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Characterization of hot gas in a 4 MW reciprocating grate boiler

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ABSTRACT

The gas concentration and temperature information from the combustion of biomass offer significant advantages to enhance the understanding of an industrial-scale biomass heating plant. The main objective of this study was to investigate the gas composition and temperature in a 4 MW reciprocating grate boiler. An extensive series of measurements was carried out, and the samples, which were drawn through different ports by means of a water-cooled stainless steel suction pyrometer, were analyzed for temperature and for O_2, CO, and NO concentrations. The results showed that the averaged NO, CO, and O_2 concentrations in the gas phase during fuel combustion in the primary chamber were 40 ppm, 3.5 and 6.5 vol.%, respectively, while the values were 80 ppm, 1.1 and 6 vol.% in the secondary chamber. Detailed gas species and temperature distributions are discussed, which provide good possibilities for the control of emissions.

1. Introduction

The worldwide major concern with greenhouse gas emissions caused by the use of fossil fuels and their limited availability has been the motivation for a rise in using biomass as a renewable source of energy. Combustion of biomass is one of the conversion routes for generating heat and power. In countries with a large forestry industry, biomass is available in large quantities as waste material from the wood industry and as forest residues [1].

Grate-fired systems have been regarded as a common and popular combustion technology for burning woody biomass [2]. The moving grate type enables the movement of fuel through the furnace to provide a more efficient combustion condition. In these furnaces, fuel is fed onto a moving grate, and the primary airflow supplies oxygen to the bed at the bottom of the grate. The primary fuel conversion takes place on the grate, and gaseous products from drying, devolatilization, and char oxidation flow upward, where secondary air is blown into the chamber to continue the combustion process. At the end of the moving grate, the bottom ash falls down into an ash pit. Grate furnaces have a high degree of fuel flexibility and can be fueled entirely by raw biomass. However, the combustion of solid biomass in these furnaces may emit a large amount of pollutants in the form of CO, CH_4, PAH, NO, and particles, and they need to be further developed to achieve a higher efficiency and improve the overall performance of the system while assuring environmental compatibility [3–6]. The residence time, mixing pattern, excess air ratio and the combustion temperature are some factors that could affect the pollutant formation during the grate combustion. Incomplete combustion of the fuel results in high emissions of unburnt pollutants such as CO and PAH [7]. There are different mechanisms of NO formation from combustion systems, including thermal NO, prompt NO, and fuel NO. Thermal NO is formed from the reaction of the nitrogen and the atomic oxygen in the air at high temperatures ($T > 1300$ °C), and thus can be considered negligible in grate boilers; systems with comparatively low combustion temperatures [8,9]. Prompt NO can be of importance in combustion of high-volatile fuels with low N content; however, fuel NO is generally regarded as the major source in solid fuel systems. Fuel NO is formed from the fuel-bound nitrogen (N volatiles and char nitrogen), and the major NO precursors among N volatiles are NH_3, HCN, and HNCO [3].

Detailed information about distributions of temperature and gas species within the furnace is of great importance in studying the formation of pollutants. Therefore, measurement of hot gas can provide valuable insights into the combustion process and operating characteristics of full-scale grate boilers. The results obtained from such field measurements can furnish input to a modeling program, and they can also be used for the validation of models [6,10]. Several comprehensive combustion modeling studies of different full-scale grate boilers have been conducted [4,7,11–16], while there is a noticeable lack of online measurement data from such boilers in the literature. It is difficult to perform detailed measurements of gas composition and temperature inside the combustor. This is because of the limitations caused by the geometry of the combustion system, as well as the tar rich environment, especially in the primary combustion zone, which causes tar deposition and probe clogging [7,17]. Apart from these limitations and problems, it is hard to maintain constant boiler operating parameters over the long time periods required for detailed characterization of an industrial unit [18].

The objective of this work was to experimentally investigate and characterize gaseous species inside a grate furnace during wood

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combustion. Measurements of gas temperatures and concentrations of CO, CO_2, CH_4, O_2, and NO were made in different zones inside the furnace, and detailed results are presented and discussed.

2. Materials and methods

2.1. Boiler description

Measurements were conducted in a moving grate boiler with a thermal capacity of 4 MW. The boiler is located at a sawmill plant and provides heat for the wood driers, as well as a local district heating system. Fig. 1 shows a schematic view of the furnace, indicating the positions of measuring ports on the side walls. The measurement ports are labeled with capital letters (B_1–B_3, C, D_1–D_3, E, F_1–F_3, and G). The furnace includes a reciprocating grate and is divided into lower and upper combustion chambers that are here denominated primary and secondary combustion chambers, respectively. The primary air is distributed through three wind-boxes beneath the grate and enters into the bed through spaces between the grate bars. A stoker pusher feeds the fuel into the combustion chamber, pushing the fuel forward on the grate. Every second row of bars is controlled by hydraulic cylinders, which move the grate bars discontinuously (few seconds of displacement and then resting for about 35 s). The biomass fed to the grate undergoes a sequence of conversion processes (i.e., drying, devolatilization, and char combustion). The conversion of the biomass along the grate can be controlled by changing the distribution of the primary airflow rate out of the wind-boxes, as well as by regulating the frequency and length of the strikes of the reciprocating grate. The bottom ash falls into a water pit at the end of the grate and is removed from the furnace. Combustible gases leaving the bed mix with the secondary air above the fuel bed, which is introduced through several ports placed in the furnace side walls. Flue gas from the outlet of the boiler is recirculated through a set of nozzles close to the secondary air ports to control the local temperature. Furthermore, flue gas recirculation enhances the turbulent mixing, resulting in a better CO burnout and NO_x reduction. In the secondary combustion chamber, the flue gas passes through a cylindrical-shaped channel in which tertiary air is added via several nozzles in the wall (between D and C ports). Each of the secondary and tertiary airflow was approximately the same as the primary airflow, which was 2274 m^3/h (Table 1). The section downstream of the tertiary air supply is a burnout zone. The hot flue gas is then conducted into a separate boiler downstream from the furnace. At the entrance of the boiler there is a vertical cylindrical shaft, with a diameter of about 1 m, in which the gas is cooled down to around 400 °C before reaching the bottom of the boiler, where the gas is distributed into the heat exchanger tubes. Passing through these tubes to the top of the boiler, the gas is cooled down to about 200 °C. Plant operating parameters and emission data of CO and NO at the boiler exit, with five-minute interval, were extracted from the internal control and monitoring system of the boiler, and the average values during the two-day measurement campaign are listed in Table 1.

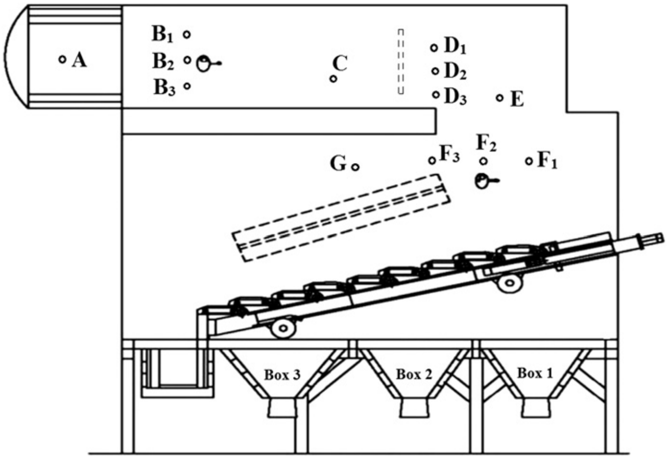

Fig. 1. A schematic view of the furnace.

Table 1
Proximate and ultimate analyses of the fuel (wt.%).

Operation parameters	Quantity
Fuel feeding rate (kg/h)	1840
Boiler load (MW)	3.2
Total flow of primary air (m^3/h)	2274
Primary airflow (box 1) (m^3/h)	906
Primary airflow (box 2) (m^3/h)	830
Primary airflow (box 3) (m^3/h)	538
Primary air temperature (K)	303
Secondary air temperature (K)	293
Tertiary air temperature (K)	293
Split ratio of fly ash to bottom ash (by weight)	20:80
O_2 concentration in exhaust gas (dry vol.%)	4
Flue gas flow (m^3/h dry)	4154
Exhaust gas temperature (K)	421
CO concentration in exhaust gas (dry volume ppm)	8.9
NO concentration in exhaust gas (dry volume ppm)	97
NO_x concentration in exhaust gas (mg/MJ)	68

2.2. Fuel

The fuel used during the measurement campaign was a mixture of wood chips, bark, and sawdust. The fuel was produced at the sawmill plant and had a moisture content of 53%. The analyses of the fuel, including proximate and ultimate analyses and determination of the net calorific values, were carried out according to the ASTM standard methods, and the data are shown in Table 2.

2.3. Experimental procedure

In this work, measurements were conducted over two days to establish the local temperatures and concentrations of gases (CH_4, NO, CO, CO_2, and O_2). The gas samples were extracted from the furnace by means of a 1.5 m water-cooled stainless steel suction pyrometer, including a type-k thermocouple. The probe was inserted into the furnace through the measuring ports and positioned at several chosen locations between the side wall and the center of the grate width (0.85 m distance from the side wall). The measurements through each port, at different locations, were carried out continuously, for 15–20 min (about 1–2 min for each location). Prompt cooling of the sampling gas is sufficient to avoid major reactions inside the probe [11]. Quenched samples from the probe were filtered and dried, and then analyzed using two infrared spectrometers. The frequency of data collection was 1 Hz. However the time resolution of the data is limited by the response time of the infrared instruments, and each set of data for gas composition represents a 5 s mean value. Deposits of fly ash particles and condensed materials clogged the probe; to maintain a high gas-flow rate, the probe was cleaned frequently by blowing with pressurized air. Additionally, deposits were regularly removed mechanically from the thermocouple. Calibration with standard gas mixtures was carried out before each measurement.

3. Combustion mode of the fuel bed

An understanding of the distribution of the conversion zones inside the fuel bed is essential for the interpretation of the measurement results. Two different combustion modes in crosscurrent bed combustion of biofuels were described by Thunman [19,20], based on theoretical and experimental results. In the traditional description of the propagation of conversion zones, here denominated Mode 1, it is assumed