



Emissions from a domestic two-stage wood-fired hydronic heater: Effects of non-homogeneous fuel decomposition



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ARTICLE INFO

Article history:

Received 24 September 2016

Received in revised form

7 April 2017

Accepted 8 May 2017

Available online 10 May 2017

Keywords:

Wood biomass

Combustion

Emissions

Non-homogeneous

Fuel

Decomposition

ABSTRACT

Accurate knowledge of the combustion gas composition is necessary for practical combustion systems where emissions reduction is a major concern. Industries use a variety of sensor technologies, many of which can be expensive. In industries that use plant biomass for heat production, a constant fuel composition is often assumed for estimation of unmeasured exhaust gas species and for the calculation of thermal efficiency. To address the fact that biomass decomposes non-homogeneously, a new analysis is developed where a 2:1 ratio of hydrogen to oxygen atoms in the fuel is assumed, thereby relaxing the constant fuel composition constraint. This analysis provides a reliable and accurate estimate of exhaust H_2O and CO_2 given commonly monitored air and fuel rates along with O_2 , CO , and NO measurements. Validation of the analysis is investigated using tunable diode laser absorption spectroscopy (TDLAS) measurements of the flue gas. Results show good agreement between the new analysis and TDLAS measurements, verifying the validity of the approach. The new analysis also provides time accurate elemental species information for interpreting the non-homogeneous fuel decomposition.

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1. Introduction

The environmental advantage of using biomass over fossil fuel has been widely discussed for power generation and heating [1–3]. Many developing nations rely exclusively on biomass for energy production, as well as rural areas in northern regions of the United States where wood fired heaters are an economically attractive alternative. However, one of the prevailing challenges using these systems is emissions. For the northeastern US, emissions from wood fired heaters are one of the leading sources of reduced air quality. To provide stricter guidelines on the certification of these systems, the Environmental Protection Agency (EPA) has recently defined specific new regulations for wood burning appliances including wood stoves, masonry heaters, pellet-burning stoves and hydronic heaters [4]. Many studies focus on the characterization of emissions from specific biomass appliances, stoves, boilers, and large scale (>1 MW) power plants [5,6]. Reduction in harmful pollutants resulting from the combustion of cellulosic based biomass materials is the primary goal of many government agencies and research developments.

Certification of these devices require an accurate representation of emissions species concentrations. Measurements of both CO_2 and H_2O are typically required for emissions-based efficiency calculations [7]. For many independent testing facilities and manufacturers, direct measurement of gas species can be cost prohibitive. Often, low cost gas sampling analyzers (Testo, Land, Wohler, etc.) are used to measure select harmful pollutants (CO and NO) directly, along with the oxygen sensors to estimate CO_2 concentrations based on an assumed constant fuel composition. In conjunction with the CO_2 estimation, H_2O is often approximated using a global reaction mechanism [4,7–16]. It is therefore subject to interpretation and inaccurate for some conditions. While non-homogeneous biomass decomposition has been extensively studied [8,14,17–21], its application in the biomass community has been relatively unexplored.

The facility and analysis for a constant fuel formulation (CFF) was developed in Ref. [15]. This study builds on reference [15] by presenting a novel variable fuel formulation (VFF) to accurately calculate the non-homogeneous decomposition of the solid fuel and major exhaust gas species (CO_2 and H_2O) using measurements commonly made in the biomass industry. Exhaust gas concentrations (O_2 , CO , and NO) and mass flow (fuel and air) measurements are used in an atom balance, assuming a 2:1 ratio of hydrogen to oxygen atoms in the fuel. Validation of the analysis is demonstrated

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Nomenclature			
MW	molecular weight	$fuel$	fuel
T	temperature	w	water vapor
X	mole fraction	i	i th species
Q	heat	tot	total
N	moles	m	mass [kg]
		\dot{m}	mass flow rate [kg/s]
		t	time [h]
		th	thermal
		del	delivered
		$stor$	stored
		$comb$	combustion
		CFF	constant fuel formulation
		VFF	variable fuel formulation
<i>Greek</i>			
η	efficiency		
Δ	$\Delta F = \int \dot{F} dt$		
<i>Subscripts/Superscripts</i>			
a	air		
b	boiler		

through non-intrusive tunable diode laser absorption spectroscopy (TDLAS) measurements of CO_2 and H_2O in the flue. CO_2 and H_2O concentrations have been previously measured using TDLAS in combustion environments [22,23]. The results from the TDLAS measurements are based on first-principles quantum spectroscopy theory, where single molecular absorption transitions are monitored to extract information regarding concentrations and temperatures of the absorbing gas species.

The novelty of the following analysis is to provide a method for calculating in real-time the changing fuel composition and major flue emissions (CO_2 and H_2O). The direct measurement of important major combustion species CO_2 and H_2O at elevated temperatures can often be cost-prohibitive. This analysis provides an accurate approach for their calculation using low-cost, routine measurements. This study also demonstrates that real-time fuel characterization for practical biomass combustion systems can improve efficiency calculations over those using a constant fuel assumption.

The rest of this study is organized as follows. Section 2 will discuss the experimental setup used in the analysis. Section 3 will detail the analysis used to calculate the exhaust species and non-homogeneous elemental fuel composition. Section 4 will discuss the results of the CO_2 and H_2O validation with TDLAS. Finally, Section 5 will discuss the major conclusions and outline the novelty of this work.

2. Facility and baseline measurements

2.1. Hydronic heater experimental setup

The test facility previously discussed in Ref. [15] is used in this study where an Econoburn (Brocton, NY) EBW-200 wood-fired hydronic heater (WFHH) is instrumented. The setup consists of primary and secondary water circulation loops, and a heat exchanger to expel heat. Fig. 1a shows the boiler setup, where the load loop contains a 300,000 BTU/h (87.9 kW) counterflow heat exchanger to transfer heat from the boiler to a cold thermal sink. The heat rate is monitored by recording the water temperatures and flow rates, providing a detailed trend of the supplied heat load.

2.1.1. Measurements of fuel and airflow

Instantaneous fuel mass burn rate is measured according to the method presented in Richter et al. 2016 [15] (see Fig. 1b). The real time fuel burn rate monitor (RTFBRM) is designed to directly measure fuel mass loss in the upper chamber as a function of time. The assembly consists of a basket suspended by two rods which run

through the top of the boiler and are sealed using Swagelock fittings. Outside of the boiler, the rods are connected to a horizontal upper cross member. The upper cross member rests on a specially designed piezoelectric-based compression load cell (Stellar Technology) which is thermally insulated from the boiler to avoid any biases induced by thermal gradients. Contact friction is minimized by using high-temperature carbon laced rope around the rods to ensure an accurate instantaneous mass measurement using LabVIEW data acquisition systems (National Instruments) at a frequency of 2 Hz. Fig. 2a shows the raw mass data and Fig. 2b demonstrates the differentiated mass loss rate with time. These measurements are used in the emission analysis discussed in section 3.

To minimize batch-to-batch variability associated with boiler operation, BIOBLOCKS[®], manufactured by Summit Wood Industries, are used as the primary fuel source. The blocks are made from 100% hardwood chips (composed primarily of red oak) and contain an average 8.3% dry-basis by mass water moisture. The exact moisture content and density of the blocks are measured in accordance with ISO standard 3130 resulting in a density of 1.15 g/cm³. A full load boiler run requires 32 blocks (\approx 62 lbs, 28 kg) to conform to current testing standards. A standard loading configuration has been adopted to produce a repeatable burn [15].

Blower air flow rates are measured using a Bosch HFM-7 mass airflow meter operating under hot film anemometry methods. Direct calibration of the Bosch meter was made with an ASME standard venturi flow meter across a wide range of flow rates to correlate output voltage to measured flow rate. Fig. 2c shows the measured air flow rate as a function of time that will be used in the emissions analysis. The sharp decrease in air flow rate seen in Fig. 2c at approximately 0.35 h is caused by the appliance damper being pulled, effectively increasing the blockage through the appliance by forcing the incoming air into the secondary and tertiary chambers before exiting. The gradual rise in flow rate starting at approximately 3 h is due to the gradual decrease in blockage as the fuel decomposes.

2.1.2. Measurements of CO , NO , O_2 , and gas temperatures

Emissions measurements are recorded using a Testo 330-2LL gas analysis meter. The analyzer is capable of taking experimental measurements of the O_2 , CO , NO , pressure, and temperature from the flue gas stream. The O_2 measurement has a range of 0 to 21% with a resolution of 0.1%. Oxygen concentration is detected via an electrochemical fuel cell with a permeable layer of electrodes that allow the flue oxygen molecules and reference air molecules to transfer ions, creating a voltage potential across the electrodes that

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