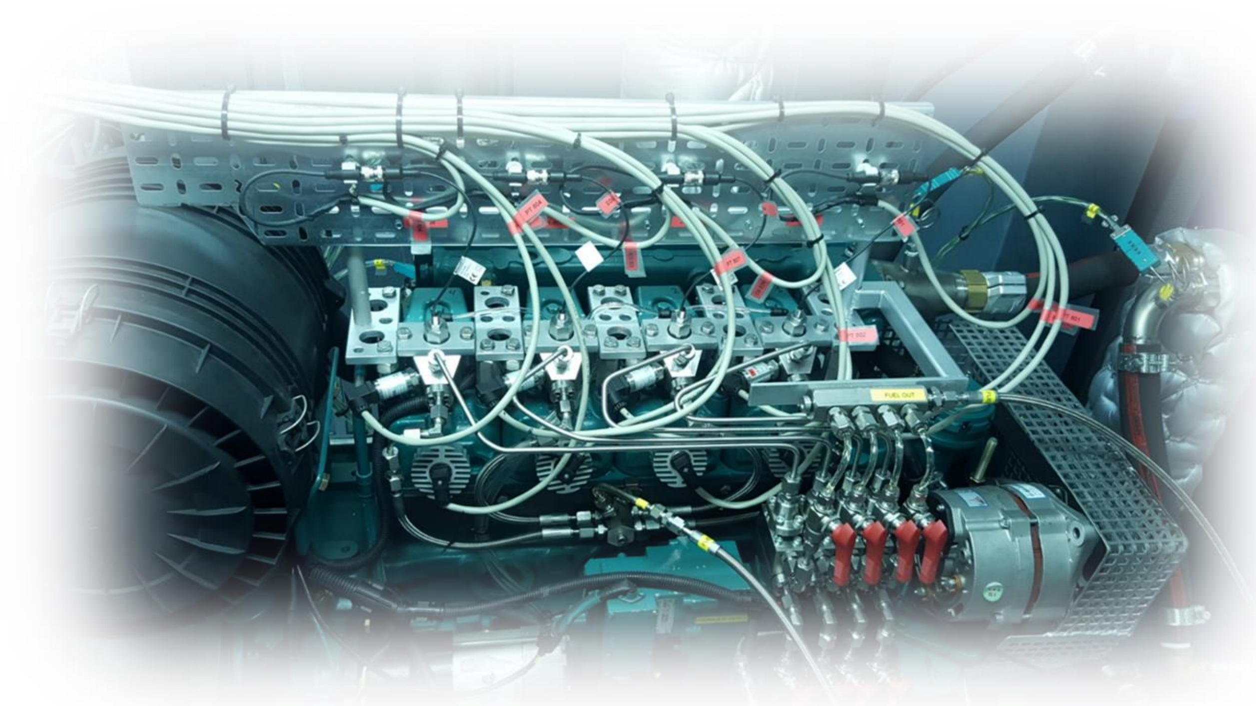
PyroWKK

Ontwikkeling van een duurzame WKK installatie door toepassing van pyrolyse olie in een gemodificeerde dieselmotor



TEHE115065
Juni 2019
Publiek eindrapport

Inhoud

Gegevens project

Samenvatting

Specifieke openbare project resultaten
1. PyroWKK project: CFD modeling and experimental validation of pyrolysis oil spraying
2. The use of fast pyrolysis oil-ethanol blend in diesel engines for CHP application
3. The use of fast pyrolysis bio-oil in a modified diesel engine

Afkortingen / abbreviations

CFD	computational Fluid Dynamics
CHP	Combined Heat & Power (=WKK)
FPBO	Fast Pyrolysis Bio-Oil
SMD	Sauter Mean Diameter
WKK	WarmteKrachtKoppeling (=CHP)

Project gegevens

Projectnummer:	TEHE115065
Projecttitel:	PyroWKK: Ontwikkeling van een duurzame WKK installatie door toepassing van pyrolyse olie in een gemodificeerde dieselmotor
Penvoerder:	BTG Biomass Technology Group BV
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Projectperiode:	01-11-2015 t/m 31-03-2019
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Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

Samenvatting

Kleinschalige, biomassa -WKK (Warmte-Kracht-Koppeling) heeft de potentie sterk bij te dragen aan een oplossing voor de Europese en Nederlandse uitdagingen om het energie systeem slim, schoon, flexibel, zeker, kosten effectief en efficient te maken. Toepassing van WKK leidt tot hoge rendementen (>80%) en hernieuwbare brandstoffen zoals biomassa en residuen kunnen worden gebruikt. Direct gebruik van vaste biomassa op kleine schaal is vaak moeilijk rendabel te krijgen vanwege relatief hoge investeringskosten, in-homogeniteit van biomassa, beperkte betrouwbaarheid en hoge operationele kosten. De hoge WKK rendementen worden bereikt door combinatie van de produktie van warmte en elektriciteit en ook koude zou kunnen worden toegevoegd ('trigeneratie'). Daarnaast kan biomassa gebaseerde WKK ('uitschakelbare produktie') ook bijdragen aan de flexibiliteit en stabilisatie van het elektriciteitsnet ter compensatie van een variabel aanbod van zon- en windenergie.

Het doel van het PyroWKK project is is de ontwikkeling van een kosteneffectieve, biomassa gebaseerd WKK systeem door gebruik te maken van pyrolyse olie als brandstof in een dieselmotor. Snelle pyrolyse is een proces waarbij organisch materiaal snel wordt verhit tot 450 – 600 °C in afwezigheid van zuurstof. Bij deze condities worden er een organische damp, gas en kool gevormd. De dampen worden vervolgens afgekoeld waarbij een vloeistof wordt verkregen genaamd pyrolyse olie. De eigenschappen van deze 'olie' wijken sterk af van fossiele brandstoffen (diesel, stookolie) zoals bijvoorbeeld de aanwezigheid van een aanzienlijke hoeveelheid water (25%), zuurgraad, lage stookwaarde (~ 16 MJ/kg) en moeizaam ontsteekgedrag (laag Cetaan getal).

Om het gebruik van pyrolyse olie in motoren mogelijk te maken kan enerzijds gedacht worden aan het verbeteren van de eigenschappen van pyrolyse olie of anderzijds aan het aanpassen van de motor. De laatste is de gevolgde benadering in het PyroWKK project. Omdat pyrolyse olie zuur is en water bevat kan snelle corrosie en erosie van motoronderdelen worden verwacht. Belangrijkste aanpassing aan de motor betreft het brandstoftoevoersysteem en zowel de brandstofpomp als de brandstof injector zal aangepast moeten worden. Brandstofpompen zijn nu gemaakt van roestvaststaal waarbij de plunjer is uitgevoerd in keramiek. Hetzelfde geldt voor de brandstofinjectoren waarbij de injectornaalden zijn gemaakt van zowel metalen als keramiek. In algemeen voldeden de onderdelen op basis van keramiek erg goed. Naast de aanpassingen aan het brandstoftoevoersysteem zijn er ook aanpassingen nodig om te compenseren voor de moeilijke ontsteking van pyrolyse olie. Hiervoor kan de verbrandingslucht worden verwarmd en/of de compressie-ratio van de motor worden verhoogd. Beide leiden tot een hogere temperatuur in de cylinder juist voor ontsteking. De compressieverhouding is verhoogd van 18 naar 22-23. In experiemnteel onderzoek wordt vaak gebruik gemaakt van elektrische elementen om lucht voor te verwarmen, maar dit is natuurlijk geen oplossing voor een commercieel systeem. Daarom is er een warmtewisselaar en controlesysteem ontworpen en geïmplementeerd om verbrandingslucht met het rookgas voor te verwarmen. Het systeem functioneert boven verwachting en blijkt zeer stabiel te zijn ook bij sterk en snel varierende bedrijfscondities (bijv. verandering van belasting).

In het project was een activiteit opgenomen met betrekking tot de modellering van brandstofverneveling. Dit blijkt een uitdagende activiteit, omdat bij een motor sprake is van zeer korte verblijftijden (milliseconden). Daarnaast kan een motor weliswaar draaien bij stationaire condities de verneveling van de brandstof is altijd een dynamisch proces. Door de lagere stookwaarde van pyrolyse olie zal voor dezelfde capaciteit ook extra brandstof geïnjecteerd moeten worden, waardoor wellicht ook een aangepast injector ontwerp nodig is. Op basis van modelberekeningen zijn er diverse injectoren geconstrueerd en getest, waarbij bijvoorbeeld het aantal gaten of de orientatie van de gaten zijn gewijzigd. Helaas bleek geen van de aangepaste injectoren tot een verbetering van de motorprestatie te leiden. Het model is primair gericht op de verneveling van de vloeistof en er is geen rekening gehouden met verbrandingsreakties. Dit was weliswaar bewust zo uitgevoerd, maar mogelijk is het toevoegen van de verbrandingsreakties noodzakelijk om het model te verbeteren.

Motortesten zijn uitgevoerd in een 1-cilinder en een 4-cilinder motor waarbij pyrolyse olie als brandstof is gebruikt. Typisch is er 20 m% ethanol toegevoegd aan de pyrolyse olie om viscositeit te verlagen en homogeniteit te verbeteren. In totaal zijn er meer dan 800 draaiuren gerealiseerd waarbij verschillende pompen en injectoren zijn toegepast. De beste injector tot nog toe hield het 183 uur vol en dit zal verder verbeterd moeten worden. Deel van de problemen zijn toe te schrijven aan de mechnische bewerkingen bij het construeren van de injector en biedt ruimte voor verbetering. Het gemeten elektrische rendement is vergelijkbaar met gebruik van diesel onder dezelfde condities. Met betrekking tot emissies geldt in het algemeen dat het gebruik van pyrolyse olie leidt tot toename in CO emissies en een verlaging in NO_X. Echter, in alle gevallen zal er toch een rookgasreiniging nodig zijn om aan de emissie regelgeving te voldoen.

In het project zijn de investeringskosten voor een WKK systeem opnieuw geëvalueerd en dit heeft geleid tot geschatte specifieke investeringskosten van iets minder dan 1,200 €/kW_e. De ontwikkeling van PyroWKK systeem wordt vervolgd in een Europees H2020 project genaamd SmartCHP (2019-2023). Dat project zal uiteindelijk leiden tot een 50 kW_e prototype inclusief de benodigde rookgasreiniging en systeemcontrole.

De belangrijkste publieke resultaten zijn samengevat in een drietal bijdragen:

1. PyroWKK project: CFD modeling and experimental validation of pyrolysis oil spraying

2. The use of fast pyrolysis oil-ethanol blend in diesel engines for CHP application

3. The use of fast pyrolysis bio-oil in a modified diesel engine

PyroWKK project: CFD modeling and experimental validation of pyrolysis oil spraying.

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1. PROJECT BACKGROUND

The Dutch government granted a TKI allowance to Biomass Technology Group (BTG), Abato, Ceratec and Eindhoven University of Technology, for collaborative public-private fundamental and applied research into ways to make diesel engines suitable for running on pyrolysis oil obtained from biomass.
It has to be noted that this is an overall summary about objectives and the project contribution from Eindhoven University of Technology (TU/e). Thus, all the subjects discussed in this document are regarding TU/e's input. This overall summary may refer for more detailed information to other 3 documents that have been prepared by TU/e: a "Journal Article" (to be submitted to a scientific journal); an "Optimization Report" that deals about a computational study to find suitable multi-hole injector characteristics for pyrolysis oil injection; and an "Experimental Report" that covers the performed experimental work with Phase Doppler Anemometry on a single-hole nozzle injector under atmospheric ambient pressure conditions.

2. INTRODUCTION AND MOTIVATION OF THE PROJECT

The motivation of this project remains in performance research about the feasibility study to switch from traditional fossil fuels to pyrolysis oil as fuel source to power diesel engines for Combined Heat and Power units [1].

Pyrolysis oil is characterized by its higher viscosity, density, acidity and Lower Heating Value (LHV) compared to diesel. Its different physicochemical properties may suppose a significant change in the fuel atomization quality inside the combustion chamber [2]. Especially due to its larger viscosity that may lead to more inefficient combustion due to the presence of larger droplets in the system. Thus, more insight about this is provided through the computational and experimental study carried out in this project.

Thus, one of the main goals of this project is to develop a quantitative understanding of the hydrodynamics of a spray of pyrolysis oil droplets moving through the combustion chamber after they have been sprayed from (one or multiple) nozzles. It was originally suggested that an advanced stochastic Euler-Lagrange CFD model based on Direct Simulation Monte Carlo could be employed.

Another important objective was to perform phase-doppler anemometry (PDA) measurements on a model spray using a model liquid with the same physical properties as pyrolysis oil. These measurements were aimed to be used to validate the CFD model for its capabilities to predict the further evolution of droplet size and velocity evolution. In the following sections an introduction about the employed tools as well as the main conclusions of this work are presented. In the conclusions section, an assessment about the satisfied objectives will also be carried out accompanied by further recommendations that can be of key relevance for the implementation of pyrolysis oil as alternative fuel source in diesel engines.

3. METHODOLOGY

In this section, general features of the computational model and the experimental technique are presented. The utilized methodology in this project can be split in a computational and an experimental part.

3.1. Experimental technique

A Laser Doppler Anemometry (LDA)-Phase Doppler Anemometry (PDA) Dantecs system has been employed in this project to perform the experimental work. The combined LDA-PDA technique provides local measurements of the droplet diameter and velocity at multiple locations throughout a fluid spray. These measurements are post-processed by means of an homemade Matlab$^($$c$) script to compute more representative parameters like the Sauter Mean Diameter (SMD) and droplet size distributions at different locations. Details about the principles of LDA-PDA technique are further explained on the “Experimental Report”.

Well-defined spray experiments have been performed using sunflower (64 cP) and paraffin oil (186 cP) as model liquids. The choice of these two liquids was justified by their significantly different value of the dynamic viscosity. Experiments with other liquids such as pyrolysis oil, diesel or other highly flammable liquids were not performed due to safety reasons. Furthermore, spray experiments with fluids of lower viscosity was not feasible due to chemical incompatibility of the setup towards aqueous mixtures. A continuous flow pump unit, which stands chemical resistance, is currently being constructed.

A continuous flow pump was supplied by Abato. This unit was coupled to a single-hole nozzle supplied by BTG in order to attain a single-nozzle spray that could be characterized by the laser equipment. The experiments were carried out at atmospheric ambient pressure conditions at an injection pressure of 200 bars.

3.2. Computational model

The CFD model consisted of a stochastic Euler-Lagrangian model that was available in OpenFoam. This model was modified in order to implement a benchmarking droplet collision model [3], that takes into account viscosity and surface tension effects on droplet size changes when droplet collisions take place within the spray. This model combines a numerical strategy to solve droplet collisions at low and high Weber numbers [4], where high ambient pressure effects (promoting droplet bouncing) are also accounted for [5].

This computational model is a parcel-based approach, where only a representative number of droplets are modelled in terms of parcels, which can be interpreted as groups of droplets.

The computational work consists of: a sensitivity analysis of a single-nozzle spray to find stable results and study the sensitivity of the model towards changes of the parcel size, computational cell size and the choice of the turbulence model ("Journal Article"); a parametric study that assess the influence of the fuel physicochemical properties on the SMD, droplet size distribution and spray-walls impingement time under high-pressure ambient conditions ("Journal Article"); and an optimization study to find suitable values of the injection angle and number of holes on a multi-hole injector nozzle spray ("Optimization Report").

It has to be noted that for the parametric and the optimization study, 2-D sketches provided by BTG have been employed to generate volumetric computational meshes of representative combustion chambers. A more detailed description of the computational model as well as the characteristics of the chambers can be found in the "Journal Article".

It is worth to mention that the Euler-Lagrange model is a very suitable model to solve spray simulations, where fuel droplets are regarded as spherical. Thus, it does not model the fuel surface or interaction of the fluid with nozzle. Thus, it is important to clarify that the model's outcome depends on the initial droplet size (Rosin-Rammler distribution) and velocity distribution.

4. RESULTS AND DISCUSSION

4.1. Experimental work

Several experiments LDA-PDA experiments have been carried out to characterize the spray characteristics with two different liquids: sunflower and paraffin oil. Measurements of the droplet size and velocity have been collected and post-processed to determine the SMD.

These experiments show that there are minor differences between paraffin and sunflower oil sprays in terms of SMD (64.92 and 62.02 μm respectively) and mean average droplet diameter (14.83 and 17.29 μm respectively). This outcome conveys that for more viscous liquids (paraffin), there are fewer large droplets than with sunflower oil. However, there is a slightly larger ratio of the liquid volume to surface area for paraffin oil (SMD), so the droplets that can be formed with paraffin oil are larger than with sunflower oil. Despite these slight differences, under these spraying conditions no significant differences were found. Besides, an small influence of the "distance to nozzle" was perceived in the droplet size pdf distributions.

One of the reasons that can cause this outcome is the low collision rate when a single spray under atmospheric ambient pressure is used. Thus, further experiment with impinging sprays or/and under high-pressure conditions are advised for further research. Another possible reason to not obtain notable differences may be due to the high atomization quality at 200 bars of injection pressure. Thus, experiments at significantly lower injection pressures than 200 bars are recommended to perform.

It should also be noted that the LDA-PDA does not detect non-spherical droplets and can only measure up to a droplet diameter up to 252 μm with the current receiver lens. Although this technique is widely well-known by its accuracy, it cannot be used in very dense spray regions (very close to the nozzle) and cannot detect droplets with irregular shape. These limitations invite to complement the presented experimental work with digital imaging techniques in order to determine the spray breakup length or/and record droplet collision events that could elucidate some more insight about the droplet collision rates/events.

4.2. Computational Study

A benchmarking collision model has been implemented and verified. Besides the model has been validated for single phase simulations and a parcel injection of fixed size has been implemented.

The sensitivity study determined that the used Euler-Lagrange model generates stable results of the droplet size distribution, time-averaged liquid volume fraction and average axial liquid velocity under certain simulation conditions. It has been shown that a parcel size of 100 droplets is sufficiently representative to solve spray dynamics simulations. Furthermore, cubic computational cells with characteristic dimension of 5 mm were found to provide very close results to the simulations' results with a more refined mesh. Besides, the choice of the turbulence model did not show a significant influence on the obtained results.

The sensitivity study also showed that under atmospheric ambient pressure conditions and high injection pressures (200 bar), the droplets shattering collisions were dominant over other type of collision events, promoting droplet breakup throughout the spray. This was confirmed by comparing overall droplet distribution to the one fed to the injector cell (via Rosin-Rammler distribution). While at low injection pressures (16 bar), the droplet size distribution shifted to larger values of the droplet diameter, conveying that droplet coalescing events (increases overall SMD) were dominant over shattering droplet phenomena (decreases overall SMD).

A very revealing feature of this study is that viscosity effects are only relevant at low injection pressures or spray conditions where low local Weber number are obtained. In this sensitivity study,a larger SMD has been obtained when a more viscous liquid is sprayed at low injection pressures (16 bar). However, at relatively high injection pressures (200 bar), negligible differences in the spray characteristics are found when liquids of greatly different dynamic viscosity (1 to 1000 cP) are sprayed.

This sensitivity analysis has been complemented with a parametric computational work to study the influence of the fuel physicochemical properties on the overall SMD and the spray-wall impingement time in a piston chamber under high ambient pressure conditions. The effect of the fuel viscosity, density, ambient pressure, injection angle and chamber geometry has been investigated.

The results show that the fuel density has a great impact on the spray-walls impingement time and SMD, while the fuel viscosity has a very slight effect. Pyrolysis oil spray has a shorter spray-walls impingement time, due to its larger density compared to diesel, potentially leading to more inefficient combustion. Whereas the larger viscosity of pyrolysis does not suppose a significant effect. Higher ambient pressures led to larger impingement times and larger SMD, due to enhanced drag forces. Besides, the results also show that an optimal value of the injection angle is coupled to the combustion chamber geometry, making necessary an optimization study if the chamber geometry is modified. Furthermore, pyrolysis oil spraying was compared to diesel's in terms of spray-walls impingement time and SMD. Although pyrolysis oil spraying showed shorter impingement with the chamber walls than diesel's, the causes of this behavior were found to not be due to its larger viscosity, but to its higher density.

A computational optimization study has also been performed to provide technical advice about injection characteristics when pyrolysis oil is sprayed. Physicochemical properties of pyrolysis oil were utilized to carry out spray simulations under high ambient pressure conditions. The outcome of this investigation advises an injection angle of 37.5 degrees and an 8-hole injector. These characteristics were found optimal to obtain a longest spray-walls impingement time.

5. CONCLUSIONS

As part of the PyroWKK project, a computational and experimental research about pyrolysis oil spraying has been performed. Implementation of a benchmarking collision model has been implemented and verified.

Regarding LDA/PDA experiments, these have shown that the fuel dynamic viscosity has very little effect on the SMD and droplet size distribution.

These results are consistent with the ones found in the computational parametric study, where ambient pressure and fuel density shower a much greater effect on the spray characteristics than the fuel dynamic viscosity. The sensitivity analysis shows that viscosity may have a greater impact on the spray characteristics at lower injection pressures than 200 bars.

The “Optimization Report” advise to use an injection angle of 37.5 degrees and an 8-hole injector to inject pyrolysis oil under high ambient pressures.

It is recommended further experimental and computational research. The combination of impinging sprays and high-speed imaging techniques may provide a sufficiently strong experimental reference to validate the model in terms of droplet size distributions.

Although the Euler-Lagrange model has shown to be a very powerful computational tool to gain more insight about pyrolysis oil spraying, this may be combined in future research with Direct Numerical Simulations (DNS) to resolve the interaction of the liquid with the nozzle and therefore resolve the gas-liquid interface. This type of research may provide relevant information to feed suitable Rosin-Rammler distributions at the injector cell in Euler-Lagrange models.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge BTG for providing 2-D sketches of the piston chambers as well suitable injectors to perform the experiments. In addition, the authors are also grateful with Abato for providing a pulsating flow pump. Finally, the authors would also like to thank Ceratec for their collaboration in the project.

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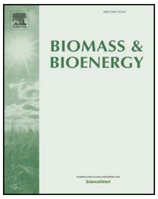
Biomass and Bioenergy 110 (2018) 114–122

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe



Research paper

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

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ARTICLE INFO

Keywords:
Fast pyrolysis oil
CHP
Diesel engine
Dynamic surface tension
Atomization

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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https://doi.org/10.1016/j.biombioe.2018.01.023
Received 2 October 2017; Received in revised form 3 January 2018; Accepted 30 January 2018

[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]:

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

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

Table 1
Overview of $FPBO_{20}$ properties.

Property (as received basis)	Unit	Ethanol	FPBO	$FPBO_{20}$ (FPBO + 20 wt% EtOH)
C	mass %	52.2	42.8	45.4
H	mass %	13.0	7.8	8.6
N	mass %		0.1	< 0.1
O	mass %	34.8	Balance	balance
Water	mass %		24.1	19.4
LHV (calc)	MJ kg^{-1}	28.9	16.4	18.7
	MJ L^{-1}	22.5	19.2	20.5
Density	kg L^{-1}	0.78	1.17	1.07
Solids	mass %		0.04	0.035
Ash	mass %		–	–
MCRT	mass %		17	14.3
pH	–		2.6	2.8
Acid number	mg KOH g^{-1}		70	47
Viscosity (40 °C)	cSt	1.1	21	12
Surface tension	mN m^{-1}	20	31	30

the volatile components in the blend and mass fraction of both is already 40%. For sure, other volatiles are present in FPBO as well and the total volatiles content might already be too high to cause micro-explosions. Ethanol as such is not an ideal fuel for a compression-ignition engine, and even more difficult to ignite than FPBO. However, it has been shown previously that adding up to 20–30% mass fraction ethanol to FPBO leads to an increase in engine efficiency [6] which is likely due to a better atomization of the fuel whatever the cause may be.

2. Materials and methods

2.1. Properties of fast pyrolysis oil

The properties of FPBOs are very different from conventional diesel or fuel oils, and as such not ideal for use in a standard compression-ignition engine. The FPBO used in this work was produced from woody biomass by the EMPYRO plant [11]. To remove any remaining particles the FPBO was filtered using a 20 μm absolute filter. The viscosity was reduced by adding 20% mass fraction ethanol to the FPBO and this blend ($FPBO_{20}$) was used in all experiments described in this paper. The properties are given in Table 1.

2.2. Dynamic surface tension of FPBO

The dynamic (non-equilibrium) surface tension of different liquids has been measured by using the bubble pressure method which will be briefly discussed while using Fig. 1. A capillary is submersed into the liquid fuel and air flows through the capillary. A bubble will be formed at the end of the capillary, and meanwhile the bubble pressure is measured. At the start of bubble formation the pressure is at its minimum. The pressure reaches its maximum value when the bubble radius equals the one of the capillary. The difference between the maximum and minimum pressure difference is correlated with the surface tension. The lifetime of a bubble (t_{life} in Fig. 1) can be controlled by setting the airflow through the capillary. During this lifetime surface active components can travel to the droplet surface, and for low lifetimes the concentration of these components is low whereas for long lifetimes the equilibrium concentration is reached.

For the experiments a SITA pro-line t15 tensiometer has been used. With this unit the bubble life time can be varied between 15 ms and 20 s, and temperatures can be up to 60 °C. The unit is calibrated with tap water as standard.

2.3. Engine testing

BTG has two compression-ignition engines available for testing, viz. a one-cylinder (1C) and a four-cylinder (4C). Basic characteristics of the engines are given in Table 2. Both units have been modified to enable fueling of different fuels including pyrolysis oil. Details of the 1C engine set-up can be found elsewhere [3,4]. The 4C engine setup has been constructed recently, and it is shown schematically in Fig. 2. The core of the set-up is a Weichai 226B engine. The complete genset has been assembled and supplied by ABATO Motoren BV, the Netherlands.

Basically, the 4C setup is similar to the 1C testunit. Three fuel vessels have been installed: one for diesel, one for rinsing fuel (N-butanol or ethanol) and one for pyrolysis oil. The latter can be preheated to 40-60 °C by means of a water jacket. Additionally, a stirrer is installed on this vessel.

The modifications of the fuel system are concerned with the substitution of 4 pumps, 4 injectors and all tubing with stainless steel items. The fuel pump is a two-stage system meaning that the original fuel pump is driving a second pump, the latter one is connected to the fuel injector (see Fig. 2). This way any direct contact of FPBO with original parts of the engine is avoided. All pumps and injectors have been made in-house from stainless steel as these parts were not freely available on the market. The design of the injector is identical to a standard injector. An electric heater is installed to preheat the incoming air up to 250 °C. Contrary to the 1C engine, the compression ratio has not (yet) been changed and kept to the original value of 18. The power output can be set by switching on electric space heaters (JOEL) of 2 kW each; in total 10 heaters are coupled to the generator and the maximum load is therefore 20 kW. This power output is roughly 40% of the rated output. In due course, additional electrical heaters will be installed to test the engine at higher capacities.

For each cylinder the outlet temperature, fuel pressure, cylinder pressure and needle lift are measured by a picoscope (Pico Technology, Picoscope 2000). To determine the fuel consumption, the fuel vessel is placed on a balance (TELL EAG-80). A exhaust gas analyzer (AGS-200, Brainbee Automotive) is installed to measure the major components in the fuel gas (CO, NO_x, HC, CO_2, and O_2).

First, the engine is started on diesel, and subsequently the inlet air heater is switched on. If the engine is running smoothly, the fuel type is switched to rinsing liquid (ethanol or butanol). The engine will run for 5 or 10 min on this fuel. Finally, the switch is made to the $FPBO_{20}$. A summary of the experimental conditions are given in Table 3.

3. Results

3.1. Measurement of the dynamic surface tension

As an example, in Fig. 3 the surface tension is shown as a function of the t_{life} for water, ethanol, FPBO and $FPBO_{20}$ at a temperature of 20 °C. It can be seen that the surface tensions of water and alcohol are hardly influenced by the bubble lifetime as these liquids do not contain any surface active components. For both FPBO and $FPBO_{20}$ a strong decrease in surface tension is observed with increasing the bubble lifetime. The value at high bubble lifetimes equals or approaches the surface tension equilibrium value ($t_{life} > 10$ s). In Fig. 4 the surface tension of FPBO is shown as a function of t_{life} and for three different temperatures. The temperature dependency of the equilibrium surface tension is very moderate. However, for short bubble lifetimes (< 1 s) large differences are observed, and at 20 °C the surface tension can be almost double the value at 60 °C. At T = 20 °C and short bubble lifetime a maximum is observed, but likely this is due to experimental difficulties. The unit repeats measurements till three subsequent measurements are within a 5% deviation. It was experienced that at high liquid viscosity and short bubble lifetime (< 0.1 s) it could take a lot of time before this criteria was met or no value was generated at all.

In Table 4 the equilibrium surface tension of different liquids is given for temperatures of 20, 40 and 60 °C, and these values correspond well with literature values. They are compared with the surface tension at bubble lifetimes of 40 ms. Differences are very small for liquids like

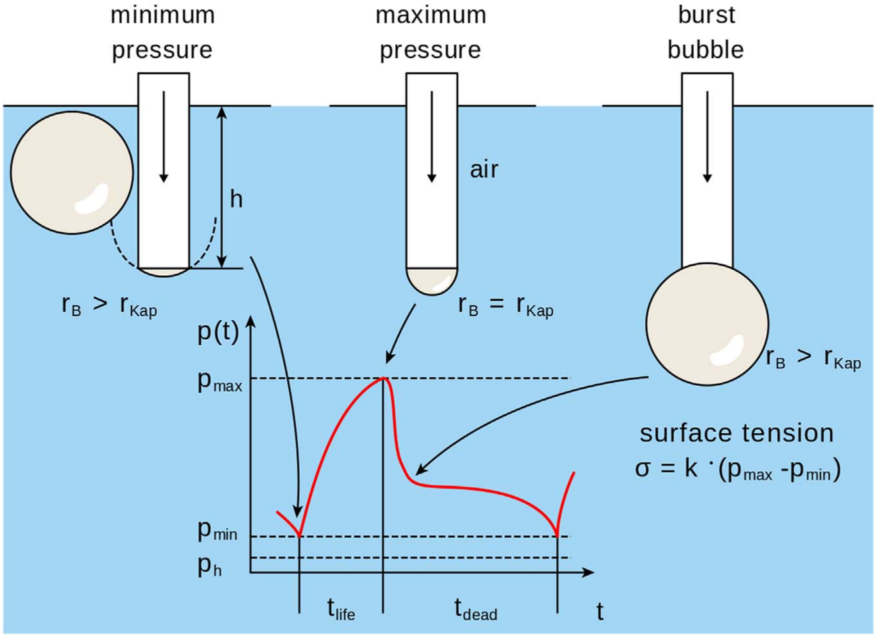

Fig. 1. Principle of surface tension measurement using the bubble pressure measurement [16]. r_B is the bubble radius, r_{kap} is the capillary radius and p the pressure in the bubble.

Table 2
Surface tension and ratio of surface tensions for different temperatures and fuels. The ratio is defined to be the surface tension at a bubble lifetime of 40 ms over a bubble lifetime of 20 s (assumed to be the equilibrium value). $FPBO_{20}$ is a blend of 80% mass fraction FPBO and 20% mass fraction Ethanol.

Reference		1C	4C
Supplier		Jiang Dong	ABATO Motoren BV
Engine model		ZH1130	Weichai 226B, turbocharged
No of cylinders		1	4
Cylinder volume	L cylinder^{-1}	1.6	1.25
Rotational speed	rpm	2250	1500
After modification	rpm	1800	1500
Max. output	kW	23	60
Compression ratio		17	18
after modification		22	18
Injection pressure	Bar	200–250	200–300
Generator		DINGOL DG274C14	Newage Stamford
Max output generator	kW	10	48

Table 3
Input data for the calculation of the Sauter Mean Diameter for different fuels at 40 °C. (FPBO subscript means the amount of ethanol).

	1-C	4-C
Power output	0–4 kW	0–20 kW
Air inlet temperature	150 °C	40–250 °C
Test Fuels	$FPBO_{20}$	$FPBO_{20}$, ethanol, butanol, diesel
Fuel preheat temperature	40–60 °C	40–50 °C
Start fuel injection	15° before TDC	8–27° before TDC

water, ethanol and diesel. For FPBO the dynamic surface tension appears to be 50–160% higher than the equilibrium value. Similar behavior was also observed for sunflower oil, but less extreme than for FPBO. In general, it was observed that the difference between the surface tension at short bubble lifetime and the one at equilibrium decreases with decreasing liquid viscosity and increasing temperature.

The droplet sizes (SMD) have been calculated for diesel and FPBO containing different amounts of ethanol as well as for pure ethanol. The input data for the calculations are listed in Table 5. Adding some ethanol to the FPBO is beneficial as it reduces i) the viscosity, ii) the

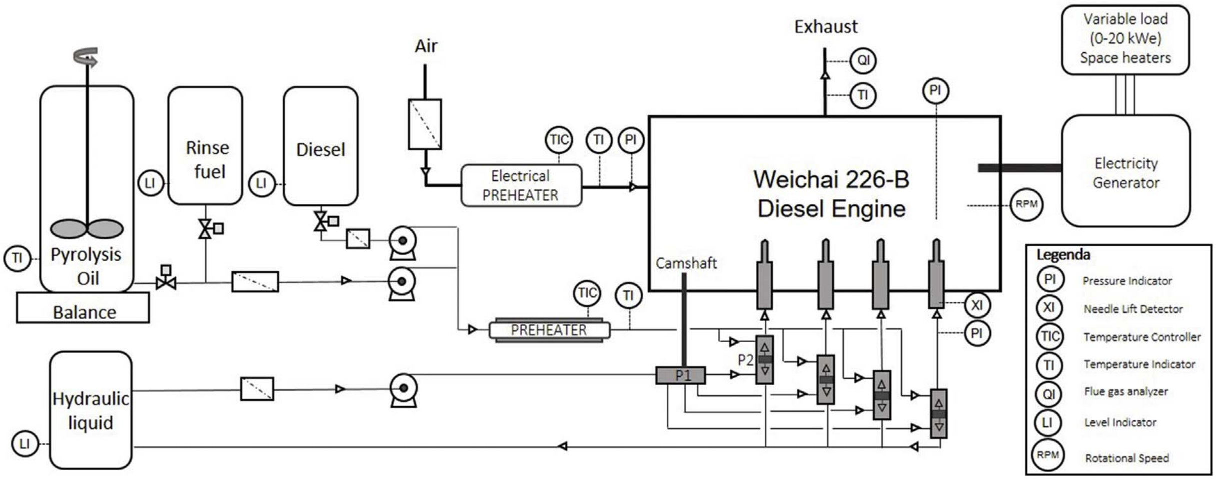

Fig. 2. Schematic process flow diagram of the 4-cylinder engine set-up.

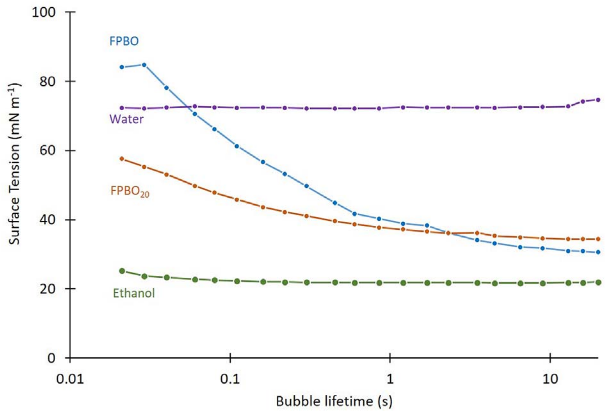

Fig. 3. Surface tension of the different liquids as a function of bubble lifetime at a temperature of 20 °C.

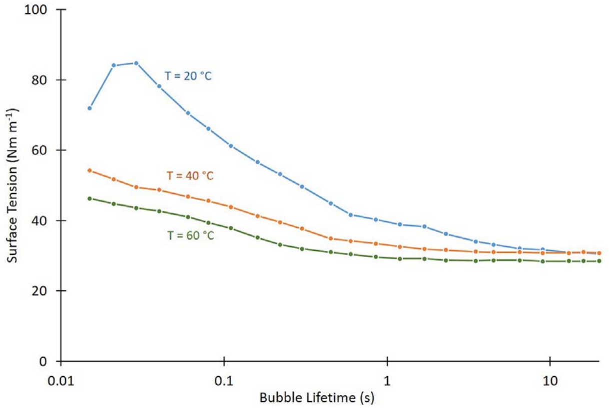

Fig. 4. Surface tension of FPBO as a function of bubble lifetime at temperatures of 20, 40 and 60 °C.

Table 4
General characteristics of the test engines.

	σ (mN m^{-1})			Ratio = $\sigma_{40ms}/\sigma_{20s}$		
Temperature [°C]	20	40	60	20	40	60
Diesel	27.2	26.2	23.6	1.1	1.1	1.1
Biodiesel	30.4	28.5	27.0	1.2	1.1	1.1
Sunflower Oil	33.5	30.2	29.5	1.9	1.6	1.4
Ethanol	21.9	20.2	18.5	1.1	1.1	1.1
FPBO	30.5	30.8	28.6	2.6	1.5	1.5
FPBO$_{20}$	34.4	30.2	29.1	1.5	1.3	1.3
Water	72.4	69.4	65.5	1.0	1.0	1.0

Table 5
Overview experimental conditions.

	P (kg m^{-3})	N (cSt)	σ_{20s} (mN m^{-1})	$\sigma_{15\ ms}$ (mN m^{-1})
Diesel	832	2.8	26.2	33.0
FPBO	1.193	21.4	30.8	55.3
FPBO$_{20}$	1071	6.9	30.2	47.6
FPBO$_{40}$	989	3.8	26.7	38.0
FPBO$_{60}$	911	2.4	23.1	32.3
FPBO$_{80}$	841	1.5	21.7	19.6
Ethanol	789	1.1	20.2	25.9

surface tension at short times and iii) the density of the fuel.

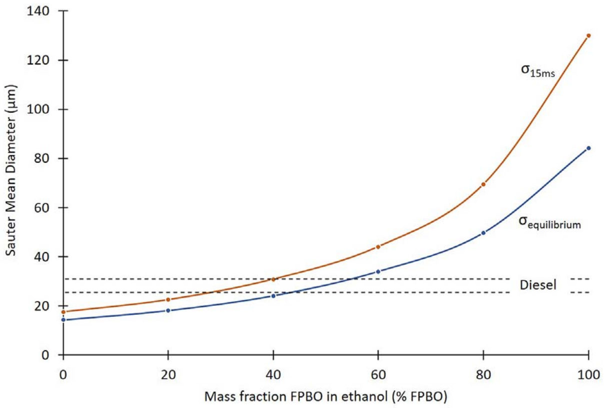

Fig. 5. Calculated Sauter Mean Diameter (SMD) for FPBO-ethanol blends based on equilibrium surface tension and non-equilibrium surface tension (at bubble lifetime of 15 ms).

For the air density a value of 18.6 kg m^{-3} is assumed (at an engine compression ratio of 22, and an air inlet temperature of 150 °C), and a pressure difference over the orifice of 250 bar for all fuels. The results of the calculations are shown in Fig. 5. The calculated droplet sizes for FPBO are significantly higher than those for diesel (dotted lines). Obviously, adding ethanol to FPBO is very effective in reducing the droplet size and thus improving the atomization. In all cases the same pressure difference has been assumed. However, due to the lower heating value of FPBO, more fuel needs to be injected compared to diesel. This means that for the same power output the pressure drop must be higher in case of FPBO resulting in smaller droplets.

Chiaramonti et al. [17] measured droplet sizes of various liquids and derived an empirical relation for the calculation of the SMD. They compared the calculated SMD with experimental data for water, diesel and also pyrolysis oil. A good agreement was obtained, but the lifetime of the droplets are unclear in this specific case. As shown by the current experiments (Fig. 2) for droplet lifetimes above 0.5–1 s the difference between using dynamic and equilibrium values of the surface tension will be very small. Therefore, when the droplet lifetime was > 500 ms no influence of the dynamic surface tension is to be expected on the experiments.

3.2. One-cylinder engine tests

Experimental results of the 1C-engine with several fuels including pyrolysis oil, as well as with different kinds of upgraded oil, have been described previously [3,4]. Initially, the engine was operated only during daytime. The engine was then started in the morning on diesel, and after about an hour switched to FPBO$_{20}$. At the end of the day the engine was switched back to diesel and then after 10 - 15 min the engine was stopped. This was repeated on a daily basis, which is obviously time consuming and the frequent starts and stops are not ideal for the operation of the engine. It is Important to demonstrate the long duration performance of the system and in particular that of the fuel injector and pump. In Fig. 6^{AB} the results are shown for the `longterm' testing of different injectors. The runtime represents the total of cumulative running hours gained during operation in daytime. The injectors are constructed in-house, and the design and materials are always the same. Over time the injectors were improved by better construction methods and improved machining. In Fig. 6^{A} the NO$_x$ emission is shown. After about 75 h the fuel injection timing was changed (by a small turn in camshaft, see [3]) resulting in higher NO$_x$ emission. Next the load was increased from 2 to 4 kW. Both changes together resulted in smoother operation of the engine beyond 105 h of runtime. During the run time for injector 3 a slight decrease in NO$_x$ emission is observed, which might be the result of a decrease in fuel atomization quality or cylinder compression (e.g. fouling). In Fig. 6^{B} the temperature difference between exhaust gas and inlet air per kW output is plotted as a function of time. This specific temperature increase is an indicator of the engine performance and relates directly to the engine efficiency. For the third

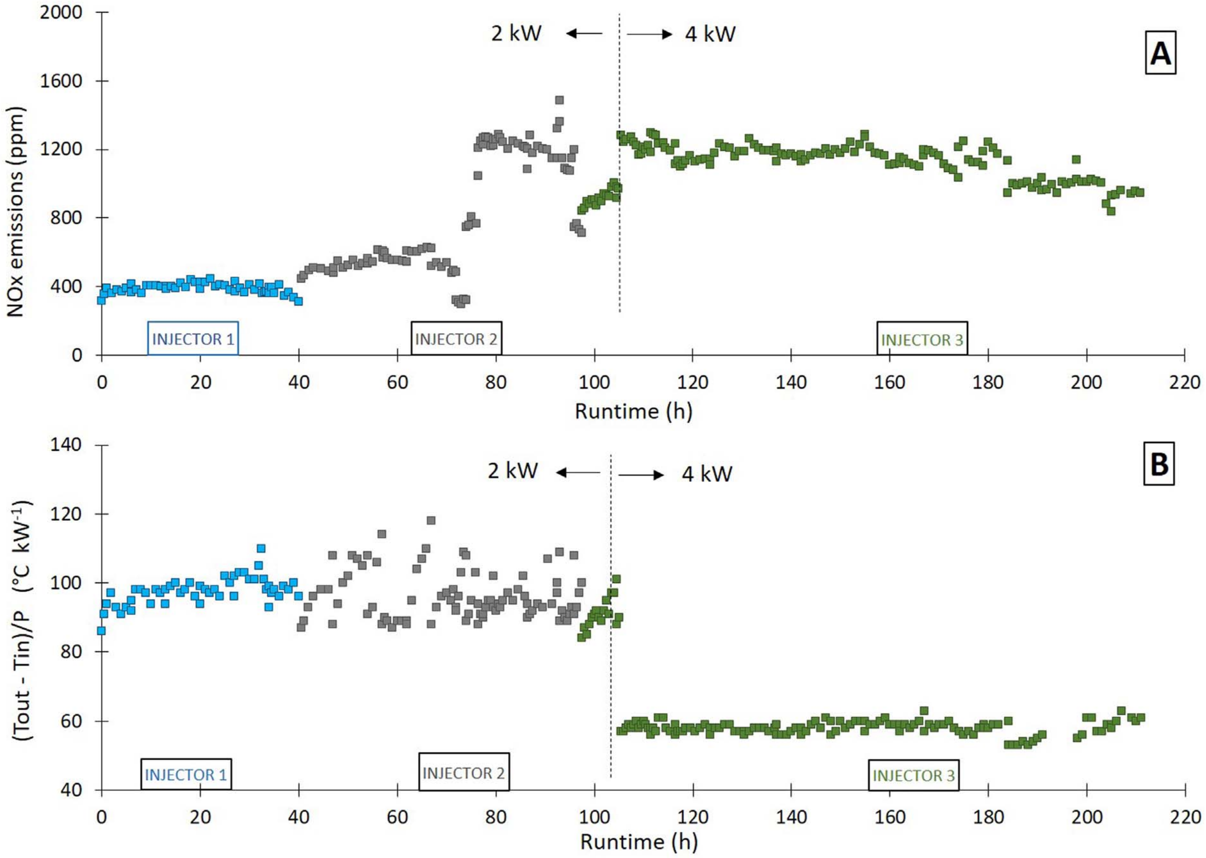

Fig. 6. [AB]: Duration test of the IC-engine at 2 and 4 kW based on daily operation A: NO_x emissions, B: Temperature difference between exhaust and air inlet gas divided per kW power output.

injector and at 4 kW load, less variations are observed due to a more stable operation. The 'best' injector survived for 126 h running on $FPBO_{20}$ using this intermittent operation. The injectors were inspected under a microscope. Injector 1 failed due a broken tip; for injector 2 a crack was observed in the top of the injector, whereas for injector 3 a crack was observed in the body of the injector. No significant changes were observed in the size of the injector holes. In all cases the same pump was used, and no visual wear could be observed.

To achieve longer runtimes, unattended and continuous operation of the engine is required. Additional safety measures are then required such as early detection of mis-operation and potential fire risk.

Meanwhile, the first unattended tests have been executed. The first run lasted 18 h and a second one 52 h. The first test was stopped automatically due to a peak in the exhaust temperature (ES-1); in the second test an error was induced by the electricity generator which triggers an emergency stop of the engine (ES-2). Both tests were carried out with the same pump and injector, and visually no wear or tear was observed on these parts. In Fig. 7[A] the air inlet temperature and the flue gas temperature are shown as a function of the operational hours, whereas Fig. 7[B] shows the power output and frequency. ES refers to an emergency stop and is generated automatically by the system if certain undesired events occur.

3.3. Four cylinder engine tests

Initially, the new 4C engine setup has been commissioned with diesel, also to enable a comparison the completely modified system (new pumps and injectors). As a result, the fuel consumption, flue gas temperatures, and CO emissions appeared to be very similar. The NO_x emissions were somewhat lower with the new pumps compared to the original system. The new pump system gives a short delay in fuel injection which results in lower NO_X emission (see also Fig. 9[A]). Besides, the fuel injection peak of the modified system is a little smoother than the original one. Likely, this results in lower peak temperatures and also in a reduction of thermal NO_X. Anyhow, in all cases the NO_x emissions will exceed allowable (European) limits and additional flue gas treatment will be needed.

3.3.1. Air inlet temperature

Next, a series of experiments were executed while using the rinsing liquids (ethanol and butanol) and $FPBO_{20}$ as fuels. The compression ratio of the engine was not changed. Instead, to overcome the poor ignition properties of FPBO (as well as of the alcohols), the inlet air was preheated. An experiment started at a high inlet temperature of 220–230 °C. Then the air preheating temperature was gradually decreased meanwhile measuring the engine performance. The emissions as well as the difference between the temperatures of the inlet air and flue gas are indicators of the combustion performance. Typically when the combustion process becomes poorer, the CO will increase (incomplete combustion) and NO_X decreases (lower peak temperatures). Furthermore, at constant power output, the flue gas temperature increases when more fuel is required to keep the system running.

Fig. 8[ABC] shows the results of these experiments. Diesel is the base case and-obviously- will combust very well over the whole range of air inlet temperatures. CO is always low, and as expected NO_X emission will decrease with decreasing air inlet temperature. Pure ethanol is the most difficult fuel to ignite and air needs to be preheated to almost 200 °C. When the air inlet temperature further drops an increase in CO, and an accelerated increase in ΔT (T_{out}-$T_{air,in}$) is observed. The NO_x concentration normally decreases with reducing the air inlet temperature. However, when the combustion becomes poor an accelerated decrease in NO_x content is observed. Below 150-155 °C is was not

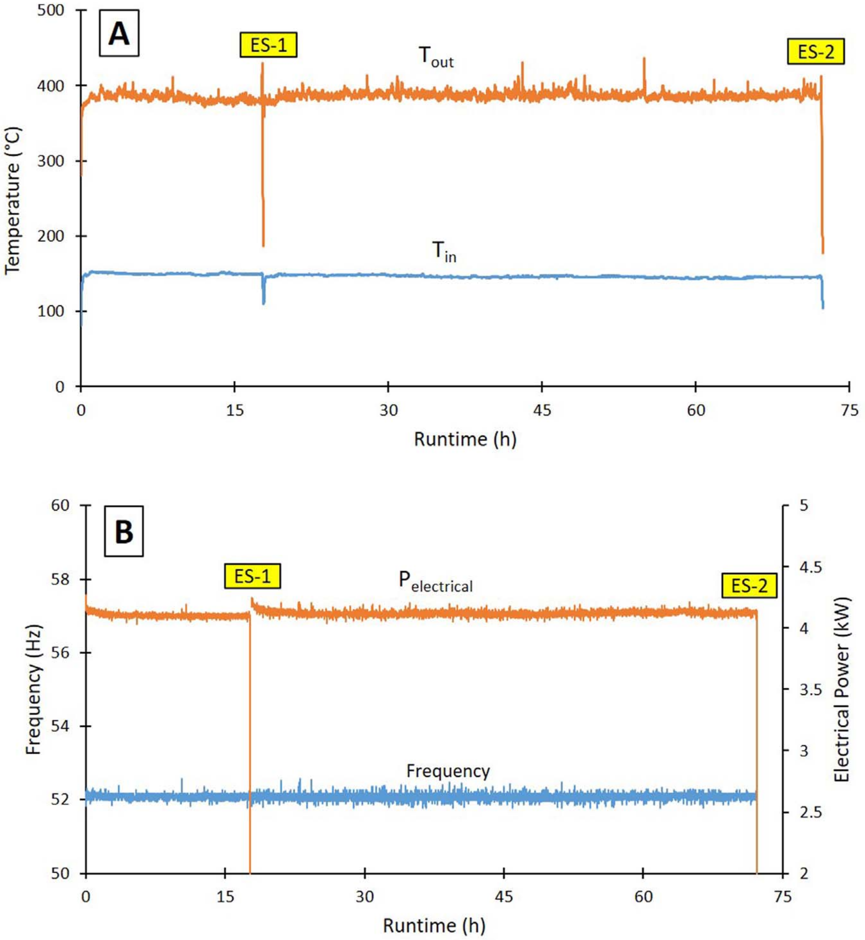

Fig. 7. ^{AB}: Unmanned operation of the 1C engine fueled with $FPBO_{20}$. ES-1 = Emergency stop due to peak in flue gas temperature. ES-2 = Emergency stop induced by generator. A: Air inlet and exhaust gas temperature, B: Electrical power output and frequency.

possible to run this engine on pure ethanol. The same phenomena are observed for butanol, but at lower air inlet temperatures. The cetane number of butanol (approx. 17) is higher than the cetane number of ethanol (approx. 8 - 10) and therefore easier to ignite. By adding some cetane improver (butanol^{++} = n-butanol + 8% mass fraction Akzo-Nobel Beraid® 3450) the critical air inlet temperature could be further reduced from around 140 to 90 °C. With respect to NO_x and ΔT no critical temperature could be observed when fueling $FPBO_{20}$ and the changes are more comparable to diesel. However, for the CO emissions the behavior was more similar to that of ethanol and butanol. All results agree very well with the observations with the 1C engine testing, see e.g. [6]. For proper combustion of $FPBO_{20}$ in the current engine set-up a minimum air inlet temperature of 150–170 °C is desired.

3.3.2. Fuel injection timing

To achieve optimal combustion and a maximum efficiency, the fuel injection timing is important when running a diesel engine. In Fig. 9^{AB} the influence of the injection timing on ΔT and the NO_x emission is shown for butanol, diesel and $FPBO_{20}$. From an emission point of view low NO_x is preferred, but typically better combustion performance is obtained at high NO_x values. For diesel and butanol a significant increase in NO_X was observed by early fuel injection, whereas for $FPBO_{20}$ only small effect was noticed. A low ΔT is an indicator for efficient and timely combustion. Problems with the injector and/or atomization are often noticed first from an increasing or fluctuating flue gas temperature. In Fig. 9^B a minimum can be seen for all three fuels; for $FPBO_{20}$ the lowest values are obtained at 12 and 16 CAD before TDC. Fig. 9^C also shows the CO emissions for $FPBO_{20}$. Early injection of $FPBO_{20}$ resulted in an increase in CO and should be avoided. It should be noted that CO measurement resolution is only 0.01 vol%. Based on these experiments it was decided to set the start of fuel injection to 16° CAD (crank angle degrees) before TDC (top dead center).

3.3.3. Fuel consumption and efficiency

Finally, the fuel consumption and efficiency was determined for different fuels as a function of the electric load. Differences in consumption for the various fuels can be directly related to the large differences in their heating values. In Table 6 the lower heating values (LHV) both on a mass and volumetric basis are given.

In Fig. 10^A the fuel consumption is shown on a volumetric basis and in Fig. 10^B the calculated efficiency is plotted using the LHVs from Table 6. The overall electrical efficiency (%) is calculated as follows:

$$\text{Efficiency} = 100\ Ø_{fuel}\ \rho_{fuel}\ LHV_{fuel} / (3.6\ P_e)$$

With $Ø_{fuel}$ the fuel consumption (L hr^{-1}), ρ_{fuel} the density (kg L^{-1}), LHV_{fuel} the heating value (MJ kg^{-1}) and P_e the electrical output (kW). Although significant differences do exist in fuel consumption and heating values the overall efficiency is very similar for diesel, butanol and $FPBO_{20}$ over the load range tested. Ethanol results in somewhat lower efficiencies. This might be due to the use of an air inlet temperature of 190 °C, which is on the low side for optimal combustion of ethanol in this engine.

4. Conclusions

It has been shown that $FPBO_{20}$ is a suitable fuel for use in diesel

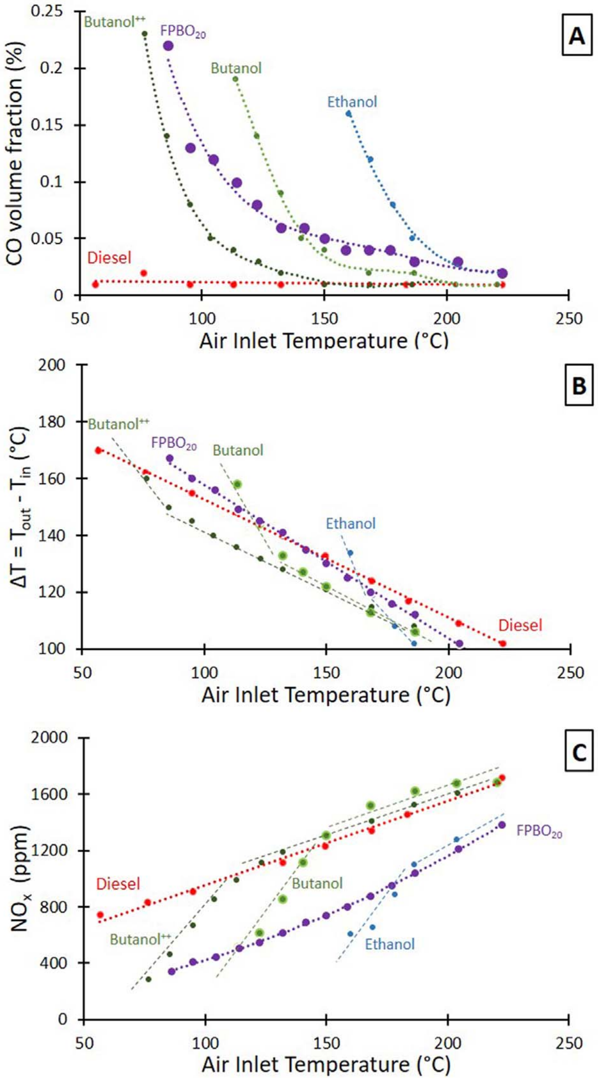

Fig. 8. ^{ABC}: Operation of the 4C-engine as a function of the air inlet temperature for different fuels. P_e = 10 kW; Fuel injection 10-12° CAD before TDC. Butanol^{++} contains 8% mass fraction cetane improver (Beraid 3450). A: CO concentration in the exhaust gas, B: Temperature difference between air inlet and exhaust gas, C: NO_x concentration in the exhaust gas.

engines, but some challenges do exist. Proper atomization of the fuel is of utmost importance, but FPBO properties are quite unfavorable in that respect. In addition to a high viscosity and high density it has been shown that proper atomization might be hindered by an apparent high surface tension at low droplet lifetimes. For pure FPBO the surface tension for very low droplet lifetimes (< 40ms) can be 2-3 times higher than the equilibrium value. Addition of 10–20% mass fraction ethanol is very helpful in improving the primary fuel atomization by reducing viscosity, density and dynamic surface tension.

A one cylinder engine (1C) has been modified and operated on $FPBO_{20}$. The fuel injector is more critical than the pump, and the longest lifetime achieved of a single injector is 126 h. To achieve complete and fast combustion of $FPBO_{20}$ both the compression ratio and the air inlet temperature were increased. Recently, a number of additional safety measures have been implemented to enable unattended operation. So far, the longest continuous run has been 52 h.

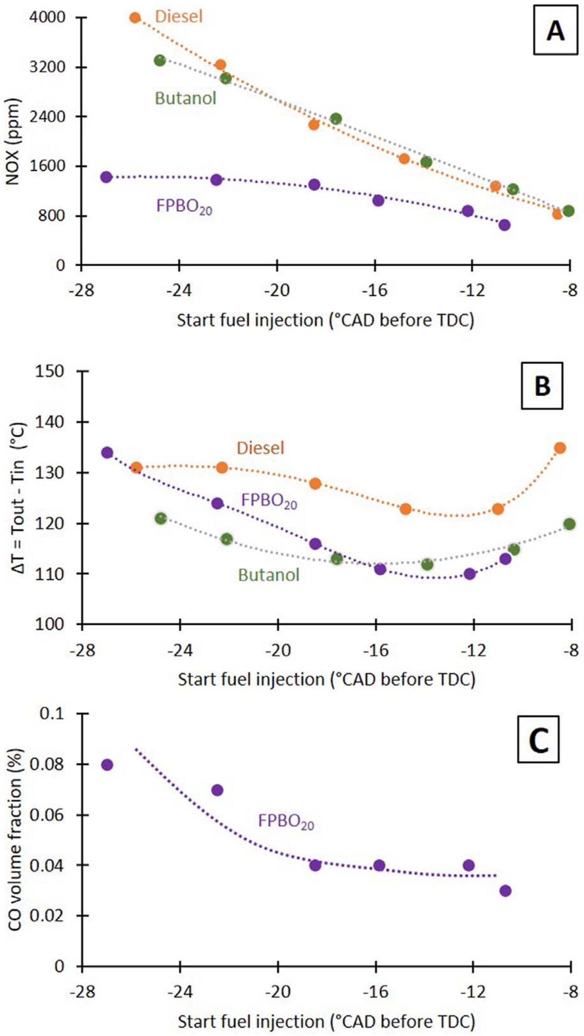

Fig. 9. ^{ABC}: Operation of the 4C engine as a function of the fuel injection timing for different fuels. P = 10 kW; $T_{air,in}$ = 190 °C. A: NOx concentration in the exhaust gas, B: Temperature difference between air inlet and exhaust gas, C: CO emission in the exhaust gas for fueling $FPBO_{20}$.

Table 6
Density and Lower Heating Values (LHV) on weight and volumetric basis for the different fuels tested.

	Density (kg L^{-1})	LHV (MJ kg^{-1})	LHV (MJ L^{-1})
Diesel	0.83	43.4	36.0
Butanol	0.81	33.1	26.8
Ethanol	0.78	28.9	22.5
$FPBO_{20}$	1.07	18.7	20.0

A four cylinder, 50 kW diesel engine (4C) has been successfully modified to enable fueling of $FPBO_{20}$. This engine can be seen as a prototype for a commercial CHP unit (100 kW–1 MW). The unit was successfully started up and initial tests are in line with the 1C experiments. The compression ratio was kept to the original value of 18, and compared to the 1C engine a higher air inlet temperature was needed. To ensure proper combustion of $FPBO_{20}$, most tests were carried out at an air inlet temperature of 190 °C. However, an air inlet temperature of around 150 °C seems to be sufficient at a compression ratio of 18. Compared to diesel the volumetric fuel consumption is significantly higher using $FPBO_{20}$, but the overall electric efficiency is very similar.

In the near-term the focus for the 1C engine is on long-term unmanned operation with the objective to achieve a few hundred hours continuous operation. For the time being, the 4C engine can only be operated in daytime and the objective is mainly to optimize the performance and increasing the power output to at least 80% the rated engine output.

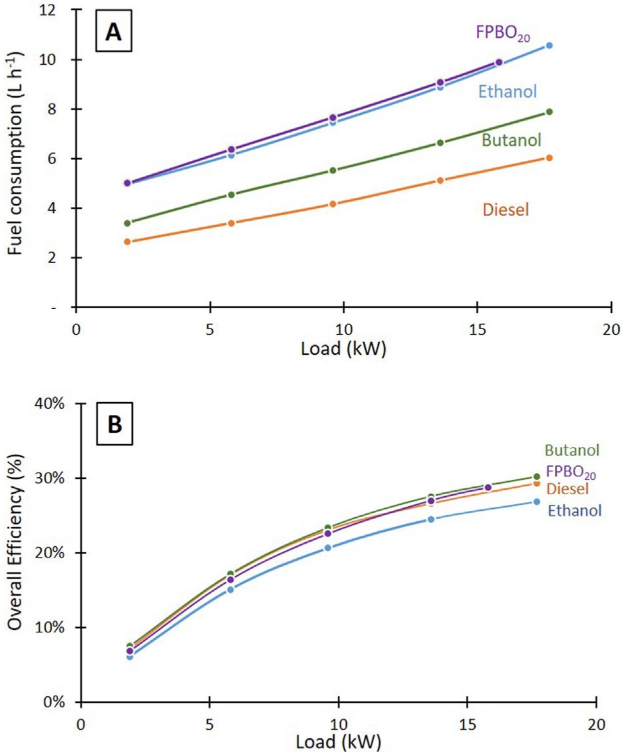

Fig. 10. ^{AB}: Fuel consumption (A) and overall efficiency (B) of the 4C engine for various fuels as a function of the electrical load. $T_{air,in}$ = 190 °C.

Acknowledgements

The work described in this paper was initiated with financial support from the Eurostars programme (CHPyro E!8096) project and continued with financial support from the Dutch TKI-BBE programme (PyroWKK, TEHE115065). Furthermore, the experimental and theoretical work performed by Marco Tarchi (University of Florence) during his internship at BTG is gratefully acknowledged.

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The use of fast pyrolysis bio-oil in a modified diesel engine

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The use of Fast Pyrolysis Bio-Oil (FPBO) in stationary diesel engines can be a valuable approach for small scale, combined heat & power (CHP) applications. However, direct application (i.e. without chemical upgrading) is challenging due to the specific properties of FPBO. The pH of FPBO is below 3 and the water content is in the range of 20 -25 wt%. As a result standard diesel engine components will quickly corrode when contacted with FPBO.

To enable fast and complete combustion of FPBO, proper atomization is of utmost importance. Compared to conventional diesel FPBO, has a higher viscosity and a higher density which will result in larger droplets. Additionally, the dynamic surface tension of FPBO is significantly higher than for diesel causing a further increase in droplet size [3,4]. Adding some ethanol to the FPBO strongly improves the atomization properties.

FPBO is difficult to ignite and special measures are required. Different approaches can be used such as increasing the air inlet temperature,

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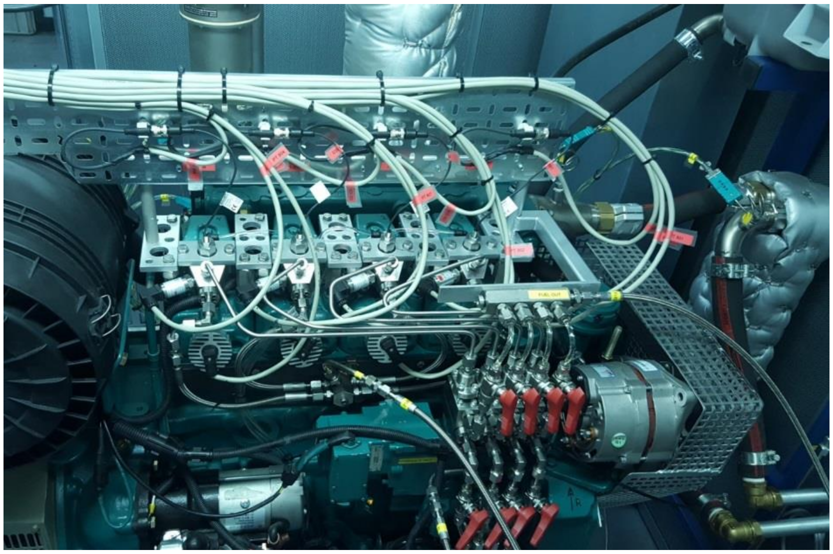

Fig. 1: Modified 4 cylinder diesel engine

Fig 2: Fuel feeding skid

The use of fast pyrolysis bio-oil in a modified diesel engine

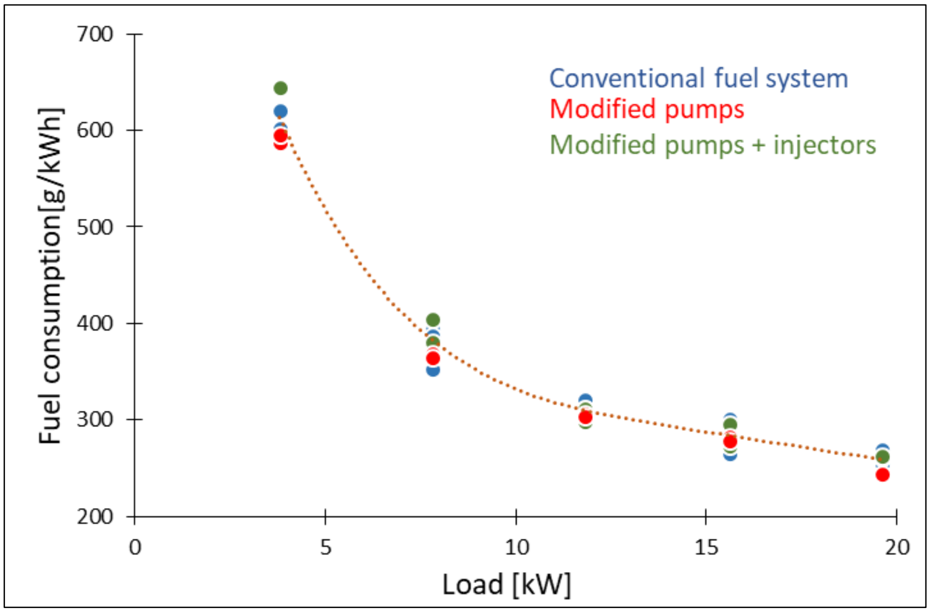

Fig. 3A: Specific fuel consumption as a function of the load

increasing the compression ratio, adding cetane improvers to the fuel, or pilot fuel injection.

Engine modification

BTG has modified two compression-ignition engines to develop this application, viz. a one-cylinder and a four-cylinder prototype. Initial work was done with the 1-cylinder engine which has the advantage that only 1 fuel injection system needs to be constructed and installed. More recently, the modification of the four cylinder engine started which can be seen as a prototype for a commercial size CHP system.

The prototype is based on the Weichai 226B engine, and the complete gen-set has been assembled and supplied by ABATO Motoren BV, the Netherlands. Subsequently, the unit has been modified by BTG to enable FPBO fueling. Four corrosion resistant fuel pumps and fuel injectors have been constructed in-house. The fuel pump is a two-stage system meaning that the original fuel pump is driving a 2nd fuel pump. The latter pump is connected to the fuel injector, and direct contact of FPBO with original parts of the engine is avoided. To overcome the poor ignition of FPBO the incoming air can be preheated; the compression ratio is kept to the original value of 18. Some pictures of the unit are shown in Fig. 1 and 2.

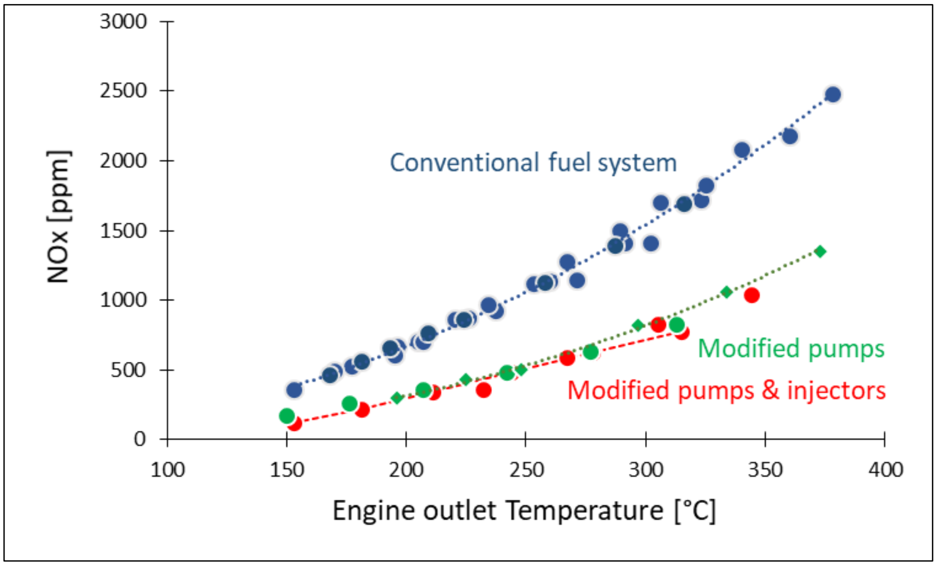

Fig. 3A: Specific fuel consumption as a function of the load

The engine is started on diesel, and subsequently the inlet air heater is switched on. If the engine is running smoothly and stable the fuel type is switched to rinsing liquid (ethanol or butanol) and engine will run for 5 or 10 minutes on this fuel. Finally, the switch is made to FPBO. So far all tests have been carried out with FPBO containing 20 wt% ethanol. The FPBO was produced by the Empyro plant from woody biomass.

Initial results

The major modification to the engine concerns the fuel feeding pumps and fuel injectors. To evaluate the new components their performance has been compared to the standard ones. Initially, reference runs have been carried out with diesel and the standard fuel pumps and injectors. Next, only the four fuel pumps were replaced with the modified fuel pumps, and the test runs were repeated with diesel as fuel. Finally, the new fuel injectors were installed and the same tests were carried out again. In Fig 3A and 3B the results of these tests are shown. Fig. 3A shows the fuel consumption for the three configurations as a function of the electrical load. Hardly any difference is

(Continued on page 13)

The use of fast pyrolysis bio-oil in a modified diesel engine

observed indicating that the system is working reasonably well. In Fig. 3B the NO_x concentration in the flue gas is shown as a function of the flue gas temperature. Tests were carried out at different engine loads (up to 20 kW_e) and different air inlet temperatures (50 – 200 °C). The new system leads to a lower NO_x content probably due to some delay in the fuel injection caused by the indirect pump system. A small change in the fuel injection timing might be implemented to get similar performance.

The fully modified system was tested with different fuels including FPBO. In Fig. 3 the specific fuel consumption is plotted in g/kWh as a function of the electrical load for diesel, butanol, ethanol and FPBO. Obviously, due to the lower heating value the consumption of FPBO will be the highest, and the specific fuel consumption will decrease with increasing load. Please note that 20 kW_e corresponds to only 40% engine load. However, the overall efficiency is nearly the same for the different fuels (see [3, 4] for further details).

In summary, it can be concluded that the 4 cylinder engine has successfully been modified to enable FPBO fueling. In 2017/2018 an extensive test program will be carried out to continue the development.

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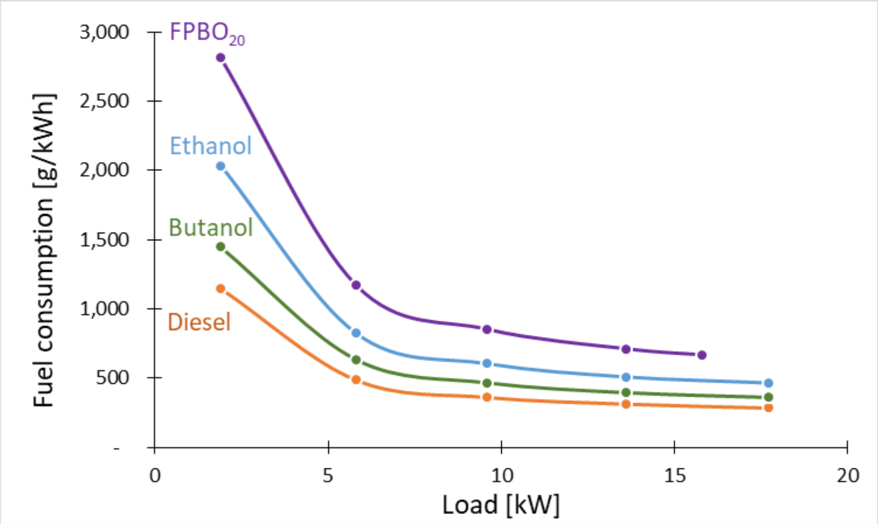

Fig. 4: Specific fuel consumption as a function of the electrical load for different fuels

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Acknowledgement

The financial support from the Eurostars programme (CHPyro E!8096) and the Dutch TKI-BBE programme (PyroWKK, TEHE115065) is gratefully acknowledged.

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