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Reaction zone monitoring in biomass combustion

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ABSTRACT

In this work we demonstrate the utilization of a machine vision-based combustion monitoring system in biomass combustion. The proposed system monitored the location of the reaction zone in a 3 MW, grate-fired biomass boiler operated at varying loads and with fluctuating fuel quality. The system can help guarantee equal primary air supply to different regions of the grate and avoid the elutriation of fly ash by providing information on the location of the reaction zone. Strong correlation was found between the reaction zone boundary location and most process parameters, indicating that the location of the reaction zone can be a useful metric in monitoring and control by providing supplementary measurements to already existing monitoring to avoid over-emissions and improve economics.

1. Introduction

Due to global climate change and depleting fossil fuel reserves it became necessary to transition towards sustainable energy production. Due to its wide availability (Bridgeman, Jones, & Williams, 2010), biomass is considered to be the only option for renewable energy generation viable in the short-term (Rosendahl, 2013). In the EU27, the dominating 91% share of biomass among renewable energy sources used for heating and cooling is projected to remain in and after 2020 (Banja, Monforti-Ferrario, & Scarlat, 2013). For heat and electricity generation from biomass, combustion is by far the most widespread technology, holding a share of over 90% (Koppejan & Van Loo, 2012).

Grate firing is the most widely used method for biomass combustion, especially in decentralized applications utilizing smaller units. This trend is due to the flexibility of grate firing in terms of insensitivity to fuel type and granularity (Yin, Rosendahl, & Kær, 2008). Grate-fired boilers have lower efficiency compared to e.g., fluidized bed combustors (Rosendahl, 2013); therefore, given the significant share of the technology in global renewable energy production, it is important to optimize their operation. Due to climate change and environmental issues, the utilization of low-quality and heterogeneous fuels is becoming more and more widespread (Ballester & García-Armingol, 2010). Grate-firing is applicable for combusting such fuels; however, the problems caused by low fuel quality — reduced efficiency, increased emissions, slagging, fouling and poor flame stability — must be alleviated; e.g., by using improved control and process monitoring (Lu, Gilabert, & Yan, 2005).

On-line monitoring and diagnostics are useful tools for optimizing combustion processes. Generally speaking, monitoring and diagnostics include both intrusive and non-intrusive methods for acquiring information about the process. Conventionally, most combustors are equipped with instruments that measure parameters such as inlet flow rates, flue gas concentrations, or local temperatures and pressures (Ballester & García-Armingol, 2010).

In most combustion technologies, the conversion of chemical to thermal energy takes place in the flame itself; therefore, the flame can be considered as the central process. It is thus no surprise that many monitoring techniques focus on collecting measurements directly from the flame. Intrusive in-flame sensors, such as thermocouples and ionization detectors can be used to obtain information about local temperature or concentration of organic species in a gas stream at low cost. However, they only provide data that represent a very localized area of space, and, in most cases, their application disturbs the aerodynamics of the process (Chedaille & Braud, 1972; Goulard, 1976; Heitor & Moreira, 1993). Non-intrusive methods, such as the different forms of optical sensors, pressure sensors and solid state gas sensors (Heitor & Moreira, 1993; Kleppe, Norris, McPherson, & Fralick, 2004; Korotcenkov, 2007) have been utilized in many cases as well. Optical methods avoid the drawbacks of intrusive techniques and typically operate in the ultraviolet (Ballester, Hernández, Sanz, Smolarz, Barroso, & Pina, 2009), visible (Demayo, McDonell, & Samuelsen, 2002) or infrared (Chong, Tan, Wilcox, Thai, Ward, & Andrews, 2008) wavelength ranges. Wide-band or multi-wavelength sensors are also available (Jie, 1999; Wójcik,

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2008). Although optical methods are non-intrusive and instantaneous, optical sensors are usually focused on a small region of the flame, or utilize spatial averaging to provide single-point measurements to characterize the process.

With the advent of digital methods, data processing and inexpensive computational resources, one of the most promising monitoring techniques is the optical imaging of the flame, coupled with real-time, on-line image processing. Many previous studies demonstrated that the observed geometrical and luminous parameters of the flame provide information on the quality and performance of the combustion process (Yan, Lu, & Colechin, 2002). Flame imaging has many advantages over conventional methods: similar to optical sensors, imaging is non-intrusive and provides instantaneous measurements; however, data are collected from the entire — or from a significant portion of the volume of the — visible flame. The acquired images contain both spatially and temporally resolved information, exceeding the capabilities of single sensors. The high data rate of digital cameras can be prohibiting, unless dedicated processing algorithms are used to condense the information to interpretable quantities — due to the rapid development and expansion of the image processing, machine vision and machine learning fields, these algorithms are readily available today (Li, Wang, & Chai, 2012; Lu, Yan, Huang, & Reed, 1999).

Numerous studies demonstrated the use of vision-based monitoring systems in combustion applications. Many methods utilize image processing to extract geometric or luminous parameters from flame images. These parameters are known to be correlated to combustion conditions or emissions (Baek, Lee, Baeg, & Cho, 2001; Chimenti, Di Natali, Mariotti, Paganini, Pieri, & Salvetti, 2004; Kurihara, Nishikawa, Watanabe, Satoh, Ohtsuka, Miyagaki, et al., 1986; Lu et al., 2005, 1999; Marques & Jorge, 2000; Tuntrakoon & Kuntanapreeda, 2003; Yan et al., 2002; Yu & MacGregor, 2004). From calibrated color images, pyrometric temperature and soot volume fraction can be computed (Draper, Zeltner, Tree, Xue, & Tsiava, 2012; Manca & Rovaglio, 2002; Schuler, Rampp, Martin, & Wolfrum, 1994). The temporal and spatial variation of the measured parameters also provide valuable insight into the combustion process (Lu, Yan, Cornwell, Whitehouse, & Riley, 2008; Xu & Yan, 2007). The measured parameters can be interpreted and utilized by control (Chen, Chang, & Cheng, 2013) and machine learning (Allen, Butler, Johnson, Lo, & Russo, 1993; Kurihara et al., 1986) algorithms, revealing the possibility of image-based control loops (Lu et al., 2005). The potential of infrared and visible imaging in optimizing power plants and large-scale waste combustors have been well-known (Daimer, Schaefers, Hartenstein, & Licata, 1998; Zipser, Gommlich, Matthes, & Keller, 2006).

In a grate-fired boiler, the fuel is transported along a moving or vibrating grate that is divided into controllable sections. The fuel is combusted before it reaches the end of the grate, where a mechanism disposes of the remaining ash. The primary combustion air is supplied from below the grate in stages, creating an intense combustion zone directly above the bed (Rosendahl, 2013). During biomass combustion, the fuel is converted in drying, devolatilization, pyrolysis, gasification and char combustion steps (see Fig. 1). The timing and control of these processes is crucial in order to obtain low emissions and high efficiency. In a grate-fired combustor, the separate processes can be controlled by controlling the fuel feeding rate, primary air flow and grate movement. In order to achieve optimal combustion, the primary air flow rate needs to be staged in a way that is appropriate for the inhomogeneously distributed fuel over the grate — on one hand, if the air flow rate is too low in a specific grate zone, combustion will be incomplete; on the other hand, too high air flow rates cause the elutriation of ash and unburnt fuel particles. Both cases increase pollutant emissions and reduce efficiency. Grate-fired boilers are typically programmed to handle a single fuel quality, for which the locations of zones of drying, devolatilization, gasification and char combustion are empirically known. However, if the fuel quality changes or a new fuel blend is being used, the technology will not operate optimally. Among other unwanted effects, suboptimal grate operation may result in uneven fuel distribution, local hotspots or "holes" of fuel on the grate or a high amount of particulate emissions due to elutriation (Vos, 2006).

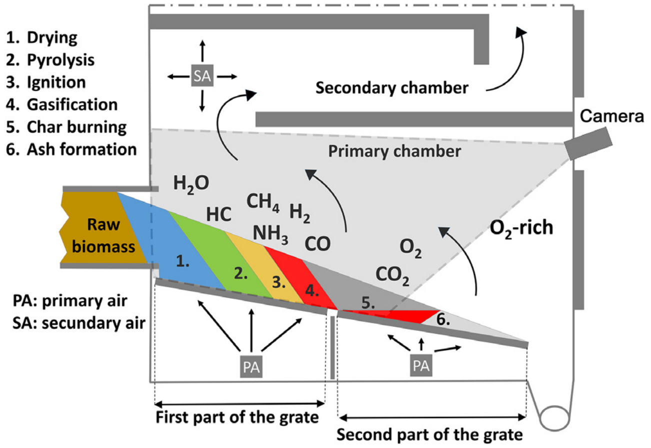

Fig. 1. A schematic drawing of the 3 MW grate-fired biomass boiler used for the experiments. Colored regions indicate zones of drying, devolatilization, combustion, burnout and ash. The location and field of view of the camera used for imaging is shown by the gray area.
Source: Adapted from Tóth, Garami, and Csordás (2017) and Yin et al. (2008)

Given the above, it is easy to see the potential benefits of an image-based flame monitoring system in grate-fired combustion: the spatially resolved information provided by the monitoring system allows for locating the reaction zone and extracting information indicative of the distribution of fuel and the rate of reaction over the grate, allowing for the adaptive programming of the combustor. Such an adaptive system is expected to increase fuel flexibility, reduce pollutant emissions and increase efficiency in most cases, by adjusting grate movement and fuel and air flow rates so that a homogeneous distribution of fuel and optimal local stoichiometry are achieved. Furthermore, the grate program can not only be adapted to changing fuel quality, but also to varying loads, making the combustion technology more robust to varying power demand as well.

Regardless of the potential benefits, to the authors' knowledge, there is a lack of studies exploring the applicability of image-based flame monitoring in grate-fired biomass combustion systems. Matthes et al. used infrared imaging to map the empty regions of the grate of a large-scale solid fuel combustor (Matthes, Waibel, & Keller, 2012). In this paper, the potential of an imaging system based on visible imaging that is capable of locating and monitoring the preceding and progressing reaction zone in a 3 MW nominal capacity boiler firing wood chips is demonstrated. By using real-time image processing, the reaction zone location is reconstructed in three dimensions. The extracted locations are correlated to operating and emission parameters.

2. Materials and methods

This section describes the relevant details of the combustion system, instrumentation, imaging and data processing. The dataset used in this work is the same as that used previously in training Artificial Neural Networks for predicting the thermal output of the system (Tóth et al., 2017). In this section, for completeness' sake, the methodologies common with Tóth et al. (2017) are summarized briefly and more emphasis is placed on the differences between the data processing approaches.

2.1. Boiler

The boiler was a 3 MW nominal capacity, sloping step grate type, counter-current (Vos, 2006) system. Wood chips were used as fuel, fed