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Characteristics of flame stability and gaseous emission of biocrude-oil/ethanol blends in a pilot-scale spray burner

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ABSTRACT

A burner system with capacity of 30,000 kcal/h was designed for the combustion of biocrude-oil and ethanol blends. An air atomizing spray nozzle with larger fuel orifice was adopted to prevent nozzle clogging, with swirl flow introduced to the combustion air for flame stabilization. Biocrude-oil was prepared from the fast pyrolysis of woody biomass and was blended with ethanol to improve flame stability and ignition characteristics. At various mixing ratios of biocrude-oil and ethanol, flame stability was determined, and gaseous emissions of CO and NO were measured. It was found that stable combustion could be achieved with up to 90 vol% of biocrude-oil. CO emissions of biocrude-oil/ethanol blends were smaller than those of pure ethanol, whereas CO concentration increased significantly in case of pure biocrude-oil due to incomplete combustion. Pollutant NO emission increased slightly with the biocrude-oil mixing ratio. The biocrude-oil burner in this study could provide a design database for industrial burner development.

1. Introduction

The utilization of renewable energy has been one of the key issues with regard to the depletion of fossil fuels and environmental problems. Nowadays, biomass is widely studied as sustainable energy source and clean fuel to prevent global warming. The emissions of CO_2 from biomass utilization are equivalent to its fixed amount from the photosynthesis; therefore, biomass can be considered a “carbon-neutral” energy source. One of the promising utilization fields of biomass is the biocrude-oil produced from the fast pyrolysis of biomass. Fast pyrolysis is a thermochemical conversion process of biomass into liquid oil through the hot vapor from the thermal decomposition of biomass particles [1,2]. There have been a large number of studies on biocrude-oil production in various types of fast pyrolysis reactors such as bubbling fluidized bed reactor, circulating fluidized bed reactor, ablative reactor, rotating cone reactor, vacuum reactor, conical spouted bed reactor, and tilted-slide reactor [3–7].

Biocrude-oil has distinctive chemical and physical characteristics in comparison with conventional petroleum fuels. It consists of hundreds of species derived from cellulose, hemicellulose, and lignin compounds in biomass and contains a large amount of water ranging from 15 to 30 wt%. The lower heating value (LHV) is typically 14–18 MJ/kg, and the volumetric energy density of biocrude-oil is 50–60% of that of petroleum fuels [2]. Moreover, it has relatively higher viscosity (10–100 cP at 40 °C) and contains solid particles. These characteristics cause different combustion behaviors from petroleum fuels, requiring thorough investigation on the combustion characteristics of biocrude-oil to be applied to practical combustors. There have been studies on the combustion fundamentals of biocrude-oil droplet [8–10] and on the combustion characteristics in thermal and power devices of industrial boilers, gas turbines, and diesel engines [11–16]. More detailed investigations on the spray combustion characteristics of biocrude-oil [17–23] have been performed as well. In the application of biocrude-oil to a diesel engine, some problems of corrosion and clogging were reported [24]. This is known to be attributable to the high acidity and viscosity of biocrude-oil, and long-term operation should be further validated in a diesel engine. In the area of industrial boiler or agricultural heating system, however, precise fuel orifice or high-pressure injection is less required, and direct biocrude-oil application might be possible with adequate burner development.

Previous studies suggest blending biocrude-oil with ethanol to

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improve spray behavior by reducing the high viscosity and to promote flame stability by increasing the overall fuel volatility [17,18,21–23]. Furthermore, the fuel and the combustion air were preheated to achieve even lower viscosity [21] and to increase flame stability, respectively; a pilot flame was adopted to assist in spray ignition near the fuel nozzle tip [22]. These techniques could improve the overall spray combustion characteristics together with flame stability. Note, however, that the corresponding components should be added to the burner, which can render complexity to the system and cause difficulties in operation. In this study, a biocrude-oil combustor that can offer stable operation was developed without additional components such as pilot burner for flame stabilization. The characteristics of flame stabilization were investigated, and gaseous emissions were also measured.

2. Materials and methods

2.1. Biocrude-oil burner setup

To investigate flame stability and pollutant emissions, a biocrude-oil burner was designed with capacity of 30,000 kcal/h (35 kW). This value was determined as a pilot scale (10%) of burner capacity of 300,000 kcal/h (350 kW) to heat a unit of a plant farming greenhouse with area of 3,300 m^2.

The burner system was composed of the burner unit, combustion chamber, fuel tank, air compressor, and flow control units for fuel and air as shown in Fig. 1. In the biocrude-oil burner, the selection of the fuel nozzle is important due to its high viscosity. The solid residue also has the potential problem of nozzle clogging during burner operation. In the atomizing nozzle for the conventional oil burner, the liquid fuel is discharged under pressure, resulting in high exit velocity from the fine orifice. In this nozzle type, the spray formation of biocrude-oil would be difficult. Therefore, in this study, an air atomizing spray nozzle with a much larger nozzle diameter than the general one was adopted to atomize biocrude-oil [25]. It is an external mix-type nozzle that is more effective for higher-viscosity liquids. As shown in Fig. 2, fuel stream was injected from the center of the nozzle with relatively lower velocity, and high-velocity annular air was introduced from a narrow slit with rim shape surrounding the liquid jet. Due to the high frictional force between the air and liquid surfaces, the liquid column disintegrated into spray droplets. Detailed studies on the air atomizing nozzle, which is also called two-fluid nozzle or air-blast nozzle, can be found elsewhere [26–29].

Biocrude-oil was prepared from the fast pyrolysis of woody biomass by the tilted-slide reactor [7]. The fuel flow rate was controlled by a micro gear pump, and all fuel supply lines together with the fuel nozzle were composed of SUS316 and Teflon tubing for chemical resistance. The fuel was preheated at 60 °C using a heating tape prior to the fuel nozzle to reduce its viscosity, which will be discussed later in more detail.

Atomizing air was supplied from the air compressor into the air atomizing spray nozzle, where pressure was controlled at 1.5 bar by an air regulator. Combustion air was also supplied from the air compressor, and flow rate was controlled at 700 LPM by a volumetric flow meter (VFC-132-EC, Dwyer Instruments, Inc.). This flow rate corresponded to the excess air of 20%. Swirl flow was introduced to the combustion air through the swirler with vain angle of 50° surrounding the fuel nozzle exit. The swirl motion of the flow forms a recirculation zone that supports not only ignition but also flame stability [30].

The combustion chamber has a cylindrical shape with diameter of 40 cm and length of 60 cm; ceramic fiber 10 cm thick was installed on the outer wall for thermal insulation. Two viewports and one ignition port were installed on the sidewalls of the combustion chamber. The flame images were taken by a digital camera (Nikon D300). Gaseous emissions including O_2, CO_2, CO, and NO were measured using a gas analyzer (MRU NOVA 2000) at a fixed point in the exhaust duct when the flame was stabilized.

A preliminary test showed that pure biocrude-oil spray made igniting and stabilizing the flame difficult. Therefore, biocrude-oil (BCO) was mixed with ethanol (EtOH) to improve the combustion characteristics at various mixing ratios. The volumetric mixing ratios were BCO:EtOH = 1:1, 3:2, 7:3, 4:1, 9:1, 1:0, denoted by BCO50, BCO60, BCO70, BCO80, BCO90, and BCO100, respectively. For the initial startup, the combustion chamber was preheated by using pure ethanol for 15 min. K-type thermocouples were installed at 10, 20, 30, 40, and 50 cm from the nozzle exit along the centerline of the combustion chamber, and temperatures were monitored by a data logger (GL820 midiLogger) every minute to determine flame stability. For each mixture case, the experiment was performed for 30 min, with the fuel then switched to another case. Before finishing the entire experiment, the nozzle was flushed using pure ethanol for 15 min.

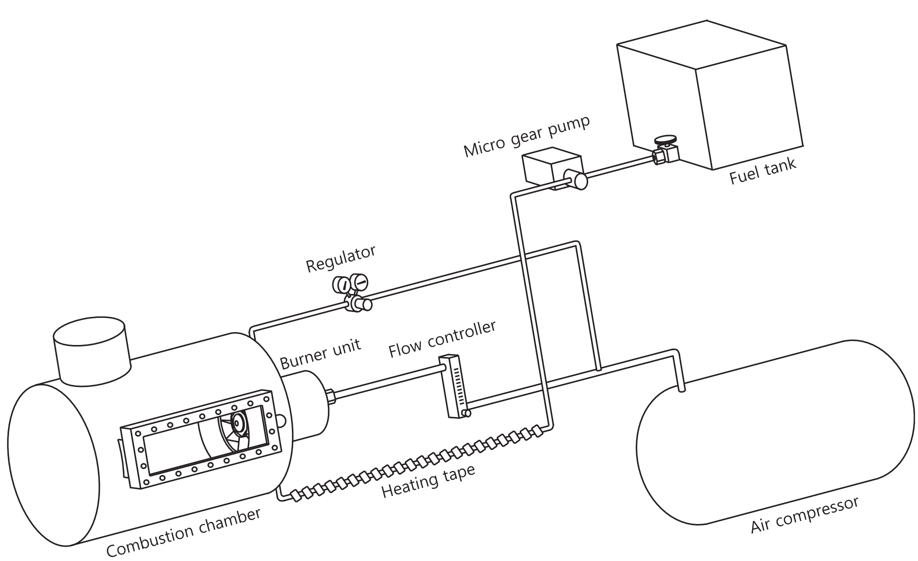

Fig. 1. Schematic of the biocrude-oil burner setup.