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Combustion characteristics of biodiesel saturated with pyrolysis oil for power generation in gas turbines

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ABSTRACT

There is a perceived need for multi-fuel burner geometries capable of operating with variable composition fuels from diverse sources to achieve fuel flexibility in gas turbines. The objective of the research covered herein is a comparison study between two liquid fuels, a biodiesel (in a pure form) and the biodiesel as a saturated mixture with a pyrolysis by-product; these two fuels were compared against a standard kerosene as a baseline. The research methodology involved two stages: firstly atomization patterns and injection regimes were obtained using a high speed imaging method, secondly a combustion test campaign was undertaken using a swirl burner to quantify the operational behaviour, species production and exhaust gas compositions of the fuels. Emissions, flame stability trends and power outputs were measured at gas turbine relevant equivalence ratios. Excess oxygen and atomization trends in the biodiesel seem to be playing a major role in the production of emissions and flame stability when compared to kerosene. Also, heavy organics seem to be acting as catalytic substances for OH production close to the burner mouth. In terms of stability and combustion, it is proposed that the saturated blend would be a viable candidate for power generation.

1. Introduction

Reliable and economically viable alternatives to current fossil fuel products are continually being sought as pressures from fuel cost, security and environmental impact act on the fuel and energy industry [1]. In terms of liquid fuels, Diesel is largely utilized in commercial, domestic and industrial applications for power and heat generation; it is also used as backup fuel in gas turbines. There has been recent interest in using bio-derived liquid fuels such as biodiesels for gas turbine operation, but naturally there are concerns as to the operability and reliability of using less synthetic, more heterogeneous substances for fuels in such high value assets. Biodiesel products are often highly oxygenated fuels and have been used as an alternative source of fuel for diesel engines to improve combustion performance. Biodiesel can be considered a more environmentally benign fuel (when compared to fossil-based fuels) in terms of sulphur content, flash point, aromatic carbon content and biodegradability, provided this fuel could be used in gas turbines without major modifications [2].

Modern gas turbines will typically operate at lean equivalence ratios, which are between 0.5 and 1.0, depending on operational load and emissions reduction across a range of power outputs. Biodiesel has demonstrated a reduction of un-burnt hydrocarbons (UHC), carbon monoxide (CO) and particulate matter (PM) without reducing the power output significantly [3]. Experiments have shown a reduction of 12% for both CO and PM emissions and 20% for UHC emissions by co-firing 20% biodiesel in diesel fuel blends. Emissions reduction was about 48% for CO and PM and 68% for UHC when using 100% biodiesel. However, some research has seen a marginal increase in NO_x (1–6%) [4]. The presence of extra (fuel-bound) oxygen has been shown to result in overall slightly leaner combustion, which has the resulting benefit of increasing the thermal efficiency [5]. Emissions such as Polycyclic Aromatic Hydrocarbons (PAH) were also found to be less prevalent during biodiesel combustion. CO_2 emissions aside, biodiesel can be

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considered a cleaner fuel than fossil-derived diesel because it has almost no sulphur content (typically less than 15 ppm), no aromatics, and contains about 10% oxygen, which can improve the overall combustion process. Biodiesel also has a comparatively high lubricity and can hence be used as a lubricating agent for traditional diesel blends [1].

Work in the area of biofuels testing has often shown promising results where emissions are comparable to control studies using fossil-based Diesel [6]. Panchasara et al. [7] studied the combustion performance of pure biodiesel against diesel–vegetable oil blends in a simulated gas turbine combustor. These experiments were performed at atmospheric pressure with air-assisted injector/atomisers in swirling flows. The results showed that fuel chemistry effects were minimal since combustion emissions for a given fuel were largely dependent on the atomization process. Campbell et al. [8] studied alternative fuels that had been deemed suitable for gas turbines focussing on vegetable oils. They highlighted several properties of vegetable oils that would require special consideration such as transportation, storage, delivery and injection into industrial gas turbines. Hashimoto et al. [9] compared the emissions of palm derived biodiesel with those of fossil derived diesel in a gas turbine burner. The result indicated that NO_X emissions for palm biodiesel were consistently lower compared to those of diesel as a function of excess air ratio, average droplet diameter, atomizing air pressure and viscosity. These results indicate that biodiesel has the potential to produce lower NO_X emissions than diesel under gas turbine conditions, contrary to the higher NO_X emissions measured in reciprocating compression-ignition engine experiments [10].

Biodiesel and diesel have notable differences in physical properties, and it is therefore necessary to study the spray characteristics of biodiesel in relation to its application in internal combustion engines and gas turbines - more so given that atomization behaviour has a significant effect on emissions. Senatore et al. [11] analysed results of an experimental study fuelling a common-rail diesel engine with 100% rapeseed biofuel, comparing their findings with a blend of rapeseed and Used Fried Oil (UFO), showing good correlation between fuels. Zhao et al. [12] observed that the spray penetration and spray cone angle of biodiesel were larger than those of diesel. Similarly, Lee et al. [13] examined the atomization characteristics of biodiesel-blended fuels using a spray visualization system and phase Doppler particle analyser. They deduced that the biodiesel blended fuels had comparable spray tip penetrations to conventional diesel but higher Sauter Mean Diameter because the viscosity and surface tension of the biodiesel were higher than the conventional diesel fuel. Being a crucial topic for the improvement in burnout and a key factor in emissions, advanced laser-based spray quantification techniques have been used and developed to understand atomization patterns for diesel and biodiesel [14,15].

The biodiesel used in the work in this paper is a by-product from a biomass gasification process; specifically a liquid condensate from the product gas cleaning process. This is a crucial stage in the thermal conversion of biomass, especially where the main product gas components CO and H_2, are used for Fischer–Tropsch synthesis or as high purity fuel [16]. Biodiesel is widely used for scrubbing the raw syngas as it efficiently removes the condensable (heavier) hydrocarbons produced from biomass pyrolysis. Experimental investigations have been carried out on similar post-scrubbing liquids where combustion of blends of pyrolytic oil, biodiesel or ethanol in engines and boilers [17,18] have proved the suitability of the approach. This has included large-scale applications and highlighted a need to standardize the trade of this product [19]. Cappelletti et al. redesigned a micro gas turbine to permit stable combustion of pyrolysis oil showing that the combustion is only stable in the combustor's secondary zone [20]. However, further works concerning the use of pyrolysis oil as fuel for gas turbines are scarce at the time of writing.

The research questions to be addressed include measurement of the physical properties, atomization behaviour, combustion characteristics, and emissions of the new biodiesel blend and how this compares with a standard kerosene. Therefore, the aim of this study is to demonstrate the potential of this saturated biodiesel for power generation as a backup fuel for Integrated Gasification Combined Cycles (IGCC) and compare its combustion behaviour with kerosene and unsaturated biodiesel. Atomization patterns and injection regimes were obtained using high-speed imaging. Calorific values, density, and surface tension were measured and proximate analyses were performed to act as a comparison between the fuels. Knowing the properties and atomization behaviour, these fuels were fired into a generic swirl burner capable of simulating real gas turbine conditions. Exhaust gas emissions, OH^* chemiluminescence and combustion stability were measured at similar flow rates, providing evidence of the potential for and constraints to using this saturated biodiesel as an alternative fuel for gas turbines.

2. Experimental setup

2.1. Characterisation

Experiments were conducted at Cardiff University, UK, and ENEA, Italy. The surface tension and density were experimentally obtained using a temperature controlled LAUDA TVT 1 Drop Volume Tensiometer. The viscosity was experimentally obtained using a U–Tube Viscometer. The Higher Heating Value (HHV) was determined by a Parr 6100 calorimeter bomb and an IKCA C4000 calorimeter using benzoic acid as reference. An ultimate analysis was carried out by using an elemental analyser, a Perkin Elmer CHN/O according to UNI EN 15104. Ash was analysed to determine the elemental content according to the methods CEN 343 or CEN 345 by using an ICP-OES Agilent 720 ES. Oxygen was calculated by difference of species. Gas Chromatography (GC) was employed by using an Agilent HP 6890 GC.

Three test fuels were used in the experimental campaign, including unsaturated and saturated biodiesels, and kerosene. Their properties are given in Table 1, with the GC analysis of the methyl esters in Table 2. The unsaturated biodiesel is derived from cooking oil, giving a composition similar to that obtained for methyl ester. The fraction of biodiesel that is included in the saturated sample has almost the same elemental composition (C 76.28%, H 12.55%, O 11.04%) as that of the unsaturated biodiesel. However, since the biodiesel has been used to clean up the gas stream from a gasification process, the saturated biodiesel represents less than half of the total mass of the final sample. Besides water, the remaining 36.8% is a complex mix of organic molecules including formic acid (molecular mass 46 g/mol) and aromatic compounds (molecular mass 200 g/mol). This scrubbing process has been carried out to improve the quality of gases in a biomass gasification system at ENEA, Italy [21].

2.2. Atomization experiments

A Delavan 0.23 mm-60°A WDB nozzle atomizer was used as the fuel injector. Atomization characterisation was performed in a spray chamber located at Cardiff University, Fig. 1. This rig offers independent control of the ambient (chamber air) pressure (up to 15 bar) and temperature (up to 150 °C), such that the chamber air conditions can range from simulated intake stroke to late compression stroke injection for characterisation of automotive applications. Reading uncertainty of the pressure gauges was