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Research paper

The use of a fast pyrolysis oil – Ethanol blend in diesel engines for chp applications

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ABSTRACT

The use of Fast Pyrolysis Bio-Oil (FPBO) in diesel engines can be a valuable approach for CHP applications. However, the properties of FPBO make this application very challenging. The purpose of this work is to develop and demonstrate the use of FPBO in modified engines.

Proper atomization of the fuel is of utmost importance and a. o. influenced by the fuel surface tension. The final equilibrium value of the surface tension is only slightly higher than for diesel, but large deviations in surface tension are observed at the short droplet lifetimes occurring in an engine's cylinder. Addition of 10–20 mass% of ethanol to the FPBO can significantly improve the atomization properties.

Two diesel engines are available at BTG, a one-cylinder (1C) and a four-cylinder (4C). Both engines have been modified and operated on FPBO. Additional safety measures have been implemented for the 1C-unit to enable unattended operation. So far, the longest continuous and stable run has been 52 h. In total, this 1C engine has been operated for nearly 400 h on FPBO or FPBO blends.

More recently, the four cylinder, 48 kW diesel engine has been modified to enable fueling with FPBO. This engine can be seen as a prototype for a commercial CHP unit (100 kW–1 MW electrical output). The unit was successfully commissioned and initial tests are in line with the 1C experiments. Due to a lower calorific value, the volumetric fuel consumption is significantly higher in case of FPBO. However, the overall electrical efficiency is very similar to diesel.

1. Introduction

Combustion of Fast Pyrolysis Bio-Oil (FPBO) in stationary diesel engines is an interesting approach for combined heat & power (CHP) applications. Even at relative small scale (< 1 MW_e) high electrical efficiencies of over 40% are achievable with this renewable fuel. Fast pyrolysis is a process in which organic materials are heated rapidly to 450 - 600 °C in absence of air. Under these conditions, organic vapours, permanent gases and charcoal are produced. The vapours are then condensed quickly to a liquid called FPBO. Typically, 50-75% mass fraction of the dry feedstock can be converted to FPBO.

However, the properties of FPBO make the direct application in diesel engines very challenging. FPBO is acidic, contains water, has a high viscosity (compared to diesel), is sensitive to polymerization and difficult to ignite. Standard fuel injectors and fuel pumps are not corrosion resistant and these parts will quickly corrode when contacted with FPBO. Stainless steel can withstand corrosion, but is often not hard enough to withstand abrasive wear and high impact. Early experience with fueling pyrolysis oil in diesel engines was gained by Wärtsilä and VTT [1,2].

The Cetane Number of a fuel is important for a compression-ignition engine, and it is inversely related to the fuel's ignition delay. A high value means easy ignition, and typical values for conventional diesel fuels are in the range of 45–55. It is hard to find any data on the Cetane Number of FPBO, but certainly it is much lower than for diesel. Maximum values reported are around 20 to 25, but also values as low as 4 are published [3–5]. To compensate for the poor ignition of FPBO a higher temperature at the end of compression is needed. This can be achieved by either increasing the air inlet temperature or by increasing the compression ratio. In previous work it has been shown that by increasing the compression ratio from 17 to 22, the air inlet temperature could be decreased by roughly 50 °C to around 70–80 °C [3]. Kim and Lee [6] increased the engine compression ratio to 28. Blends of pyrolysis oil-butanol could be combusted without any air preheating, but significant amounts of cetane improver were added. The pyrolysis oil content was limited to 30% mass fraction at maximum. Previously, we found that adding cetane improvers is not very effective for improving the combustibility of FPBO [3] unless very large quantities are used

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[1,2]. Alternatively, a pilot fuel like conventional diesel might be considered to support the ignition of FPBO. In that case, a small amount (~5 - 20%) of a second fuel is injected via a separate feeding line. Lee and coworkers [7,8] investigated the fueling of pyrolysis oil-ethanol blends in diesel engines while using diesel and biodiesel as a pilot fuel. Successful experiments were carried out for pyrolysis oil contents up to 40% mass fraction. No information was provided on the duration of the testruns. From a cost point of view severe upgrading of FPBO to improve fuel properties is undesirable for stationary CHP. Good overviews on the specific challenges and approaches for using FPBO in engines have been published by Chiaramonti et al. [9], and more recently by Hossain and Davies [10].

This paper focuses on the modification of conventional diesel engines and its testing with crude pyrolysis oil.

1.1. Atomization of FPBO

1.1.1. Primary droplet formation

Atomization of the fuel into very fine droplets is of utmost importance to achieve fast and complete combustion. In a diesel engine the combustion should be completed in the millisecond range (< 15 ms). The atomization "quality" of fuel sprays depends largely on the fuel properties. An indication is given by the Sauter Mean Diameter which can be derived from the following empirical equation [12]:

$$SMD = 0.1855\ \nu^{0.385}\ (\sigma\ \rho_f)^{0.737}\ \rho_{air}{}^{0.06}\ \Delta P^{-0.54}$$

SMD = Sauter Mean Diameter (μm), ν = the kinematic viscosity (cSt), σ = the surface tension (mN m^{-1}), ρ_f = the density of the fuel (kg/m^3), ρ_{air} = the density of the air (kg m^{-3}), and ΔP = the pressure difference over the orifice (bar). Data on the viscosity and the density of different types of FPBOs are available in literature, see e.g. [13,14]. Both properties depend on temperature and water content, but the sensitivity of the viscosity is more marked. Preheating the fuel is effective in reducing the viscosity to acceptable values. Increasing the water content is not desired because it lowers the heating value and it may cause phase separation. Experimental data on the surface tension of FPBO is scarce, and normally based on equilibrium conditions. However, actual values for multi-component mixtures depend on the life-time of a droplet and equilibrium may not be achieved in an engine. Surface active components need a certain time to reach the surface of a droplet, and for a short droplet lifetime the surface tension can be significantly higher than the final (equilibrium) value. Tzanetakis et al. [15] evaluated the disparity between non-equilibrium and equilibrium surface tensions on a time scale of seconds to tens of seconds. At 25 °C the non-equilibrium value was about 5% higher than the equilibrium value, and the difference decreased with increasing temperature.

However, in a diesel engine the droplet lifetime will be in the order of only a few milliseconds and the effect could be very different. To study this effect the dynamic surface tension of FPBO was measured using a bubble-pressure tensiometer.

1.1.2. Micro-explosions

FPBO is a multi-component mixture containing components covering a very wide boiling range. In such a multi-component fuel mixture so-called micro-explosions may take place, and these micro-explosions are beneficial in fuel sprays as they create smaller droplets. Micro-explosions are causing a fragmentation of a droplet due to internal pressure built-up. This phenomena was observed for diesel-water emulsions, and a positive effect is claimed as it would lower the particle emissions due to the decrease in droplet size [18]. Micro-explosions only occur in multi-component fuel droplets containing components with very different volatility. Volatile components inside a droplet evaporate and expand rapidly causing a disintegration of the droplet. If the concentration of volatiles is relatively low partial/local disintegration takes place which is called "puffing" by Avupalati et al. [19]. They studied puffing and micro-explosions for diesel-biodiesel-ethanol blends. Initial droplet diameters were 1–1.5 mm, which is much larger than normally observed in diesel engines. Avupalati et al. [19] concluded that when micro-explosions take place in the primary droplets also micro explosions were observed in secondary (~300 μm) and tertiary ones (~80 μm). Micro-explosions in the smallest droplets took place on a time-scale of milliseconds, and this case can be very relevant for the droplet formation in diesel engines. As mentioned before, the occurrence of micro-explosions depends on the concentration of volatiles. Below 10% mass fraction ethanol only puffing was observed, between 10 and 40% mass fraction ethanol micro-explosions did occur, and above 40% neither puffing nor micro-explosions were found. The fragments after micro-explosions were at least 5-10 times smaller than the original droplet. The experiments of Avupalati et al. were carried out at ambient pressure, but fuel atomization in a diesel engines takes place at elevated pressure (some tens of bar). Wang and Law [20] studied the occurrence of micro-explosions of multicomponent blends and water-oil emulsions at pressures up to 5 bar. They concluded that increasing the absolute pressure even enhances the possibility of micro-explosions. Furthermore, the authors state that -on basis of theoretical considerations-it is reasonable to expect similar observations at higher pressures like in internal combustion engines.

An extensive study on the burning of pyrolysis oil droplets was carried out by d'Alessio et al. [21]. Fast pyrolysis oils from three different suppliers were fed to a drop tube furnace at 300-850 °C. Droplet sizes were either in the range of 50–100 μm, or 300-600 μm. During heating a first temperature plateau around 100 °C was observed due to the evaporation of water. After a further temperature rise to 500 °C swelling, bubbling and micro-explosions could be observed by making use of a fast speed camera. Swelling occurs due to the vaporization of light components inside the droplet ('bubbling'), and the droplet diameter may even increase up to a factor of 2–3. A further increase in internal pressure leads to micro-explosions (or puffing). Ignition and burning of the FPBO started around a temperature of 600 °C.

More recently, Teixeira et al. [22] studied the micro-explosions in pyrolysis oil droplets by fast heating of a single droplet on a heated alumina disk in a nitrogen atmosphere. Pyrolysis oils were used as such or they were treated by adding methanol or by removing solids. The addition of methanol caused a delay in the occurrence of micro-explosions, but the effect was fairly limited at methanol concentrations up to 25% mass fraction. Complete removal of solids from the oil led to a strong decrease in the explosion frequency and the authors concluded that some solids are required to initiate a micro-explosion. They also suggest the formation of a polymer shell from the highly reactive components present in pyrolysis oil. As a consequence, the volatile components cannot escape so easily from the droplet, leading to a pressure build up inside the droplet which finally results in a micro-explosion.

Hou et al. [23] studied the droplet formation and ignition of fuel oil/bio-oil blends at 300 and 500 °C in air. At 300 °C, swelling and micro-explosions are observed but no ignition, whereas at 500 °C also ignition takes place. With increasing bio-oil content in the blend, the micro-explosions and random behavior occur more frequently and more quickly. The authors explain the occurrence of micro-explosions by a diffusion-limit model. The droplet is quickly heated and volatiles at the surface of the droplet will evaporate. It results in a high viscous outer layer and a more volatile core. The volatile components in the core will evaporate and cause a high internal pressure resulting in the explosion of the droplet.

In this work, a blend of 80% mass fraction FPBO and 20% mass fraction ethanol has been used as the engine fuel. Most likely, the addition of ethanol will result in smaller droplet sizes during primary atomization (decrease SMD). Ethanol addition reduces the viscosity, density and dynamic surface tension. With respect to secondary atomization or the occurrence of swelling, puffing or micro-explosions it is hard to draw any conclusions. Water and ethanol can be considered as