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Spray and combustion characteristics of biodiesel: Non-reacting and reacting

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ABSTRACT

The cold spray and spray combustion characteristics of palm biodiesel were investigated and compared with baseline Jet-A1 fuel. Both fuel sprays were generated from an airblast type atomizer and compared under the same atomizing air-to-liquid mass ratio (ALR). Under non-reacting spray condition, droplet velocity profiles for both sprays peak at the centerline due to high atomizing air momentum, while the droplet size is smallest at the spray core. Palm biodiesel generated slightly larger droplet size compared to Jet-A1 due to the effect of higher viscosity and lower volatility. Utilising an airblast atomizer-based swirl burner, spray flames of Jet-A1 and palm biodiesel were established and compared under continuous, steady swirl conditions. The droplet velocity and diameter distributions within the reacting spray flames were significantly different compared to non-reacting spray due to interaction with swirl air flow and flame within the combustor. Spray flame reaction zones obtained via OH^* chemiluminescence imaging showed that fuel droplets evaporated rapidly within 20 mm from the burner outlet. Reacting Jet-A1 flame showed smaller droplet size compared to biodiesel due to higher vaporisation rate and close proximity to flame reaction zone. Palm biodiesel showed consistently lower NO_x but slightly higher CO emissions per unit energy compared to Jet-A1 under a range of ALR tested.

Introduction

Fuel flexibility is a desirable feature for gas turbine system from the view point of reducing harmful emissions and operating cost. In recent years, rapid development of alternative fuel has enabled application of biodiesel in gas turbine operation. Biodiesel is a type of fuel derived from living organism either from plant or animal fat via a process known as transesterification (Van Gerpen et al., 2004). Biodiesel consists of a mixture of methyl esters with physical properties comparable to fossil-based diesel fuel. On molecular level, biodiesel is characteristically oxygenated with higher molecular weight but contains lower energy density than diesel. The interest of applying biodiesel in gas turbine largely stems from the merits of renewability, sulphur-free and potentially cleaner combustion. However, due to differences in quality of biodiesel depending on feedstock, rigorous testing have to be performed to characterise the spray, combustion and emission performance to ensure the suitability and reliability of biodiesel in gas turbine.

There have been reports from several groups that applied biomass-derived alternative fuel using liquid swirl flame burners (Hashimoto et al., 2008; Panchasara et al., 2009) and industrial gas turbines (Molière et al., 2007; Liu et al., 2009). Hashimoto et al. (2008) reported lower NO_x emission for palm biodiesel compared to diesel under gas turbine operating conditions. In another separate study using jatropha pure oil (JPO) and jatropha biodiesel/methyl esters (JME) conducted by the same group, it was reported that CO emission for JPO was higher than diesel and JME, whereas NO_x emission was similar for all the fuel tested especially at fixed air flow rates. Another interesting finding was that increasing biofuel mixing ratio for JPO and JME with diesel resulted in reduced radiation intensity and soot emission (Hashimoto et al., 2014). Erazo Jr et al. (2010) compared the emissions of canola biodiesel against diesel fuel using a spray flame burner. The droplet Sauter mean diameter for canola biodiesel spray was found to be smaller than diesel fuel spray under reacting condition. In-flame temperature measurement showed that canola biodiesel flame was lower

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than diesel. Emission wise, lower CO and NO emissions were shown by canola biodiesel spray flame.

Investigations of biodiesel in micro gas turbine systems have been shown feasible by several groups. Chiaramonti et al. (2013) characterised the combustion performance of rapeseed vegetable oil, biodiesel, vegetable oil/biodiesel blend using a Garrett GTP 30-67 liquid fuel micro gas turbine engine. The result showed that higher level of CO emission was obtained for vegetable oil, biodiesel and blends compared to diesel. However, lower CO emissions can be achieved by preheating the fuels. NO_x emission was found to be similar for all the fuels tested. Habib et al. (2010) tested a range of methyl esters derived from soy, canola, recycled rapeseed and methyl esters/Jet A blend in a 30 kW gas turbine engine. Combustion of biodiesel/Jet A blend and biodiesel resulted in reduced static thrust and thrust-specific fuel consumption but increase in thermal efficiency. CO and NO emissions were found to be lower for biodiesels and blends. The benefit of lower CO and NO emissions from using biodiesel was also reported by Krishna (2007) in a 30 kW micro gas turbine engine (Capstone C30) test operating with soy biodiesel. Bolszo and McDonell (2009a,b) investigated the atomization and evaporation characteristics of soy biodiesel in a Capstone C30 gas turbine atomization system under non-reacting condition. Inferior atomization of biodiesel was observed when compared to diesel. Larger biodiesel droplet was found to have longer evaporation lifetime that contributes to the increase of NO_x emissions. By increasing the atomization air-to-liquid mass ratio, better atomization quality with smaller biodiesel droplet size was achieved and subsequently led to the reduction of NO_x emission when combusted.

Due to the complex nature of swirl combustion in gas turbine which involves spray atomization, swirl flow and chemistry reaction, spray characteristics need to be studied in detail to understand the dynamics of fuel droplets, flow-droplet interaction and effect of flow-droplet mixture on flame. The combustion characteristics of biodiesels under reacting spray conditions have previously been reported (Chong and Hochgreb, 2012, 2014b). The present study aims to extend the understanding of spray of biodiesel under conditions which were previously not reported, including the spray structure and droplet characteristics under non-reacting and reacting conditions to elucidate the differences. The emission performance is also examined based on the variation of air flow rates for the present model gas turbine burner.

Materials and methods

Fuel tested

The fuels used in the present experiment were palm biodiesel/methyl esters (PME) and Jet-A1 fuel. The winter grade PME, sourced from Carotino Sdn. Bhd. (Malaysia), conforms to the European Union's EN14214 biodiesel standard. Biodiesel is oxygenated compound comprises of a mixture of long chain fatty methyl esters with no aromatic rings or sulphur. The composition of PME is approximated as 43.1% methyl oleate, 39.5% methyl palmitate, 10.4% methyl linoleate and 5% methyl stearate (Gopinath et al., 2009). The baseline Jet-A1 fuel is sourced from Conoco Limited, UK. Jet-A1 fuel comprises of a mixture of hydrocarbons including aromatics with no oxygen molecule. Comparison of the fuel properties is shown in Table 1. Jet-A1 contains higher H/C ratio than PME. The approximate molecular weights for PME and Jet-A1 are 296 g/mol and 153 g/mol respectively. On fuel physical properties, PME is slightly denser due to higher molecular weight. PME is more viscous and has higher flash point compared to Jet-A1. However, PME has lower energy content by approximately 17% per mass basis compared to Jet-A1.

Table 1
Properties of Jet-A1 and PME.

Properties	Jet-A1	PME
Supplier	Conoco	Carotino
Approx. formula	$C_{11}H_{21}$	$C_{19}H_{36}O_2$
H/C ratio*	1.98	1.89
C/O ratio*	–	9.83
Spec. gravity 15 °C	0.81	0.88
Viscosity 40 °C (cSt)	–	4.5
Pour point (°C)	–	−18
Flash point (°C)	38	174
Boiling range (°C)	166–266	>215
LHV (kJ/kg)	43,150	36,770

Test rigs

A non-reacting spray facility was utilised to investigate Jet-A1 and PME sprays established via an internal mix airblast atomizer (Delavan: SN type-30610-1). The fuel and air orifice diameters at the atomizer exit are $d_f = 0.5$ mm and $d_a = 1.73$ mm respectively. Details of the atomizer geometry and internal structure are elaborated in Chong and Hochgreb (2014a). The twin-fluid atomizer was supported by a horizontal beam and fixed to a vertical stand. The atomizer outlet faced downward and the spray droplets generated were collected using a container. The fuel and atomizing air flow rates were metered and regulated independently using two separate mass flow controllers (MFCs): Coriolis-type (Bronkhorst: M13 mini CORI-FLOW, 0.4% accuracy) and thermal-type (Bronkhorst: F-203AV, 1% accuracy), respectively. Both streams of fuel and air were delivered to the atomizer at ambient room temperature of 20 °C. The schematic of the non-reacting spray rig and flow delivery system is shown in Fig. 1a.

A liquid swirl flame burner consisting of an airblast-type atomizer (same injector used in non-reacting spray facility), a swirler (8-blade, 45° fixed-vane, 1.5 mm thickness) and a combustor wall was utilized for the reacting sprays investigation. The atomizer was positioned concentrically with the swirler and combustor wall. The geometric swirl number is 0.78 based on the vane angle and geometry of swirler. The combustor wall is made from quartz tube with the geometry of 100 mm in diameter and 180 mm in length. The atomizing air and fuel were supplied through a thermal-type (Bronkhorst: F-203AV; ±1% full scale accuracy) and Coriolis-type (Bronkhorst: M13 mini CORI-FLOW; ± 0.4% full scale accuracy) MFCs. The main air flow was supplied to the burner plenum using a thermal-type MFC (Bronkorst: F-201AV; ± 1% full scale accuracy). The main air flow was preheated to 350 ± 5 °C with two in-line air heaters (750 W/heater) arranged in series. The burner was heated with three rope heaters (Omega: 500 W/rope) and insulated with high temperature cotton wool to maintain the elevated main air temperature at the burner outlet. The schematic of the liquid swirl flame burner is shown in Fig. 1b.

Operating conditions

The Jet-A1 and palm biodiesel sprays were examined under non-reacting and reacting conditions. For non-reacting sprays, both fuel sprays were established at the same air/fuel mass ratio of 2 at open unconfined environment. For establishment of reacting spray flame, the atomized fuel mixed with preheated main swirling air flow at the burner outlet prior to ignition. Both reacting spray cases were established at the same power output of 6 kW and equivalence ratio of $\phi = 0.47$, with the atomizing air-to-liquid ratio fixed at 2 for both cases. The operating conditions for all the test cases are shown in Table 2. The slightly higher PME fuel mass flow rate