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Investigation into the performance and emissions of a stationary diesel engine fuelled by sewage sludge intermediate pyrolysis oil and biodiesel blends

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ABSTRACT

This paper studies the characteristics of blends of biodiesel and a new type of SSPO (sewage sludge derived intermediate pyrolysis oil) in various ratios, and evaluates the application of such blends in an unmodified Lister diesel engine. The engine performance and exhaust emissions were investigated and compared to those of diesel and biodiesel. The engine injectors were inspected and tested after the experiment. The SSPO-biodiesel blends were found to have comparable heating values to biodiesel, but relatively high acidity and carbon residue. The diesel engine has operated with a 30/70 SSPO-biodiesel blend and a 50/50 blend for up to 10 h and there was no apparent deterioration in operation observed. It is concluded that with 30% SSPO, the engine gives better overall performance and fuel consumption than with 50% SSPO. The exhaust temperatures of 30% SSPO and 50% SSPO are similar, but 30% SSPO gives relatively lower NO_x emission than 50% SSPO. The CO and smoke emissions are lower with 50% SSPO than with 30% SSPO. The injectors of the engine operated with SSPO blends were found to have heavy carbon deposition and noticeably reduced opening pressure, which may lead to deteriorated engine performance and exhaust emissions in extended operation.

1. Introduction

Sewage sludge is the main solid waste of the wastewater treatment process. Over 1.5 million tonnes of sewage sludge are produced in the UK each year [1]. Nowadays, sewage sludge is being increasingly considered as a valuable clean energy resource, as it is abundant in volatile matter like most organic waste materials that can possibly be recovered and transformed into quality pyrolysis oil and gaseous fuels. The production of sewage sludge derived liquid and gaseous fuels, rather than direct incineration or landfill, which is the most common sludge disposal methods nowadays, can greatly reduce the associated air pollution and carbon footprint.

Pyrolysis of biomass and organic containing waste materials is a well-recognised thermal conversion route for converting organic volatiles into liquid fuels. In the early 1980s, Bridle et al. [2] conducted experiments using a dried mixture of raw and activated waste sludge in a retort type reactor to produce pyrolysis oil. Since then, reactors such as fluidized-bed reactors, fixed-bed reactors and microwave reactors, and processing methods such as acid pretreatment and metal oxide catalysis cracking, have been applied to sewage sludge pyrolysis [3–8]. These allowed researchers to evaluate the pyrolysis of sewage sludge at different scales and to produce different types of oils; however, as with pyrolysis oils from general biomass, sewage sludge pyrolysis oils were limited in heating value to a range of 14–25 kJ/kg. This was mainly due to a large amount of water (20–70 wt%) in the oil. The organic phase would not usually separate from the aqueous phase unless it was centrifuged [3–10]. This is now considered as one of the major barriers to wide application of the oils.

Application of waste/biomass derived pyrolysis oils has also been attracting interest from researchers more recently. A large number of studies have been published on the use of pyrolysis oil in various applications such as combustion in furnaces, boilers, gas turbines and internal combustion engines [11–23]. The use of pyrolysis oil in internal combustion engines is particularly interesting, because of the relatively high efficiency of conversion to electricity.

A number of investigations on using pyrolysis oils in diesel engines have been carried out, but none of these have used sewage sludge derived oil. Most have used wood pyrolysis oils derived from

Abbreviations: SSPO, sewage sludge pyrolysis oil; BD, biodiesel; D, diesel; AFR, air-fuel ratio; SFC, specific fuel consumption; CO, carbon monoxide; NO_x, nitrogen oxides; HHV, higher heating value; LHV, lower heating value; AC, alternating current; ASTM, American Society of Testing and Materials; KF, Karl Fischer.

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fast pyrolysis to test the engine performance and exhaust emissions. Solantausta et al. [12] investigated using hardwood derived fast pyrolysis oil (20.5% water content and 18 MJ/kg LHV) in a 4.8 kW Petter AVB diesel engine. By adding fuel ignition improver to the pyrolysis oil, the engine was able to achieve 50% of rated load. However, difficulties in fuel ignition were encountered and injector nozzle coking rapidly occurred. Exhaust emissions were comparable to those of conventional diesel fuel. Shihadeh et al. [13] tested wood derived fast pyrolysis oil (16.3 kJ/kg heating value and 26.3 wt% water content) in a Ricardo single-cylinder DI diesel engine. It was difficult to achieve reliable ignition without pre-heated air intake. The engine stopped working after 6 h due to damage to the fuel injection system. Significant carbon deposit was found in the combustion chamber and on exhaust valves, which indicated the high carbon residue and poor combustibility of the pyrolysis oil according to the author. Blowes [14] reported a study on wood derived fast pyrolysis oil containing 25 wt% of water and 0.9 wt% of char (having a pH of 2.6, a viscosity of 43.8 cSt at 40 °C and a LHV of 15.8 MJ/kg) in an Ormrod dual fuel diesel engine, with diesel fuel pilot injection. Much impaired combustion was in evidence from significant visible smoke and high CO emissions. A subsequent experiment for the same type of oil running in an engine supplied with oxygen enriched air showed an improved combustion quality. Chiaramonti et al. [19] carried out an experiment on a single cylinder 5.4 kW Lombardini engine running on emulsions of crude bio-oil and diesel. A dramatic increase in CO emission and a decrease in thermal efficiency were observed after 50 min of engine operation, resulting from significant damage to the injectors and the fuel pumps caused by corrosion from the oil emulsion.

It can be concluded from previous studies that most of the operating problems of the diesel engine were directly related to the poor quality of pyrolysis oils, such as low heating value, low ignitability and high carbon residue. These problems indicate much work needs to be done before pyrolysis oil fuelled diesel engines can become a reality. Improvements need to be made in pyrolysis oil quality and modifications to the diesel engine. The present work considers a new type of sewage sludge derived intermediate pyrolysis oil and its use in an unmodified diesel engine generating system in blends with biodiesel. The paper will address: (i) the characteristics of SSPO (sewage sludge intermediate pyrolysis oil) and SSPO-biodiesel blends; (ii) the performance and exhaust emissions of a Lister-type diesel engine running on SSPO-biodiesel blends.

2. Materials and methods

2.1. Pyrolysis oil production

The SSPO used in this study was produced from sewage sludge feedstock provided by the Netheridge Sewage Treatment Works, part of Severn Trent Water Ltd (UK). The sludge was anaerobically digested and dewatered at the sewage treatment plant. The sludge was thermally dried in an oven and was then pelletised to form feedstock pellets at a size of approximately 5 mm in diameter and 10 mm in length (Φ5 mm*10 mm).

The Pyroformer intermediate pyrolysis reactor was recently patented by Hornung and Apfelbacher [24] at Aston University. The reactor is made from carbon steel. It is a horizontal cylindrical reactor containing two co-axial rotating screws, where the inner screw conveys the feedstock forward through the reactor and the outer screw recycles some of the product char backwards for heat exchange and for catalysis of the vapour-phase pyrolysis reactions, leading to lower molecular weight condensable vapours and increased permanent gas content (CH_4, H_2, CO). The reactor is heated externally by four separated heating jackets along the length of the reactor. The heating jackets can heat the reactor outer surface to 550 °C. There is one biomass feeding inlet and two product outlets, i.e. vapour outlet and char outlet. The EBRI (European Bioenergy Research Institute) laboratory scale Pyroformer unit is 180 cm in length and has a diameter of 20 cm. It can process a variety of types of biomass raw material in pellet form with a maximum feed rate of 20 kg/h. The full process, as shown in Fig. 1, comprises a feeding hopper, the Pyroformer reactor, hot gas filter candles for removal of entrained char and solid particulates, a shell and tube water cooled condenser for condensing of the liquids and an electrostatic precipitator for gas aerosol removal. Further details for the pyrolysis system are also available in the authors' previous publications [20,25,26].

Prior to a run, the Pyroformer reactor is initially purged with nitrogen to eliminate any air, and is then heated to a temperature of 450 °C. The pelletised sewage sludge is then fed at a rate of 15 kg/h, with the screw speeds set to achieve a solids primary residence time of about 3–4 min. The evolved gases and vapours pass through hot gas filter candles which are also heated to 450 °C. The condensable vapour is then cooled in a cold-water condenser to form the pyrolysis oil, while the permanent gases can be flared or collected after they pass through an electrostatic precipitator.

The yields of liquid, permanent gas and solid product were 40 wt%, 12 wt% and 48 wt% respectively (with the gas yield calculated by difference). The collected liquid separates naturally under gravity into two phases, an organic phase at the top (25 wt%) and an aqueous phase at the bottom (75 wt%), after a few hours of production.

2.2. Fuel blends preparation and characterisation

The diesel fuel oil used in this study was standard commercial diesel fuel purchased from a local petrol station. The biodiesel fuel oil used was transesterified waste cooking oil (mainly methyl ester), as produced and supplied by a local biodiesel company.

A previous study has described a systematic characterisation of pure SSPO and has compared it to commercial diesel and biodiesel [25]. The cetane index of SSPO, which is low, raises concerns over poor ignitibility and combustibility and may result in unreliable engine operation. In addition, SSPO is found to have relatively high viscosity, acidity and carbon residue. Hence pure SSPO is not likely to be suitable as a diesel engine fuel. Instead, this work considers blends of SSPO with biodiesel at 30/70 and 50/50 volumetric ratios, which were prepared manually for the engine tests. The blends are considered physically stable as no phase separation was observed after 100 days.

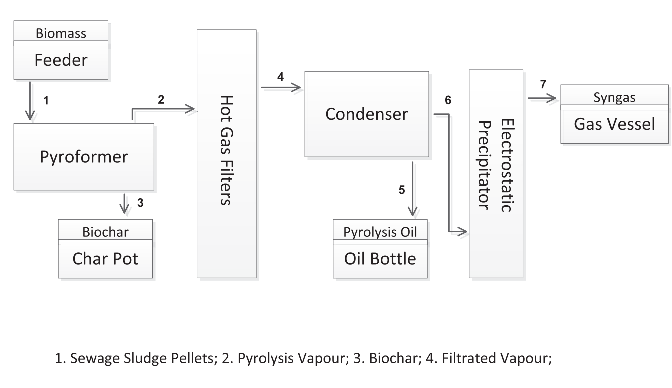

Fig. 1. Schematic scheme of the intermediate pyrolysis system. 1. Sewage Sludge Pellets; 2. Pyrolysis Vapour; 3. Biochar; 4. Filtrated Vapour; 5. Pyrolysis Oil; 6. Permanent Gas; 7. Aerosol-free Gas.