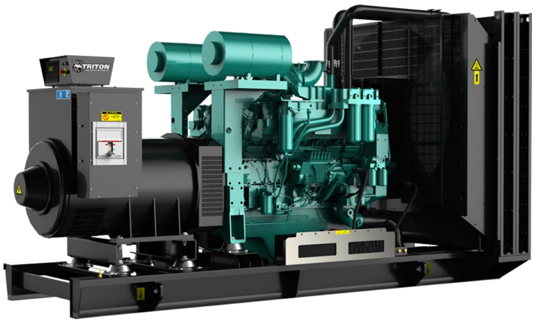
2019

North Lincs Engineering



Switching to low carbon fuels from Low Grade Waste Streams

GREEN FUELS FOR STATIC DIESEL GENERATORS

NORTH LINCS ENGINEERING LTD

Contents

Figures

Glossary of Terms

B100 – Pure biodiesel, this fuel is not blended with EN590 at all.

Big Rig – a 36 ltr reaction vessel with various ancillary components specially made for the Feasibility Study by University of Glasgow.

BFO – Boiler Fuel Oil, the residual waste left at the bottom of the distillation column when manufacturing B100 EN14214.

Dial Test Indicator (DTI) - a delicate measuring instrument used to determine small differences in the height or width of mechanical components.

Distillation Column - A piece of equipment used to separate a mixture into its separate components

EN590 – Automotive/red diesel EU standard, used for baseline tests to compare with test sample data.

Gas Emissions Towers – A set of devices that measure emission levels of a multitude of gasses from the exhaust systems of engines.

GCMS - Gas chromatography–mass spectrometry (**GC-MS**) is an analytical method that combines the features of gas-chromatography and mass spectrometry to identify different substances within a test sample. Like liquid chromatography–mass spectrometry, it allows analysis and detection even of tiny amounts of a substance.

Life Cycle Analysis (LCA) – A technique used to assess environmental impacts associated with the stages of the life cycle of a process.

Load Bank – A device which develops and electrical load, this is used in conjunction with the alternator on test cells.

Pyrolysis – a thermal reaction process which decomposition of long chain hydrocarbon into shorter chains. Typically used for gasification into Synthetic gas. In this case to partially pyrolysis into liquids.

TATA – Waste oils from the rolling of steel.

Torrefaction – a thermal process to convert biomass into a coal-like material and is a mild form of Pyrolysis, in this case to create a liquid fuel rather than solid.

BEIS Industrial Fuel Switching Competition: Phase 2 TRN 1674/10/2018

Feasibility Study

December 2019

NLE Report - Abridged Version

Executive Summary

The consortium was made up of 4 principle organisations; North Lincs Engineering Limited (NLE and Lead on the Grant Bid), Argent Energy (AE) and 2 Universities; University of Glasgow and University of Lincoln. There were small sub-contractors to undertake lab testing etc.

NLE was formed in 1963 and specializes in Heavy Marine Engines and large-scale diesel generators. NLE have been maintaining and servicing engines successfully running on the ‘better’ alternative fuels such as Used Cooking Oil and higher quality Rapeseed oils (Canola) for many years. NLE have also been deeply involved in providing solutions to using more difficult fuels such as Beef Tallow derived from the whole animals including bones, various Chicken Oils including high temperature and high pressure recovered oils, 3rd press Canola which produce gums and resins in the fuel lines and injectors, as well as Heavy Fuel Oil in marine engines.

Over the years NLE have helped to develop various technologies to reduce or eliminate many of the problems with these alternative fuels. Some are fuel processing technologies to allow the successful use of Beef Tallow for stationary IC engines (https://core.ac.uk/download/pdf/9837903.pdf) with the University of Birmingham for Jon Pointon and Sons Ltd.

Other specialist help included technologies to de-gum fuel systems, modify fuel delivery systems to handle difficult and inconsistent feed stocks such as the chicken oils, engine technologies to create a cleaner burn in the chamber, re-mapping engines to prevent exhaust valve burn out, etc. etc.

Argent Energy produce in excess of 200,000 tonnes of road grade B100 from their 3 plants (2 in the UK and 1 in the Netherlands) and is the largest bio-fuel producer from waste in the UK. Argent take the relatively high-quality Fats, Oils and Greases (FOG) from water treatment plants and sewers and convert this into B100 for adding to Diesel to produce biodiesel for cars, trucks and buses.

There is limited supply of these quality FOG’s and as the demand for biodiesel has increased the market price for these waste streams is at an all-time high.

To increase production to meet the growing demand Argent need to develop different waste streams sources and different production methods to increase output.

The purpose of this Feasibility study is to investigate lower quality feedstock for their potential as a fuel for static diesel generation due to the ability to add technologies to make difficult fuels work which would not be possible on moving plant such as trucks or buses.

There is a clear need to raise the amount of fuels from waste as these wastes are currently going to land fill which then degrades to Methane. The opportunity is to extract economically all the calorific value from these materials.

The consortium includes 2 Universities; University of Glasgow has worked with Argent Motherwell on many research initiatives previously and will lead on the fuel processing. University of Lincoln has a long established relationship with NLE build up over many years and Industrial Professor Ron Bickerton who has 50 years in diesel at the highest level (and who designed the engine we will be using for test cell 2) and will support NLE with his mechanical expertise.

This is a very high impact project with the intention of producing 100's of thousands of tonnes of fuel for diesel generators from waste currently being thrown away.

Overview

The aim of the Industrial Fuel Switching initiative is to identify and test the processes and technologies required for industries in the UK to switch to low carbon fuels.

The resultant outputs will reduce the UK's carbon emissions and the cost of decarbonization by accelerating the commercialisation of innovative clean energy technologies and processes into the mid-2020s and 2030s. This collaborative feasibility study comprised of 4 partners, NLE, AE, UoL and UoG. The study was divided into 4 Work Packages: WP1 -Pre-treatment sampling. Evaluating feedstock handling & transfer model into biocrude; WP2 - Sample Fuel processing. Working through processes to create sample fuels & LCA and TEA; WP3 - Fuel Module and Emissions. Modify fuel module to handle fuels and commission the full emissions towers and WP4 -Engine Combustion Testing and Emissions Measurement.

Operating the Big Rig with TATA and BFO feedstocks

This report covers the work done on the Big Rig and a summary of GCMS data collected over the project for different feedstock and fuel samples. It should be noted that smaller systems existed, such as the F1 and RIPV, but had to be modified to produce fuel samples from both the liquid and solid feedstocks, the solid feedstock processing led to a unique design to reduce the likelihood of pipe blockages.

1. Introduction

Based on the results from the two smaller systems, a larger 36 L reactor was designed and built. This used internal electrical cartridge heaters, gas heating or a combination of both. In the summary of the work below, in section 5, the predominant heating source was gas (propane gas burner) unless otherwise noted.

Prior to the experiments, some samples of the feedstock were placed in a tube and allowed to stand overnight; there was no visible separation of phases (e.g. water and oil) which led to the feedstocks being treated as delivered.

2. Big Rig Fabrication

A schematic of the system and system components for the Big Rig is shown in Figure 1. Because of the size of the rig electrical heating was expensive and complex, consequently a gas burner and furnace were designed and fabricated (Figure 2) to sit around the lower half of the reactor. The outer material was made from a plaster of Paris. Once assembled on the rig, a flow-rate controlled, pumped air supply had to be used to provide sufficient control of the flame to enable a steady reactor temperature and prevent the flame from extinguishing. A stress analysis was also done, data not shown and pressure ratings calculated.

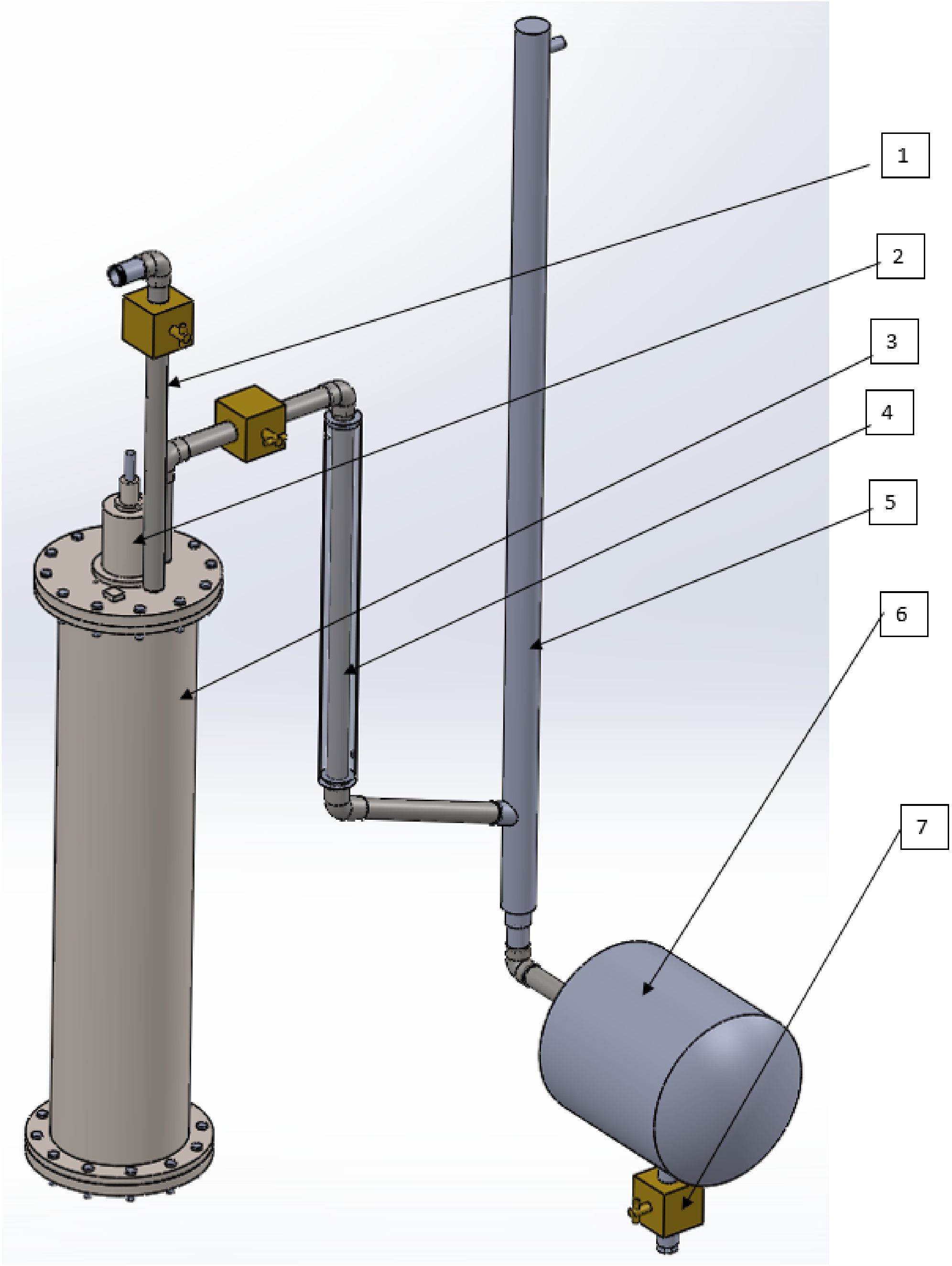


Figure 1 - Schematic of the Big Rig and system components

Number	Part
1	Feedstock inlet from pump
2	Rotary seal, motor not shown
3	Reactor
4	Heat Exchanger
5	Splitter
6	Collection Vessel
7	Valve

Figure 2 - Gas Burner

Figure 3 shows the part- assembled Big Rig, with the rotary seal and stirrer installed on top of the system, the rotary seal was designed and fabricated in house. As with the F1 system (small rig), provision was made to collect the gases from the system, condense and collect the liquids. Figure 4 shows the assembled rig.

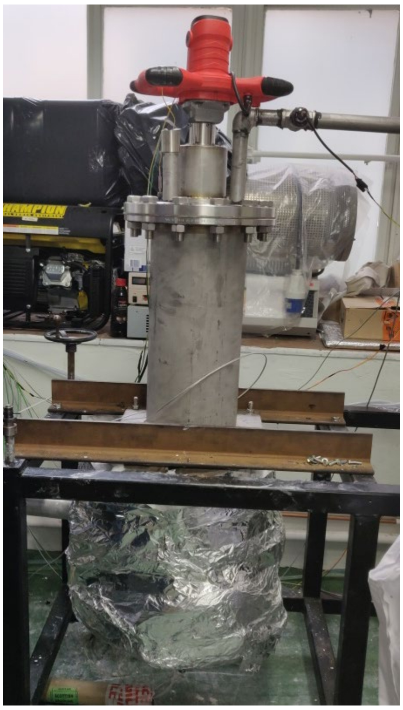


Figure 3 - Big Rig burner assembly and rotary stirrer on top

Figure 4 - Assembled system; reactor, gas outlet, burner exhaust, condenser, liquid collection line, vacuum pump

3. Instrumentation and Control Systems

For the smaller two rigs (F1 and RIP-V) instrumentation was deployed to measure temperature and pressure but the system needed to be expanded for the Big Rig. The Arduino platform was used as the core of the instrumentation and control system and this was integrated with excel software to allow real time monitoring (about 1 Hz) and control of the pyrolysis operation. As a result, the system offered a high level of control and robustness for low cost with an open source protocol.

Two Arduino Mega ADK microcontroller (ATmega2560) boards were coded in C/C++ to provide the operators with variety of online information, such as temperature, pressure and flow at different critical points of the pyrolysis system during running. It also allowed control of all of the important instruments involved in the operation, such as power-up of the heating systems and pumps (e.g. air supply for the propane gas burner and fuel feed-in pump); with these effective service control mechanisms the operators had greater autonomy and flexibility to focus on the experiments. It should be realised that there are dangerous safety issues and risks with pyrolysis which were addressed throughout the work to ensure safe operation. The safety risks include a high pressure system, which for the Big Rig was designed to be about 10 Bar and a critical burst pressure of about 30 Bar, high temperature, naked flames, potentially noxious gases (especially with MONG, Matter Organic non-glycerol, which was not processed further than preliminary experiments because of the gaseous emissions). A safety pressure valve was fitted to the systems to avoid over pressure and various regulators to allow control of the pressure on either side of the system (i.e. pyrolysis and condenser side). It should be noted that these were not automated because of time and cost constraints.

The following diagrams illustrate details on the control system for the different setups. Figure 5 shows the system for the smallest rig, F1, with a reactor size of 60 mL; this system was modified from a torrefaction/pyrolysis system and a gas condenser line had to be fabricated, and the system mounted vertically. The fuel produced from this system was successful tested in an engine and this system was scaled to the Big Rig, with a 36 L capacity.

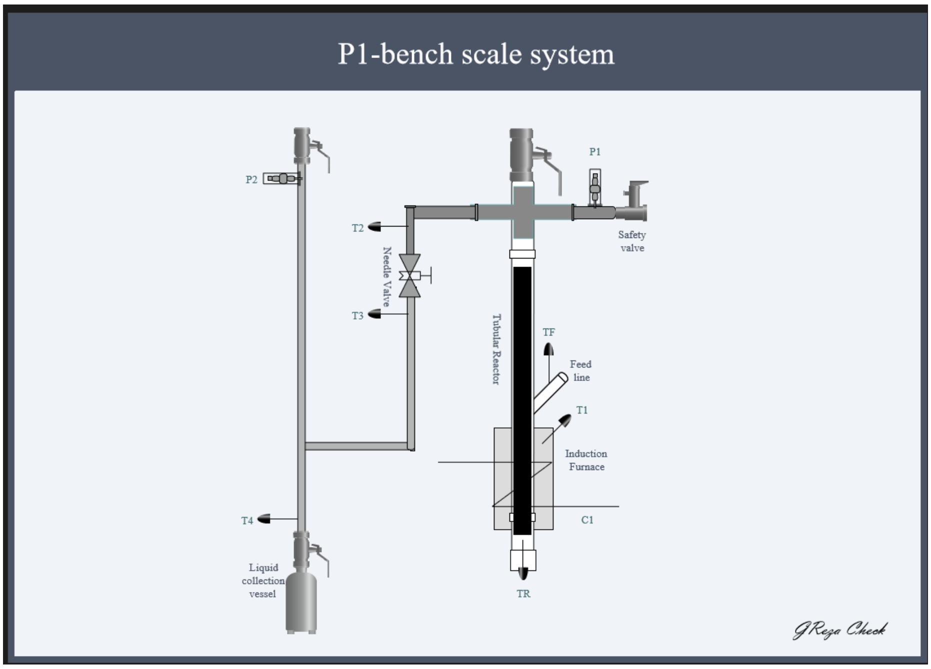


Figure 5 - Bench Scale System

5, F1 system, 60 mL reactor, instrumentation T1 = Furnace temperature, T2 = Temperature before needle valve, T3 = Temperature after needle valve, T4 = Liquid collected temperature, TF = Temperature of feed line; applicable for semi-batch protocols, TR = Temperature inside-bottom of the tubular reactor. P1 = Pressure in tubular rector side, P2 = Pressure in cooling and phase splitting line. C1 = Control of furnace temperature

The second system, shown in Figure 6, shows RIP-V, with a reactor volume of 2.6 L. Again this was modified from a torrefaction and pyrolysis system to include gas collection, condenser and liquid collection systems. With the larger volume, solids were tested in this system. This was a unique system that was designed for the heavy gas phase that was observed during solid feedstock processing on F1, where the pipes became blocked. The fog pit screens (FPS) were successfully processed with no blocking of the system. To our knowledge, no one has managed to process these feedstocks in this way, as well as some fuel production (too small from this rig for further use), the clear liquid samples may have application in anaerobic digestion.

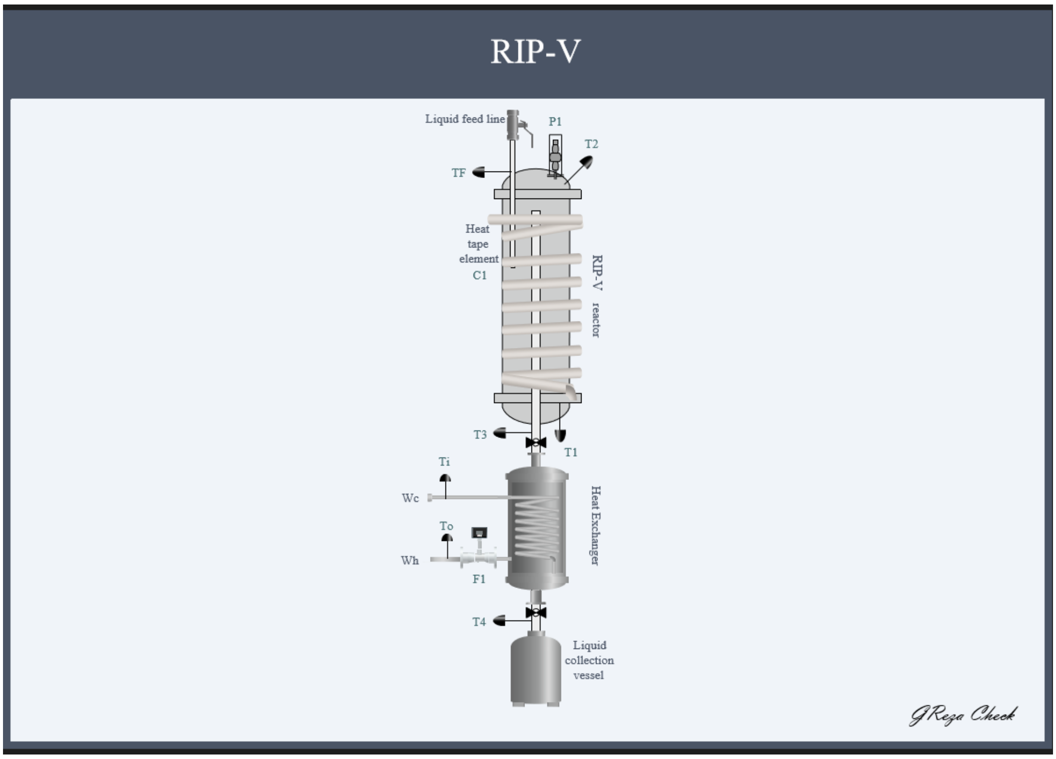


Figure 6 - RIP-V 2.6L reactor

Figure 6 2.6 L reactor, T1 = Temperature inside-bottom of the reactor, T2 = Temperature inside-top of the reactor, T3 = Temperature of reactor output and before Heat exchanger, T4 = Temperature of the liquid collection and after Heat exchanger , TF = Temperature of liquid feed line; applicable for semi-batch protocols for liquid feedstock, Ti = Temperature of coolant water into Heat exchanger, To = Temperature of coolant water out of Heat exchanger, P1 = Pressure in RIP-V rector, F1 = Water coolant flow, C1 = Control of heat tape element

Figure 7 shows the instrumentation and control system for the Big Rig, it is seen that the system is considerably more complex and more sophisticated control systems were needed to make the system run more efficiently. This system was a completely new build and based on the results in the early phases of the work.

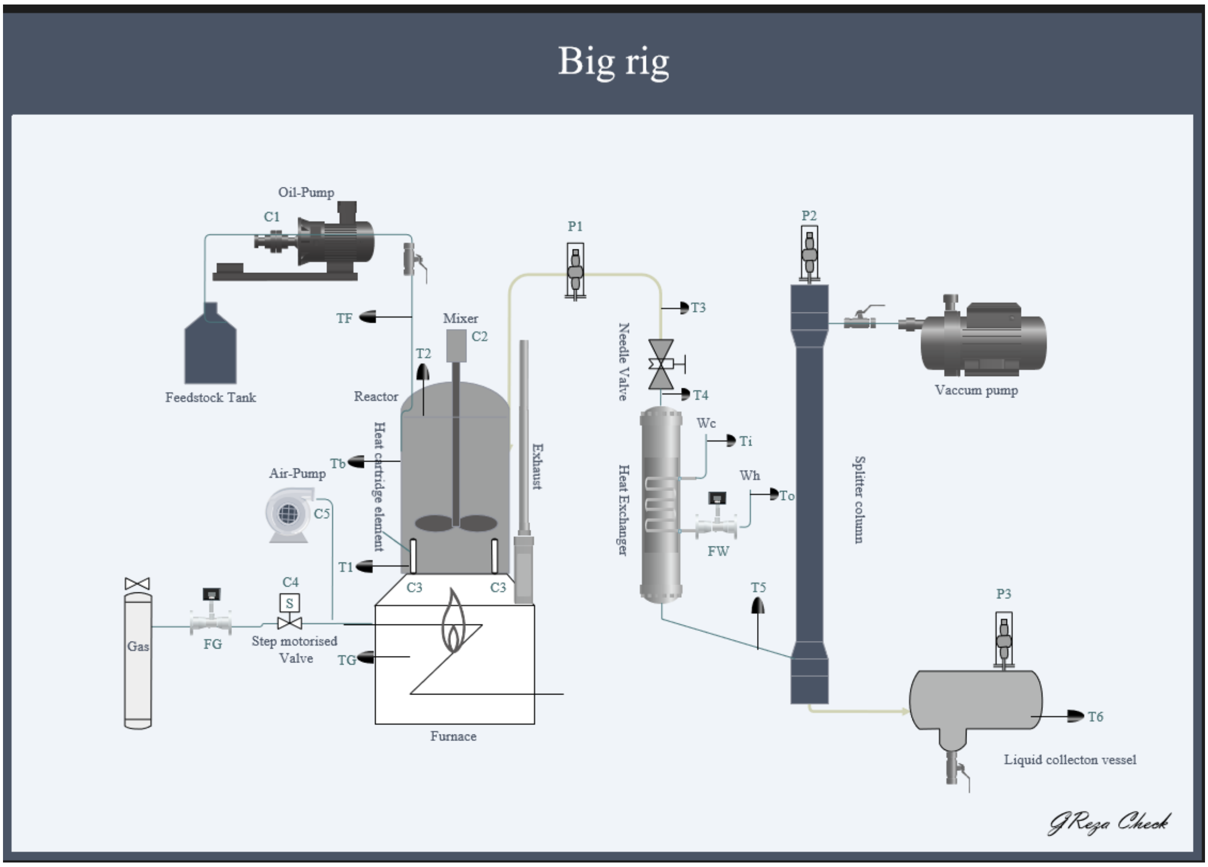


Figure 7 - Big Rig with 36L reactor

Figure 7, Big Rig with a reactor capacity of 36 L. T1 = Temperature inside-bottom of the reactor, T2 = Temperature inside-top of the reactorT3 = Temperature before needle valve, T4 = Temperature after needle valve and before Heat exchanger, T5 = Temperature after Heat exchanger, T6 = Temperature inside liquid collection vessel, TF = Temperature of feed line; applicable for semi-batch protocols, TG = Temperature of gas furnace, Tb = Temperature body of reactor, between middle and top, Ti = Temperature of coolant water into Heat exchanger, To = Temperature of coolant water out of Heat exchanger, P1 = Pressure in Big rig rector, P2 = Pressure in splitter column, P3 = Pressure in liquid collection vessel, FW = Water coolant flow, FG = Gas flow, C1 = Control of oil-pump, C2 = Control of Mixer, interval and speed, C3 = Control of heater cartridges, C4 = Control of gas ignition, C5 = Control of air-pump.

4. Results

A summary of the experiments on the Big Rig for liquid feedstocks, TATA and BFO, are given in Table 1, where the feedstocks and the volume of the products that were produced are shown. It is seen that the yields varied from 64% to 91%. The process i.e. either batch or semi-batch influenced the yield significantly. An automated feedstock feed-in line was also fabricated.

Table 1 Summary of experimental results using the Big Rig, volume processed and yields

Big rig-Test Code	Date	Feed	Volume (mL)	Pro-cess	Products	Volume (mL)	Yield (%)
2	01.10.2019	TATA	5000	Batch	centrifuged	2200	64
3	04.10.2019	TATA		Batch	Un centrifuged	1000	
6	16.10.2019	TATA	8500	Semi-Batch	Watery Distillate Oily distillate Left in reactor	1300 1000 5000	91
7	22.10.2019	TATA	6000	Semi-Batch	Distillate Left in reactor	2500 2500	83
8	31.10.2019	TATA	15000	Semi-Batch	1st Distillate 2nd distillate Left in reactor	4600 900 7900	89
SUM			**34500**			**28900**	**84**
10	05.11.2019	BFO	10000	Batch	Distillate Left in reactor	300 8800	91
11	07.11.2019	BFO	10000	Batch	Distillate Brown Distillate Golden Left in reactor	2750 525 5800	91
SUM			**20000**			**18175**	**91**

Temperature and pressure profiles were recorded, the fuel samples were packaged and sent to NLE, see Figure 8.

Figure 8 - Samples sent to NLE for refining and engine testing

5. GCMS and Feedstock Analysis

There were certain tests that could be done in house at Glasgow and within the consortium; this included some GCMS analysis, measurement of CV and viscosity measurements. However, because of the work being done it was felt that Py-GCMS would yield useful results on the feedstock and the impact of process parameters, no commercially available facility could be found in the UK. Analytix Limited, however, kindly sent samples to America for testing on one of their Py-GCMS rigs.

6. Life Cycle Analysis

Methodology

Life cycle assessment (LCA) is a standardised tool for evaluating the possible environmental impacts of a product, process, or system. It assists in identifying hot spots e.g. excess CO_2 produced, in a system's life cycle and thus shows opportunities for improvement. An LCA consists of four sequential phases, i.e. goal and scope definition, inventory analysis, impact assessment, and interpretation. LCA was carried out with GaBi and in-house MATLAB code. GaBi is a designated LCA software, which was used to evaluate the avoided environmental impacts by displacing electricity and heat otherwise generated by natural gas and to model the environmental impact of diesel consumption. The impact categories considered in GaBi follow ReCiPe 1.08 Midpoint methodology. The entire LCA is conducted in accordance with ISO 14040 (Finkbeiner et al., 2006).

In the analysis, the functional unit (FU) is taken to be the treatment of 1 tonne of feedstock (i.e. BFO, TATA, Fog Pitscreens) using the technology. A system can become overly complex to include every single impact or process and thus, it is important to define suitable system boundaries. The system boundary and a basic flow chart of the different processes are shown in Figure 9. The model was developed to support analysis of other applications in the future

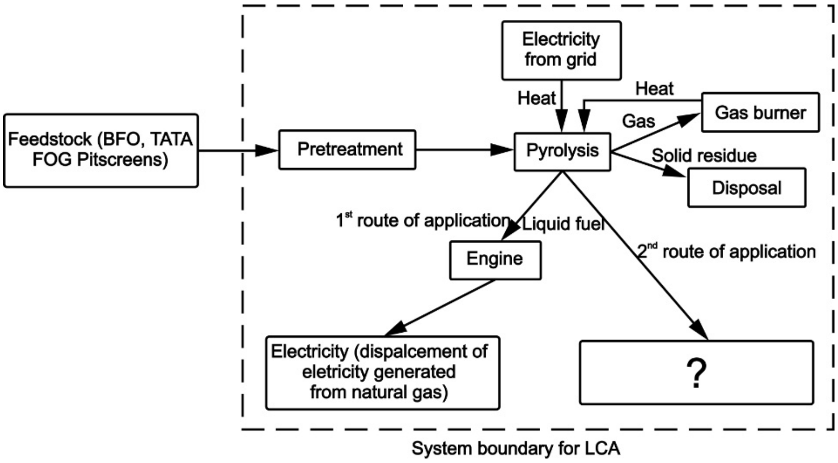
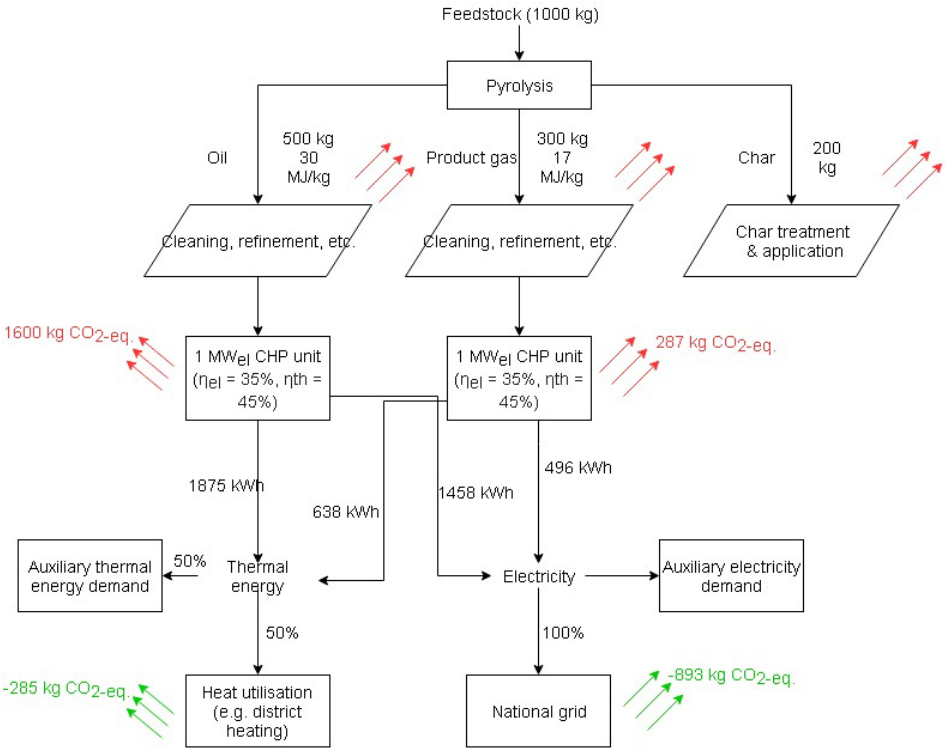


Figure 9 - System boundary of the LCA

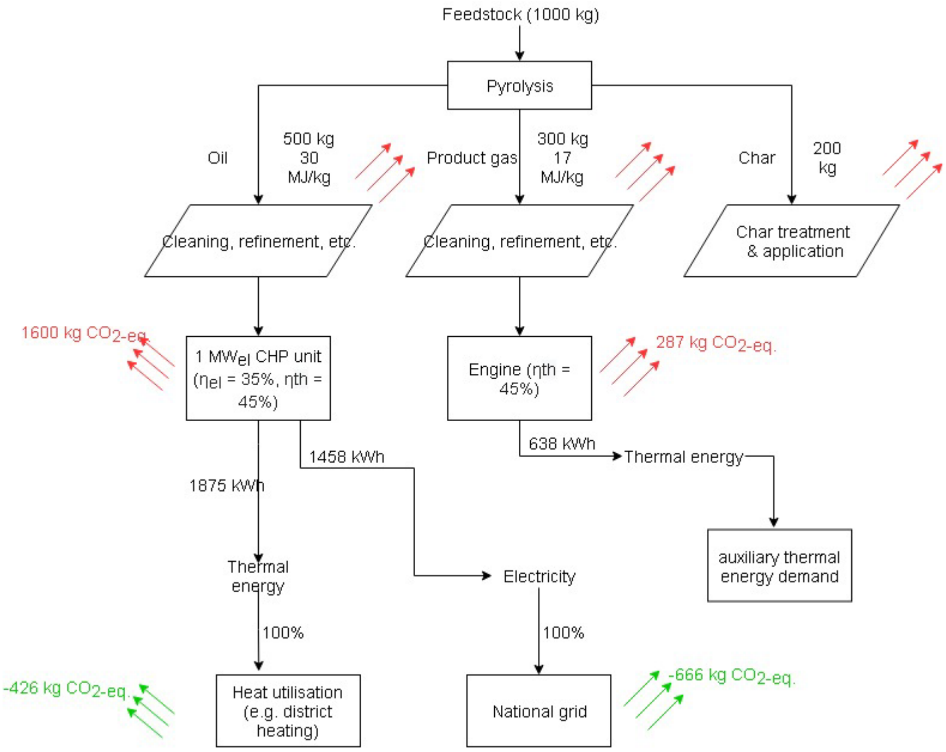
To simplify the model, environmental impacts related to the generation and transport of feedstock were neglected. As shown by the experimental data, the yields of different products are highly variable based on the feedstock and conditions applied. The yields (50 wt.% oil, 30 wt.% product gas, and 20 wt.% biochar) of products in the LCA are estimated based on a summary of literature data regarding waste cooking oil and sewage sludge (Trabelsi et al., 2018, Liu et al., 2013, Righi et al., 2013) and the experimental data of this work, in practice there is some control over the partitioning of products and this combination was selected to provide one possible route forward. Of course, for electricity production from the feedstocks, the primary focus will be on delivering liquid fuels at scale. This facilitates the adoption of relevant process data (e.g., electrical and heat efficiency) that was reported in the literature and was only measured on the available systems in this project. Assumptions would have to made over scaling. Note the biochar was included as an option because it has the potential to impose a major positive environmental impact (carbon saving); however, it is not considered in the LCA, making the results obtained in this study conservative and because the fraction of solid residues was demonstrated to be relatively small when the parameters were set for liquid production.

The electricity and heat generated are assumed to substitute electricity and heat generated by natural gas. Avoided emissions due to displacing electricity and heat otherwise generated by natural gas were modelled using the inbuilt GaBi processes “Electricity from natural gas” and “Thermal energy from natural gas”. Both processes are country specific to the UK with a reference year of 2016. It is stated that the data is valid until 2021 (Thinkstep, 2019). Other process parameters are shown in Figure 2, which detail the steps involved in the model and its development, showing CO2 emissions for different scenarios. In a) the electricity and heat generation is considered from oil and gas, b) derived oil is used to generate electricity and heat, and any gas residues are used to generate heat to support the endothermic processes for pyrolysis. It should be noted that there was a lot of incondensable gases that were produced in the Big Rig which could be used to run the system, at least in part if not fully. Augmenting the system increases process efficiency and reduces emissions. And in c) oil is solely used to produce electricity and gas to produce system heating.

(a)



(b)



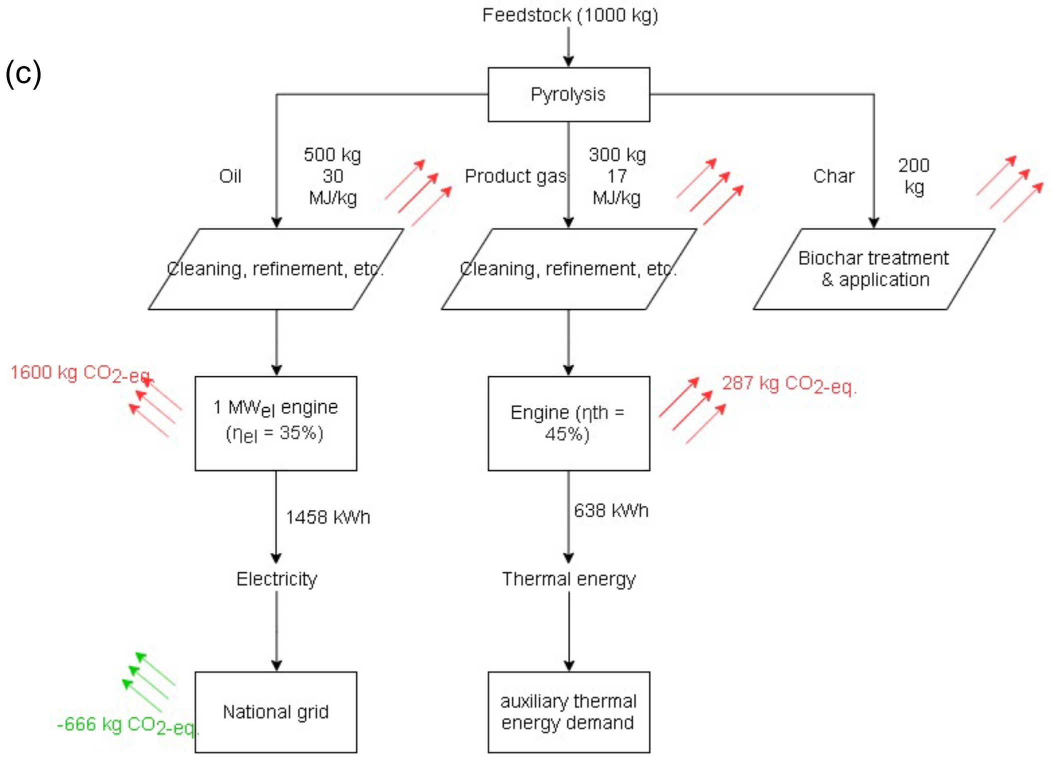


Fig.2. (a) Scenario 1: the oil and product gas are used in CHP units for both electricity and heat generation; (b) Scenario 2: the oil is used to generate electricity and heat, while the product gas is used to generate heat to support the pyrolysis process; Scenario 3: the oil is used to generate electricity, while the product gas is used generate heat to support the pyrolysis process.

Results

For process scenario 1, the feedstock is converted into 50 wt.% oil (calorific value=30 MJ/kg), 30 wt.% product gas (calorific value=17 MJ/kg), and 20 wt.% char with the bio-oil and gas being used in two CHP units (electrical efficiency of 35% and thermal efficiency of 45%). 50% of the heat generated from the gas is used to support the auxiliary thermal energy demand of pyrolysis. In this case, an annual treatment of 1,500 tonnes of waste will save ~900 tonnes of $CO_{2\text{-eq}}$ compared with the conventional landfill-based practice based on our preliminary analysis (0.7 tonnes of $CO_{2\text{-eq}}$/tonne of feedstock vs 1.3 tonnes of $CO_{2\text{-eq}}$/tonne of feedstock).

For process scenario 2, the oil is used to generate electricity and heat while the product gas is used to generate heat to support the systems. In this case, an annual treatment of 1500 tonnes of waste will save ~750 tonnes of $CO_{2\text{-eq}}$ compared with the conventional landfill-based practice based on our preliminary analysis (0.8 tonnes of $CO_{2\text{-eq}}$/tonne of feedstock vs 1.3 tonnes of $CO_{2\text{-eq}}$/tonne of feedstock).

For process scenario 3, the oil is used to generate electricity while the product gas is used to generate heat to support the systems. In this case, an annual treatment of 1500 tonnes of waste will save ~150 tonnes of $CO_{2\text{-eq}}$ compared with the conventional landfill-based practice based on our preliminary analysis (1.2 tonnes of $CO_{2\text{-eq}}$/tonne of feedstock vs 1.3 tonnes of $CO_{2\text{-eq}}$/tonne of feedstock). Table 1 summarises the carbon saving potential of different implementation scales compared with waste landfill.

Table 1. A summary of the carbon saving potential of different implementation scales compared with waste landfill.

Scale	Waste capacity	Scenario 1	Scenario 2	Scenario 3
1	6,000 t/y	3,600 t $CO_{2\text{-eq}}$	3,000 t $CO_{2\text{-eq}}$	600 t $CO_{2\text{-eq}}$
2	100,000 t/y	60,000 t $CO_{2\text{-eq}}$	50,000 t $CO_{2\text{-eq}}$	10,000 t $CO_{2\text{-eq}}$

It is clear then that the rationale for using static engines for electricity production, where emissions can be captured is essential to improve the different scenarios considered. Scenarios 1 and 2 consider CHP as a counter factual, where in practice for the plant the heat can be used to save on emissions from sya propane heating of the rig.

Limitation

The LCA is based on reported values in literature for such parameters as calorific values of products, efficiencies, and process emissions, which makes the results of indicative value only and does not reflect the true scale of what could be achieved with electricity production for the waste scenarios being developed at scale by the consortium. There are also potential scaling effects on the process parameters, affecting the estimation of the carbon saving potential of up-scaling systems. Uncertainty analysis (e.g., with a Monte Carlo simulation-based method) is needed to quantify the confidence level of the results statistically upon the availability of more systematic data for the systems of different scales.

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7. Problems encountered during the project

At the outset, it was thought that two of the existing systems in Glasgow could be used to produce the samples; however, it was apparent that these would have to be modified to collect the distillates and F1 moved to a vertical system. This led to a design for the larger reactor that was much more complex than was first thought necessary, and with a fill factor that was lower. Consequently, the design and build phase for all the systems took a lot longer which led to delays in the experimental work. Additionally, while the smaller systems could be used relatively easily the larger rig, with of course the larger associated risks, was much harder to handle. And with the larger reactor volume, more feedstock is required for process optimisation. Unfortunately, because of these matters and lack of feedstock, it was not possible to optimise the process for TATA and BFO.

It was also found out that the solid feedstocks supplied by Argent were only analogue models, with three different samples available. All of these were processed in the RIP-V, 2.6 L reactor; however, it should be reiterated that they were potentially unsafe and required specially handling. They contained a large number of insects and flies which became a hazard in the laboratory, the samples were contained in plastic containers, as supplied, double bagged in bin liners, and then placed in metal oil drums. Samples were taken quickly and in a well-ventilated area, however, UoG of was not equipped to handle this feedstock at scale and this process is more suited to an industrial site that a University laboratory. A further and important health hazard was the ventilation of the area where the experiments were being done. Whilst extraction was used, it was clear in some of the processing that the fumes produced where potentially extremely hazardous. This was particularly the case for MONG, where for preliminary trials a small leakage was very reactive and irritated the eyes. This feedstock was not further examined because of these dangers and the lack of extraction and scrubbers in the laboratory at the University of Glasgow. Also, with BFO feedstock processing on the Big Rig, the fumes were considerably worse than on the small rig and smelt differently. It was not clear whether this was because of a different batch of the BFO was used or just because of the much larger volumes of the materials processed and the subsequently larger emissions. Further work will require the installation of scrubbers and completely sealing the reactor in an enclosed housing; this is currently done for gasification system we have in house and needs to be replicated for the pyrolysis systems, lack of time and capital prevented this from being done in the timescales available for the feasibility study.

Pre-treatment of the feedstock plays an important part in reducing the energy needed for pyrolysis, where ideally any water is removed through settling or centrifuging. Pre-treatment was attempted for some of the samples, including free standing in a tube and pre-centrifuging but there was no separation of any water phase identified. It should be noted that different samples of the TATA feedstock were used on the Big Rig compared to the work done on RIP-V; it was known that the TATA samples had a higher water content, but it transpired that they were higher than originally thought, which led to poor quality distillates and fuel samples. The process parameters that were used for producing successful samples using RIP-V were translated to the Big Rig to produce distillate.

After NLE received the samples, there was some phase separation. And it was clear that much of the distillate from the Big Rig was only water-based and the samples from inside the reactor were too thick to process directly. More time would be needed to optimise the process parameters to produce the distillate. This is important work, however, as it led to developing the protocol for scaling the plant to commercial scale. Here, it is proposed that more detailed experiments are done on the feedstock over a wider range of parameters, with more rapid GCMS analysis of the distillate to speed this process. This includes pre-treatment to remove water, something that could not be achieved at Glasgow in the feasibility study, and only at small scale (or very large scale with their 7 t/hr systems) at NLE.

In scaling and running the plant, the input feedstock needs to be fully characterised and the process parameters optimised; it therefore makes sense to have a small duplicate rig that can process the incoming new feedstock, to identify process parameters for that delivery, and identify any potential problems that may occur before processing the larger volumes. Instrumentation and control of the plant is also critical for maximising yields and product quality. As alternative feedstocks are sought, their behaviour, water and fuel content need to be mapped.

Real time water concentration techniques are also being developed at Glasgow, which would allow real time control of the pyrolysis process and separation and identification of the distillate phases. Furthermore, the TATA samples appear to be an emulsion which could not be separated easily prior to pyrolysis. A more thorough investigation into pre-centrifuging before thermal treatment would be done for the pilot plant development to avoid large scale dewatering during the pyrolysis process, where the availability of oxygen from the water phase may severely degrade the fuel product.

The LCA model needs to reflect the design for the scaled systems more accurately and take account of downstream emission control technology.

Based on these results, two system designs were considered for scaling. An iterative design process led to the submission for liquid and solid phase handling. However, the quality, composition and composition variance of the feedstock needs to be understood in more detail to model the likely output yields and usable fuel.

NLE Cleaning of Fuel, Fuel Delivery to Engine, Fuel Feasibility & Emissions testing

8. Introduction

The Work Packages for NLE Phase 2 Feasibility was to evaluate the fuels produced from UoG by running on NLE's existing Test Facilities, namely the single cylinder Lister for small scale initial results then on our endurance engine the Perkins 100kW test rig. This engine typically requires around 1,000kg of fuel to run a limited trial.

To obtain best results both test engines needed upgrading to record very accurate emissions on Signal Gas Analysers (which had been in storage for 9 years) and accurately measure 'real' fuel consumption. I.E. All engines are designed to run on EN590 and NLE are aware of the requirements to modify the standard configuration to optimise and set-up for the fuels we will be testing. These modifications have been developed by NLE across a broad range of fuels and engine types. These modifications even include - EN14214 (B100% Bio-Fuel) as they all have different fuel combustion and consumption profiles and figures, especially if it is being worked across a varying power curve.

On our 1st visit to UoG labs following the Grant Submission it became clear that the production of significant quantities of fuel batches was going to be impossible within the confines of the UoG lab premises, so NLE reviewed the requirement and undertook – at its own expense – to make a medium size fuel testing cell using a small 4 cylinder CI engine.

This would involve significant extra expenditure than budgeted but would provide a testing facility to run smaller batches of fuel samples in the quantities that UoG could realistically produce.

Below is a breakdown of the new fuel test cell specifically built for the testing.

9. Test Cell 2 – Deutz 4-cylinder engine with alternator

D2008L04 - 4 Cylinder Deutz

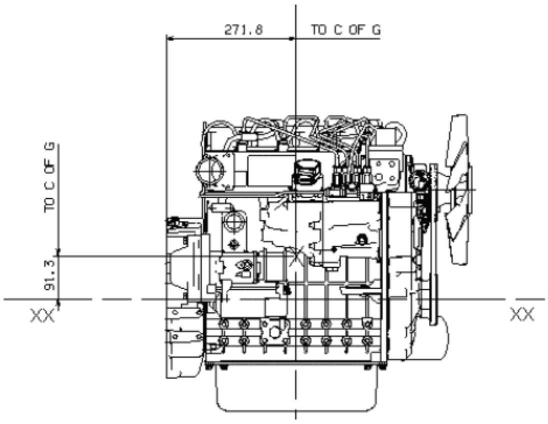


Figure 10 - Deutz 4-Cylinder naturally aspirated IDI engine

This is a Deutz 4 cylinder naturally aspirated IDI Engine.
This particular engine is a part of the development engines made for tuning and refining from the GOLD reference engine we also hold on Deutz behalf.
.

The Power Curve

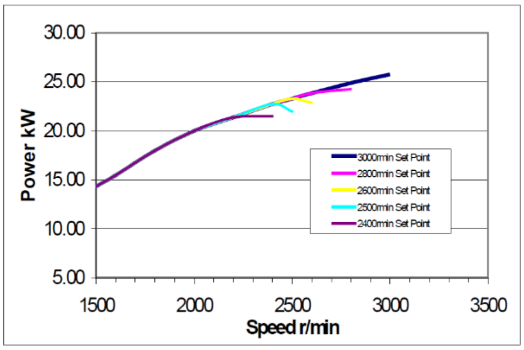


Figure 11 - Deutz 4-Cylinder N/A power curve

This engine produces 26kW at full load at 3,000 RPM.
We need to run the engine at 1,500 RPM to allow the alternative fuels the maximum amount of time to full combust in the chamber.
I.E. running at 3,000 would mean the total duration of burn would be half and we need to ensure all the long chains have time to complete ignition.

Exhaust Gas Emissions

Figure 12 - Signal Gas Emissions Towers

Signal Emissions towers with full calibration gases. Records NOx, CO, CO2, THC and O2.
Includes prefilters, gas ovens, gas separators.

Data Collection

Figure 13 - Server grade data desk with extensive data collection capabilities

Data Desk with full server grade computer data collection. Records all sensors and weather data.
In cylinder combustion sensor, 16 Pico log channels for fuel injection and exhaust gas temperatures.
8 channels of Campbell Scientific for Thermistors and Dyno control.
Full weather station.
Fuel weight scale to 1g recording per second.

Figure 14 - Lab grade variable voltage DC power supply

Variable Voltage controller to 3 decimal places.
Kistler combustion probe amplifier.
Marsden Plate scale monitor connected to data logger for continuous weight recording in 1g increments during trials

Fuel Measurement

Figure 15 - 30kg Marsden scale

30kg Marsden plate scale in 1g increments with stainless steel tea urn containing fuel samples.
We have 2 scales, 1 for starter fuel and 1 for sample fuel (we use a smaller scale if we have limited sample fuel for greater granularity of results)
The temperature of both fuels is carefully monitored and recorded during trials.

Deutz Euro 4 IDI engine

Figure 16 - Deutz 4-Cylinder N/A engine with modifications and sensors attached

Covers, heaters and insulation removed for viewing purposes.
14 X Various temperature sensors on fuel tanks and lines including special probes

Fuel temperature probes

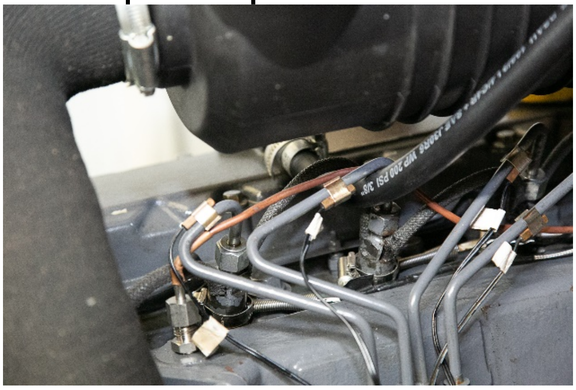


Figure 17 - High accuracy temperature sensors for data collection

Covers, heaters and insulation removed for viewing purposes.
4 X T type clamp on Injection Temperature sensors
4 X K type Exhaust gas sensors
T types Fuel tank sensors
T types Water temperature Sensors
T type Air Intake temperature sensors
All linking to the 16 channels on the Pico Loggers
4 X RTD Thermistors on the fuel lines linking to Campbell Data logger

Data Creation devices

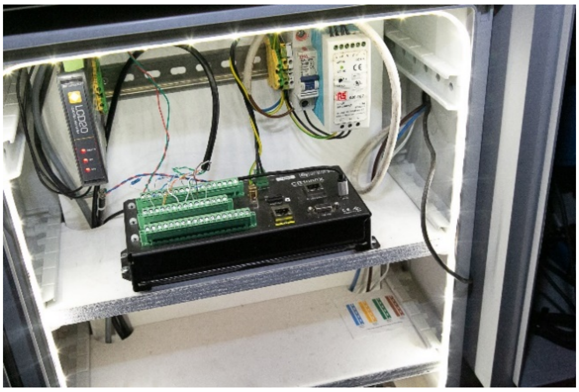


Figure 18 - Campbell Scientific CR1000X & LCD20 load cell amplifier

Campbell Scientific CR1000X data logger
LCD20 load cell amplifier from Dyno Load cell for conversion to feed voltage generator for Dyno control at data desk.

Figure 19 - Picolog automotive data loggers

2 X 8 Channel Pico Loggers for recording fuel tank, lines, Injector and Exhaust gas temperatures.
Pico Scope 4 channel oscilloscope to record and display Combustion Profile from Kistler in chamber pressure sensors

Figure 20 - Deep Sea engine controller

Control Panel with small Deep Sea engine controller for basic engine parameters with basic analogue oil, water, volts etc.

Heat exchanger rather than a bolt on radiator and engine fan

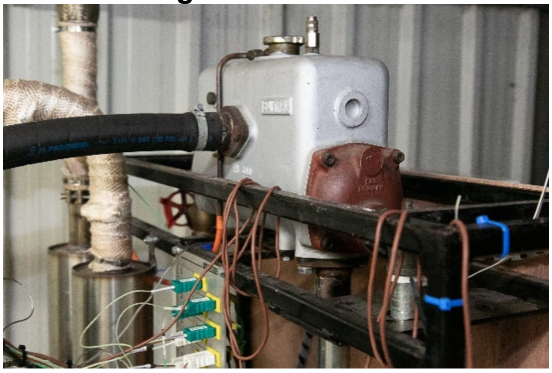


Figure 21 - Bowman header tank heat exchanger

Bowman Heat exchanger for engine cooling. There is no radiator fan cooling the engine during trials.

External Radiator and Variable speed water pump for engine and Dyno cooling

Figure 22 - External radiator, fan & water pump

External radiator and variable speed water pump housed outside the test cell building.

Weather recording

Figure 23 - Weather capture station

Weather capture station situated immediately outside the test cell close to the air intake and exhaust.

Figure 24 - Weather station wireless unit

The unit measures temperature inside and outside, Relative humidity, wind direction and speed etc. It is connected to the internet and uploads live for use to use as required.

Calibrated Load Banks and Dyno

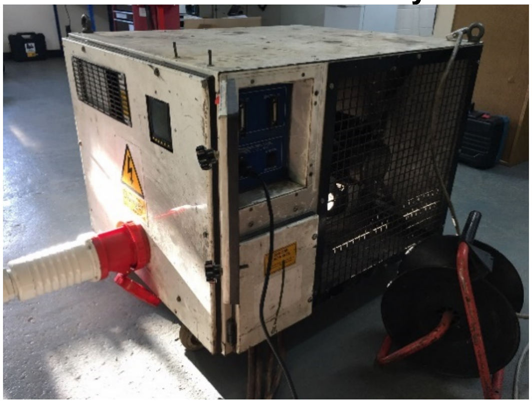


Figure 25 - 100kW load bank

The 100kW load bank that allows steps of 1kW increments to tune the load to the power curve of the engine under different speeds etc. (only useable when Dyno is fitted).

Figure 26 - 80kW Froude Dynomometer

80 kW Eddy Current dyno. Currently removed awaiting repair and servicing.

Figure 27 - Spare load bank

Spare load bank that is being modified to provide 100W granular loads for further testing of fuels.

10. Test Cell 3 – Single cylinder engine with alternator

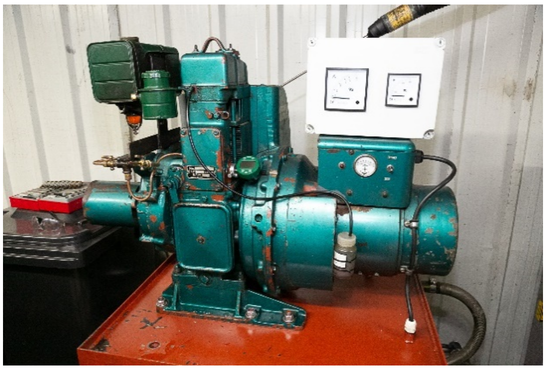


Figure 28 - Single-Cylinder Lister Diesel engine

Single Cylinder Lister engine and alternator.
This has been modified to have a simple fuel change-over system to run EN590 then the sample fuel.
The exhaust is connected to the Signal exhaust Gas towers for full emissions measurement.
Designed to run very small fuel samples to provide a rough guide to fuel consumption and emission.

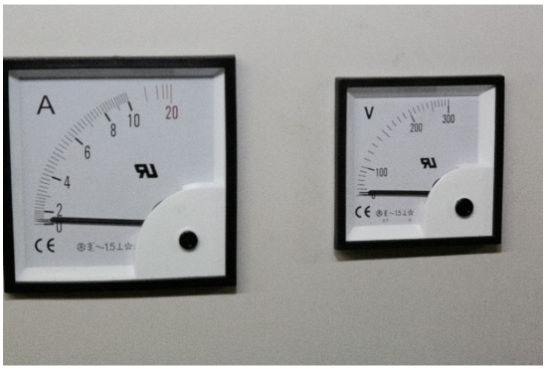


Figure 29 - Current and Voltage meters

The Current and Voltage are recorded to indicate the stability of the fuel to ensure correct 50Hz phase output.

Figure 30 - Fuel DTI

A DTI is connected to the 'Rack' which controls the amount of fuel being presented to the injector to maintain load and Hz.
This is a good guide to indicate the calorific value of the sample fuel and to check against theoretical values to indicate if the fuel is being presented to the engine correctly. i.e. Viscosity, temperature, filtration quality, etc. Deviations from theoretical will require investigation.

We us a special heated container placed on a 0.1g scale to measure fuel consumption. The image shows example of the small quantities of fuel we can measure.

Figure 31 - Small fuel quantity measurement

11. University of Glasgow Fuel Arrival

The fuel samples delivered by the University of Glasgow are as follows:

Samples were divided up into test codes (2 through 11) and different samples of each test code were delivered (i.e. watery distillate, pyrolyzed oil left in reactor).

- Test code 2 & 3 – Non-Centrifuge, Centrifuge
- Test code 6 – Watery Distillate, Pyrolyzed oil left in reactor, Non-Centrifuge, Distillate & Centrifuge
- Test code 7 – Pyrolyzed oil left in reactor, Distillate
- Test code 8 – Pyrolyzed oil left in reactor, 1st Distillate, 2nd Distillate
- Test code 10 – Pyrolyzed oil left in reactor, Distillate
- Test code 11 – Pyrolyzed oil left in reactor, Distillate Gold, Distillate Brown

12. University of Glasgow Fuel Sample De-Watering, Cleaning and Polishing

- All batches contained large quantities of water upon arrival. This caused a delay to the cleaning process as this quantity of water was unexpected due to the quality of fuel that was communicated prior to arrival. Therefore, the fuels required settling in distillation columns.

Samples cleaned as of writing this report

- Test code 2 & 3 – Distillate & Non-Centrifuge
- Test code 6 – Non-Centrifuge, Distillate & Centrifuge
- Test code 7 – Distillate
- Test code 8 – 1st Distillate, 2nd Distillate
- Test code 11 – Distillate Brown, Distillate Gold

13. Separation, Filtration and Cleaning

Settling

The settling process was carried out for all currently filtered samples (see list above) in distillation columns under heated conditions using an oven at varying temperatures (See figure 32 & 33 below for distillation column equipment used).

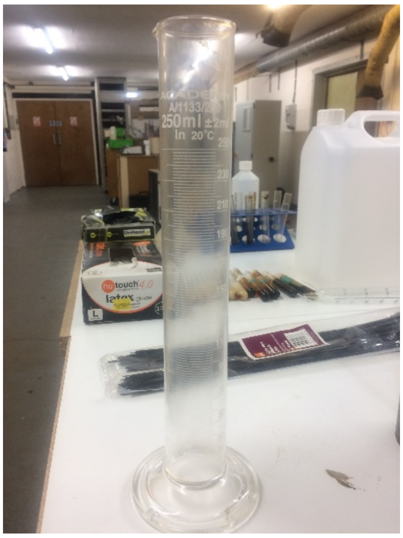


Figure 32 - Distillation Column

Distillation Column
Using multiple Pyrex settlement columns to allow the fuel to separate.
It was found that the fuel separated quicker in a controlled temperature.
Each fuel seemed to settle at different temperatures.

Figure 33 - Example fuel separation - Test code 11 Distillate Brown

Example Fuel Separation – Test code 11 Distillate Brown
This fuel settled best at 30 degrees.

This process took varying durations from between ~6 hours to a few days of settling before the water could be sufficiently separated from the oil. This then allowed all the oils to be pipetted off and transferred to their own containers.

A Few images (Figure 34 & 35) illustrating the separated oil and water are shown below:

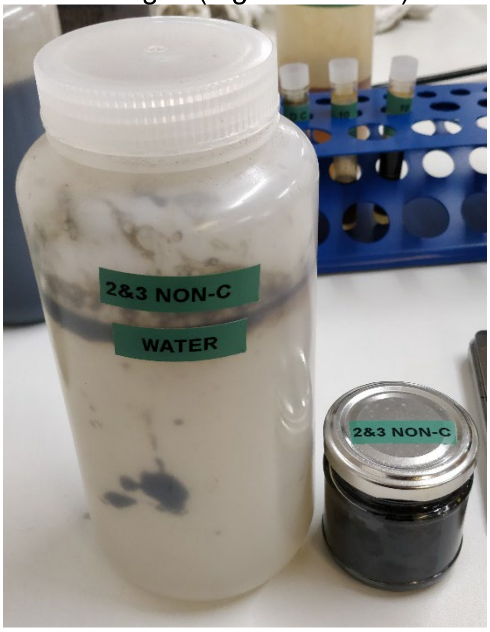


Figure 34 - 2 & 3 Distillate, Non-Centrifuge

Opposite shows the significant quantities of water compared to the oils in this sample.

Figure 35 – Test code 8 1st Distillate

Again the quantities of oil to water was significant but the percentage of oils recovered was higher.

Figure 36 - Heated filtering of fuel samples

Extensive filtering
Each of the samples was filtered extensively in a heated and controlled environment for up to three days depending on the quantity of solids using 12v Facet pump, multiple paper filter within a highly controlled oven.
An example image, Figure 14, of this can be seen opposite.

Figure 37 - Test code 7 Distillate after full filtration

The samples were regularly centrifuged filtering to obtain readings pertaining to how much solid matter was contained in each oil. An example of a de-watered, fully filtered sample of the Test code 7 Distillate can be seen in Figure 15 as an illustration.

Figure 38 - Test code 8 1st Distillate De-gassing

When we prepared this sample for engine running we discovered there was still steam rising when we heated the fuel. We then undertook a de-gassing by heating in an oven at 95°C. This was done for 5 hours to evaporate all the water out of the oil.

After this another Zahn cup test was done on the sample to find the required temperature due to the change in viscosity as no water present in the fuel.

14. Filtration Problems

There were some fuels that would not pass through our filtration system, even at an elevated temperature of ~70°C.

These fuels were:

- Test Code 8 2nd distillate – Due to repeated blocking of filters
- Test Code 2 & 3 Centrifuged – Due to repeated blocking of filters
- Test Code 2 & 3 Non-Centrifuged – Insufficient amount of fuel to attempt to filter
- Test Code 6 Distillate Centrifuged - Insufficient amount of fuel to attempt to filter

Zahn Cup testing

After separation and filtration of the fuels, two samples were selected that looked the most viable for running in Test cell 2. This was due to time constraints.

The samples chosen were:

Test code 8 1st Distillate &;

Test code 11 Distillate Brown.

The Zahn cup test was done by heating the two samples to 100°C in an oven and taking time readings for every degree lost (i.e. 100°C, 99°C, 98°C) until they reach around 40 seconds to complete the test. This is due to the maximum time for a Zahn cup test with regards to clean fuel injection being around 35 seconds due to viscosity of the fuel.

Zahn cup graphs/tables for these two samples can be found below.

Zahn cup graphs/tables for these two samples can be found below. The data below only shows +/- 5°C from the crucial 35 second mark that pertains to a low enough viscosity for injection.

Test code 8 1st Distillate

Tempera-ture (°C)	Time Taken (s)
71	32.32
70	32.76
69	33.01
68	33.64
67	33.96
66	34.52
65	35.57
64	35.88
63	36.17
62	36.68
61	36.99

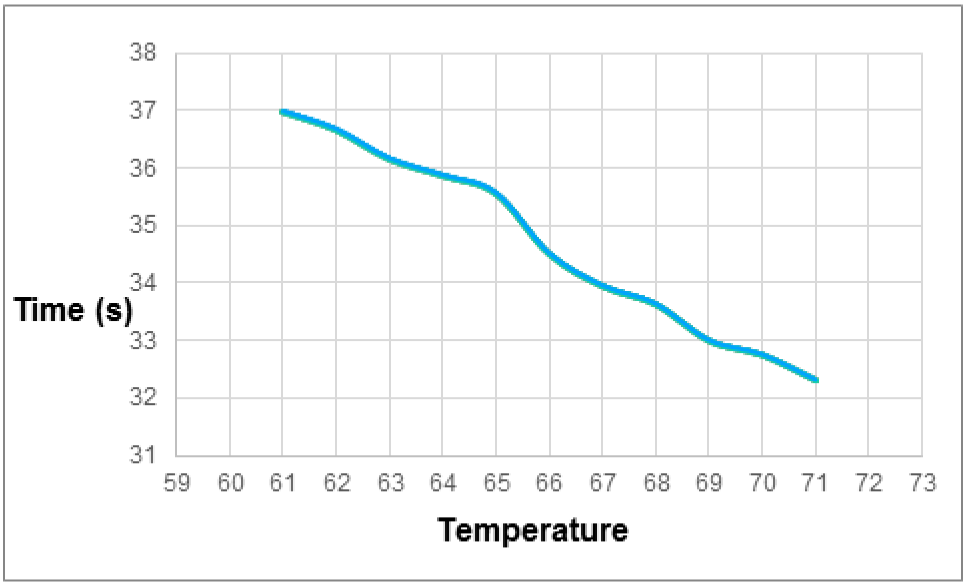


Figure 39 - Test code 8 1st Distillate Zahn cup test graph

Test code 11 Distillate Brown

Temperature (°C)	Time Taken (s)
50	31.59
49	32.43
48	33.04
47	33.67
46	34.12
45	34.87
44	35.88
43	36.65
42	37.32
41	38.29
40	39.17

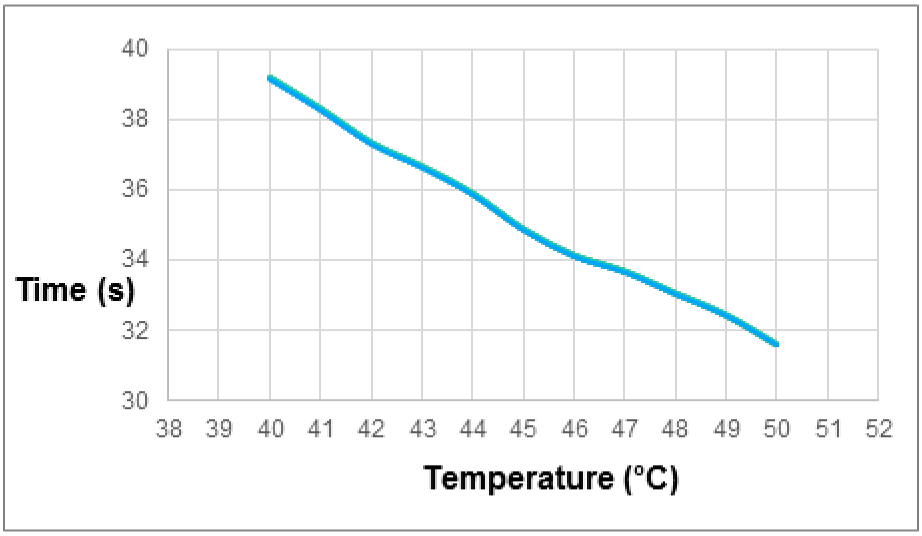
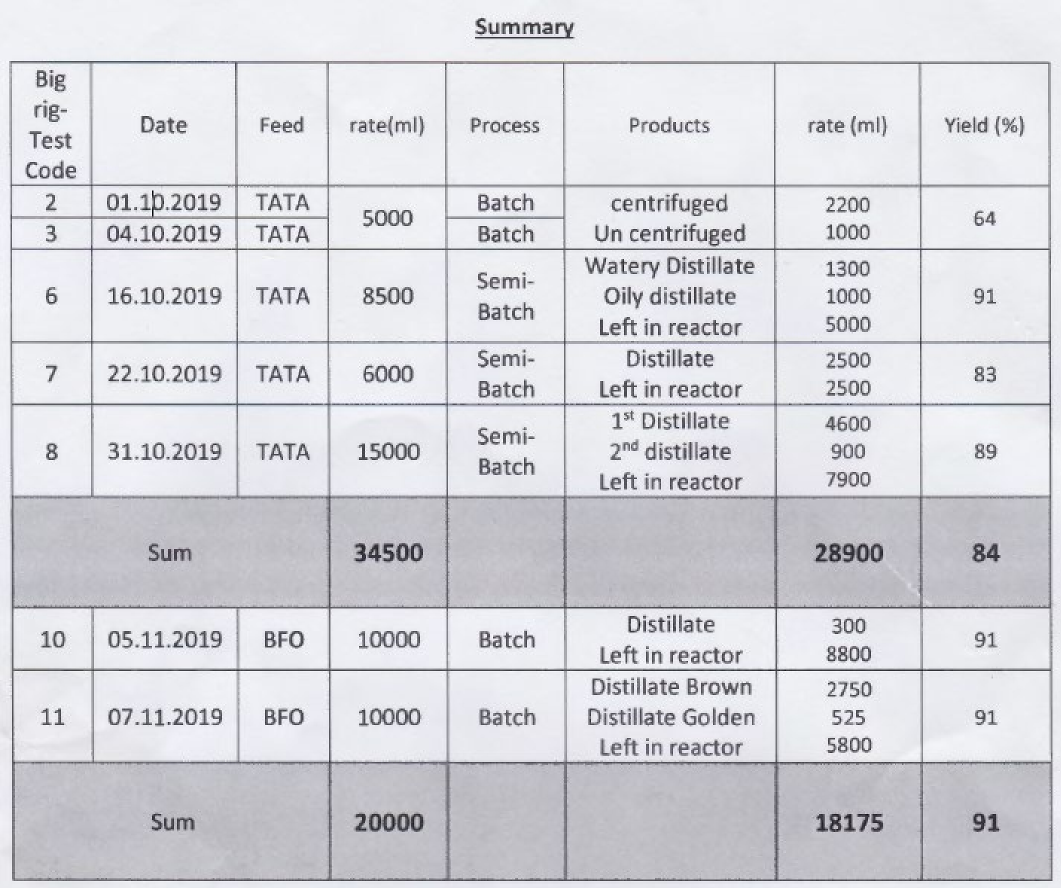


Figure 40 - Test code 11 Distillate Brown Zahn cup graph

15. Results

In total, the delivery contained **47.075 litres** of fuel samples. The datasheet for the received fuels is below in Figure 41.



Summary

Big rig-Test Code	Date	Feed	rate(ml)	Process	Products	rate (ml)	Yield (%)
2	01.10.2019	TATA	5000	Batch	centrifuged	2200	64
3	04.10.2019	TATA		Batch	Un centrifuged	1000	
6	16.10.2019	TATA	8500	Semi-Batch	Watery Distillate Oily distillate Left in reactor	1300 1000 5000	91
7	22.10.2019	TATA	6000	Semi-Batch	Distillate Left in reactor	2500 2500	83
8	31.10.2019	TATA	15000	Semi-Batch	1st Distillate 2nd distillate Left in reactor	4600 900 7900	89
Sum			**34500**			**28900**	**84**
10	05.11.2019	BFO	10000	Batch	Distillate Left in reactor	300 8800	91
11	07.11.2019	BFO	10000	Batch	Distillate Brown Distillate Golden Left in reactor	2750 525 5800	91
Sum			**20000**			**18175**	**91**

Figure 41 - University of Glasgow Fuel Sample Datasheet

The combined weight of all fuels after cleaning, filtering and the removal of water was **5.491kg**.

The weights for each individual sample after cleaning can be seen in the table below.

Test Code	Sample	Fuel Weight (g)	Water Weight (g)	Total Weight (g)
2 & 3	Distillate & Non-Centrifuge	55.54	803.4	858.94
	Distillate & Centrifuge	1508.9	0*	1508.9
6	Non-Centrifuge	7.4	680.4	687.8
	Distillate & Centrifuge	91.1	53.9	145
7	Distillate	392.3	1761.1	2153.4
8	1st Distillate	568.4	3306.3	3874.7
	2nd Distillate	269.8	267.2	537
10	Distillate	8.7	231.6	240.3
11	Distillate Brown	2223.8	0	2223.8
	Distillate Gold	365.6	0	365.6
Total		**5491.54**	**7103.9**	**12595.44**

Note: the major part of the disparity between the delivered total volume and separated total weight is due to not including the Pyrolyzed oil left in the reactor. Testing showed considerable solid particles that would cause significant engine problems.

Note * Test code 2 & 3 Distillate & Centrifuge proved too difficult to separate given the time constraints. It is understood that these samples were not given sufficiently high process temperatures by University of Glasgow as these were the first feedstocks processed. Re-running these sample through the reactors again should make them usable. However, the feasibility study was to test and learn the correct processing temperatures and pressures and this information inputted to the calibration of the valves and propane gas heating systems.

16. Discussion

The excessive amount of water in the delivered fuel leads to the conclusion that, after extensive cleaning, the yields for useable fuel are very low, in some cases there is a limited amount of fuel to run in the engine.

For example, the useable fuel taken from the 3.875kg sample of Test code 8 1st Distillate is 568.4g. This amount of fuel will only produce a very short test on the Deutz 4-Cylinder engine in Test cell 2.

Any samples offering less than 500g of useable fuel are unfeasible for running in Test cell 2, these samples must be run on Test cell 3 due to fuel consumption.

The two Zahn cup tests after being cleaned and treated showed a temperature to viscosity profile of;

- In excess of 65°C for **Test Code 8 1st Distillate**
- In excess of 45°C for **Test Code 11 Distillate Brown**

This was confirmed in NLE’s injector shop using one of our fuel injector testing rigs.

17. Conclusions

The various samples of Tata waste oils received contained more water held in an emulsion than was previously thought and therefore produced a lower ‘quantity of oil yield’ than was anticipated. A de-watering of the waste before reaction vessel is highly recommended as this would ensure we were only reacting oils and make the consistency of the reaction more controllable. We expected this result to a degree, but the results and the labour to undertake this work on lab bench equipment proved to be extremely time consuming and could have been avoided if production equipment was used.

The Test Codes 2 & 3, 6, 7 and 8 had varying viscosities and each batch seemed to be better than the previous as UoG controlled the reaction parameters. UoG ran out of time for test Code 10 and 11 and shortened the reaction period therefore leaving part-processed fuel in the reaction vessel.

These left-over residues are not suitable for engine use without significant further processing as they contained significant amounts of ‘ash’ type deposits.

18. Recommendations

Both fuels produced some positive results. However, the failed processes indicate that significant further development on the exact pressure, temperature, reaction time, vacuum, distillation height etc is required to ensure a consistent output.

A continuous production style pre-cleaning and post cleaning including a separate distillation purification last stage would make the fuel processing significantly easier than the very small batch handling we had to undertake.

19. Fuel Sample Testing

Lister Testing

4 fuel samples were tested on the Lister single cylinder test cell in July and August to provide initial data to UoG and to decide on the fuels to progress with.

Testing BFO

We combined sample 2 & 3 together as also sample 4 & 5 to provide 2 lots of around 80cc of filtered fuel. Although the samples were small and the trial would be very short, the results were very encouraging. The trials were carried out using an analog DTI (now replaced with a digital) and the emissions were recorded using a Horiba Lab Quality multi gas emissions analyzer as the Signal full emissions towers had not yet been repaired and commissioned.

Lister Single Cylinder with Generator

Figure 42 - Single-Cylinder Lister engine with DTI fitted

This has been upgraded with a DTI fitted to the fuel injection rack that clearly shows the 'throw' based on fuel delivery. This has proven a simple but effective way of 'seeing' the difference between the test fuels and the baseline EN590 and EN14214.

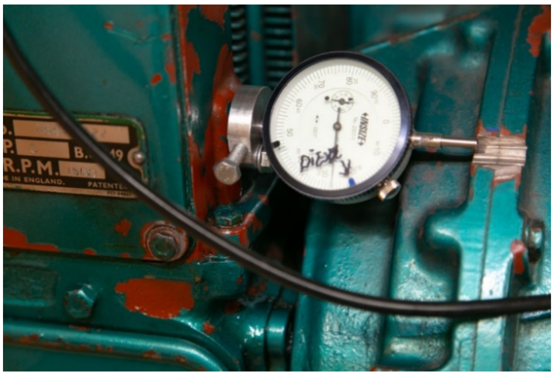


Figure 43 - Lister engine running sample 2 & 3

Put simply the Lister must inject more of the test fuel to maintain the 50Hz frequency of the attached generator compared to baseline fuels.
Sample 2 & 3 were tested and showed promise – see consumption graphs below.

Sample 2 and Sample 3

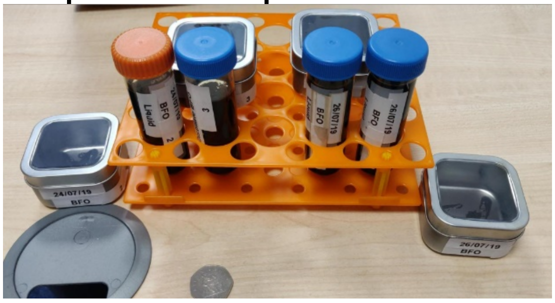


Figure 44 - Test sample viles for Lister engine

Vile 2 and 3 (left) is one fuel type from UoG
Vile 4 and 5 (right) is a second run.
Both fuels were derived from BFO and broke down the long chains into Alkanes and other aromatic HC's – chemical analysis is being undertaken – awaiting results.

EN590 Diesel Baseline Emissions

Figure 45 - EN590 diesel emissions

The single cylinder is not an efficient combustion engine.
The 14.54% vol of O_2 shows a higher value than you would expect on a more sophisticated engine.
Hydrocarbons are higher due to inefficient combustion.
Other values are normal

Sample 2 & 3 BFO Pyrolysis Emissions

Figure 46 - Pyrolised BFO emissions (2 & 3)

Surprisingly the emissions are similar although fuel consumption increased (see graph)
The NO was lower than EN590 which may be due to lower GCV and therefore cooler combustion.
Requires lab testing and further work.

Sample 4 & 5 BFO Pyrolysis Emissions

Figure 47 - Pyrolised BFO emissions (4 & 5)

Very low NO figure compared to EN590
Slightly better fuel consumption.
Slightly less stable running than Sample 2 & 3.
Requires lab testing but looks encouraging.

Fuel Consumption on Lister

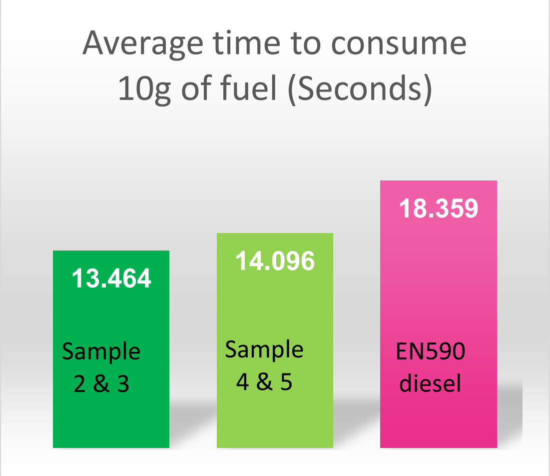


Figure 48 - Single-Cylinder Lister fuel consumption

Extensive baseline of EN590 and EN14214 under different RH and temperature conditions have shown significant variation on engine as expected. Baseline and testing were done under same weather conditions.
Need GCV to evaluate against test. Although lower energy than EN590 the test fuel is close to EN14214

Initial feedback

We did not have enough fuel to allow us to filter before running the test. This is suspected to be why the engine ‘hunted’ during the run as there were clearly black particles suspended in the fuel. However, it ran better than we could have anticipated before the test – very encouraging.

TATA Steel Samples 1, 2 & 3

Sample 1 (Vacuum Filtered)

Figure 49 - TATA Steel Sample 1 emissions

O2 18.26%: Failed sensor

CO 0%: Failed Sensor

HC 12ppm: Unreliable Result, expected sensor failure

CO2 2.14%: Unreliable Result, expected sensor failure

NO 249ppm: Unreliable result, expected sensor failure

NOX (corrected for O2 15%) 663.1

Sample 2 (Centrifuged)

Figure 50 - TATA Steel sample 2 emissions

O2 18.49%: Failed sensor

CO 0%: Failed Sensor

HC 10ppm: Unreliable Result, expected sensor failure

CO2 2.14%: Unreliable Result, expected sensor failure

NO 258ppm: Unreliable result, expected sensor failure

NOX (corrected for O2 15%) 631.6

Sample 3 (Centrifuged and blended with B100 50:50)

Figure 51 - TATA Steel sample 3 emissions

O2 18.64%: Failed Sensor

CO 0%: Failed Sensor

HC 12ppm: Unreliable result, expected sensor failure

CO2 2.16%: Unreliable result, expected sensor failure

NO 254ppm: Unreliable result, expected sensor failure

NOX (corrected for O2 15%) 556.5

Conclusion

Horiba unit was sent back to have the appropriate sensors replaced; however, a corrected figure cannot be supplied as there was an insufficient amount of fuel to re-run the trial.

Due to the consistency of unreliable emissions results provided by the Horiba unit, the set of emissions towers from Signal Group previously mention in this document have been installed and calibrated to ensure accurate and granular results for any trials going forward.

Both Test Cell 1: Single Cylinder & Test Cell 2: 4 Cylinder, have been connected to the Signal Group Emissions Towers

Sample 1, 2 and 3 Consumption with Baselines from B100 & EN590

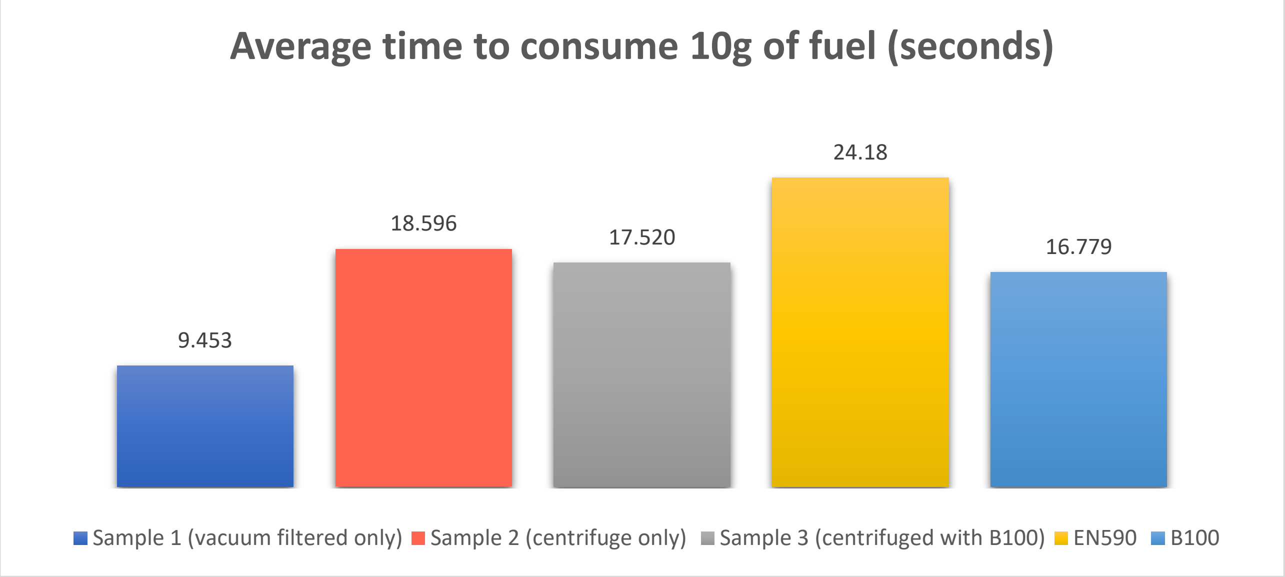


Figure 52 - B100 & EN590 fuel consumption baselines

Sample 1, 2 and 3 Emissions with Baselines from B100 & EN590

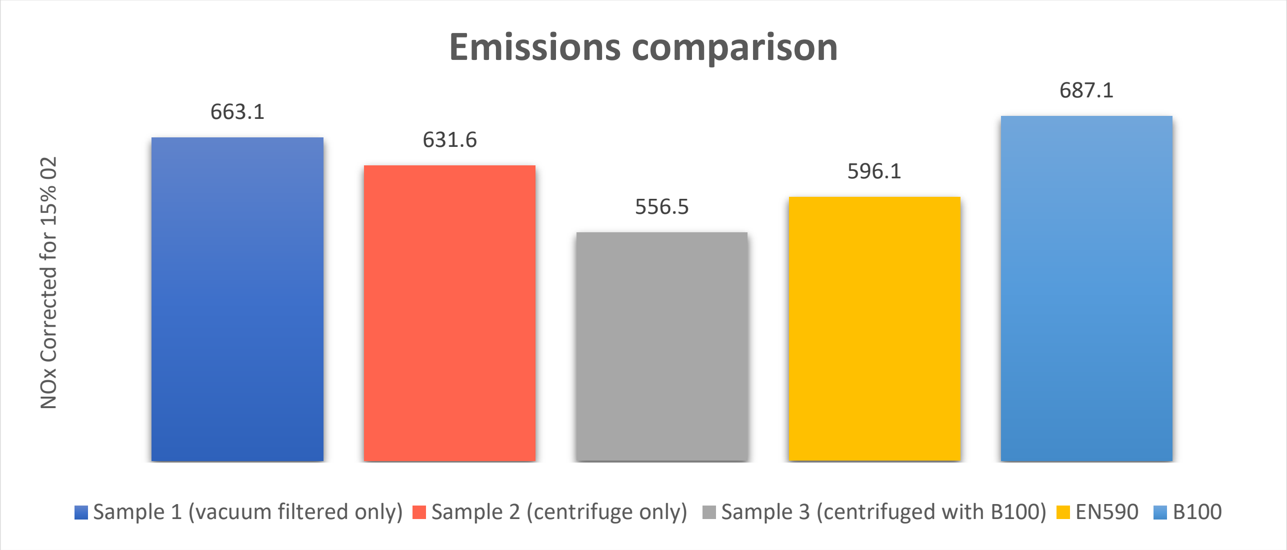


Figure 53 - B100 & EN590 emissions baselines

*It is to be noted that the B100 trial was conducted in different weather conditions to that of the other tests

20. Deutz Fuel Testing

Dozens of fuel trials were run to calibrate the Deutz engine, undertaken over several months. Multiple fuels were used to act as a proxy for the expected fuel to be received from UoG.

These include B100, cleaned used cooking oil, burnt used cooking oil, HAO and EN590.

Evaluation of the result of each fuel was investigated with Prof Ron Bickerton of UoL (the original designer of the Deutz engine we were using) and recommendations as to timing modifications, calibration discussions, additional features such as water and ethanol injection were discussed.

During these calibration trials we unfortunately had a failure of the Dyno and had to replace it with an alternator to undertake these trials and therefore had to run a new set of calibration trials while we wait for the Dyno to be repaired.

During these trials it was agreed to run the engine at 75% load at 1,500 RPM as this would allow us to calibrate accurately with EN590 and still be able to run a poor fuel with lower calorific value (which would ‘die’ if the load was placed on the 100% power band.

Once fully calibrated the EN590 baselines achieved a 2% variance from theoretical values.

Below is an EN590 baseline on Test cell 2 prior to running the cleaned fuel samples. This test was performed using a load bank at 9kW, giving 9.33kW of continuous load.

The baseline test was performed for 30 minutes to allow for a good amount of granular data capture.

21. Results

The EN590 baseline test results are shown below.

CONSUMPTION FIGURES

TIME	Weight (kg)	Time taken	Consumption (g)	Engine speed (RPM)	Engine load (kW)	g/kWh	g/kW*.88
13:05:44	7.808	n/a	n/a	1508	9.336	n/a	n/a
13:07:43	7.71	**00:01:59**	**98**	1506	9.338	**317.488**	**279.390**
13:10:44	7.565	**00:03:01**	**145**	1515	9.333	**309.009**	**271.928**
13:13:44	7.422	**00:03:00**	**143**	1525	9.333	**306.440**	**269.667**
13:16:44	7.282	**00:03:00**	**140**	1519	9.338	**299.850**	**263.868**
13:19:45	7.141	**00:03:01**	**141**	1520	9.34	**300.259**	**264.228**
13:22:43	7.002	**00:02:58**	**139**	1512	9.335	**301.150**	**265.012**
13:25:45	6.862	**00:03:02**	**140**	1508	9.335	**296.650**	**261.052**
13:28:47	6.722	**00:03:02**	**140**	1508	9.338	**296.555**	**260.968**
13:31:45	6.584	**00:02:58**	**138**	1506	9.338	**298.887**	**263.021**
13:34:45	6.446	**00:03:00**	**138**	1497	9.342	**295.440**	**259.987**

RESULTS

TRIAL LENGTH	Time taken	Total Fuel Used	Average Consumption (g)	Engine speed (RPM)	Engine Load (kW)	g/kWh	g/kW*.88
0:32:00	**00:02:55**	**1.499**	**136.273**	**1500**	**9.336**	**301.552**	**265.366**

EMISSIONS READINGS

TIME	NO (ppm)	THC (ppm)	CO (ppm)	O2 (%vol)	Corrected to 15% O2
13:05:44	748	101	485	8.1	**344.8**
13:07:43	754	96	460	8.13	**348.4**
13:10:44	750	121	383	8.3	**351.2**
13:13:44	757	111	323	8.43	**358.2**
13:16:44	715	82	248	8.5	**340.2**
13:19:45	685	92	218	8.62	**329.1**
13:22:43	663	80	178	8.57	**317.25**
13:25:45	671	93	224	8.75	**325.8**
13:28:47	679	106	270	8.93	**334.68**
13:31:45	680	85	187	8.71	**329.1**
13:34:45	640	80	168	8.72	**310.02**

Emissions RESULTS					
Total Time	NO (ppm)	THC (ppm)	CO (ppm)	O2 (%vol)	Corrected to 15% O2
00:32:00	**695.83**	**93.25**	**274.83**	**7.91**	**8.54**

EN590 calculations			
Load	9.337	kw	
Usable Calorific Value Calculation			
Calorific Value	45300	kJ/kg	These figures are from Digest of UK Energy Statistics
Density	0.832	kg/m3	
Calculation	**37.6896**	kJ/litre (Usable power per litre)	
Energy			
Fuel used	1,499	Grams	
Run time	32	minutes	
Per second	0.7807292	g/s	
Energy In	35.367031	KJ/s	
Actual Weight	**2810.63**	**g/hr (measured Red Diesel)**	
	301.02	**g/kwh**	
Energy in Chemical	**27612**	kw/h	
Efficiency Calculation			
Engine Efficiency	**26.40%**	Engine efficiency based on diesel including 12% alternator loss	
Actual Consumption	**361.81**	**Litres/MW fuel consumption**	
Costs Calculation			
Fuel Price per Litre	£ 0.611		
Cost to produce 1MW	£ 221.06	Actual Consumption* Price/Litre	

Temperature Charts

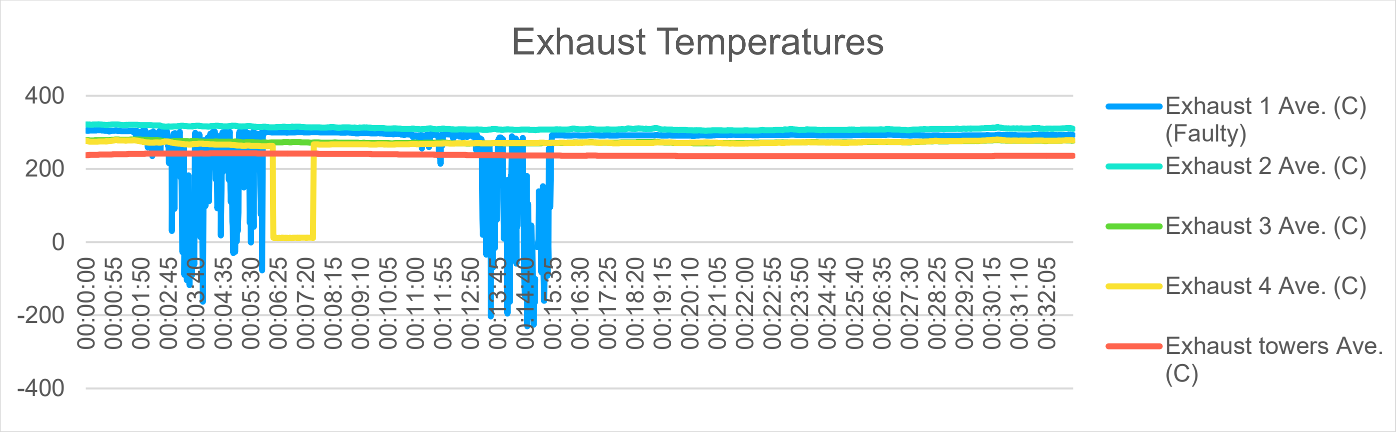


Figure 54 - Deutz 4-Cylinder EN590 exhaust temperatures (9kW)

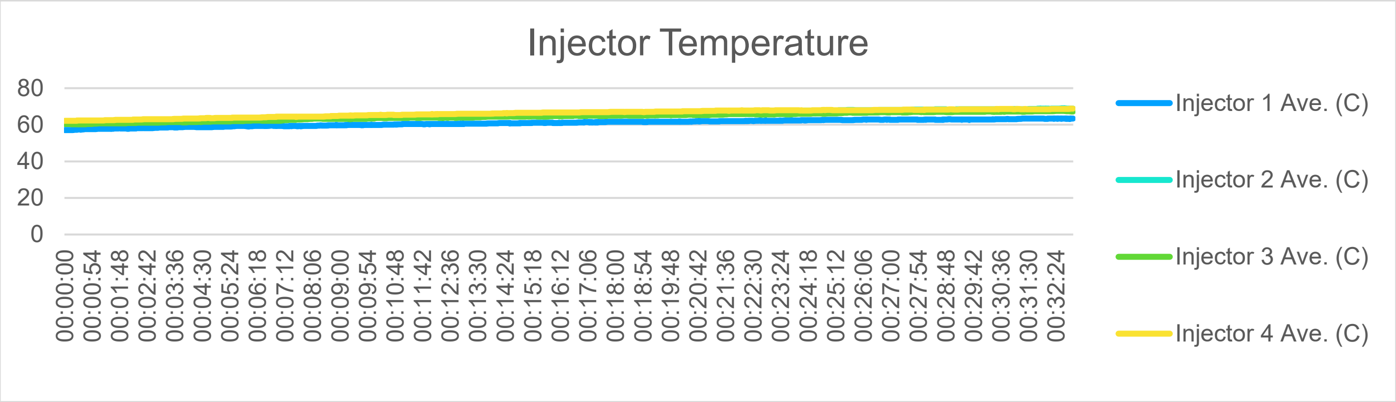


Figure 55 - Deutz 4-Cylinder EN590 injector temperatures (9kW)

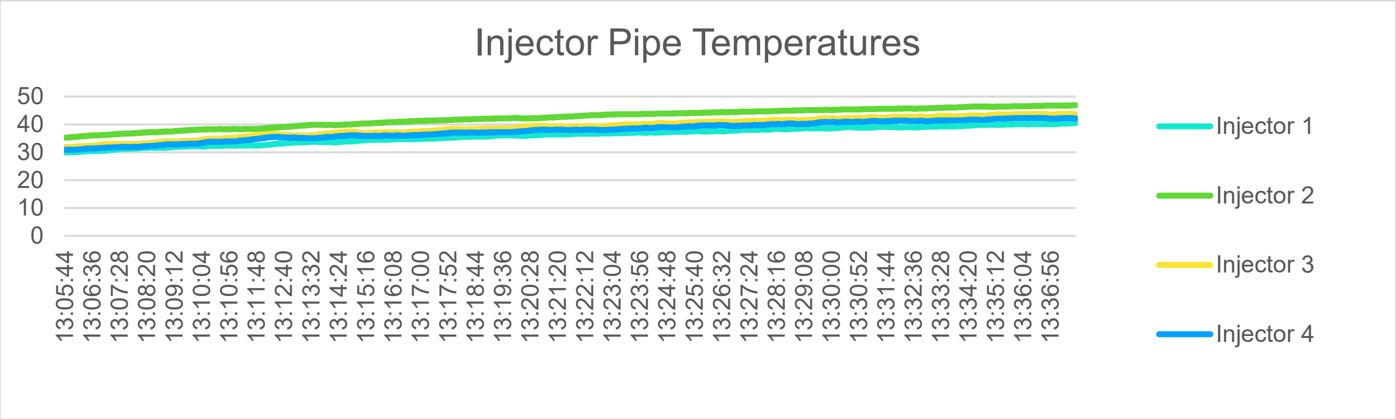


Figure 56 - Deutz 4-Cylinder EN590 injector pipe temperatures (9kW)

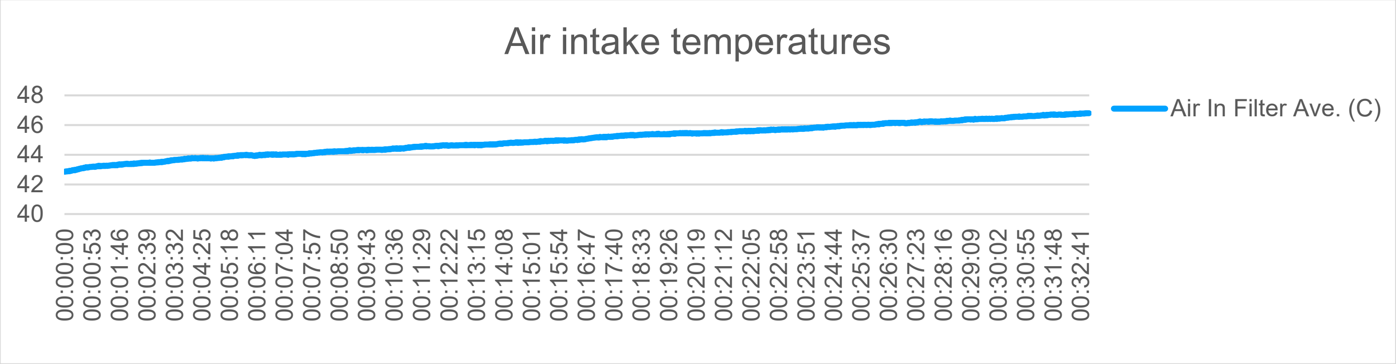


Figure 57 - Deutz 4-Cylinder EN590 air intake temperature (9kW)

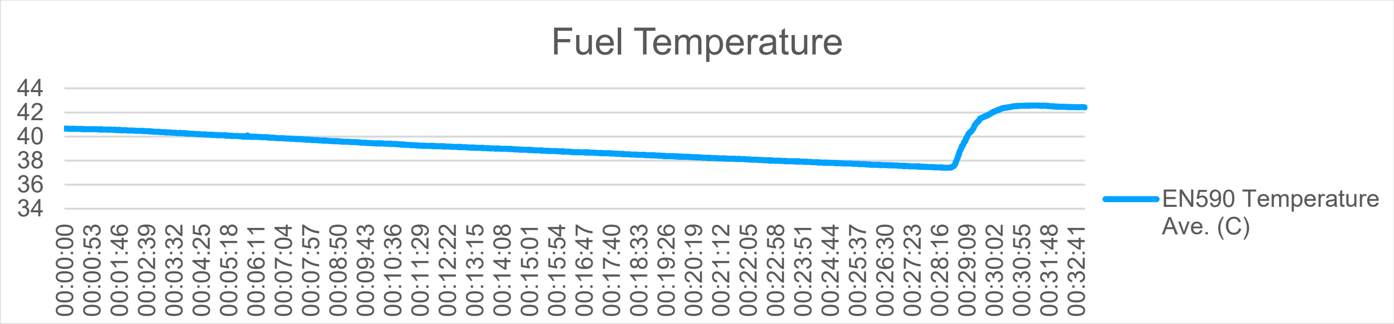


Figure 58 - Deutz 4-Cylinder EN590 fuel temperature (9kW)

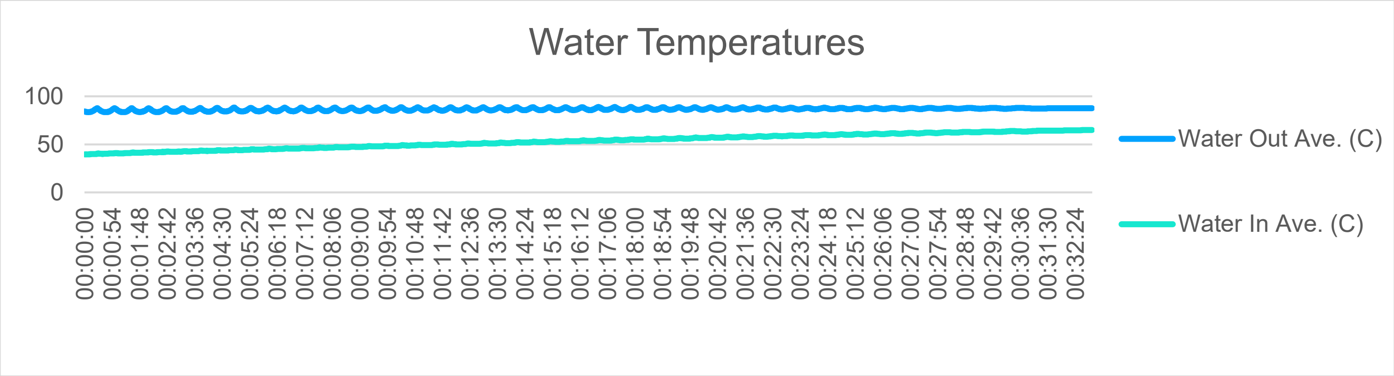


Figure 59 - Deutz 4-Cylinder EN590 water temperatures (9kW)

Combustion Profile

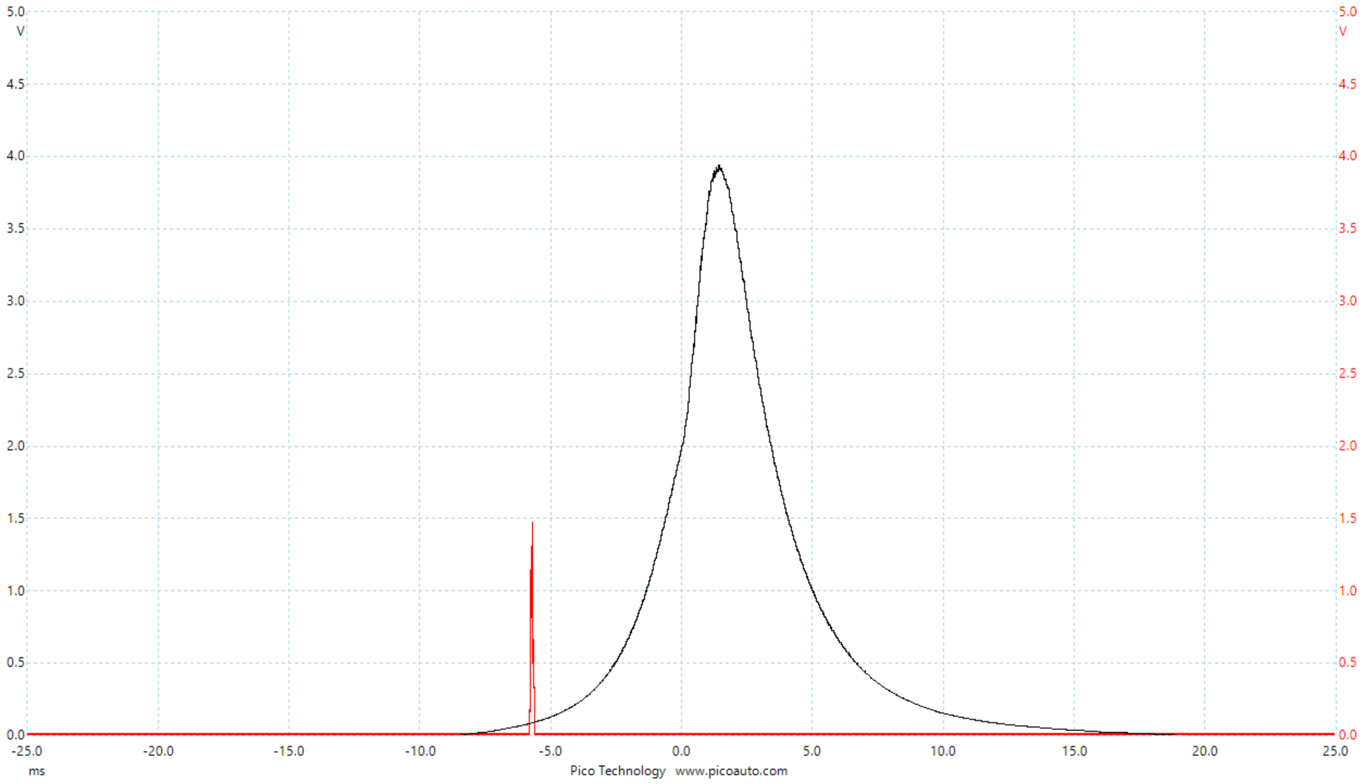


Figure 60 - Deutz 4-Cylinder EN590 combustion profile (9kW)

Fuel Samples Trials

Test code 8 1st Distillate

Test code 11 Distillate Brown

22. Discussion

We still need to complete further work on preparing the fuel for testing. However, the initial results from the above trials were very encouraging. Both fuels would benefit from a more granular reaction procedure to refine the carbon-length chains to a more homogenized level.

23. Conclusions

The Test code 8 1st Distillate sample again proved to have very high calorific value and emissions, although higher than we would like, were within parameters for post-combustion clean-up.

Test code 11 Distillate Brown had expected calorific value but higher total hydrocarbons. We believe this is due to higher than recommended reaction temperatures, producing shorter carbon-length chain aromatics.

We are reasonably convinced that with a full pre-cleanup process prior to reaction vessel and a post-cleanup process including potential distillation, these fuels would be close to being workable with refinements on the reaction vessels to tune the fuels to optimum results.

24. Recommendations

Further work is required in a more conducive environment than a science lab in the centre of Glasgow for working with these raw feedstocks to the fullest extent. University of Glasgow can only operate small quantities due to the nature of the feedstocks, therefore it as recommended that anything other than the smallest scale fuel refinement takes place at a site with a Waste Collection and a Waste Incinerator Directive license.