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A modeling approach to co-firing biomass/coal blends in pulverized coal utility boilers: Synergistic effects and emissions profiles

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ABSTRACT

Pulverized coal power plants in Chile are evaluating to reduce CO_2 emissions by co-firing coal with biomass, which is CO_2-neutral. A computational fluid dynamics model was used in this study to predict the performance of a 150 MW commercial boiler co-firing pulverized coal with pine sawdust. Synergistic effects were identified by burnout, thermal and hydrodynamic profiles. Co-firing was simulated with 5% of biomass substitution, and feeding in the first level of burners. The model was validated using data from the power plant. The results show an expected decrease in SO_2 emissions and a negligible reduction in heat transferred to the water tubes (0.6%). Biomass presence increased the burning rate of fuel particles, as shown by higher CO_2 emissions and a lower CO concentration, per unit of thermal power. The model reveals synergistic effects, proved by an increase in temperature, due to an early combustion of biomass particles, increase in the coal combustion rate, and a better temperature distribution in the boiler. These synergistic effects were compared with results obtained at bench scale reported in the literature. Thus, it was concluded that a relatively small replacement of coal by biomass could significantly improve the fuel combustion process and the boiler performance.

1. Introduction

The generation of electricity is the essential engine and the base for sustainable economic development of a country. Thus, low-cost power generation along with an independence from fossil fuels in its energy matrix would allow South American countries to reduce their fixed costs and offer the opportunity to enter into new markets. In recent years, Chile has made a great effort to include conventional and unconventional renewable energies in their energy matrix. However, the transition from conventional energy to renewable energy sources and clean technologies to generate energy independence from fossil fuels is slow, requiring regulations to introduce these technologies into the energy matrix [1]. In this context, Chile has recently approved a new legal regulation that demands the utilization of 10% of unconventional renewable energy in the thermoelectric sector [2].

As special feature, Chile accounts for more than 15 million hectares of native and forest plantations and an average yield of 20–40 m^3/ha/y [3]. Furthermore, at about 4 million of tonnes/year of woody residues (14,000 GWh/y) are produced from forestry activities. These residues can replace an important fraction (viz. 25%) of the internal coal demand for electricity production in coal-fired systems leading to a more sustainable energy matrix [3]. Therefore, there is an interesting opportunity to transform the installed generation units into systems capable to process biomass/coal blends, which will favor the reduction of fossil-derived emissions as well as the increment in the share of local resources used for energy production.

To achieve this goal, co-firing of coal with biomass has become a feasible alternative to existing pulverized coal power plants. However, extensive and costly field tests are frequently needed to analyze the performance in existing utility boilers, and the co-firing of coal with biomass may interfere with the normal operation of the power plant [4]. Numerical simulations may be used to study the co-firing process, predicting the behavior of the combustion process within the boiler, reducing the number of experimental tests by designing appropriate field tests, and establishing the

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Nomenclature

A	Pre-exponential constant [s^{-1}]
A_P	Particle area [m^2]
C_P	Specific heat [kJ kg^{-1} K^{-1}]
Do	Oxygen diffusion coefficient [m^2 s^{-1}]
E	Activation Energy [kJ $kmol^{-1}$]
d_P	Particle diameter [m]
d_e	Mean particle diameter [m]
h	Convective coefficient [W m^{-2} K^{-1}]
I	Radiation intensity [W sr^{-1}]
m_P	Mass particle [kg]
$m_{p,0}$	Initial mass particle [kg]
$m_{p,daf}$	Initial mass dry ash free particle [kg]
R	Surface kinetic rate [m^2 s^{-1}]
T_P	Particle temperature [K]
T_∞	Local temperature of the gas phase [K]
Y_i	Mass fraction of the i-species [kg kg^{-1}]

Greek symbols

ε_P	Absorption coefficient
Θ_R	Radiation temperature [K]
γ	Dispersion factor
σ	Stefan-Boltzmann constant (5.67×10^{-8} [W m^{-2} K^{-4}])

Abbreviations

BFG	Blast Furnace Gases
CEMS	Continuous Emission Monitoring System
CFD	Computational Fluid Dynamics
COG	Coke Oven Gas
CPD	Chemical Percolation Devolatilization model
DO	Discrete Ordinate radiation model
DPM	Discrete Phase Model
DTRM	Discrete Transfer Radiation Method
EDM	Eddy Dissipation Model
EDC	Eddy Dissipation Concept model
EPA	Environmental Protection Agency
FG	Functional Group devolatilization model
LHV	Lower Heating Value [kJ kg^{-1}]
PDF	Probability Density Function for transport species
PKE	Palm kernel extract
RANS	Reynolds Averaged Navier-Stokes (equations)
RNG	Renormalization Group model
RSM	Reynolds Stress Model
RTE	Radiative Transfer Equation
SST	Shear Stress Transport model
SIMPLE	Semi-implicit Method for Pressure-Linked Equations
TGA	Thermogravimetric Analysis
WSGGM	Weighted Sum of Gray Gases Model

optimum operating conditions. Among the different combustion technologies, integration of a biomass firing system into a pulverized coal boiler could be far more challenging than integration of a biomass firing system into a grate-fired boiler or a fluidized bed combustor because the burner aerodynamics and fuel properties have a much greater impact on combustion and the formation of pollutant emissions [5].

Computational fluid dynamics (CFD) has been applied successfully to study pulverized coal combustion and co-firing coal with biomass in different aspects, e.g., to study the effects produced in the performance of a low-NO_X multi-fuel burner by substituting the feed from coal to straw [6]. A significant number of CFD models have been developed for co-firing of coal with biomass but only a limited number of the CFD models have been applied on an industrial scale or have been validated by experimental tests in large power plants (See Table 1),. Some of these models have been used to study the influence of operational factors related to the biomass feeding conditions: mean particle size, substitution level of coal by biomass and feeding location in the furnace.

The main conclusions of the studies summarized in Table 1 are as follows: 1) A limit exists in the maximum biomass substitution level and particle size that can maintain a reasonable boiler efficiency [4]. Some authors show a maximum of 20% of mass substitution due to technical limitations [13], e.g. the milling capacity and power consumption. Pallarés et al. [4] propose to maintain the mill power consumption at optimum values for a cost-efficient combustion process. The mean diameter of the biomass particles must be in the range of 0.5–1 mm. 2) The mean particles size is the most influential factor in biomass combustion efficiency to obtain an adequate burnout. Low mean particles diameter (0.5–1 mm) increase the combustion rate and the temperature in the near burner region, requiring low residence time and obtaining higher combustion efficiencies than particles with mean diameters higher than 1 mm [4]. 3) Particles of biomass with larger diameters run the risk of reaching the hopper without being completely burned. Thus, it is desirable to feed these particles to the burners located at higher elevations [7]. In the case of small-diameter biomass particles, CFD simulation results show that if biomass is fed into the lowest level of burners, higher temperatures and heat fluxes to the walls are obtained, than when biomass is fed at higher levels [14]. 4) The operational parameters are unaffected by co-firing biomass at a low thermal loading [7]. However, the temperature at the furnace exit is slightly increased at a low thermal loading of biomass, so there is no expectation of intensification of slagging/fouling in the convective zone [7]. However, higher ratios biomass/coal than 20 wt% in the co-firing process could produce a decrease in the furnace exit temperature, thus enhancing the possibility of slagging/fouling [9]. 5) A decrease in SO_2 and NO_X emissions should be obtained because of the lower contents of sulfur and nitrogen in the biomass fuel. A reduced availability of nitrogen in the blend of course results in a fuel NO_X decrease [7]. 6) When biomass is incorporated into a co-fired burner, or when an existing low NO_X coal-fired burner is retrofitted with biomass, the air supply should be finely tuned. The air supply should be sufficient to ensure that the excess air will not reduce the flame temperature but will provide sufficient oxygen in zones where volatiles are released to promote the homogeneity and char combustion [15]. Normally, in pulverized coal combustion, an adequate air excess is normally between 15 and 20% [16].

These CFD models have been developed to study the macroscopic response of coal plants under co-firing conditions. However, limited information is available about the possible synergies between coal and biomass during the combustion process. In this field, thermogravimetric studies under an inert atmosphere and a low heating rate of 5–50 K/min are typically used to study synergistic effects during the co-firing process. The results are quite controversial. Some studies indicate that no interactions occur in the pyrolysis and combustion of coal-biomass blends [17–20], whereas several other studies present an increase in the gas/volatile yield and composition, so a higher reactivity of the coal-biomass blends depends on the mixing ratio and temperature [21–24]. Even if there is no interaction between the coal and the biomass during the devolatilization process, the heat released from

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