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Spray atomization of bio-oil/ethanol blends with externally mixed nozzles ☆

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ABSTRACT

Experiments were conducted to investigate the properties of sprays of pyrolysis oil (bio-oil) blends with ethanol using an air assisted atomization nozzle operated without combustion. This was done in order to explore the potential for pyrolysis oil combustion in industrial and residential furnaces. The liquid samples investigated were bio-oil blends with ethanol (EtOH), neat ethanol and diesel. The bio-oil:EtOH blends were prepared in concentrations of 20:80 and 40:60 vol%. Twin-fluid externally mixed nozzles SU2, SU4, and SU5 with liquid orifice areas of 0.40, 1.82 and 5.07 mm^2, respectively, were used in the spray experiments. The liquid and atomizing air flow rates as well as temperature were controlled to maintain constant liquid flow rates (cc/s) equivalent to 30 and 50 kW energy input. Images of atomized spray droplets were measured to determine their size and velocity. Results show that it is possible to spray bio-oil/ethanol mixtures containing up to 40% bio-oil that has a low water content (12.60%). High viscosity and a tendency to coagulate were the main drawbacks; however, the 20:80 bio-oil:EtOH blend and neat ethanol in all three nozzles exhibited spray characteristics similar to that of diesel over atomization air flow rates of 15–30 SLPM.

1. Introduction

Conversion of biomass to energy has attracted substantive interest among policy and decision makers in recent years. Climate change, largely caused by greenhouse gases emitted by the combustion of fossil fuels, and the fact that the world's fossil fuel reserves may decline in the near future [1] prompts the search for sustainable alternatives. The availability of sustainable and reliable energy sources is essential to economic growth for developing and developed nations. "While Africa gives off less greenhouse gasses than any other part of the world, it will be the most threatened by climate change," as stated by US President Barack Obama during a visit to Africa [2]. Biomass energy resources possess numerous advantages which include renewability and the fact that they are more evenly distributed across the world than fossil fuel resources. However, conversion of biomass resources to energy presents challenges due to feedstock variability and heterogeneity. This leads to variation of fuel quality, consequently affecting the performance of combustion systems.

One of the current biomass conversion technologies that has tremendous potential for rural development is fast pyrolysis [3]. Fast pyrolysis is the thermal decomposition of biomass in the absence of oxygen which is done at a high heating rate in order to obtain high yields of liquid products. Fast pyrolysis is a promising technology for the production of fungible fuels [4,5,6,7]. The resulting pyrolysis oil is a renewable "green" fuel. Its use could be important in addressing energy resource issues such as local availability of energy sources and reduction in harmful emissions encountered in fossil fuel combustion [8]. Owing to their small design footprints, pyrolysis systems are amenable to distributed scale economy rather than large-scale. Therefore their implementation could involve cooperative agriculture whereby they are deployed at the village and farm scales where the biomass is used as a feedstock. This could allow for utilization of the bio-oil in a centralized combustion plant for power generation within a community [9]. Although pyrolysis oil can be produced in high yields (~60–70%) by using fast pyrolysis, the liquid is unstable thereby presenting serious challenges to its use as fuel for internal combustion engines. Trials in direct injection engines have been conducted [10,11]. However, acidity, high water content, high oxygen content, variable volatility, and the presence of char all contribute to

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Nomenclature

Units of terms

σ	surface tension (N/m)
ρ	density (kg/m^3)
μ	dynamic viscosity (cP)
$\dot{m}$	mass flow rate (kg/s)
D	diameter (m)
m	mass (kg)
EtOH	ethanol
HHV	higher heating value (MJ/kg)
SMD	Sauter mean diameter (μm)
SLPM	standard liters per minute
U	velocity (m/s)

Subscripts

A	air
L	liquid
o	liquid orifice
R	relative velocity

atomization problems; other issues associated with its use are ignition delay, increased coking, and increased particulate emissions.

Bio-oils are viscous and possess slight shear thinning characteristics [12]. There has been some success reported on the use of pyrolysis oils in burners [12,5,13]. Most liquid fuel burners use nozzles to disperse liquids into smaller droplets (sprays) to allow for better mixing of the fuel and oxidant that will take part in subsequent combustion. Among the many types of nozzles which are available, air-atomized (twin-fluid) nozzles are the most widely used [14,15]. Of the air-atomized nozzles, atomizers creating hollow cone sprays are preferred as they provide better mixing and stable flame [16]. In air-atomized nozzles the high-velocity air stream introduces a series of instabilities in the liquid stream, causing it to break into smaller droplets [17]. Additionally, with reference to burners that use twin-fluid nozzles, the non-Newtonian characteristics of bio-oil could have negative effects on droplet formation or atomization [18,17].

Sprays of palm oil blends with diesel had been characterized by using phase Doppler particle analysis method, and it was found that the high viscosity of vegetable oils resulted in sprays having large Sauter mean diameter (SMD) values and small spray angles [19]. However, major challenges still remain in the use of neat vegetable oils due to their high viscosity which prevents efficient atomization in combustion systems [20].

Droplet combustion rates of pyrolysis oils are about 2–3 factors less than that of light diesel [10,21]. This results from its high density and high latent heat of vaporization. Additionally, the wide range of volatility exhibited by the numerous components in pyrolysis oil results in droplet fragmentation and micro-explosions, reducing the burning rate and consequently, combustion efficiency. Hence, the use of bio-oil as fuel in combustion systems is challenging due to the resulting problems such as poor atomization, ignition delay, propensity to coke, and increased particulate emissions [22,23]. It should also be noted that, bio-oils are combustible but not flammable, attributable to the presence of nonvolatile components. To expand pyrolysis oil utilization in combustion systems, the appropriate burner system need to be developed that mitigate some of the issues identified with spray atomization. Because of this, a study on the non-combustion spray characteristics of pyrolysis oils is important and can contribute to the understanding of spray characteristics exhibited by different nozzle sizes and spray conditions. While various studies in spray atomization of other types of bio-oils have been done, (for example that reported by Fan et al. [24] and Kim et al. [25]), the externally-mixed nozzle types (previously been used to successfully atomize high viscosity liquid fuels) have not been attempted or fully explored for pyrolysis oils.

The aim of this study is to investigate the spray characteristics of bio-oil/ethanol blends in an externally mixed nozzle within three size ranges at different spray conditions. This can aid in selecting, designing or retrofitting burners for combustion chambers to effectively handle the efficient combustion and greater utilization of pyrolysis oils. Blends of pyrolysis oil with ethanol were used to control viscosity so as to advise the incremental effect of viscosity and the extent of pyrolysis oil utilization. Ethanol was chosen because it is a good solvent, can be used as fuel, and can be produced sustainably from biomass. In order to understand the spray characteristics, the variation in droplet sizes and discharge velocity of bio-oil blend sprays were compared with that exhibited by diesel (No. 2 fuel oil) using different sizes of air-assisted atomization nozzles at constant bio-oil flows equivalent to an energy input of 30 and 50 kW.

2. Methodology

2.1. Materials

The bio-oil used in these experiments was a composite mixture of bio-oils created from switchgrass (60%), miscanthus (20%), and elephant grass (20%), by volume. Each constituent bio-oil was produced in a bubbling fluidized bed reactor [7] under nitrogen atmosphere at 500 °C. The ethanol used was Koptec 200-proof alcohol. Diesel (No. 2 fuel oil) used was purchased from a local gasoline service station in Wyndmoor, Pennsylvania.

Bio-oil and ethanol blends were prepared in the laboratory by mixing the bio-oil and ethanol in beakers at room temperature. On a volumetric basis, the 20% and 40% bio-oil component were mixed with ethanol making up the rest to obtain 20:80 and 40:60 bio-oil:EtOH blend components respectively. The measured amounts of bio-oil and ethanol were poured into a beaker and stirred until well mixed.

The samples, including the control liquids (i.e., the diesel and ethanol) were analyzed to determine their physical and chemical properties. The viscosity of the liquid fuel samples was measured in a Grabner Minivis II viscometer at 25 °C. Density was determined by drawing 1 mL of each liquid into a syringe and weighing it on an analytical balance. The carbon, hydrogen, and nitrogen contents were determined by a ThermoElectron 1112 series – flash elemental analyzer, with oxygen content determined by difference. The water content of each sample was determined by Karl Fischer titration. Heat of combustion was estimated from the Institute of Gas Technology (IGT) correlation (Eq. (1)) using the elemental analysis results [26]. Eq. (2) was used to estimate the theoretical Sauter mean diameter for droplets from a plain-jet air-blast atomizer [27,28]. The equation used to calculate liquid flow rate based on a given energy input, and the derivation for calculations of secondary air required can be found in the Supplementary Material.

$$\mathrm{HHV(kJ/kg)} = (\%\mathrm{C} \times 341) + (\%H \times 1343) - (\%N \times 120) - (\%O \times 120) \qquad (1)$$