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Technical Note

A large depth of field LIBS measuring system for elemental analysis of moving samples of raw coal

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ABSTRACT

We present preliminary results of laboratory tests carried out on moving samples of coal by means of an innovative LIBS system with a large depth of field. The measuring system has been conceived to operate on line in a coal fired power plant. To duplicate at laboratory level the real situation, the coal samples are sequentially positioned under the measuring head by means of a translation/rotation unit that allows reproducing the behavior of the raw coal transported by a conveyor belt. Experimental results show that both carbon and hydrogen concentration as well as the content of some inorganic components (Al, Ca, Fe, Si) can be evaluated with good accuracy.

1. Introduction

On-line elemental analysis of coal is of primary importance for power industry, mainly for what concerns fuel cost and combustion process optimization. Combustion efficiency, as well as coal price, in fact, strongly depend on the coal calorific value, which in turn is strictly related to the average carbon and hydrogen content of the delivered feedstock [1,2]. In addition, inorganic components in coal (such as Si, Al, Fe, Ca) do have a direct impact on the ash fusion temperature and thus on the boiler operating conditions. The presence of low melting oxides in the ashes, in fact, is responsible for the formation of undesired vitrified ash deposits (slagging) on the boiler pipe bundles, which affect the heat exchange and the overall boiler efficiency [3–5].

Commercially available analyzers, suited for installation on the coal conveyor belts, already exist and in the last years have been used both in coal mines and in coal fired power plants. Their principle of operation deals either with nuclear source-based technologies, utilizing a Prompt Gamma Neutron Activation Analysis (PGNAA), or with X-ray techniques, like X-ray fluorescence (XRF). However, both these techniques exhibit strong drawbacks. PGNAA are cumbersome devices and their utilization has to fulfill severe safety requirements (due to the presence of neutrons sources), while XRF based instrumentation has difficulties in analyzing low atomic number elements such as C and H.

Because of its promising features, laser-induced breakdown spectroscopy (LIBS) [6] has been identified as a viable method for the on-line analysis of coal in substitution of the existing techniques. LIBS systems, in fact, are compact, do not require sample preparation, can be operated on-line also in the presence of hostile environments and the results of the analysis can be obtained in a short time. A number of studies have been carried out so far to check the validity of this technique for the characterization of coal samples (see for example references [7–17]). Most of them, however, refer to measurements performed under almost ideal conditions. That is, coal samples are crushed prior the analysis and pressed to pellets to produce a flat rigid surface, furthermore, samples are kept at a fixed distance to the focusing lens. In this way irradiance of the impinging laser beam can be controlled and the collecting optics can easily be conjugated to the (fixed) position where the plasma plume is generated, thus optimizing the collection efficiency. To our knowledge, only two LIBS measuring systems have been utilized so far for on-line characterization of raw coal samples in real field conditions [16,17]. In one case [16] the system has been installed in a coal mine (in South Africa) and, since the instrument working distance was limited to ± 2 cm, an ultrasonic sensor was used to enable a moving optics to maintain a fixed distance from the sample with changes in coal height of the order of ± 12.5 cm. In the other case [17] the LIBS system did not include an automatic control of the focusing mechanism (i.e. the focusing/collection optics is fixed) but it has been installed in a peculiar position, not usually available in other plants, where the height variation of the coal stream would not exceed its working distance (about 5 cm). In both cases no further studies have been published. It should also be mentioned that several studies have been conducted on the instrumental design of stand off LIBS systems utilizing a coaxial based optical configurations, aimed at the analysis of distant objects [18,19] and moving targets [20].

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In the present work we describe preliminary results of laboratory tests carried out on moving samples of coal by means of a mirror based LIBS system with a large depth of field. The measuring system has been designed to operate on top of conveyor belts that carry the raw coal in coal fired power plants. To replicate at laboratory level this situation, the coal samples (in the form of raw material) are sequentially positioned under the measuring head by means of a translation/rotation unit that allows reproducing the typical experimental conditions found in real industrial plants.

2. Experimental apparatus

2.1. The LIBS system

The measuring system is schematically shown in Fig. 1. The excitation beam is provided by a Quantel Brio Q-switched Nd:YAG laser operating at 1064 nm. Main technical specifications of the laser source are: 100 mJ energy per pulse, 4 ns pulse duration, 20 Hz maximum pulse repetition rate, 4.5 mm output beam diameter (measured at $1/e^2$ of the Gaussian profile). At variance with more conventional LIBS configurations, to increase the laser irradiance up to the plasma ignition threshold, the beam cross section is reduced by means of a Galilean telescope. This solution, in fact, provides a mildly focused beam with a large Rayleigh range (about 20 cm), so that the resulting irradiance on the sample becomes almost independent of the focusing distance. In our case the beam irradiance at the beam waist is about 1.3 10^8 W/mm^2, which is more than one order of magnitude greater than the threshold for the plasma ignition in the coal.

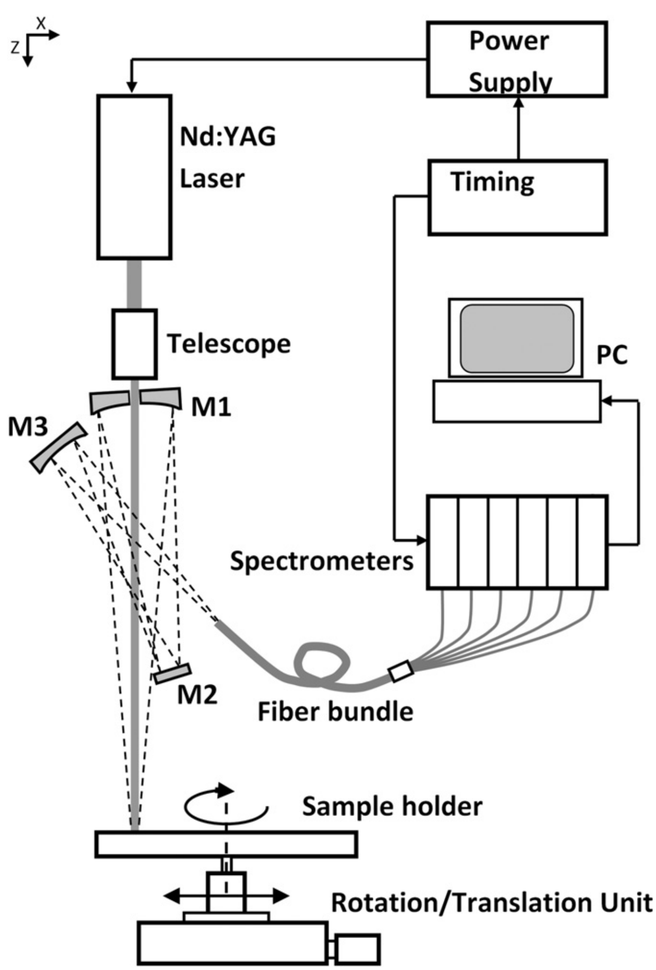

Fig. 1. Schematic representation of the LIBS system.

As far as the collection optics is concerned, it should be emphasized that in our application both the distance and angular position of the emitting plasma can vary from shot to shot with respect to a fixed off-axis optical system (due to both the irregular shape of the raw coal and its random assembling on the conveyor belt). It is therefore mandatory to have a collection optics operating backwards with a large depth of field. It should also be considered that refraction based optical systems (i.e. lens systems) suffer from chromatic aberration and can hardly be used in the presence of an incident radiation with a wide spectral range (from 180 to 900 nm in our case). Commercially available achromatic lens systems, properly designed to operate from the UV to the NIR spectral region, do exist (like e.g. air spaced doublets and triplets), however these optical components are very expensive and their aperture is usually quite small. For these reasons we decided to use a reflection based collection optical system. Different solutions have been evaluated [21]. One of the most promising configurations is represented by the folded path — two spherical mirrors arrangement, shown in Fig. 1.

In this scheme the light coming from the plasma plume is collected by the holed spherical mirror M1, placed at one meter from the plasma (to fulfill on line installation constraints), that reflects the incoming light onto the spherical mirror M3 (having the same curvature radius) via the flat mirror M2. The light impinging onto the mirror M3 is then focused onto the input face of the fiber bundle that brings the light signal to the spectrometers.

As anticipated, this configuration is immune from chromatic aberration. In addition, it allows both to avoid coma (typical of parabolic mirrors) and to correct, to some extent, the spherical aberration. Main drawback is represented by the astigmatism, an aberration that occurs when the propagation direction of the light impinging on mirrors M1 and M3 starts deviating from their optical axis [18]. To minimize astigmatism, the angle between the optical axis of mirror M1 and the laser optical axis should therefore be maintained as small as possible. However, the presence of the folding mirror M2 (that has to be sufficiently large to collect enough plasma radiation) unavoidably introduces a misalignment between the mirror M1 optical axis and the propagation direction of the impinging light. The use of mirrors with a longer focal length, that in principle should minimize this misalignment, would cause a reduction of the collection efficiency and an increase of the system size. On the other hand, mirrors with shorter focal lengths not only will increase the aforementioned misalignment but also they would increase the numerical aperture of the optical system that no longer would match the one of the collecting optical fiber. A trade-off between mirrors size and curvature radius is therefore mandatory. The best compromise between these parameters brings to a final configuration that exhibits a depth of field of 17.8 cm when the distance between the mirror M1 and the plasma plume is one meter. This result has been obtained from the simulation reported in Fig. 2. Fig. 2a shows, in a gray scale, the collection efficiency of the whole optical system, i.e. the fraction of the light collected by the system and actually fed into the optical fiber as a function of the position occupied by a point like source of unitary power. The depth of field has been evaluated as the FWHM of the curve that we get by plotting the collection efficiency evaluated along the optical axis as a function of the position (Fig. 2b). For the development of the optical system we used both the commercial optical design software WinLens3D and a custom ray tracing program properly tailored for calculating the collection efficiency of our system. The first one was used to define the overall system configuration, while the second one allowed performing fine tuning of the system and provided more accurate values for collection efficiency.

The light emitted by the plasma plume is analyzed by means of six rack mounted Czerny–Turner spectrometers coupled with CCD array sensors (Avantes), covering a spectral region ranging from 180 nm to 900 nm with a spectral resolution ranging from 0.06 nm to 0.15 nm, according to the selected spectrometer. Synchronization between the laser source and the spectrometers is obtained by properly setting the delays between the laser external trigger and the trigger that controls