Ente per le Nuove tecnologie,
l'Energia e l'Ambiente

Ministero dello Sviluppo Economico

RICERCA SISTEMA ELETTRICO

MILD Combustion Simulation of Coal Water Slurry

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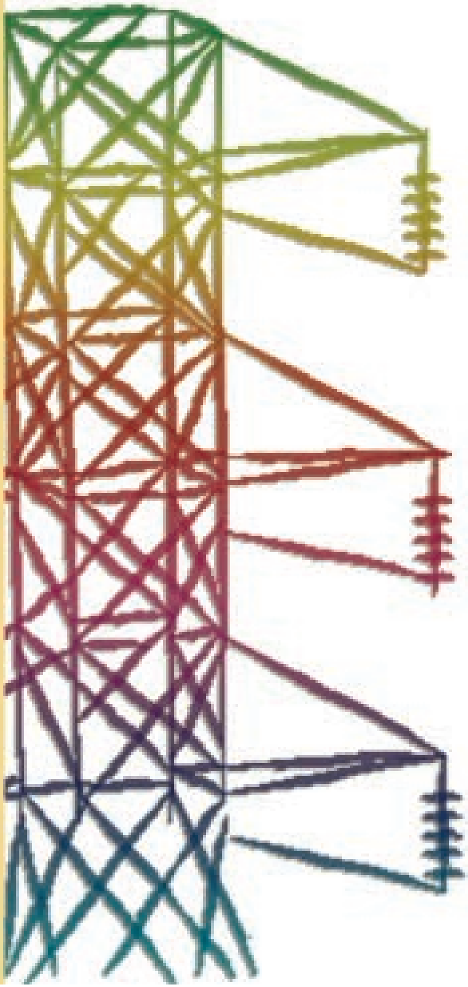

Report RSE/2009/93

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Aprile 2009

Report Ricerca Sistema Elettrico
Accordo di Programma Ministero dello Sviluppo Economico - ENEA
Area: Produzione e fonti energetiche
Tema: Tecnologie innovative per migliorare i rendimenti di conversione delle centrali a polverino di carbone - Sviluppo di un sistema di combustione di tipo "flameless" per impianti di produzione di elettricità con ridottissimi livelli di emissione di inquinanti e CO_2
Responsabile Tema: Stefano Giammartini, ENEA

Mild Combustion Simulation of Coal Water Slurry

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1. Introduction

In the combustor under study, the combination of fuel, generically waste, and oxygen makes it possible to reach high temperature of over 2000°C. This thermal fluid dynamic situation guarantees maximum efficiency and ensures complete destruction of dioxins and furans precursors, PAH and toxic matter introduced with waste, while the pressure provided ensures the supply of oxygen in all work conditions and in every point of reactor. The particular uniformity of the reaction conditions is strengthened by the recirculation of reaction gasses which, after being cooled, are recycled with oxygen and re-introduced in the reactor. The thermal content of flue gasses is then used for steam production. Since the working condition adopted, a flameless combustion could be present. In flameless oxidation mode, the feeding of oxidising air and fuel gas is performed separately with high injection velocities and this represents an extreme staging of combustion. The high temperature of the recirculated combustion products is used to initiate and maintain this mode of combustion. The flame can then no longer be seen and combustion is, for the most part, distributed throughout the volume of the combustion chamber. The relative homogeneity in temperature and in composition of the combustion chamber is a notable characteristic of the process. As a result of the reduction of temperature peaks in the flame, the mean temperature level of the furnace zone can be increased, reducing NOx, without leading to local overheating in the vicinity of the burners. The heat transfer to the product can thus be considerably increased. In addition, the noise level induced by the combustion is greatly reduced. Numerical simulations for different working condition have been executed, using coal water slurry as solid fuel, by mean of FLUENT® code (V6.3). Combustion has been modelled with the eddy dissipation concept model, while the P1 model has been adopted for radiative heat transfer. The k-ε realizable model has been chosen for turbulence.

2. Slurry particles physical modelling

In this type of combustion chamber fuel is introduced by mean of steam used as propellant at very high velocity and recirculated gasses enriched with oxygen are partially swirled. Solid fuel particles are simulated as a second discrete phase, added to the continuous phase. The trajectories, the mass and heat transfer, of these discrete phase are solved in a Lagrangian reference frame. So the strong coupling between discrete and continuous phases is taken into account: the physics of particles and gasses impact each other. Continuous phase turbulence determines instantaneous turbulent velocity fluctuations on the particle trajectories. The dispersion of particles due to turbulence in the fluid phase has been predicted using the stochastic tracking model: by computing the trajectory for a sufficient number of representative particles, the random effects of turbulence on the particle dispersion is accounted for. The equation of particle trajectory is written equating the acting forces, in a Lagrangian reference frame (for the x direction in Cartesian coordinates).

During its motion, slurry particle undergoes several phases: inert heating, water vaporization, coal devolatilization, char combustion.

The particle temperature is evaluated balancing the sensible heat change in the particle, the convective, radiative and latent heat transfer between the particle and the continuous phase.

Vaporization starts when the temperature of the particle reaches the vaporization temperature, T_{vap}, and continues until the particle reaches the boiling temperature, T_{bp}, or until the volatile fraction is completely consumed. The rate of vaporization is related to the gradient of the vapour concentration between the droplet surface and the bulk gas.

The convective boiling of the particle starts when the temperature has reached the boiling temperature, T_{bp}, and while the mass of the particle exceeds the non-volatile fraction.

While the particle boils, its temperature is assumed constant. The energy needed and the mass evaporated, appear as a negative source in the energy equation and a positive source in the transport equation for the specie considered, respectively

The volatiles release starts when the temperature of the particle reaches the devolatilization temperature and the water content is completely evaporated, and continues until the volatile fraction in consumed. The model used to calculate the rate of devolatilization is the single kinetic rate [1]. It assumes that the rate of devolatilization is first-order dependent on the amount of volatiles remaining in the particle.

After the volatile component is completely released, a surface reaction starts, following the stoichiometric requirement. When the combustible fraction is totally burned, the residual continue the heating or cooling process. The kinetic/diffusion-limited rate model assumes that the surface reaction rate is determined either by kinetics or by diffusion rate. Here, the model of Baum and Street [2] and Field [3], is applied: a diffusion rate coefficient and a kinetic rate are weighted to determine char combustion rate. Chemical reaction on the internal surface and pore diffusion are taken into account in the kinetic rate.

Due to slurry water content, the wet combustion option was used.

3. Continuous phase physical modelling

Particles and continuous phase history are obviously strongly coupled. Momentum exchange, heating of particles, evaporation, devolatilization and char combustion result in a positive/negative source for the equations of species involved, for energy equation and for momentum equations.

In the k-ε turbulence model [4, 5] two additional equation are solved, one for the turbulence kinetic energy (k) and one for its dissipation rate (ε). The first is an exact equation, while the second one is obtained using physical reasoning.

The turbulence-chemistry interaction model used is the the eddy-dissipation-concept model (EDC), which allows to use detailed kinetic schemes and is able to capture non equilibrium phenomena, such as ignition and blow-off.

The P-1 radiation model [7, 8] is the simplest case of the more general P-N model, which is based on the expansion of the radiation intensity I into an orthogonal series of spherical harmonics.

Radiative gas properties are modelled by the weighted-sum-of-gray-gases model (WSGGM) [9, 10]. Particles radiation interaction has been taken into account.

4. Simulations

The recirculated gasses are introduced into the cylindrical furnace (diameter 1 m, length 5 m) through an annular duct provided of swirling blades. At the centre there is the fuel duct, which is transported by water vapour used like propellant. Fuel is injected as particles of large dimensions and at high velocity, in the way to obtain a fine atomisation. We have not simulated slurry particle break-up, but we have imagined introducing them already atomised, with a Rosin-Rammler diameter distribution (min $d=1*10^{-6}$ m, mean $d=4.5*10^{-5}$ m, max d=3*10^{-4} m, spread parameter=1.36). Recirculated gasses mass flow rate is 2480 kg/h, at 511 K, with the following mass composition:

CO_2 61.74%-- H_2O 30.83%-- O_2 3.17%-- N_2 4.26%

The mass flow rate of oxygen added is 1100kg/h. Coal water slurry flow rate is 509.01 kg/h with 28% by volume of water. Water vapour mass flow rate is 180 kg/h. Coal type used in the simulations has 25.04% of volatiles, 54% of char and 15.7% of ash (dry) with a low calorific value of 23.76 MJ/kg, while the ultimate analysis is: 66.10% C, 4.80% H, 6% O, 1% N and 1% S. The devolatilization temperature is 773 K, while in the devolatilization model the pre-exponential factor and activation energy are 2*10^5 and 7.4*10^7 J/kgmol. In the kinetic/diffusion surface combustion model the mass diffusion limited rate constant is 5*10^{-12}, the kinetic limited rate pre-exponential factor is 6.7 and kinetics limited rate activation energy is 1.138*10^8 J/kgmol. The stoichiometric ratio for char combustion is 2.67 (mass of oxygen/mass of carbon). The kinetic scheme of Glarborg, made of 33 species involved in 150 reactions was applied.

Combustion chamber has been considered non-adiabatic, with a heat transfer coefficient of 9 W/m^2K and a refrigerant temperature of 343 K. The operating pressure is 4 bar.

Four CFD simulations have been executed:

1. Standard operation (boundary conditions above)
2. Bigger granulometry (mean d=1*10^{-4} m)
3. Higher recirculated gasses temperature (773 K)
4. Higher recirculated gasses mass flow rate and temperature (5083 kg/h and 773 K)

The first three cases examined are fairly similar regarding the flow pattern: we can see the formation of two vortices externally respect furnace axis. Because of fuel energetic mass flow, introduced at high velocity, it cannot be slowed down adequately by recirculation vortices formed by swirled oxidant (fig. 1a). Also maximum temperatures reached are the same, about 1800 K (fig. 2 a,b,c).

It is useful to remember that before volatiles release begin and, successively, char burns, particles water content must be evaporated. For case one, devolatilization happens between 0.6-0.7 m (fig. 3a) from inlet and successively burnout begins (fig. 4a), finishing at over one half of furnace. In the second case, the bigger particles size causes a wider devolatilization (fig. 3b) and a longer burnout (fig. 4b). For the third case, the higher inlet temperature determines a more rapid devolatilization and burnout, located between 0.25 and 0.65 m from inlet (fig. 3c, 4c).

In the last case the flow pattern is completely different (fig. 1d). The two vortices are located in the left corner of the furnace. The augmented swirled oxidant flow rate introduced has sufficient energy to slow down fuel flow. In this working conditions, oxygen concentration in the oxidant is not larger than 18% in mass, while in the previous tests it reaches 32%. For this reason, although sudden water evaporation and volatiles release (fig 3d), combustion is delayed and distributed in a wider zone (fig. 5) and temperatures level are much lower (1500 K, fig. 2d), looking like a mild combustion. In general, case 4 boundary conditions seam to guarantee the best performance in terms of flow field and therefore flame stability. Moreover, realize high temperatures in order to destruct probable pollutants, is not necessary in the case of coal water slurry. In the other three cases, in particular velocity field plays an unfavourable role.

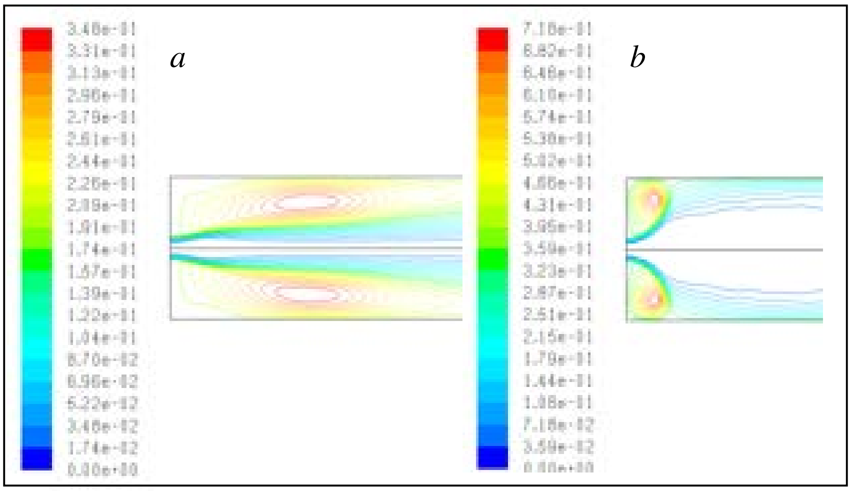

Fig. 1 Stream function (kg/s). a) Case 1, Case 2, Case 3, b) Case 4.

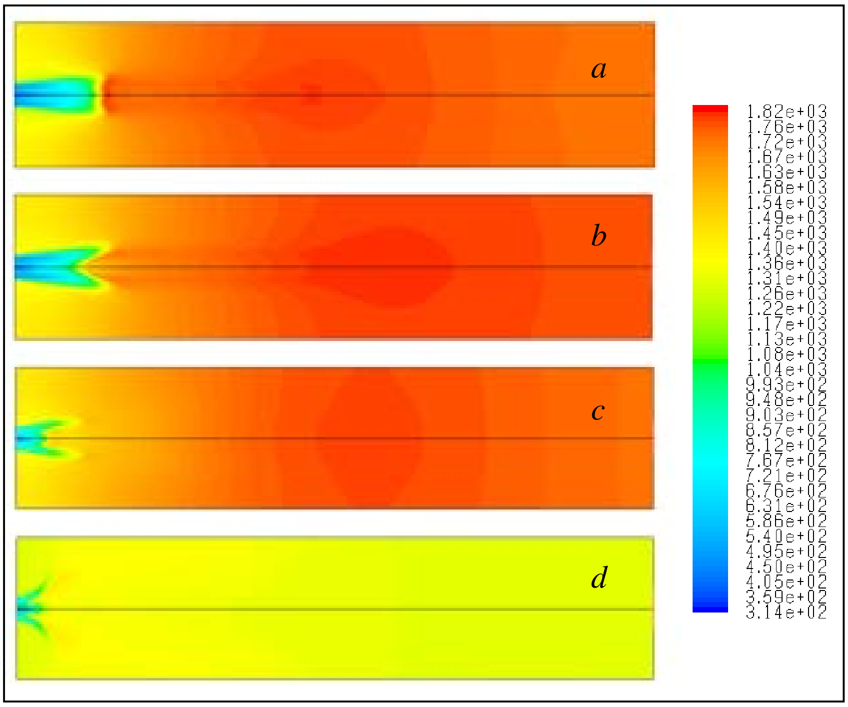

Fig. 2 Temperature (K). a) Case 1, b) Case 2, c) Case 3, d) Case 4.

5. Conclusions

We have shown some simulations on an industrial reactor for disposal of industrial and hazardous waste fed with slurry of pulverized coal. We have used a very simple chemical model but, despite this, the results of the simulations give us some important indications as, for instance, the fact that the presence of water influences in decisive way the combustion process and the thermal exchange. As we could expect, a larger recirculated flow at higher temperature, are favourable to mild combustion. We will study more detailed chemical models and the production of pollutants as, for example, nitrogen and sulphur oxides.

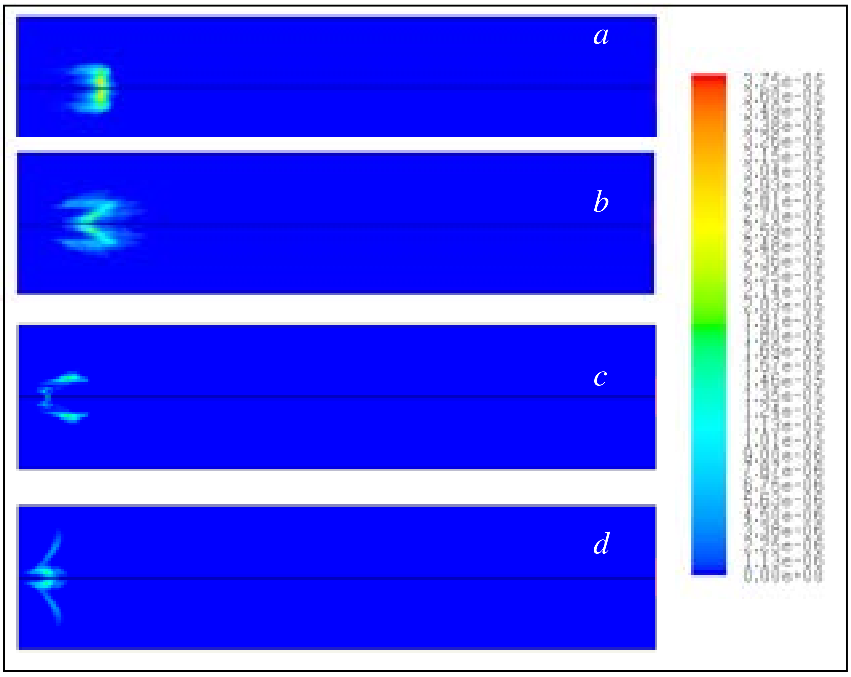

Fig. 3 Volatiles emission rate (kg/s). a) Case 1, b) Case 2, c) Case 3, d) Case 4.

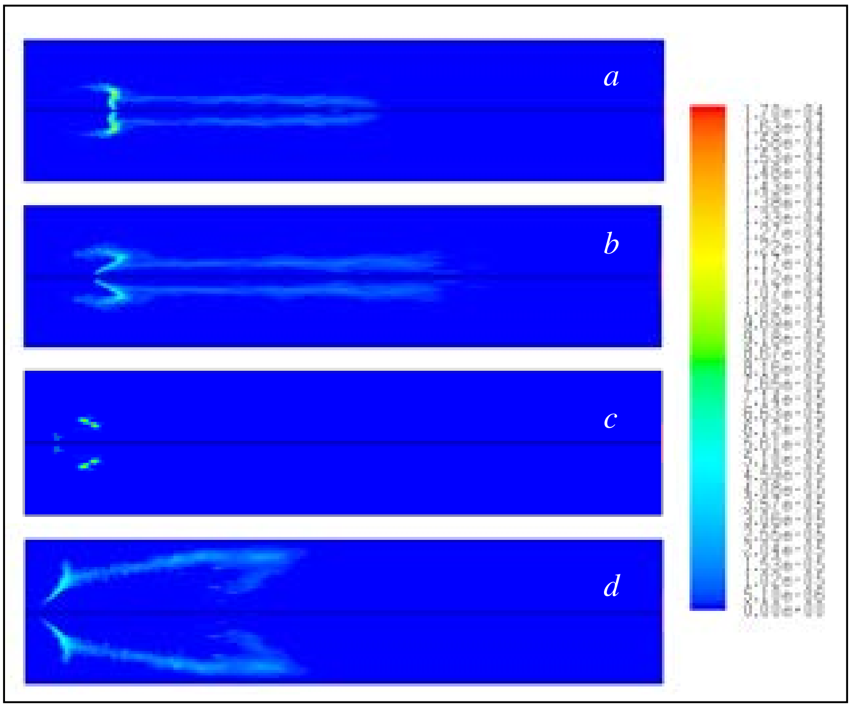

Fig. 4 Char combustion rate (kg/s). a) Case 1, b) Case 2, c) Case 3, d) Case 4.

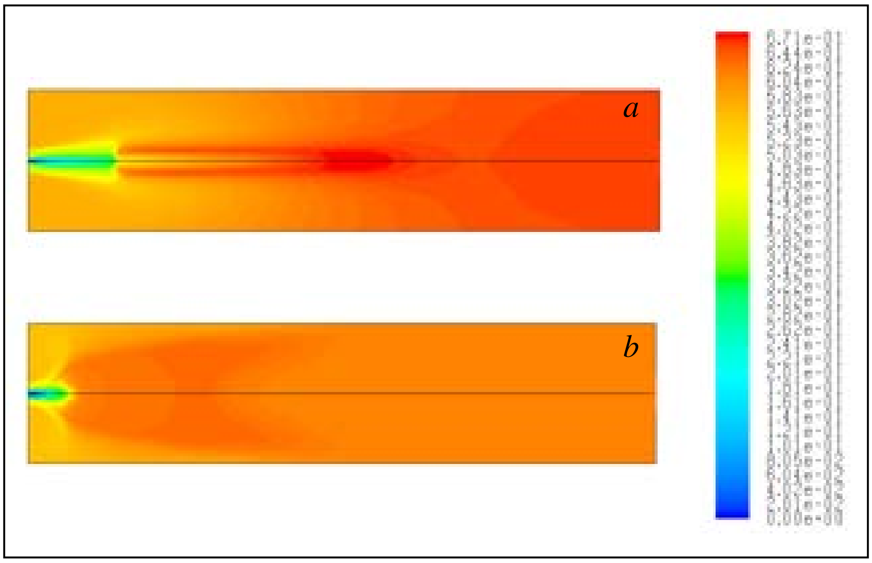

Fig. 5 CO2 mass fraction. a) Case 1, b) Case 4.

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