of coal worldwide already exceed the reserves of natural gas and oil, so coal will still be used for a long time. A case closer to reality is the presence of the largest coal reserves in Brazil. However, the burning efficiency and clean use of this fuel are the main problems in combustion processes. In Brazil, which are used mainly for electricity production in large utility boilers, the coal reserves are enough to meet the next 1,109 years demand, considering the consumption levels of 2006 (EIA/U.S. Department of Energy, 2009).

In the last decades researches have been developed in order to search new ways to the electric energy production with minimal environmental impact, mainly related to emissions of carbon dioxide in the atmosphere, one of the most causer of the called greenhouse effect. However, in most
part of the world the increase of this productivity is still related to fossil fuel, like mineral coal and natural gas in combustion processes in furnaces from big thermal power plants.

Eaton et al. (1999) present a revision of combustion models. The models are generally based on the fundamental conservation equations of mass, energy, chemical species and momentum, while the closure problem is solved by turbulence models such as the k-ε (Launar and Sharma, 1974), combustion models like Arrhenius (Kuo, 1996; Turns, 2000), Magnussen - EBU - “Eddy Breakup” (Magnussen and Hjertager, 1976), radiative transfer models based on the Radiative Transfer Equation - RTE (Carvalho et al., 1991) and models to devolatilisation and combustion of solid and liquid fuels. Li et al. (2003) numerically investigated the combustion process using only a two-fluid model (instead of the Eulerian gas - Lagrangian particle models) for simulating tree-dimensional turbulent reactive flows and coal combustion. To improve the simulation of the flow field and NOx formation, a modified two-phase turbulence model and a second-order-moment (SOM) reactive rate model were proposed. The results indicate that a pulverized coal concentrator installed in the primary air tube of the burner has a strong effect on the coal combustion and NOx formation.

Xu et al. (2000) employed the CFD code to analyses a coal combustion process in a front wall pulverized coal fired utility boiler of 350 MWe with 24 swirl burners installed at the furnace front wall. Five different cases with 100, 95, 85, 70 and 50% boiler full load were simulated. Comparisons were addressed, with good agreement between predicted and measured results in the boiler for all, but one case thus validating the models and the algorithm employed in the computation.

In a numerical investigate, Yin et al. (2002) evaluated a performance of a 609 MW tangentially fired pulverized-coal boiler, with emphasis on formation mechanism of gas flow deviation and uneven wall temperature in crossover pass and on NOx emission. To achieve this purpose and obtain a reliable solution, some different strategies with the existing researches are used. Good agreement of simulation results with design parameters and site operation records indicates this simulations pretty reasonable and thus the conclusions of the gas flow deviation, emissions, combustion and heat transfer are reliable. Kumar and Sahur (2007) studied the effect of the tilt angle of the burners in a tangentially fired 210 MWe boiler, using commercial code FLUENT. They showed the influence of the tilt angle in the residence time of the coal particles and consequently in the temperature profiles along the boiler. Follow in the same line, Asotani et al. (2008), also using the code FLUENT, studied the ignition behavior of pulverized coal clouds in a 40 MW commercial tangentially fired boiler. The results for unburned carbon in ash and for outlet temperature were validated respectively by the operating data and by the design parameter. A qualitative comparison between the results for temperature and ignition behavior in the vicinity of the burners was made, using the images of a high temperature resistant video camera system.

Nimmo et al. (2008) describe a novel use for tire rubber pulverized fuel in a NOx re-burning process which may have an application in power station boilers using a tire of clean technology. This method of disposal could represent a way of combining waste disposal, energy recovery and pollution control within one process. A preliminary study of micronized tire combustion was undertaken to identify the suitable size ranges for application in NOx reduction by re-burning. They tests were performed in a down-fired, pulverized fuel combustor (PFC) operating at about 80 kW. Superior combustion characteristics, i.e. burnout were achieved with particle sizes less than 250 µm. Parameters studied, were, reburn zone stoichiometry and reburn fuel fraction. Additionally, the carbon content of the ash was carefully monitored for any effect on burnout at the fuel rich reburn stoichiometries. The NOx reductions achieved with tires are compared with reburning with coal. NOx reductions up to 80% were achieved with tires at half of the reburn fuel feed rate required to achieve the same reductions by coal.
In other work, Higuera (2009) presented a study about the devolatilization of an isolated coal particle moving relative to the surrounding gas. It was numerically simulated using a competing reaction model of the pyrolysis and assuming that the released volatiles burn in an infinitely thin diffusion flame around the particle or not at all. He assessed the temperature of the particle is assumed to be uniform and the effects of the heat of pyrolysis, the intraparticle mass transfer resistance, and the variation of the particle radius are neglected. The effects of the size and velocity of the particle and of the temperature and oxygen mass fraction of the gas on the particle and flame temperature histories, the devolatilization time and the yield of light and heavy volatiles are investigated too.

Park et al. (2010) have investigated a computational fluid dynamics (CFD) analysis of the furnace at the Youngeung Power Plant in South Korea, he make a simulation about effects of burner and SOFA settings, firing patterns and coal blending on the boiler efficiency and pollutant formation, as well as the combustion efficiency. The models are coupled by exchanging temperature and heat flux values on furnace walls and heat exchangers at each iteration of the calculation to ensure that the final converged solution is a self-consistent solution for the combined furnace, boiler and turbine system. The Ansys CFX (Ansys Inc., 2004) software was used to develop the CFD model, this model has been validated for a typical operating condition by comparing the simulated results with the plant data, and good agreement is obtained, confirming that the coupled model has the capability to contribute significantly to the comprehensive optimization of the boiler operation as well as acting as a problem solving tool.

Recently, Silva et al. (2010-a) studied, using the commercial code CFX (Ansys Inc., 2004), a behavior of pulverized coal combustion in a 160 MWe commercial tangentially fired boiler erected in the core of the Brazilian coal reserves region, with the objective of simulating the operation conditions and identifying inefficiency factors. The results of simulations indicates that this software is perfectly capable to solve this kind of problem and it is possible obtain good agreement between the experimental and simulations data, to become an important tools to predict different situations of boiler operation and even so to be used for design of this equipment. At the same line, Silva et al. (2010-b) studied a combustion of pulverized coal into the boiler of a thermal power plant using a commercial software CFX © Ansys Europe Ltd., of a two different kinds of manufactured coals were numerically tested in a thermal power plant installed at the southern region of Brazil using the actual burning conditions of the boiler, the results include a residence time of the fuel into the combustion chamber, temperature fields, flow fluid mechanics, heat transfer and pollutant formation, as well as the CO and NOx concentrations, aiming to determinate the best conditions to burn the investigated coals. This study allowed achieve the most efficient boiler operation parameters, with decreasing costs of electricity production and reduction of environmentally harmful emissions.

In the present work the commercial CFD code CFX © Ansys Europe Ltd. was used to study the pulverized-coal combustion process in a 160MWe thermal power plant, with the objective of simulating the boiler operation conditions using three different kinds of Brazilian benefited coal, the CE3100 and CE4500, aim to identify possible operation problems and try to obtain data about the pollutants formations, temperature and concentrations fields for each benefited coal used, indicating the best option of the benefited coal to be used. The same thermal charge will be used for all cases into the boiler for comparisons questions.

2. MATHEMATICAL FORMULATION
A steady-state combustion of raw coal in air for a boiler combustion chamber is considered in order to determine the temperature, chemical species concentrations and the velocity fields for multi-component-flow (gas mixture and raw coal particles), as well as to study the influence of the operational parameters on the combustion process for different kind of Brazilian coals and NO\textsubscript{x} formation for studied fuels. The complete chemical reaction of the raw coal used at this work, including two devolatilisation processes, is modeled according to the basic scheme showed in Fig. 1. As basic assumptions, it is considered that the mass fractions of volatiles are 0.3636 of methane and 0.6364 of carbon monoxide, and that the combustion processes of these volatiles occur at finite rates. The methane oxidation is modeled by two global steps, given by:

\[
2CH_4^{(16)} + 0.22N_2^{(28)} + 3(O_2^{(32)} + 3.76N_2^{(28)}) \rightarrow 2CO^{(28)} + 4H_2O^{(18)} + 11.5N_2^{(28)}
\]
\[
2CO^{(28)} + 1(O_2^{(32)} + 3.76N_2^{(28)}) \rightarrow 2CO_2^{(44)} + 3.76N_2^{(28)}
\]

(1)

where the carbon monoxide oxidation is modeled by the second reaction above.

The hydrogen oxidation is modeled by:

\[
2H_2^{(2)} + O_2^{(32)} \rightarrow 2H_2O^{(18)}
\]

(2)

The formation of NO\textsubscript{x} is modeled by Zeldovich mechanisms using two different paths, the thermal-NO and the prompt-NO, where the first, that is predominant at temperatures above 1800 K, is given by tree-step chemical reaction mechanisms:

\[
O^{(16)} + N_2^{(28)} \rightarrow NO^{(18)} + N^{(14)}
\]

(3)

\[
N^{(14)} + O_2^{(32)} \rightarrow NO^{(30)} + O^{(16)}
\]

(4)

In sub or near stoichiometric conditions, a third reaction is also used

\[
OH^{(17)} + N^{(14)} \rightarrow NO^{(30)} + H^{(1)}
\]

(5)

where the chemical reaction rates are predicted by combined Eddy Breakup - Arrhenius model, where the prompt-NO is formed at temperatures lower than 1800 K. The complete mechanism is not straightforward. However, De Soete proposed a single reaction rate to describe the NO source by Fennimore mechanism, which is used at this work, and the combined Eddy Breakup - Arrhenius model are used for predict this chemical reaction rate.

Scalar transport equations are solved for velocity, pressure, temperature and chemical species. The bulk motion of the fluid is modeled using single velocity, pressure, temperature, chemical species and turbulence fields (CFX Inc., 2004).

2.1. Mass and species conservation

Each component has its own Reynolds-Averaged equation for mass conservation which, considering incompressible and stationary flow can be written in tensor notation as:
\[
\frac{\partial \langle \rho_i U_j \rangle}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \langle \rho_i (\dot{U}_j - \bar{U}_j) \rangle \right) + S_i
\]

(10)

where \( \dot{U}_j = \sum (\rho_i U_j) / \rho \). \( \rho \) and \( \bar{\rho} \) are the mass-average density of fluid component \( i \) in the mixture and average density, respectively, \( x \) is the spatial coordinate, \( \dot{U} \) is the vector of velocity and \( \bar{U}_j \) is the mass-averaged velocity of fluid component \( i \). The term \( \langle \rho_i (\dot{U}_j - \bar{U}_j) \rangle \) represents the relative mass flow, and \( S_i \) is the source term for component \( i \) which includes the effects of chemical reactions. Note that if all the equations represented by Eq. (10) are added over all components, and the source term is set to zero, the result is the standard continuity equation.

The relative mass flow term accounts for differential motion of the individual components. At this work, this term is modeled for the relative motion of the mixture components and the primary effect is that of concentration gradient. Therefore,

\[
\rho_i \langle \dot{U}_j - U_j \rangle = \frac{\rho D_i}{\bar{\rho}} \frac{\partial \rho_i}{\partial x_j}
\]

(11)

where \( D_i \) is the kinetic diffusivity. The mass fraction of component \( i \) is defined as \( \dot{Y}_i = \rho_i / \rho \).

Substituting this expressions into Eq. (9) and modeling the turbulent scalar flows using the eddy dissipation assumption it follows that

\[
\frac{\partial}{\partial x_j} \left( \rho \dot{U}_j Y_i \right) = \frac{\partial}{\partial x_j} \left( \rho D_i \left[ \frac{\mu}{Sc_i} \dot{Y}_i \right] \right) + S_i
\]

(12)

where \( \mu_i \) is the turbulent viscosity and \( Sc_i \) is the turbulent Schmidt number. Note that the sum of component mass fractions over all components is equal to one.

2.2. Momentum conservation

For the fluid flow the momentum conservation equations are given by:

\[
\frac{\partial}{\partial x_j} \left( \rho \dot{U}_j U_j \right) = -\frac{\partial p^*}{\partial x_j} - \frac{\partial}{\partial x_j} \left( \mu_{eff} \frac{\partial \dot{U}_i}{\partial x_j} \right) + \frac{\partial \dot{U}_i}{\partial x_j} \delta_{ij} + S_{\dot{U}}
\]

(13)

where \( \mu_{eff} = \mu + \mu_i \), and \( \mu \) is the mixture dynamic viscosity and \( \mu_i \) is the turbulent viscosity, defined as \( \mu_i = C_p \rho k / \epsilon \). The term \( p^* = p - (2/3)k \) is the modified pressure, \( C_p \) is an empirical constant of the turbulence model and equal to 0.09. \( p \) is the time-averaged pressure of the gaseous mixture, and \( \delta \) is the Krönecker delta function. \( S_{\dot{U}} \) is the source term, introduced to model the buoyancy and drag force due to the transportation particles, and other mathematical terms due to turbulence models.
The Boussinesq model is used to represent the buoyancy force due to density variations. The k-ω model are used to provide the turbulence on the flow (Menter, 1994).

2.3. Energy conservation

Considering the transport of energy due to the diffusion of each chemical species, the energy equation can be written as

\[
\frac{\partial}{\partial x_j} \left( \rho U_j \dot{h} \right) = \frac{\partial}{\partial x_j} \left( \frac{k}{\epsilon} \frac{\partial h}{\partial x_j} \right) + \sum_i \rho D_i \frac{\partial \dot{Y}_i}{\partial x_j} + \frac{\mu_t}{\epsilon} \frac{\partial \dot{h}}{\partial x_j} + \overline{S_{rad}} + \overline{S_{rea}} \tag{14}
\]

where \( \dot{h} \) and \( c_p \) are the average enthalpy and specific heat of the mixture. The latter is given by \( c_p = \sum_a \dot{Y}_a c_{p,a} \), where \( c_{p,a} \) and \( \dot{Y}_a \) are the specific heat and the average mass fraction of the \( \alpha \)-th chemical species, \( \kappa \) is the thermal conductivity of the mixture, \( \mu_t \) is the turbulent Prandtl number, and \( \overline{S_{rad}} \) and \( \overline{S_{rea}} \) represent the sources of thermal energy due to the radiative transfer and to the chemical reactions. The term \( \overline{S_{rea}} \) can be written as:

\[
\overline{S_{rea}} = \sum_a \left[ \frac{\dot{h}_a^0}{MM_a} + \int_{\bar{T}_{ref,a}} \frac{c_{p,a}}{\bar{T}} d\bar{T} \right] R_a \tag{15}
\]

where \( \bar{T} \) is the average temperature of the mixture, \( \dot{h}_a^0 \) and \( \bar{T}_{ref,a} \) are the formation enthalpy and the reference temperature of the \( \alpha \)-th chemical species. To complete the model, the density of mixture can be obtained from the ideal gas state equation (Kuo, 1996; Turns, 2000),

\[ \rho = \rho \overline{MM} \left( \frac{\bar{T}}{\bar{R}} \right)^{-1}, \]

where \( \rho_p \) is the combustion chamber operational pressure, which is here set equal to 1 atm, and \( \overline{MM} \) is the mixture molecular mass. The aforementioned equations are valid only in the turbulent core, where \( \mu \gg \mu_t \). Close to the wall, the logarithmic law of the wall is used.

To consider thermal radiation exchanges inside the combustion chamber, the Discrete Transfer Radiation Model - DTRM is employed (Carvalho et al., 1991), considering that the scattering is isotropic. The effect of the wavelength dependence is not considered, and the gas absorption coefficient is considered uniform inside the combustion chamber and its value is 0.5 m\(^{-1}\). The radiative properties required for an entrained particle phase are the absorption coefficients and scattering phase function, which depend on the particle concentration, size distribution, and effective complex refractive indices. However, optical properties of coal are not well characterized (Eaton et al., 1999). Generally, as a starting point to arrive at a tractable method for calculating radiative properties, the particles are assumed to be spherical and homogeneous. At this work, the heat transfer from gas mixture to particle considers that the particles are opaque bodies with emissivity equal to one, and the Hanz-Marshall correlation is used to model the heat transfer coupling between the gas mixture flow and the particles (CFX Inc., 2004). 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 (Xu et al., 2000). Conversely, heat transfer in the tube banks, which were
simulated 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 were also modeled assigning quadratic directional loss coefficients to the porous media, computed from the tube bank geometry data (Knudsen et al., 1958).

2.4. The E-A (Eddy Breakup – Arrhenius) chemical reactions model

The reduced chemical reactions model employed in this work assumes finite rate reactions and a steady state turbulent process to volatiles combustion. In addition, it is considered that the combined pre-mixed and non-premixed oxidation occurs in two global chemical reaction steps, and involving only six species: O₂, CH₄, N₂, H₂O, CO₂ and CO and NOx. A conservation equation is required for each species but nitrogen. Thus, one has the conservation equation for the α-th chemical species, given by Eq. (12), where the source term, Sᵢ, considers the average volumetric rate of formation or destruction of the α-th chemical species at all chemical reactions. This term is computed from the summation of the volumetric rates of formation or destruction in all the k-th equations where the α-th species is present, \( R_{αk} \). Thus, \( \bar{R}_α = \sum_k R_{αk} \). The rate of formation or destruction, \( R_{αk} \), was obtained from a combined Arrhenius-Magnussen model, the EBU-Arrhenius (Eaton et al., 1999). Such relations are appropriate for a wide range of applications, for instance, laminar or turbulent chemical reactions with or without pre-mixing. Such, the rate of formation or destruction of the chemical species is taken as the lowest one between the values obtained from each model. It follows that Silva et al. (2007) used this formulation in this work to simulate the combustion process of methane and air in a cylindrical chamber obtaining good results.

2.5 The coal decomposition

Pulverized coal particles are treated at this work as non-interacting spheres with internal reactions and heat transfer and full coupling of mass, momentum and energy with the gaseous phase. The combustion of coal particles is a two stage process: the devolatilisation of raw coal particle followed by oxidation of residual char to leave incombustible ash. The devolatilisation was modeled with two competing reactions (see Fig. 1) 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. (2003). The model adopted for the char burn out computes the rate of the reaction taking into account the rate of diffusion of oxygen within the pores of the char particle and its partial pressure at the particle surface (Kanury, 1975). Particle size plays an important role in the char combustion process and is usually modeled by a statistical distribution like the one developed by Rosin-Rammler (Brown, 1995), with the parameters adjusted from pulverized coal analysis.

![Diagram of coal decomposition](image)
2.5.1 The coal devolatilisation model

The devolatilisation of the coal is modeled using the generic Arrhenius reactions capability in two steps (Ubbayakar et al., 1976) in which two reactions with different rate parameters and volatiles yields compete to pyrolyse the raw coal. The first reaction dominates at lower particle temperatures and has a yield $Y_1$ lower than the yield $Y_2$ of the second reaction which dominates at higher temperatures. As a result, the final yields of volatiles will depend on the temperature history of the particle, and will increase with temperature, lying somewhere between $Y_1$ and $Y_2$. In this model, the mass fraction of the raw coal is specified as the mass fraction of volatiles (here methane and carbon monoxide, see Fig. 1) since all this material could be converted to volatiles.

At time $t$, it is assumed that a coal particle consist of mass of raw coal ($OC$), mass of residual char ($chC$) after devolatilisation has occurred, and mass of ash ($A$). The rate constants $k_1$ and $k_2$ of two reactions determine the rate of conversion of the raw coal:

$$\frac{dC_o}{dt} = -(k_1 + k_2)C_o$$

the rate of volatiles production and the rate of char formation is, respectively, given by

$$\frac{dV}{dt} = (Y_1k_1 + Y_2k_2)C_o$$

$$\frac{dC_{ch}}{dt} = ((1-Y_1)k_1 + (1-Y_2)k_2)C_o$$

2.5.2 The field char oxidation model

The oxygen diffusion rate is given by $k_s(p_e - p_s)$, where $p_e$ is the partial pressure of oxygen in the furnace gases far from particle boundary layer and $p_s$ is the oxygen pressure at the particle surface. The value of $k_s$ is given by $k_s = D_{ref} R_p \left( \frac{T_p - \tilde{T_s} \left(2T_{ref}\right)^2}{p_A} \right)^\alpha / \bar{p}$, where $R_p$ is the particle radius, $T_p$ is the particle temperature, $\tilde{T_s}$ is the far-field gas temperature, $p_A$ is atmospheric pressure, $D_{ref}$ is the dynamic diffusivity, and $\alpha$ is the exponent with value 0.75. The char oxidation rate per unit area of particle surface is given by $k_c p_s$. The chemical rate coefficient is given by, $k_c = A \exp\left(-\frac{T_c}{T_f}\right)$, where the parameters $A$ and $T_c$ depends on the type of coal. The overall char reaction rate of a particle is given by $(k_{ch}^{-1} + k_c^{-1})^{-1} C_o A d R_e^2 \bar{p} / p_A$, and is controlled by the smallest of the two rates, $k_c$ and $k_{ch}$.

3. BOILER DESCRIPTION

The boiler under consideration is part of a pulverized coal (PC) power plant operating in a subcritical steam cycle. The tangential firing combustion chamber is rectangular in shape with four
burners firing from each corner, thus creating a large vortex in the center of the chamber. The evaporation process occurs mainly in the steel tubes covering the boiler walls. In the upper middle of the boiler are the reheater (LTR, HTR), super-heater (LTS, HTS) and economizer (ECO2) tube banks. The second stage of the boiler comprises a large rectangular curved duct, the first economizer (ECO1) tube bank and the regenerative air heater (Ljungström). From there the flue gases are directed through the electrostatic precipitator to the chimney. Figure 2-a shows the general disposition of the boiler heat exchangers and burners. The primary and secondary air paths are also shown, departing from the fans (PAF, SAF) through the air heater and coal silos (only for the primary air) to the burners. The burner disposition at the corners is shown at Fig 2-b. They are aligned with the diagonal lines with a horizontal angular displacement in order to create a vortex in the flow.

![Diagram of boiler components]

Figure 2 - (a) General disposition of the boiler components; (b) Horizontal cross section.

4. MESH SETTINGS AND CONVERGENCE CRITERIA

The domain under consideration comprises the first stage of the boiler: the combustion chamber with the burners at the corners and the heat exchangers until the top. The entrance to the second stage was considered the outlet of the domain. The discretization was done using tetrahedral volumes, and the grid details are depicted in Fig. 3. Other type of mesh volumes were not used due to software license limitations. As the boiler height corresponds to only six equivalent diameters of the boiler, the boundary layer is not developed at the whole domain. Nevertheless, prismatic volumes were used at the walls in order to capture the boundary layer behavior. Due to computational limitations, the mesh size used has approximately $1.5 \times 10^6$ elements, using mesh refinements in the combustion reactions zone. The convergence criterion adopted was the RMS – root mean square of the residual values, and the value adopted was $1 \times 10^{-5}$ for all equations.
5. BOUNDARY CONDITIONS

The boundary conditions were obtained from the design data set and also from the daily operation data sheets. The operating conditions considered were the rated ones, for 160 MWe. The parameters of operations were considered for each benefited coal as follow, as well as the chemical composition of two beneficed coals is show in Tab. I. For booth cases was considered the same air excess and the same thermal charge.

Case I: Benefited coal CE3100 from Brazil

Inlet: The inlet conditions are those for air and coal flows entering the domain from the burner nozzles. Total primary and secondary combustion air and pulverized coal mass flow rates were set as 79.5 kg/s, 50 kg/s and 100 kg/s respectively. Temperatures of primary air and coal, and secondary combustion air were set as 542 K and 600 K respectively. Pulverized coal size was modeled by a probabilistic distribution and limited between 50 μm and 200 μm.

Case II: Benefited coal CE4500 from Brazil

Inlet: The inlet conditions are those for air and coal flows entering the domain from the burner nozzles. Total primary and secondary combustion air and pulverized coal mass flow rates were set as 27.19 kg/s, 85.15 kg/s and 36.5 kg/s, respectively, aim to consider the sensible heat of de inlet air and energy of inlet fuel flow, maintaining the same thermal charge of case I. Temperatures of primary air and coal, and secondary combustion air were set as 542 K and 600 K, respectively. Pulverized coal size was too modeled by a probabilistic distribution and limited between 50 μm and 200 μm.
Table I – Chemical composition of two beneficed coals.

<table>
<thead>
<tr>
<th>Coal Chemical Species</th>
<th>Case I: Coal CE 3100</th>
<th>Case II: Coal CE 4500</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Base</td>
<td>Wet Base</td>
</tr>
<tr>
<td>Char</td>
<td>33.21 %</td>
<td>27.74 %</td>
</tr>
<tr>
<td>Ash</td>
<td>54.78 %</td>
<td><strong>45.76 %</strong></td>
</tr>
<tr>
<td>Oxygen</td>
<td>7.92 %</td>
<td>6.62 %</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.34 %</td>
<td>1.95 %</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1.14 %</td>
<td>0.95 %</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.61 %</td>
<td>0.51 %</td>
</tr>
<tr>
<td>Humidity</td>
<td>0.00 %</td>
<td>16.47 %</td>
</tr>
</tbody>
</table>

For the two cases the outlet boundary condition to the flue gas was set as the mean static pressure with a value equal to -400 Pa. The same way, 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, outlet temperature and thermal radiation coefficients were set for that two wall regions. The wall emissivity was set 0.6 and all the others regions, as inlet and outlet regions, it were considered as blackbodies. The methodology employed in the present work has been tested and validated in Silva et al. (2010-a), presenting good agreement. In this work, the coal sulfur was considered inert on the combustion processes, and its mass fraction was sum on the ash mass fraction. Following the work, will be implemented a chemical reaction for this chemical species.

6. NUMERICAL METHOD

The flow fields inside the boiler (velocity, temperature, concentrations, etc.) were numerically determined with the commercial software Ansys CFX 11, based on the finite volume method (Patankar, 1980). The “power-law” scheme was selected for evaluating the fluxes at the control volume faces. The velocity-pressure coupling was solved by the SIMPLE algorithm (Patankar, 1980). Since the conservation equations are non-linear, relaxation factors were used.

7. RESULTS

Here the simulation results were analyzed and compared for both cases. The main available parameters were the temperature and mass fraction of some chemical species, as well as the stream lines and vectors field of the flow into the outlet. As mentioned, two cases were evaluated: coal combustion for CE3100 and CE4500. Figures 4 and 10 show the stream lines, vectors field, temperature field and the mass fraction field of CO, O2, N2 and NO into the boiler. The simulation results were analyzed and compared for both cases.

Figure 4 shows some stream lines of the flow for both cases, coal 3100 and 4500. It is possible to verify that the coal 4500 the swirl that occur under the burner lines is most compacted, if compared with the CE3100. This characteristic appears due to lower speeds used to the CE4500, as a consequence of the lower mass flow necessary to maintain the combustion process to this fuel, that as a higher energetic value e less quantities of ashes.
Figure 4 - Stream Lines: (a) CE3100; (b) CE4500.

Figure 5 shows the temperature field for a transversal vertical plane into the boiler to the coal CE3100 and the coal CE4500. It is possible to verify that the temperature field in this plane into the boiler are similar for both cases, and are too physically coherent. However, to burner process with the coal CE4500 the temperatures in upper region of the boiler are smaller if compared with CE3100. The lower velocities for CE4500 allow that the energy of flue gases to be better absorbed by heat exchangers above the combustion chamber, remaining a lower residual energy remaining in the flue gas at the top of the boiler. This shows better burn efficiency for this process using the CE4500 on this boiler.

The Fig. 6 shows the velocity vectors in a horizontal plane into the boiler under the temperature field in the two burner lines. The Figs. 6-a and 6-b show the temperature field in the first burners line for CE3100 and CE4500 respectively. The Figs. 6-c and 6-d show the temperature field in the last burners line for CE3100 and CE4500 respectively. It's possible to observe lower temperatures for CE3100 comparing with CE4500, tangent to central vortex, due to higher flow speeds in the CE3100 process, who increases the vortex speed preventing the atmospheric air injected in the burners to be totally directed into the burn region, decreasing the temperature and efficiency of the process with coal CE3100.
Figure 5 - Temperature field for a vertical plane into the boiler: (a) CE3100; (b) CE4500.
Figure 6 - Velocity vectors on plane temperature: (a) CE3100 first burner line, (b) CE4500 first burner line, (c) CE3100 last burner line, (d) CE4500 last burner line.

The Fig. 7 following show a comparison of the CO concentration fields in flue gases to the combustion process of pulverized coal for CE3100 and CE4500, on the same vertical transverse plane in the boiler shown in pervious figure. Observing the Fig. 7 it can note that for CE4500, which requires lower flow rates to maintain the thermal charge into the boiler and with that lowers velocities as a consequence, have been as a result a bigger residence time of fuel, here the char particles and also yours volatile, in the flame region of combustion chamber (region of burners), this area shows that the higher temperatures, like Fig. 5, thereby improving a fuel combustion. The Tab. II indicates more clearly the significant reduction of CO for the CE4500 compared with the CE3100, in the burning conditions used. Still, in Fig. 8, that presents the field of oxygen concentration in the same plane, as a consequence, it's possible to see that oxygen is almost totally consumed in both cases, being more intense the consumption for the process of burning CE4500. For the both cases, because of operating with excess of air, oxygen remains in the flue gas on the outlet region of the boiler.
In the Fig. 8 below presents comparison of the concentration fields to O₂ for the combustion process of pulverized coal: CE3100 and CE4500. Realize that the higher O₂ concentration occurs on jets input, as expected, because the pure atmospheric air used as a oxidant presents the higher concentrations of oxygen. However it appears that there is in the combustion process using the CE3100, a high concentration of O₂ over all the peripheral region of the central vortex core (see fig. 4), formed by the flow of flue gases inside the boiler, again as a consequence of higher speeds operated with CE3100 to maintain the flow and thermal charge required for the demand of steam generation, since the CE3100 has a lower heat value. For these velocities, the centrifugal forces produced by the drain ends up causing a barrier to the penetration of combustion air in this central vortex, and consequently the O₂, significantly affecting the rates of chemical reaction in the burning process. For the pulverized coal CE4500 the fuel flow rates are about 25% lower, to maintain the same thermal charge required in the steam generator and, thus, these centrifugal forces is also smaller.
The Fig. 9 following show a comparison of the concentration fields to N₂ for the two kind of coal, also on the same plane. For the combustion process using the pulverized coal CE4500, it appears that it is practically homogeneous the distribution of N₂ mass fraction inside the boiler, while for the combustion process using the pulverized coal CE3100 is a similar behavior obtained for O₂ concentrations, to the same reasons, i.e., the higher N₂ concentrations are in the outskirts of the central vortex formed by the flue gases.

The Fig. 10 shows a comparison of the NO concentration fields, on the same vertical transverse plane into the boiler. It appears that there isn’t the formation of this chemical species on the jets of the boiler input. At this work, only was included the “thermal” and “prompt” mechanisms for predict this pollutant formation, that require high temperatures and the presence of N₂ and O₂ for forming the NOx, and these conditions are not present in the inlet jet region. The fuel-NO will be implemented on the formulation at the sequence of this work. In other regions of the boiler, the NOx is present. However, in relation to the NOx concentration fields generated for two different coals on the combustion process, it was found a significant difference, as shown in Fig. 10. For the coal CE3100 there is a lower concentration of NOx and your distribution takes places more homogeneous at the top of the boiler, just above the region comprising the combustion chamber.
Figure 9 - Nitrogen mass fraction for a vertical plane into the boiler: (a) CE3100; (b) CE4500.
As practically not having the presence of $O_2$ inside the vortex, conditions for NOx formation in this region are less favorable. The high-speed flow moving to the periphery of the NOx formed over the region just above the burners. In the case of coal CE4500 due to lower speeds fuel and supply air, the NOx formed at the ends of the jets does not dissipate so severely, and is conducted in a more concentrated across central vertex formed by the flow of flue gases. Observing the Tab. II, it appears that the production of NOx using coal CE4500 is higher compared to CE3100, but this difference is not so significant, indicating no major problems for the burning of beneficiated coal CE4500. It also appears that the coal CE4500, for operating conditions evaluated, the most efficient in the combustion process in comparison with coal CE3100, because the mass fractions of methane ($CH_4$) and carbon monoxide (CO) decreased because of lower velocities in the inlet jets resulting in an increased residence time of coal particles in the region of turbulent flame.

Table II – Average mass fraction of the chemical species at the outlet flue gases.

<table>
<thead>
<tr>
<th></th>
<th>Coal CE 3100</th>
<th></th>
<th>Coal CE 4500</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute value</td>
<td>Relative</td>
<td>Absolute value</td>
</tr>
<tr>
<td>Temperature</td>
<td>724.85 K</td>
<td>583.529 K</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>2.7588x10^{-5} [kg/kg]</td>
<td>27.580 ppm</td>
<td>1.5920x10^{-6} [kg/kg]</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.220418 [kg/kg]</td>
<td>22.042 %</td>
<td>0.232534 [kg/kg]</td>
</tr>
<tr>
<td>$CH_4$</td>
<td>2.6563x10^{-7} [kg/kg]</td>
<td>0.265 ppm</td>
<td>6.19368x10^{-8} [kg/kg]</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>0.05403 [kg/kg]</td>
<td>5.403 %</td>
<td>0.0542986 [kg/kg]</td>
</tr>
<tr>
<td>N$_2$</td>
<td>0.695099 [kg/kg]</td>
<td>69.510 %</td>
<td>0.692457 [kg/kg]</td>
</tr>
<tr>
<td>NOx</td>
<td>4.6898x10^{-6} [kg/kg]</td>
<td>4.698 ppm</td>
<td>4.8812x10^{-6} [kg/kg]</td>
</tr>
<tr>
<td>$O_2$</td>
<td>0.0304151 [kg/kg]</td>
<td>3.041 %</td>
<td>0.020704 [kg/kg]</td>
</tr>
</tbody>
</table>
8. CONCLUSIONS

Based on the study realized on this work, it’s appears that the coal CE4500, for operating conditions evaluated, was the most efficient in the combustion process in comparison with coal CE3100. These results were found due to the benefited pulverized coal CE4500 to have a higher heat value if compared with the CE3100, and, besides, also a smaller percentage of ash thereby facilitating the combustion processes, thus making most efficient the burns of CE4500 on this case.

9. ACKNOWLEDGEMENTS

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10. REFERENCES


11. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.