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Spray combustion characteristics of kerosene/bio-oil part I: Experimental study

S.I. Yang*, M.S. Wu, T.C. Hsu

Department of Power Mechanical Engineering, National Formosa University, Yunlin County, 63202, Taiwan

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ABSTRACT

Applying bio-oil generated through thermochemical conversion in power plants is a crucial problem in current energy studies. In this study, varying proportions of cedar sawdust bio-oil produced through fast pyrolysis were mixed in the kerosene samples to analyze their spray combustion characteristics with various oxidizer velocities. These results indicated that the spray angle increased with increased oxidizer velocity, reducing the droplet distribution. Moreover, the turbulence effect enhanced the effect of mixing the vaporized droplets and the oxidizer, thereby hastening and intensifying the combustion and shortening the flame length and lift off. The bio-oil produced through fast pyrolysis contained various types of volatile substances. Therefore, increasing the bio-oil proportion in kerosene reduced the spray combustion regime. Additionally, when the volume percentage of bio-oil in kerosene reached 15%, the low heating value of the bio-oil lowered the flame temperature in combustion. Furthermore, the emission of various substances during combustion was closely correlated with the oxidizer velocity and bio-oil proportion.

1. Introduction

Environmental damage and energy insufficiency in recent years have prompted an increasing number of studies on alternative energy. According to statistical data from the International Energy Agency [1], in 2012, oil constituted approximately 31.4% of the global total primary energy supply, whereas bio-fuel and wastes represented approximately 10.0%. Furthermore, oil constituted approximately 40.7% of energy consumption, and bio-fuel and wastes represented approximately 12.4%. Regarding sectoral use, 63.7% of the oil was used in the transportation sector, and 8.5% was used in the industrial sector. Furthermore, oil use was the source of 35.3% of the global CO_2 emissions. These statistics indicate that oil is the most prominent type of energy consumed and the primary cause of global CO_2 emissions. Currently, oil is primarily used for transportation and industrial operations through spray combustion. Bio-fuel energy production has increased annually, and replacing fossil fuel with the liquid fuel generated using bio-fuel and wastes in existing power systems has become a critical problem. In past years, bio-oil, which is produced through the thermochemical conversion of biomass residues, has replaced some fossil fuels for powering internal combustion engines and boilers. Pyrolysis is a thermochemical conversion approach for biomass [2–4] and involves converting biomass to usable liquid fuel in a mid-temperature (450°C–600 °C) and atmosphere environment. The compositions of biomass affect the characteristics of thermal pyrolysis products. Biomass is composed primarily of cellulose, hemicellulose, and lignite as well as other types of extracts and minerals. The fast pyrolysis of biomass generates 70–75 wt% of feedstock bio-oil, depending on the biomass type and composition [5–8]. Ferdous et al. [5], Yang et al. [6], and Wang et al. [7] investigated the characteristics of the cellulose, hemicellulose, and lignite in various types of biomass in a pyrolytic environment through thermogravimetric analyses, and found that the aforementioned three primary biomass substances exhibited different pyrolytic behaviors at varying environmental temperatures. Thus, creating each type of feedstock requires a unique pyrolytic temperature and bio-oil yield [8–10]. Numerous studies have examined the characteristics of biomass fast pyrolysis products by using reactors [8–13] such as fluidized bed [8], fixed bed [9,10], circulating fluidized bed [11], cyclone [12], and tubular reactors [13]. The results revealed that the types of reactors and operating parameters used influence the yield and characteristics of bio-fuel and subsequently its storage and application.

* Corresponding author. Tel.: +886 5 6315432; fax: +886 5 6312110.
E-mail address: ianyang@nfu.edu.tw (S.I. Yang).

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Bio-oil is created through the thermochemical conversion of biomass and thus has physical and chemical properties that are distinct from those of fossil diesel, kerosene, and gasoline. Mixing bio-oil and fossil fuel is difficult and typically requires emulsion [14]. The liquid fuel is atomized into droplets and mixed with oxidizers before it is combusted in a combustion chamber. The process of spray combustion is considerably complex and is affected by several factors such as droplet size, velocity and distribution, reacting flow and temperature fields, fuel and fuel-air ratios, and pressure–droplet interactions. Because bio-oil and petroleum fuels have distinct characteristics (e.g., oxygen content, volatility distribution, viscosity, aging, and corrosiveness), their combustion characteristics differ. Therefore, adding bio-oil to a petroleum fuel changes the original air–fuel ratio and combustion characteristics of the fuel [15]. The resulting mixed fuel enables generating steady, self-sustaining flames and exhibiting higher particulate and CO emissions. Different biomass materials generate distinct types of bio-oil. Stamatov et al. [16] employed three biomass materials to produce bio-oil, which was then mixed with ethanol and subjected to combustion. Their results showed that the flame produced by the mixed fuel was shorter, wider, and brighter than that of a pure diesel fuel; this difference was mainly caused by how the bio-oil changed the physical and chemical properties of ethanol and thereby changed its combustion characteristics. Moreover, Tzanetakis et al. [17], Zheng and Kong [18], and Lehto et al. [19] have adopted various biomass materials to produce and mix bio-oil with petroleum fuels, which were then used to conduct spray combustion and investigate the atomization and combustion characteristics of different types of bio-oil. The atomization quality was evaluated using the Ohnesorge number. Their results indicate that bio-oil produced through different biomass materials features dissimilar physical properties, which in turn changes its atomization level and chemical properties; accordingly, the combustion characteristics are affected. The aforementioned studies have confirmed that the composition of bio-oil influences its spray combustion properties and effectiveness. Therefore, the present study examined the compositions and blending of kerosene and bio-oil generated through the pyrolysis of cedar wood. The spray combustion characteristics and flame light emission of the blended fuel were analyzed to investigate the effect of bio-oil on the flame generation and pollution emissions of kerosene. The results can serve as a reference for upgrading bio-oil-related technology and optimizing the designs of spray combustion nozzles.

2. Experimental methods

This study examined the combustion characteristics of kerosene mixed with cedar pyrolysis bio-oil by using a spray-atomized combustor, as displayed in Fig. 1. The fuel and air coaxially entered the combustor through the fuel inlet. The liquid fuel was atomized to droplets by the nozzle orifice. Air entered the combustion chamber from the two axial sides of the combustor to induce the burning of the fuel droplets. A constant fuel flow rate was employed, with varying air inflow rates.

Fig. 2 illustrates the spray combustion test platform used in this study to explore the combustion characteristics of the kerosene mixed with cedar pyrolysis bio-oil. The platform comprised the spray-atomized combustor (Fig. 1), fuel supply systems, a photographic system, temperature and emission analyzers, particle image velocimetry (PIV), and a particle measurement system. The bio-oil and kerosene were mixed with two different emulsifiers and stored in the fuel tank [14]. The fuel tank was composed of pressurized nitrogen bottles, high-pressure liquid storage tanks, high-pressure pipes, seamless pipes, flow meters, and adjustable metering valves. The liquid fuel in the storage tanks was forced into

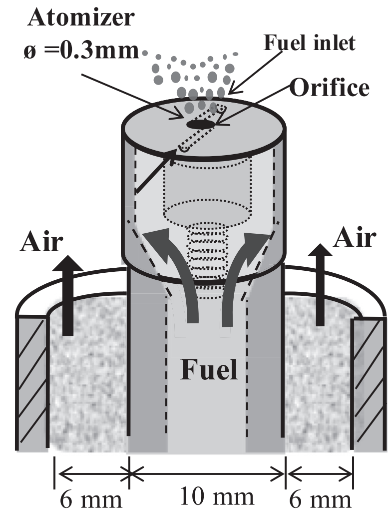

Fig. 1. Spray-atomized combustor.

the spray-atomized combustor by the pressurized nitrogen and atomized into droplets. The spray nozzle was installed in the flame holder composed of 4 glass sides. Attached on one of the sides was a thermocouple to measure the fire temperature distribution, and the exhaust gas was assessed at the top of the combustor chamber.

The cold reaction flow distribution in the combustor was measured through the PIV, and the droplet size distribution was evaluated using a laser diffraction particle size analyzer. Fig. 2 illustrates the PIV system, in which the light source was provided by a 5 W/532 nm Nd:YAG continuous wave laser (CWL). The laser light passed through the central axis of the spray flow field, while an 800 $\times$ 600 pixel high-speed camera captured images at a rate of 5000 fps with exposure time of approximately 80 μs.

The laser diffraction particle sizing system, in which a Malvern SprayTECH laser diffraction particle size analyzer (LDPA) was used as the measuring device. In the spray field, particle size at six positions was measured. The measurable range of particle size was 0.1 μm–1000 μm. The SMD obtained from the LDPA was analyzed to explore the effects of viscosity and GLR on particle size. SMD was calculated using Eq. (1).

$$SMD = \frac{\sum D_i^3 n_i}{\sum D_i^2 n_i} \quad (1)$$

The reaction flow field was recorded directly by using a high-speed camera, and the chemiluminescence of the flame waves was observed to determine the characteristics of the air–droplet mixture.

3. Results and discussions

The spray combustion characteristics of kerosene mixed with the cedar sawdust bio-oil was examined. The oily-phase product of pyrolysis bio-oil produced from cedar sawdust was mixed with kerosene, atomized into droplets, and mixed with the air and combusted to measure its combustion characteristics. The experiment was conducted to analyze the effect of various air flows with a constant fuel flow (Table 1) on the spray combustion characteristics of the mixed products.

The primary factors affecting the spray combustion efficiency were the formation and vaporization of droplets, fuel characteristics, and oxidant–droplet mixture properties. Fig. 3 depicts the relationship between the combustion and cold reaction flow fields.