Biomass and Bioenergy 117 (2018) 102–114

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

The effects of nozzle design on the combustion of wood-derived fast pyrolysis oil

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ARTICLE INFO

Keywords:
Pyrolysis oil
Pyrolysis liquid biofuel
Combustion
Spray
Nozzle design
Pollutant emissions

ABSTRACT

Researchers examined how nozzle design influences the combustion and emissions of a 10 kW, pure fast pyrolysis oil (FPO) flame from a swirl burner within an insulated combustor using an internally mixed air-blast nozzle. No other studies are known that conducted a detailed investigation of the effect of nozzle design on the combustion and emissions of a pure FPO spray flame. FPO (also called bio-oil or pyrolysis liquid biofuel) is a biofuel made from waste wood, but its properties, especially its high water content, make efficient combustion challenging. Combustion experiments showed how carbon monoxide (CO) emissions, nitric oxide (NO) emissions, carbonaceous residue, flame stability and nozzle coking were influenced by the nozzle's mixing chamber diameter and outlet number/diameter, angle and total area. Ultimately, an optimized nozzle was designed that achieved a self-sustaining FPO flame with excellent stability, low emissions and low coking; it also operated under "cold-start" conditions and at steady-state conditions, did not require a pilot flame to maintain a stable, seated flame. The results show that with careful nozzle design, FPO is able to perform very effectively in burners and can therefore help to facilitate the replacement of fossil fuels.

1. Introduction

The reduction of greenhouse gas emissions from the combustion of fossil fuels has motivated the search for alternative fuels. Biomass derived fast pyrolysis oil (FPO) (also called bio-oil or pyrolysis liquid biofuel) is often regarded as the most feasible renewable fuel to facilitate the replacement of petroleum fuels in combustion applications [1]; and it is also the lowest cost liquid biofuel available [2]. A detailed life cycle assessment concluded that greenhouse gas emissions from power generation could be reduced by 77–99% just by switching current facilities from fossil fuels (natural gas, fuel oil and coal) to FPO [3]. Currently, FPO is beginning to replace heavy and light fuel oils in large-scale industrial furnaces and boilers [4–7] and the world's first combined heat and power plant, running on FPO, was commissioned in 2013 by Fortum in Finland [8].

FPO can be made from a wide variety of biomass feedstocks, but it is commonly a wood-derived fuel (as it is for the research in this paper). Wood feedstocks provide the best quality fuel because of their higher energy density and yield along with their lower ash, nitrogen and water content compared to fuels made from other feedstocks [2,9–13]. The FPO used in this study was made from waste wood in a circulating fluidized bed reactor, illustrated in Fig. 1, which involves the decomposition (or thermal cracking) of the biomass feedstock in the absence of oxygen at 400–500 °C for about 2 s [14].

FPO's composition and properties still present unique atomization and combustion challenges that need to be addressed. A detailed comparative analysis of typical FPO, the FPO used in this research and conventional fuels is provided in Table 2 in Section 2. FPO typically has a water content of 15–30% which causes combustion instabilities, a low energy density, poor ignition, a lower flame temperature and an elevated surface tension, but a reduced fuel viscosity. Other combustion challenges arise because FPO is oxygenated, acidic (requiring stainless steel for whetted components), thermally unstable (ages at room temperature), contains char, ash and fuel-bound nitrogen, has limited volatility and rapidly polymerizes at elevated temperatures above 80–90 °C. Aging causes a decrease in volatility and heating value and an increase in viscosity, non-evaporative components (including solids) and water content; all of which degrade atomization and combustion processes and increase emissions [6,11,17–22]. Blending FPO with alcoholic solvents, such as ethanol, has been shown to significantly lower viscosity and surface tension (as does fuel preheating), while stabilizing the fuel against aging and improving many of its poor properties, including its low volatility. However, blending also can significantly increase fuel costs, reducing FPO's potential for commercialization [6,11]. Enhanced combustion performance of FPO has been demonstrated when blended with ethanol [11,18,20,23–28] or when co-fired

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https://doi.org/10.1016/j.biombioe.2018.07.002
Received 16 February 2018; Received in revised form 21 June 2018; Accepted 4 July 2018
0961-9534/

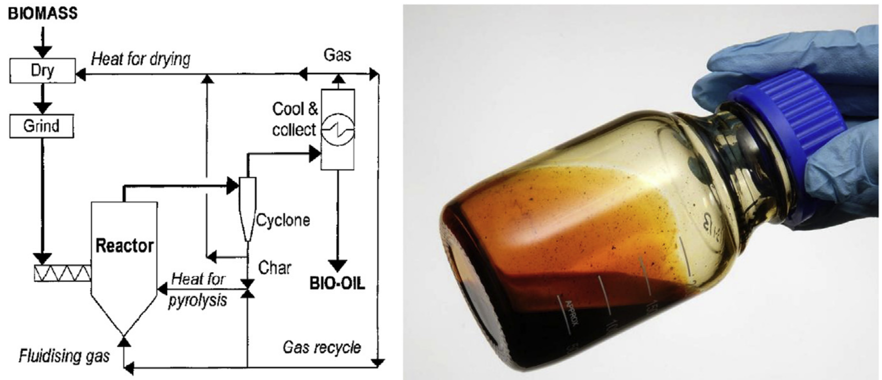

Fig. 1. A schematic of the fast pyrolysis process [15] (left) and the final FPO product [16] (right).

with conventional fuels such as natural gas [5,6,29], but this research project aims to show the potential of FPO as a sustainable energy alternative in its own right, without any blending with other fuels.

Fine spray atomization is needed for FBO due to its limited volatility and slow ignition. As a result of its fuel properties, FPO typically requires a longer residence time for complete oxidation compared to standard petroleum fuels [30,31]. Efficient atomization relies predominantly upon three fuel properties: viscosity, surface tension and density; viscosity is generally considered to be the most crucial property and density the least crucial [32]. FPO requires more energy (from airflow if using a twin-fluid nozzle) to be effectively atomized because for FPO at 80 °C, its surface tension and kinematic viscosity are around 33 mNm^{-1} and 6×10^{-6} m^2s^{-1} respectively while diesel at 40 °C has properties around 23×10^{-3} Nm^{-1} and 3×10^{-6} m^2s^{-1} respectively [11]. If not properly atomized, fuel droplets will be much larger and combustion efficiency will be substantially reduced.

Twin-fluid nozzles generally achieve primary atomization with air and are internally or externally mixed, the former giving higher efficiencies while the latter removes flashback dangers during combustion. For these nozzles, airflow rate is often the most crucial parameter for improving spray quality with asymptotic behaviour above a certain point [32]. In reacting sprays, a higher atomizing airflow rate also induces strong turbulence that enhances fuel/air mixing, but consequently also increases the local shear rates which, if too high, can cause the flame to extinguish. Twin-fluid nozzles are often less sensitive to liquid properties, particularly viscosity, especially if internally mixed [33]. Twin-fluid air-blast nozzles are characterized by their use of high amounts of air at low pressures for atomization [34].

Classic atomization mechanisms, where external forces cause instabilities which ultimately grow to form droplets, depending on initial liquid dimensions and viscosity, no longer occur for twin-fluid nozzles above a certain value of relative velocity and/or air/liquid impingement angle. Beyond this point, atomization switches to a so-called "prompt" mechanism where the liquid disintegrates almost instantaneously before instabilities can form or grow [34–36]. With prompt atomization, drop sizes are mainly determined by the magnitude of the air velocity component normal to the liquid, along with the air-to-liquid mass flow ratio (ALR) and surface tension [34]. Relying on surface tension for atomization is advantageous for FPO sprays since this property tends to differ less than its viscosity compared to conventional fuels.

This study was based upon previous FPO combustion research in a swirl burner [37,38] which indicated that FPO was very sensitive to burner operating parameters, particularly the atomizing airflow. When the airflow was not optimal, the flame would easily destabilize or blowout due to the fuel's low volatility and poor ignition characteristics, making it difficult to address the multitude of other atomization and combustion challenges [37,38]. Further progress with FPO combustion could not be made without an understanding of how to optimize the nozzle characteristics and spray pattern.

The overall goal of this research is to understand the how nozzle design characteristics, such as nozzle dimensions and atomizing air flowrate, influence the stability and emissions of the FPO combustion. Studies have shown that internally mixed twin-fluid nozzles are an effective strategy for FPO atomization, especially compared to externally mixed twin-fluid [18] or pressure atomized nozzles [39,40], but the key design parameters that contribute to these nozzles' effectiveness have not been researched extensively. With this knowledge, an optimized nozzle was developed that produced a strong, seated flame with low coking and low emissions without using fuel blending or a secondary fuel. On an industrial scale, secondary fuels can be prohibitively expensive, reducing commercial adoption of this fuel for sustainable power generation [6].

2. Experimental methodology

The combustion experiments utilized a swirl burner within a double-insulated combustor at a fuel energy throughput of 10 kW (about 5.93×10^{-4} $kg\,s^{-1}$), as illustrated in the schematic diagram in Fig. 2. Primary combustion air was pulled in with a stack fan at 5.7×10^{-3} – 6.0×10^{-3} $kg\,s^{-1}$ which was found to minimize CO emissions and nozzle coking in preliminary testing. This primary air was then passed through a swirl box (swirl number of 3.38 [37,38]) before entering the combustor to induce hot-gas recirculation back towards the nozzle in order to improve fuel ignition. The primary airflow rate was kept constant throughout all the combustion experiments since it controls the recirculation dynamics of the combustor which were previously shown to be critical parameters for important combustion characteristics, such as coking and flame stability [37,38]. The primary air was heated to about 175 °C and then used to heat the FPO up to 80 °C, also heating the atomizing air in the process. A 0.3–0.35 kW methane/oxygen pilot flame system was used for fuel ignition and to stabilize the FPO flame during regular operation. Considering the primary combustion air, the pilot flame and the atomizing air, the combustion had an equivalence ratio of 0.58–0.61, 64–72% excess air and 7.4–8.0% O_2 in the exhaust. The effect of varying the atomizing air was within the error margin of the primary air flow rate. The burner was started on ethanol and heated, for about 45 min, until the exhaust temperature was above 500 °C, at which point the fuel was switched to FPO and allowed to reach steady state as determined by CO emissions. Two quartz viewports allowed for direct visualization of the flame and the nozzle. The FPO was delivered to the burner using a gear pump retrofitted with polyether ether ketone gears as this polymer is compatible with FPO [41] and a scale was used to continuously monitor the fuel mass flow rate into the combustion chamber. Full details of the experimental methodology are available [42].

CO emissions were used to assess combustion quality. Exhaust emissions were pulled through a Fourier Transform Infrared (FTIR)