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Oxy-combustion Behavior of Torrefied Biomass Particles

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Abstract: A fundamental investigation was conducted on the combustion characteristics of torrefied biomass in both air and O₂/CO₂ gases containing 21% or 30% oxygen mole fractions. These gases simulated oxy-combustion environments. The targeted torrefied biomass types were waste crops, both herbaceous and woody. The experimental setup that was used in this investigation consisted of a drop-tube furnace, operated at a wall temperature of 1400 K, a high-speed high-resolution camera. Entire luminous particle combustion profiles of single particles were recorded by means of high-speed high-resolution cinematography. Combustion of these particles took place in two phases. Initially, volatiles evolved and burned in spherical/ellipsoidal envelope flames; then, upon extinction of these flames, char residues ignited and burned. Replacing air as the furnace background gas with 21%O₂-79%CO₂ reduced the luminosity of flame and the lengthened the burnout times; and increasing the oxygen mole fraction further to 30% increased the luminosity of the flame and shortened the burnout times.

Keywords: *Biomass, Combustion, Oxy-fuel, Luminosity*

1. Introduction

Coal combustion emits an abundance of toxic pollutants into the environment and is directly responsible for a large degree of air pollution and damage to the ecosystem. Despite this, in 2017 it was still responsible for roughly 30% of the total electricity generation in the United States. On the other hand, biomass combustion accounts for approximately 1.7% of the US total electricity generation [1]. To increase the impact of renewable energy sources and decrease the world's dependence on coal, co-firing blends of biomass and coal together is an appealing option to reduce the emission of environmental pollutants [2-6]. Co-firing is a low cost, sustainable alternative that involves blending coal samples with traces of biomass fuels during combustion in conventional coal-fired furnaces and has the potential to reduce both the consumption of fossil fuels and the amount of pollutants released into the air during the combustion process [7]. Biomass is both plentiful and versatile when it comes to energy production, but raw biomass has several drawbacks that infringes upon its efficiency, including variable physical properties, low energy densities, high moisture absorption, and low bulk density [8-10]. It is beneficial to pretreat the biomass through torrefaction to improve several of these properties and allow for optimal combustion [8, 11, 12]. Torrefaction is the thermal treatment of the biomass that revolves around slow roasting samples to reduce the oxygen content within the biomass, while increasing calorific value, energy density, and hydrophobic properties. This makes a higher quality biomass for combustion, storage, and

transportation that mimics the behavior of traditional fossil fuels [13, 14]. In a conventional setting, coal-biomass blends are fired within an air-filled furnace, however it is of technological interest to utilize oxy-combustion during this process, as combustion effluents are meant to be sequestered underground. Oxy-combustion refers to the process of burning the fuels in a mixture of oxygen and recycled flue gas (95% CO₂) as opposed to ambient air [15-18]. One study conducted by Riaza et al. [19] burned raw biomass single particles in both air and O₂/CO₂ environments, used to simulate oxy-combustion, in order to contrast combustion behaviors. Another study, conducted by Shan et al. [20], analyzed the ignition behavior of single biomass particles, specifically raw pine and raw rice husk. Riaza et al. [21] burned single particles of raw biomass and measured their burnout times during oxy-combustion. However, a study on the oxy-combustion behaviors of torrefied biomass appears to be absent in the literature, therefore, this research further investigated combustion characteristics and parameters of torrefied biomass in both air and simulated oxy-combustion environments. This goal was accomplished by making direct measurements of single particle burnout times of six different torrefied biomass types both in air and in environments containing 21% or 30% oxygen mole fractions in carbon dioxide.

2. Methods / Experimental

2.1. Preparation of samples

Pulverized corn straw and rice husk were harvested in Harbin province of China and were provided by Harbin Institute of Technology. Miscanthus originated from an agricultural farm in Germany (Sieverdingbeck-Agrar). Beechwood was sourced from trees grown in the Netherlands. Pulverized miscanthus and beechwood were provided by Ruhr-University Bochum, Germany [22]. Sugarcane bagasse was obtained from a bio-ethanol production plant in Brazil. DDGS (Distiller's Dried Grains with Soluble) was provided by a North American ethanol-producing company. Torrefaction of all samples was carried out in a laboratory-scale muffle furnace in nitrogen. The furnace was charged with small amounts (a few grams) of millimeter-size particles of biomass and, subsequently, they were heated to 275°C with heating rates in the order of 10 °C/min. Upon reaching the final temperature, each sample was treated at constant conditions for 30 min. All torrefied biomass fuels were air-dried, chopped in a household blender, and size classified by sieving to obtain size cuts of (212-300 µm) based on the findings of previous study in this laboratory [23, 24]. In a different study [25], it was observed that the torrefaction process reduced the particle aspect ratios and enhanced the uniformity of particle sizes. The Proximate analysis and the Ultimate analysis of the biomass fuels on a dry basis, are given in Table 1. Those analyses, as well as the determination of the heating value of the torrefied biomass fuels, were performed at the Harbin Institute of Technology, according to GB/T 212-2008, GB/T 30733-2014, GB/T 30733-2014 and to GB/T 213-2008 Chinese standards, see Ref. [26].

Table 1. Chemical compositions of six types of torrefied biomass

Rank / Fuel Source	Biomass (Torrefied at 275 °C for 30 min)					
	Herbaceous			Crop-Derived		Woody
	Corn Straw	Miscanthus	Sugarcane bagasse	Corn DDGS	Rice Husk	Beechwood
Proximate Analysis (dry basis)						
Volatile matter (%)	67.55	75.00	73.74	71.46	55.62	72.20
Fixed Carbon (%)	24.56	22.30	23.49	21.09	21.58	27.30
Ash (%)	7.89	2.70	2.71	7.45	22.80	0.50
Ultimate Analysis (dry basis)						
Carbon (%)	52.77	52.80	55.82	58.22	44.16	55.40
Hydrogen (%)	5.32	5.70	5.45	6.32	4.41	5.30
Oxygen (%) (by difference)	32.46	38.6	34.94	22.98	26.73	38.88
Nitrogen (%)	1.50	0.18	1.00	4.00	1.22	0.18
Sulfur (%)	0.07	0.46	0.03	1.01	0.03	0.31
Calcium (%)	0.56	0.55	0.44	0.15	0.35	0.19
Sodium (%)	0.02	0.04	0.03	0.80	0.02	0.01
Potassium (%)	1.19	0.97	0.06	1.50	0.73	0.19
Magnesium (%)	0.29	0.14	0.06	0.32	0.08	0.07
Chlorine (%)	0.18	0.03	0.01	0.12	0.04	0.02
Heating Value (MJ/kg)	19.4	20.1	20.3	23.7	16.1	20.9

2.2. Experimental Apparatus and Procedure

The combustion behavior of single particles of torrefied biomass samples of this study was monitored in an electrically-heated, laminar, drop-tube furnace, also manufactured by ATS. That furnace is fitted with a water-cooled stainless-steel injector and with a transparent quartz tube with an inner diameter of 7 cm. The length of radiation zone is 25 cm, heated by eight hanging molybdenum heating elements. A schematic of the combustion setup is shown in [Fig. 1](#). Fuel particles were entrained in a metered stream of air and gas mixtures (O_2/CO_2) of two different compositions (21% and 30% O_2). O_2 and CO_2 gases were supplied by wall-mounted cylinders; their blending proportions were controlled with *Matheson* rotameters, in conjunction with appropriate charts supplied by the manufacturer, and were verified by real-time gas analysis. The flowrate of different gas mixtures (O_2/CO_2) was 0.25 L/min through a flow straightener and 0.25 L/min through the furnace injector. Fuel particles were introduced through a hole on the top of the injector, by placing a small number of particles at the tip of a beveled needle syringe, introducing the needle into the injector hole and giving it a gentle tap until single particles were seen burning in the furnace. Pyrometric observations of those particles were conducted from the top of the furnace injector, details of the pyrometer optics, electronics, calibration, and performance were given in [\[23, 27-29\]](#). An *Edgetronic* Self-Contained Digital High-Speed Broadband video camera was used, at speeds of 2000 frames per second. The camera was fitted with an *Olympus-Infinity*

Model K2 long-distance microscope lens to provide high resolution images of the combustion events.

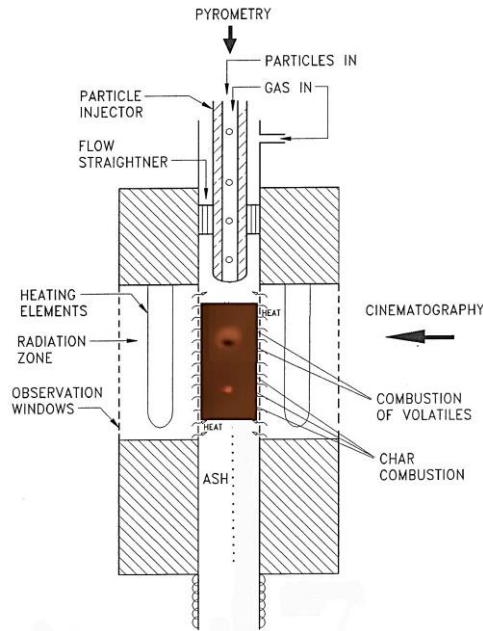


Figure 2. Schematic illustration of the drop tube furnace.

3. Results and Discussion

3.1. Combustion Observations in Air and Simulated and O₂-CO₂ Environments

Combustion experiments were conducted on single particles of the following six torrefied biomass samples: corn straw, miscanthus, sugarcane bagasse, DDGS, rice husk and beechwood in air 21%O₂-79%N₂, as well as in 21%O₂-79%CO₂ and 30%O₂-70%CO₂ environments. High-speed, high-resolution cinematographic snapshots of single torrefied biomass particles are shown in [Fig.3](#). Therein photographic sequences are shown for particles from different biomass types and different background gases, all at $T_{wall}=1400$ K, at different instances of their burnout histories. The combustion behaviors of the various types of torrefied biomass particles appear to be rather similar, despite differences in their physical and chemical properties, such as mass, shape, aspect ratios, surface structure and roughness, porosity, volatile content and chemical composition. All torrefied biomass particles in this size range of (212-300 μ m) appeared to ignite homogeneously and to burn in two phases: volatile matter combustion and char combustion. The particles ignited very close to the injector tip at the top of the DTF, immediately upon entering the radiation zone. Upon ignition, the flames surrounding individual particles grew bigger and increasingly luminous. For all biomass fuels at all gas compositions, the envelope flames had spherical or ellipsoidal shapes. In cinematographic observations, the volatile flames could be identified easily for these torrefied biomass particles since their volatiles contain tars, which pyrolyzed and formed soot which, in turn, burned with high luminosity. Upon replacing air with a mixture of oxygen and CO₂ the particles burned in lower-luminosity spherical envelope flames. Upon extinction of the volatile flames, luminous burning of the chars commenced. Thereafter, the diameters of the chars decreased as they burned to extinction.

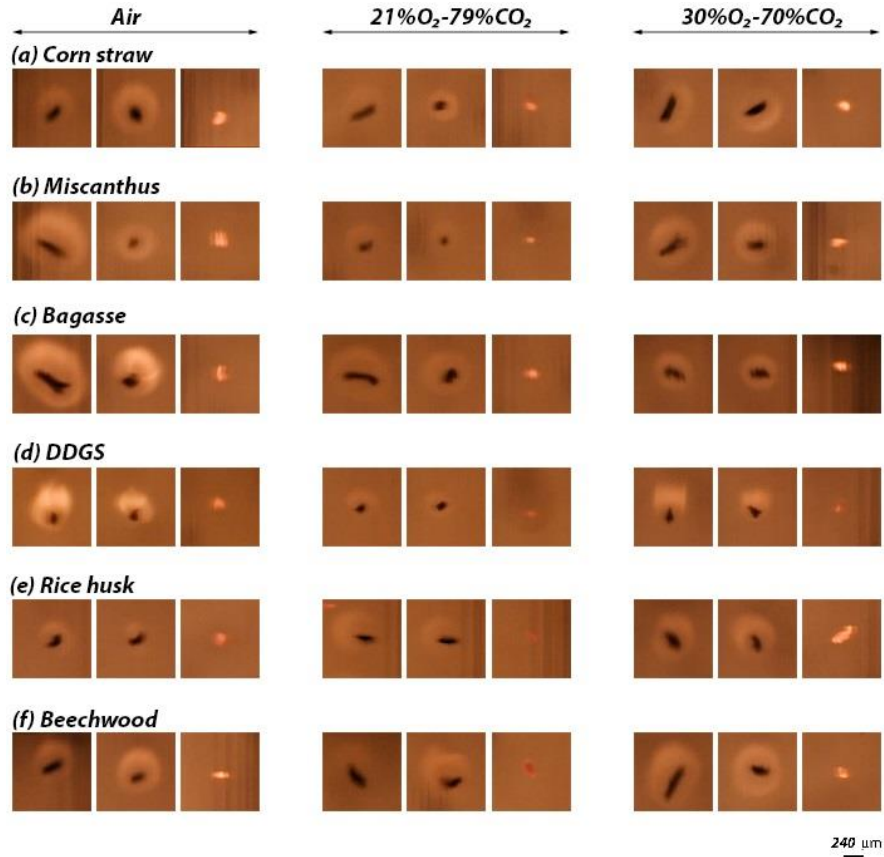


Figure 3. Images from high-speed high-resolution cinematography of single raw and torrefied biomass particles burning in air in a DTF operated at $T_{\text{wall}} = 1400$ K. Nominal initial particle sizes were in the range of 212–300 μm .

3.2. Combustion Burn-out Times:

Burnout times of volatiles and chars of the torrefied biomass particles with in air, 21%O₂-79%CO₂ and 30%O₂-70%CO₂ are shown in Figs. 4a and 4b. In each range, the combustion histories of over 20 particles were recorded and average times were calculated. Standard deviation errors are shown in each point. All burnout times were measured by optical pyrometry. Char burnout times were longer, by factors of 2, than volatile matter burnout times for all six torrefied biomass types. The volatile matter burnout time refers to the amount of time it takes for each particle to complete just the volatile phase of its combustion process. In the case of 21%O₂/CO₂ environment, the recorded volatile burnout times were in the range of 30-80 ms, whereas in the 30% O₂/CO₂ environment the corresponding recorded times were in the range of 20-50 ms. Conventional air combustion produced volatile matter burnout times ranging from 30-70 ms, falling within the thresholds generated by the combustion in 21% and 30% O₂/CO₂. By estimating the oxygen level based on this data, it can be reasoned that oxygen levels ranging from 22-29% would be needed to produce similar volatile matter time values to that of standard air. This wider range can be attributed to the variation between each biomass type. Additional experiments are needed to verify this estimation.

The char burnout time refers to the duration of the char phase in the combustion process for a torrefied biomass particle. In the case of 21%O₂/CO₂ environment, char burnout times were

recorded in the range of 80-30 ms, whereas in a 30%O₂/CO₂ environment char burnout times were in the range of 50-70 ms. Standard air combustion produced burnout ranging from 80-100 ms, falling within the thresholds generated by 21% and 30% oxygen concentration.

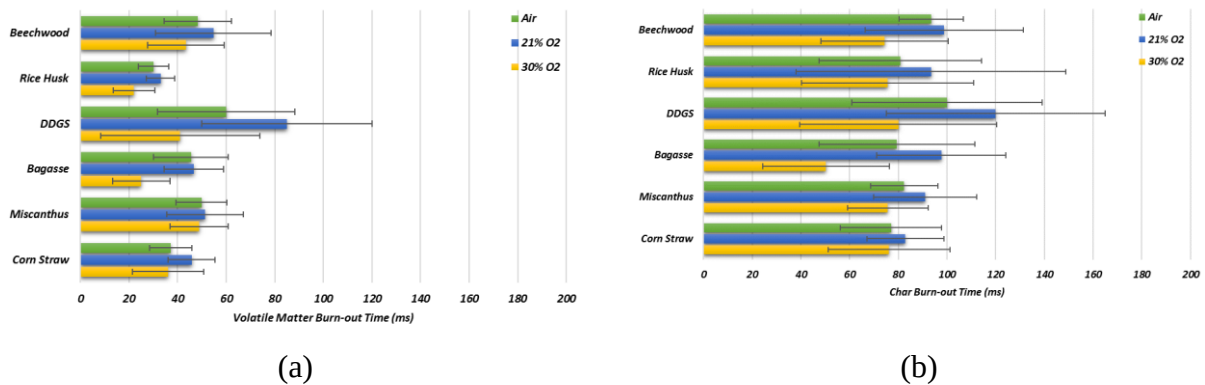


Figure 3. Experimental data on combustion times of (a) volatile flames (b) chars of torrefied biomass particles in three ranges within 212-300 μm in a DTF at $T_{\text{wall}} = 1400 \text{ K}$ in air.

Again, by estimating the oxygen level based on this data, it can be approximated that oxygen levels ranging from 21-29% would be needed to produce similar volatile matter time values to that of standard air. This wider range can be attributed to the structural and compositional variations in the biomass types. Yet again, additional experiments are needed to verify this estimation.

The total (cumulative) particle burn-out times were obtained by adding both the volatile matter burnout times and char burnout times, and are shown in Fig. 4. For combustion in the 21%O₂/CO₂ environment, the biomass fuel particles experienced burnout times within the range of 130-200 ms, while particles burning in the 30%O₂/CO₂ environment experienced shortened burnout times, in the range of 75-160 ms. The shorter times can be attributed to the more intense combustion behavior that is observed the higher oxygen concentration. Combustion conducted in the standard air environment resulted in burnout times in the range of 120-160 ms, but when analyzing the specific biomass types, it was estimated that average oxygen concentrations in the range of 24-29% would be necessary to have an equivalent simulated oxy combustion environment that is equivalent to air combustion in relation to the total particle burnout time.

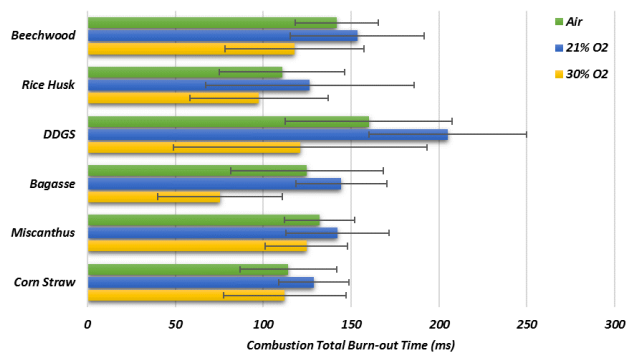


Figure 4. Comparison of cumulative combustion times of single torrefied biomass particles of 212-300 μm burning in a DTF at 1400 K in air.

4. Conclusions

In this work, six torrefied biomass fuels were burned in a laboratory laminar-flow electrically-heated drop-tube furnace, fitted with a transparent quartz tube at a furnace temperature of 1400 K. High temperature, high-heating rate combustion of these biomass samples, pulverized and sieved in the nominal size range of 212-300 μ m, occurred in the single particle mode. High-speed high-resolution cinematography of the fuel particles at their initial states were used to assess the combustion behavior of the fuels. Such observations revealed that biomass particles experienced intense fusion, shrinking, and apparent spheroidization during high-heating-rate high-temperature devolatilization. Replacing the background gas from air to an oxy-fuel atmosphere, at 21%O₂ in CO₂ reduced the luminosity of flame and prolonged the burnout times of the biomass particles; whereas increasing the oxygen mole fraction in CO₂ to 30% increased the luminosity of the flame and shortened the burnout times of the biomass particles.

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