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Experimental analysis of biomass co-firing flames in a pulverized fuel swirl burner using a CCD based visualization system

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ABSTRACT

Biomass co-firing with pulverized coal in conventional, large-scale power plants is considered a low-cost strategy to reduce CO_2 emissions and fossil-fuel dependence. This work analyzes the effects of biomass co-firing in the physical characteristics and oscillation patterns of the flame, by means of a digital imaging system installed in a 500 kW_{th} semi-industrial scale swirl burner. The system is based on a monochrome CCD (Charged Couple Device) camera of high-speed frame rate (120 frames per second). Processing stage comprises the digital analysis in the spatial and spectral domain of recorded videos. Several co-firing flames with two biomass fuels (*Cynara cardunculus* and *Populus* sp.) were investigated, at substitution percentages ranging from 0% to 15%, energy basis. Spatial analysis of swirling flames highlights the effects of biomass addition in terms of luminous fluctuation rates and symmetry properties. With the joint analysis of flame derived parameters and CO emissions, flame flicker has been proved as a potential indicator of combustion performance. Additionally, a deeper investigation of luminous flame signal throughout its resulting histogram, have found new outcomes in the identification of instabilities of combustion process. Kurtosis and skewness parameters have shown an interesting response when CO emissions increase resulting in a promising option to develop monitoring and control systems based in non-intrusive measurements.

1. Introduction

Within the current energy scene, pulverized coal combustion at industrial scale faces the challenge of maintaining high efficiency and low pollutant emissions. Due to the relatively large existing coal reserves in the world, power generation from coal will continue to be prominent during next decades. Among all electricity generation technologies, biomass co-firing in conventional power plants has been considered one of the most attractive strategies to minimize the environmental impact of power generation from coal [1–3].

Biomass use for thermal purposes can contribute to the reduction of CO_2 emissions and the mitigation of the current dependence on fossil fuels. Nevertheless, in spite of its numerous advantages, the introduction of a new fuel with different properties in a furnace specifically designed to burn coal might produce some operational instabilities which could jeopardize energy system efficiency [4,5]. In this sense, an important task related to control and monitoring of the process must be implemented in order to prevent operational problems and assure high safety standards.

Optical methods based on charged coupled devices (CCDs) and digital image processing techniques can help to achieve this aim, given that they are not intrusive and provide on-line information of the process [6–9]. Only a few experimental works have been performed using digital techniques focused on assessing possible impacts of biomass co-firing processes. Lu and coworkers characterized several co-firing flames through geometrical and dynamical flame parameters evaluating their behavior under different operational conditions [10]. They used five different types of biomass (Swedish wood, straw, palm kernels, wood pellets and high-protein biomass) in various proportions and with different injection methods. Their main results revealed differences in ignition points and brightness. This and other works of the group were also focused on flame temperature estimation by means of two color pyrometry [11,12], in both gas [13] and pulverized fuel flames [14,15].

Biomass co-firing impacts have been also analyzed through measurements of species concentration and particle sampling over the flame [16,17]. Volatile content of biomass fuels causes more luminous flames with higher combustion intensity near the burner region [16]. Other important changes were also found in flame structure due to the comparatively higher size of biomass particles which causes an increase of the size and frequency of fuel-rich eddies [17]. Nevertheless, a more detailed spatial analysis of co-firing flames compared to pure coal flames becomes necessary.

The current experimental work evaluates coal-biomass co-firing impacts in a pulverized fuel swirl flame by means of digital image

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processing procedures including two-dimensional characterization. Experiments were carried out on a 500 kW_{th} combustion test facility [18]. Two biomass fuels (herbaceous and forestry biomass samples) has been tested in order to provide a suitable research field including different types of biomass. Flame behavior has been characterized by its main physical features such as light intensity, luminosity contours, fluctuation and oscillatory properties. Relationships between those features and operational parameters have been established identifying qualitative and quantitative differences that highlight the influence of biomass in the combustion process. The scope of the present work achieved a good level of detail in spatial characterization of the flame and it establishes promising relationships between flame parameters and emissions. This represents a potential tool for monitoring and control of the combustion process.

Section 2 includes, on the one hand a complete characterization of all fuels used in the study along with a brief description of the test program. Experimental combustion facility and visualization system are then referred. On the other hand a detailed explanation of the processing procedure and all the considered parameters is provided. Section 3 gathers all the results in two different subsections whereby the influence of biomass co-firing is analyzed in terms of flame spatial characterization and quantitative indicators investigation. Finally, Section 4 summarizes the main conclusions and findings of the current research.

2. Materials and methods

2.1. Fuels

Two different biomass fuels and one coal type were used in the tests. The reference coal is currently burnt at Spanish power plants. It is a high volatile South African coal with low sulfur content, pulverized to a mean particle size of 0.045 mm. Regarding biomass fuels, two types of biomass used for thermal purposes were chosen for the study: a herbaceous energy crop (*Cynara cardunculus*), and a woody biomass from poplar residues (*Populus* sp.). Proximate and ultimate analyses are shown in Table 1. Main differences in analytical data between fuels are the remarkable higher volatile content in biomass fuels and their higher moisture compared to coal. Particle size distribution of fuels (see Fig. 1) were obtained using the standard methods for sieve analysis of coal (ASTM D 410-84) and biomass (CEN/TS 15149-2:2006). Maximum biomass particle size was 0.500 mm and the mean particle diameter around 0.200 mm in both cases.

2.2. Experimental system and test program

The experimental test facility consists of a 500 kW_{th} swirl burner of vertical design and downward oriented (Fig. 2), specially designed for pulverized coal, biomass and blends. The combustion chamber comprises three water-cooled rings being coated with refractory concrete in the upper part to promote flame stability. The swirl burner was scaled-down from standard coal PF (pulverized fuel) burners [19] to reproduce actual conditions of industrial utility boilers. It is composed of two coaxial injectors of primary air-fuel and secondary air streams. The latter is swirled using a tangential swirl generator and it is preheated up to 250 °C in order to enhance the combustion process. Injection temperature of primary air corresponds to 15 °C approximately (room temperature). Dimensions of primary and secondary annular ducts are 0.107 m and 0.175 m (outer diameter), respectively. The rest of furnace dimensions can be seen on Fig. 2. The facility relies on a multi-fuel feeding system that allows the on-line regulation of the mass flow with good accuracy [20]. Table 3 shows the experimental flow rates of air and fuels depending on the substitution percentage of biomass. The complete and detailed description of the facility is available in Ref. [21]. The concentration of the main species present in flue gas (CO, CO_2, SO_2, NO_x and O_2) is continuously measured using a gas sampling probe located in the stack and connected to a complete set of standard analyzers. An advanced SCADA system (Supervisory Control and Data Acquisition) provides the on-line visualization and recording of operational parameters and emissions [22].

Flue gas temperature inside the furnace is measured by an standard thermocouple (S type) which is located just below the refractory rings. Its position is indicated in Fig. 2. This temperature increases during the tests because of the transient warming of refractory walls. Nevertheless, the increment was not more than 4.85% during the experiments. Given its influence on flame brightness [23] the comparison is done for videos acquired under similar temperature conditions. As the aforementioned thermocouple (Section 2.2) sub-estimates the temperature in a 10.56% because of the inherent radiation [24], the actual gas temperature during the experimental tests ranges from 1057 °C to 1111 °C at the measured point (Fig. 2). Additionally to the indicated measurement point (Fig. 2), the combustion facility is fully instrumented and has 12 temperature measurement points into the refractory walls. Temperature level of refractory walls is also taken into account in order to set up the same operational conditions.

In Fig. 2 it can be seen that the visualization is system placed at the first refractory ring of the combustion chamber where a suitable view of the root flame can be registered. Fig. 3 illustrates the flame area captured by the system with respect to the burner position. A charged coupled device (CCD) monochrome camera is the central component of the system. Besides its high acquisition speed (120 frames per second (fps) on normal operation) the camera holds a remote head of 17 mm diameter highly suitable for difficult access areas. The active sensor placed on this head provides a resolution of 656(h) × 494(v) active pixels. A protective system completes the setup providing purging air and cooling water by means of a temperature controlled cylindrical probe (further details can be found in Ref. [21]).

Experiments were performed to compare the combustion behavior of different kinds of biomass fuels blended with coal and their possible influence on flame development and physical appearance. To this end the biomass proportion on fuel mixture was varied covering different ratios: 10% and 15% (energy basis, e.b.). For the sake of comparison, similar operational conditions were maintained during the trials and fixed at their nominal values (Table 2). Overall combustion test time was approximately 10 h, including preheating of refractory walls. Biomass is introduced after a preheating stage with coal and its percentage is adjusted according with the test plan. Once the combustion process is stable the camera records several videos all along the course of the experiment. Each video is composed of a temporal collection of 5200 images gathered during an approximate period of 42 s.

Flue gas emissions during the tests followed the expected trends according to the substitution percentage and type of biomass in each test [25]. CO levels suggest a good combustion completion in all cases. Meanwhile NO_x and SO_2 decrease with increasing biomass share, as expected, due to the lower sulfur and nitrogen content of the fuels (Table 1) [26].

Table 1
Fuels characterization.

	Coal	Poplar	Cynara
Moisture (as received, %wb)	3.60	8.20	10.09
Proximate analysis (%d.b)			
Ash	13.40	3.24	8.90
Volatile matter	26.00	82.56	77.00
Fixed carbon	60.60	14.20	14.10
Ultimate analysis (%d.b)			
Carbon	69.60	45.73	46.25
Hydrogen	4.00	5.80	4.94
Nitrogen	2.05	0.23	1.05
Sulphur	0.50	0.00	0.12
Oxygen	10.45	45.00	38.74
HHV (MJ/kg),(d.b)	27.80	17.19	19.32