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Numerical Investigation of Oxy-Mild Combustion of Pulverized Coal in a Pilot Furnace

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Abstract

The Conventional coal-fired plants are large contributors to air pollution and greenhouse gas. The combustion generates pollutants such as oxides of sulphur, nitrogen, and carbon as well as fine organic and inorganic particulates. The new technologies able to reduce drastically the pollutant emissions and facilitate to use of coal in an environmentally more friendly way, are commonly known as clean coal technologies (CCT). In this context the CCS technologies play an important role to reduce the CO_2 emissions. The only form with truly zero CO_2 emissions in existence today is pre-combustion gas separation, namely, the combustion of fuel using oxygen instead of air. It is well known that burning pulverized coal in pure oxygen increases the flame temperatures, thus also increases NO_x emissions. Therefore, to moderate the flame temperature and reduce NO_x the oxygen is mixed with recycled flue gas (RFG). This approach to reduce CO_2 emissions is often called oxy-firing or oxy-fuel combustion. The purified CO_2 stream is then compressed and condensed to produce a manageable effluent of liquid CO_2, which can be sequestered for storage (CCS) or for use in subsequent processes (CCR). MILD (Moderate or Intensive Low Dilution) or HiTAC (High Temperature Air Combustion) is an innovative combustion technology and probably the most important achievement of the combustion technology in recent years. In MILD combustion the reactions take place in almost the whole volume of the combustion chamber. This leads to temperature and species concentration fields uniform in the chamber. The fuel is oxidized in an environment that contains a substantial amount of inert gases (N_2, CO_2, H_2O) and low oxygen concentrations. This is caused by an internal recirculation of combustion products generated by injecting preheated air jets into the combustion chamber with very high momentum, bringing the temperatures close to the combustion products temperature, reducing the NO_x emissions. Because both technologies allow reductions of pollutant emissions, the aim of this work is to demonstrate the advantages of a combination of these two combustion technologies in order to analyze the temperature and specie concentrations field, the CO_2 and NO_x emissions by means of CFD. The goal is understand if it is possible to combine the MILD combustion and OXY one in order to reduce the NO_x emissions, and capture the CO_2.

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1. Introduction

In the recent years, the energy and environmental issues have become of primary importance. The environmental issues are linked both the pollutant emissions, such as nitrogen oxide (NO_x), sulfur oxide (SO_x), and GreenHouse Gas (GHG) emissions, which are responsible of the climate change. Since the coal probably will become the predominant fuel for the world [1] the efforts of the research teams to find new combustion technology in order to decrease both pollutant and greenhouse gas emissions are very significant. Combustion technologies which use preheated air above the 1000 °C is well known as HiTAC. This technology has demonstrated excellent contribution in term of reduction of nitrogen emission. The oxy fuel technology, instead, is different from the previous. It uses pure oxygen for the combustion, in order to produce a CO_2 – enriched flue gas. This condition allows to sequestrate the CO_2 once the water is condensed. Another advantage is the reduction of NO_x emissions linked to the low temperature in the combustion process. The aim of this work is understand what happened if the two technologies are combined. The literature provides several experimental and numerical works about the HiTAC and oxy-fuel combustion. Schaffel et al [2] performed numerical simulation on a pilot furnace. He et al. [3] conducted numerical studies of MILD combustion based on the Suda's experiments [4]. The study of the effect of CO_2 concentrations on the NO_x emissions in coal combustion recycled CO_2 is performed by Okazaki and Ando [5]. The characteristics of MILD and oxy-combustion have been investigated in a laboratory-scale furnace using natural gas by Pengfei Li et al [6].

The main goal of this paper is to provide a preliminary study of the mild-oxy combustion of pulverized coal. Clearly, the operating condition that can be utilized are wide. For this reason, the author focuses the numerical simulations on a single operating condition. It is expected that, the oxygen injected into combustion chamber at high momentum, generates an internal recirculation of flue gases in order to obtain the mild condition and at same time produce a lot amount of CO_2. Although the mild combustion is already a technology friendly environment, it is expected that the combination of these two technologies could further reduce the nitric oxide emissions.

Acronyms

CPD	Chemical Percolation Devolatilization
EDM	Eddy Dissipation Model
MILD	Moderate or Intensive Low Dilution
HiTAC	High Temperature Air Combustion
NMR	Nuclear Magnetic Resonance
IFRF	International Flame Research Foundation
RANS	Reynolds Avarage Navier Stokes
CFD	Computational Fluid Dynamics
RTE	Radiation Transfer Equation
SIMPLE	Semi-Implicit Method For Pressure-Linked Equations
PRESTO	PREssure STaggering Option
CCT	Coal Capture Technologies
RFG	Recycled Flue Gas
CCS	Carbon Capture and Storage
CCR	Carbonation Calcination Reaction

2. Mathematical Model

In this work several sub models have been considered to predict in the correct way the termo-fluid dynamics field of the combustion process. These models concern the gas phase and the coal particles. The gas phase has been described by steady state partial differential equations for mass, momentum energy and species, while the trajectories of pulverized coal particles are solved in a Lagrangian reference frame by integrating the force balance on the particles.

First of all, sub routines are employed to describe the coal combustion. It is mainly based on these four processes: heating, drying, devolatilization and char combustion. The coal used is a high bituminous A coal and the numerical simulations have been performed on the furnace of IFRF [7]. The proximate and ultimate analysis of coal can be found in the work of Schaffel et al. [2]. The CPD model has been considered for the devolatilization model. A non-linear correlation allows to obtain the five parameters for the CPD model [8]. The standard CPD model implemented in Fluent provides only the devolatilization rate. The char combustion is modelled by the Intrinsic model [9], which allows to obtain the rate of char oxidation. The intrinsic model is based on the Smith's work [10] and the input parameters for the Guasare coal are given by Schaffel work [2].

In this study, it has been considered two homogenous reactions, for the oxidation of the volatile species and oxidation of carbon dioxide, and one heterogeneous reaction for the char combustion. Clearly, the rate of char combustion is provided by the Intrinsic model, while the combustion of gas species is governing by the interaction between the turbulence and chemistry. The EDM (Eddy Dissipation Model) [11] has been chosen for the turbulence chemistry-interaction in order to determine the rate of two homogenous reactions. It depends on the k and ε values provided by the k- ε model [12] used in this work for the turbulence model to close the RANS equations. The thermal radiation is computed by solving the heat transfer equation (RTE). To solve this equation several models are provided by the CFD code. In this work, the P1 radiation model has been chosen. The trajectory of the pulverized coal particles is predicted in a Lagrangian reference frame by means the integration of the force balance on the particle. It can be assumed that there are four different mechanism of the formation of NO_x: the thermal, the prompt, by means N_2O and the fuel NO_x. In this work the extend Zeldovich mechanism [9] have been used for the thermal NO_x. The concentrations of O-radical and OH-radical are calculated using partial equilibrium approach [13]. It is assumed that all fuel nitrogen, both volatiles and char, is converted into HCN. The HCN release and depletion rates are given by De Soete expressions [14]. The prompt nitrogen oxide is modelled according to the De Soete [14] chemical reaction rate. It is often assumed that N_2O is at quasi-steady state. Furthermore, It has been considered the reburning in gas phase, following the Chen works [15], and the reburning on char particles following the Levy one [16].

3. Numerical Simulations of Mild and Oxy-Mild Combustion

The furnace has square cross-section of 2X2 m for an internal length of 6.25m. Further details of the geometry and experimental results can be found in several works [2-13]. The computational domain has been discretized by 700000 structured cells as shown in the Figure 1. A grid sensitivity analysis has been performed by considering two grids: 700000 and 1200000 cells has been tested. The test has shown results very similar and the smaller grid presents a number of cells enough to consider the problem mesh-independence [2]. The grid is finer in the region near the coal and air jet.

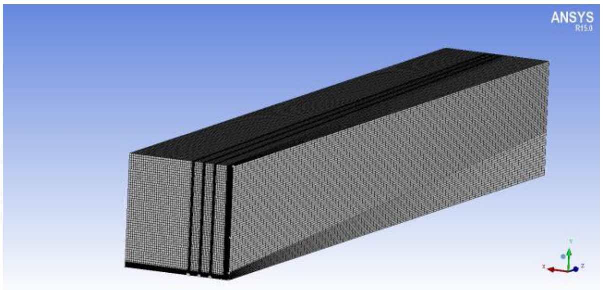


Fig. 1. Geometry and computational grid of a quarter furnace

The mass, momentum and energy conservation equations are solved using the finite volume technique. The CFD code ANSYS® FLUENT, rel. 15.0 is used to perform the numerical simulations. Because the flow developed in the combustion chamber is at low speed and incompressible ($M < 0.3$), the pressure-based approach is used to solve the governing equations. In this work, two cases have been considered. The first case is focused on the mild-coal combustion in furnace, while the second one on the oxy-mild combustion of coal. Oxy combustion because the second jet is a mixture of oxygen and carbon dioxide. Mild because the oxygen is injected at high temperature with high momentum. Thus, the goal is the combination of advantages of mild and oxy combustion, reducing the NO_x emissions and at the same time allowing the capture of CO_2. In the both cases the burner works with a stoichiometric ratio of $\lambda = 1.2$. To get this condition it has been important to keep the same oxygen mass flow in both cases. In other words, all simulations have been performed maintaining the same oxygen excess in the air jet. In the Table 1 and Table 2 are summarized the boundary conditions for both cases and for the two inlets. The fuel thermal input is 580 kW, while the comburent thermal input is 300 kW. Thus, the total thermal input is 880 kW for the case 1. For the case 2, the comburent thermal input is about 390 kW.

Table 1. Boundary conditions for the secondary inlet

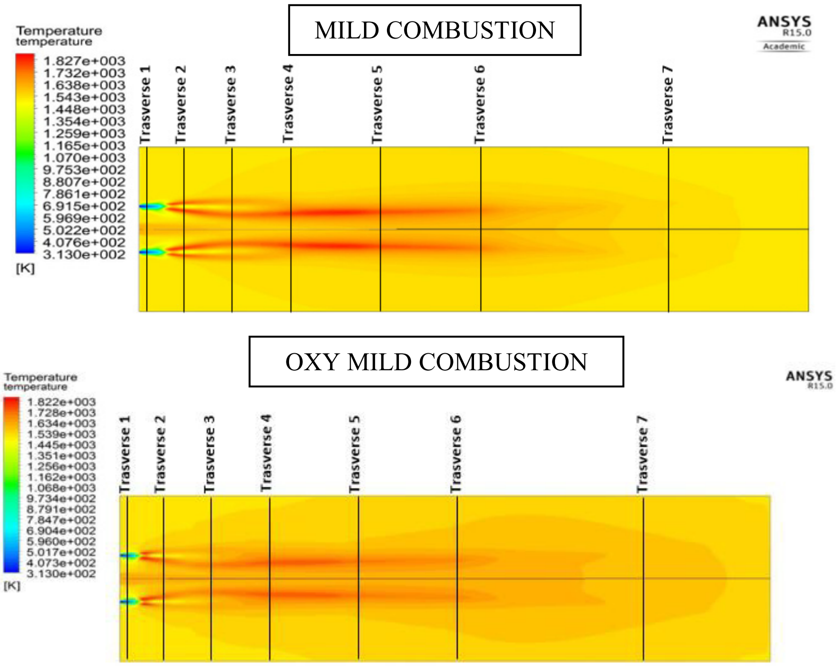
	Mass Flow rate [kg/h]	Coal Mass Flow [kg/h]	T [K]	Composition (vol%)	Oxygen Mass Flow [kg/h]
Case 1	675	66	1623.15	CO_2 8.1%, O_2 19.7%, N_2 57.2%, H_2O 15.1%, NO ppm (dry)	138.5
Case 2	675	66	1623.15	O_2% 19, CO_2 81%	138.5

Table 2. Boundary conditions for the primary inlet

	Mass Flow rate [kg/h]	T [K]	Composition (vol%)
Case 1	130	313.15	O_2 21%, N_2 79%
Case 2	130	313.15	O_2 21%, N_2 79%

4. Results and Discussion

In this section will be shown the results for the cases analyzed in term of temperature, specie concentrations and NO_x pollutant emissions. The Fig. 2 (a) shows the contour plot on the symmetry section of temperature for the two cases, while the Fig. 2 (b) shows the comparison for the temperature along the six radial trasverses. The trasverses have been considered at the following distances from the burner: 0.15 m, 0.44 m, 0.735 m, 1.32 m, 2.05 m, 3.22 m. The base case (only mild) is in agreement with the experimental results measured by Orsino et al. [7] and provided by several works [2-13]. The temperature level and the peak of temperature are very similar in both cases. The peak temperature occurs from the second transverse until the fourth one and it assumes the value around 1800 K for the first case and 1700 K for the second one. For the fourth and fifth trasverse the level and peak of temperature is slightly overestimated respect to the experimental results. It expected that from the fourth trasverse downwards the level temperature keep flat, but evidently the numerical simulations overestimate the results. It is worth noting that the oxy mild combustion provides a temperature level lower than the only mild combustion. This is due to the specific heat of CO_2 is higher than N_2 when the temperature is around the typical flame temperature. This condition affects the production of Thermal NO_x , but It is well known that in coal combustion they represent a little percentage of the total NO_x, but either way it is important take in account in order to obtain very low NOx emissions.


MILD COMBUSTION
Temperature
temperature
1.827e+003
1.732e+003
1.638e+003
1.543e+003
1.448e+003
1.354e+003
1.259e+003
1.165e+003
1.070e+003
9.753e+002
8.807e+002
7.861e+002
6.915e+002
5.969e+002
5.022e+002
4.076e+002
3.130e+002
[K]
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Trasverse 2
Trasverse 3
Trasverse 4
Trasverse 5
Trasverse 6
Trasverse 7
ANSYS
R15.0
Academic
OXY MILD COMBUSTION
Temperature
temperature
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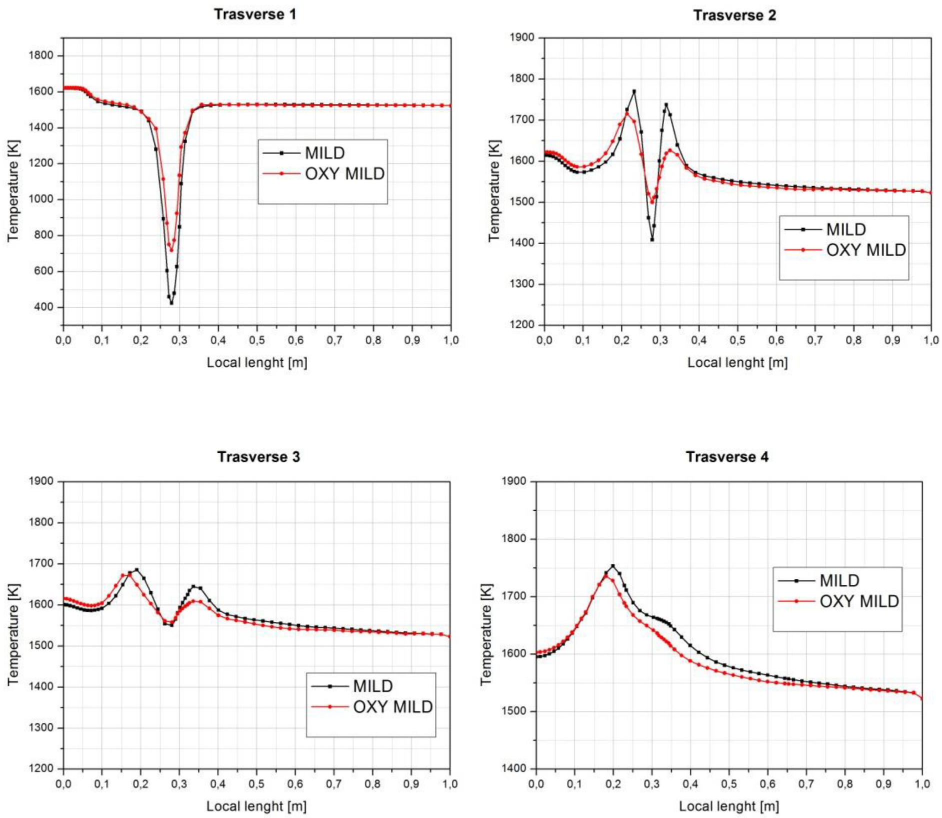
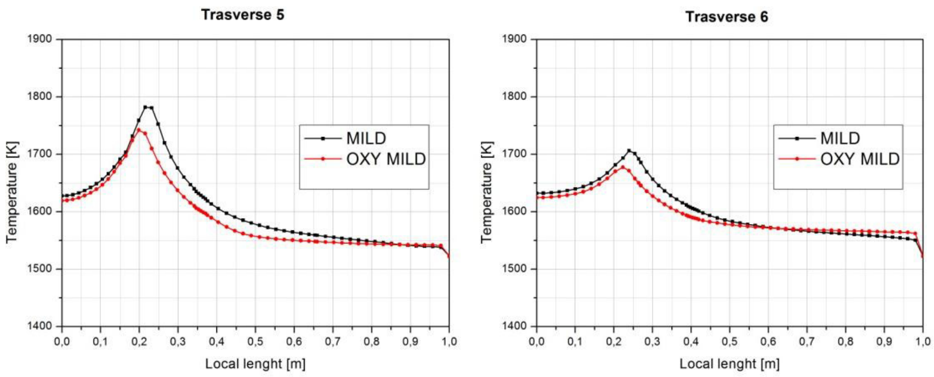
1.728e+003
1.634e+003
1.539e+003
1.445e+003
1.351e+003
1.256e+003
1.162e+003
1.068e+003
9.734e+002
8.791e+002
7.847e+002
6.904e+002
5.960e+002
5.017e+002
4.073e+002
3.130e+002
[K]
Trasverse 1
Trasverse 2
Trasverse 3
Trasverse 4
Trasverse 5
Trasverse 6
Trasverse 7
ANSYS
R15.0

(a)

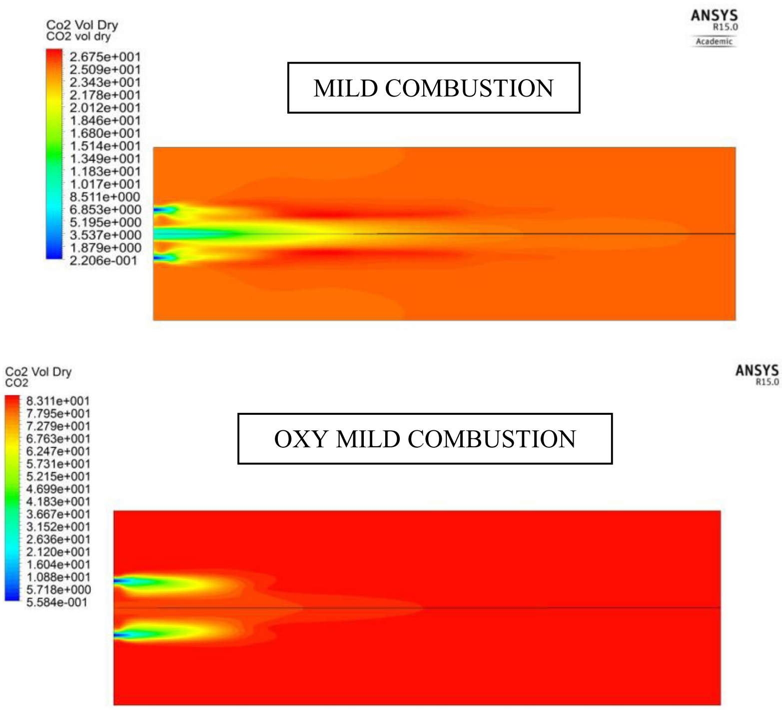

Trasverse 1
Temperature [K]
Local lenght [m]
MILD
OXY MILD
Trasverse 2
Temperature [K]
Local lenght [m]
MILD
OXY MILD
Trasverse 3
Temperature [K]
Local lenght [m]
MILD
OXY MILD
Trasverse 4
Temperature [K]
Local lenght [m]
MILD
OXY MILD



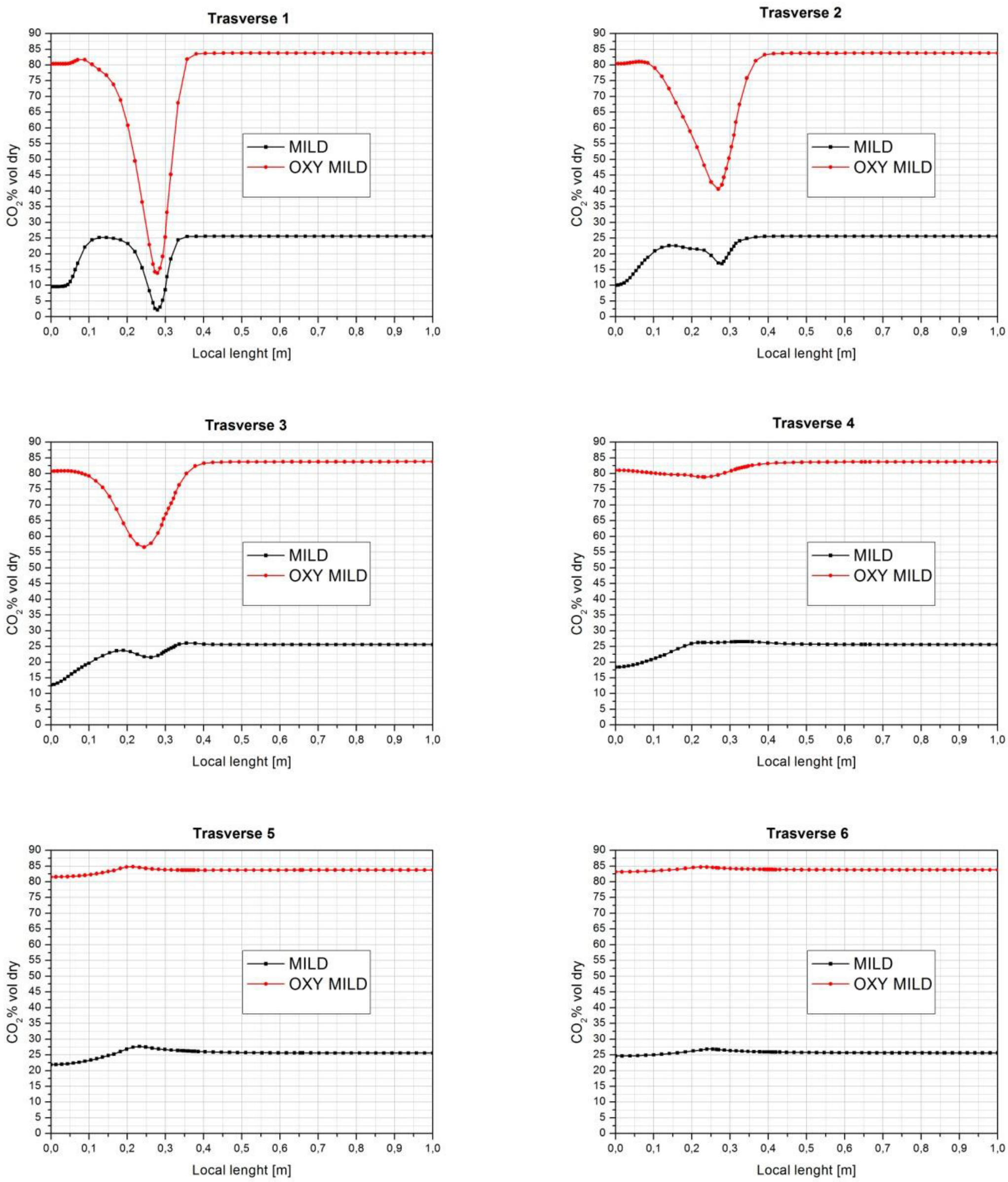
(b)

Fig. 2. (a) Contour plot of temperature for Mild and Oxy combustion; (b) Temperature profiles of numerical results for different trasverses.

The carbon dioxide contour plot is shown in the Fig. 3 (a), while the Fig. 3 (b) shows the carbon dioxide concentration profile along the seven trasverses. In this case, the difference is huge in term of values of concentration. Clearly, this is due to the oxy condition in the second case. The oxy mil combustion allows to fill the furnace with high level of carbon dioxide. This condition is very important because allows to capture in easy way the carbon dioxide. The percentage of carbon dioxide concentration at the outlet of furnace is between the 80% and 85%. The more value of CO_2 concentration is high and more it easy to capture it. Good values are above the 90%. To get this could be substituted the transport air with carbon dioxide, in order to eliminate the nitrogen in the combustion process.



(a)



(b)

Fig. 3. (a) Contour plot of carbon dioxide concentration for Mild and Oxy combustion; (b) Carbon dioxide concentration profiles of numerical results for different trasverses.

Another aspect that the author has analyzed is the formation of NO_x according to the model proposed. In the first case the NO_x emissions are due to all types of NO_x especially thermal and fuel. In the second one is mainly owing to the fuel NO_x. The second case shows lower values of NO_x rather than the first one, because the thermal NO_x are practically missing, and the fuel-NO_x are lower than the first case due to lower values of oxygen concentration-

Keep in mind that the fuel NO_x increase when the oxygen concentrations grows. In the Table 3 are given the numerical results of NO_x concentration at the furnace outlet.

Table 3. Computed values of NO_x concentration at the furnace outlet

Case	NO_x ppm dry	NO_x @6% O_2
1	323	272
2	270	222

5. Conclusions

In this study It has been performed a preliminary study on the potentiality about the oxy-mild combustion of pulverized coal. The idea of the author is to combine the advantages of two technologies in order to investigate the temperature, specie concentration profiles and the NO_x pollutant emissions in a pilot furnace. Sub routines have been used to model the combustion of coal. Specially, It has been examined the influence of a CO_2 dilution in the oxidizer respect to the standard case (only Mild combustion). The results show the advantages of oxy-mild combustion in term of NO_x emissions. This condition allows to understand how future works about this new technology can improve the efficiency of combustion process in order to obtain environmentally-friendly technologies. Anyway, the external recirculation of carbon dioxide needs to high electrical power, thus to avoid this lost efficiency in the system, the CO_2 can be used as a primary jet by transporting the coal. Probably, this condition could provides good results as well, with the advantage to reduce the electrical power for external recirculation. The author is working about the oxy mild combustion on the boilers in order to encourage the development of this technology for the electricity production with very low environmental impact.

Acknowledgements

I would like to thank my research advisor Prof. Mario Amelio for his precious guidance and support.

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