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Particle emissions and size distribution across the DPF from a modern diesel engine using pure and blended GTL fuels

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Abstract

A Gas to liquid (GTL) fuel was investigated for its combustion and emission performance in an IVECO EURO5 DI diesel engine with a DOC (Diesel Oxidation Catalyst) and DPF (Diesel Particle Filter) installed. The composition of the GTL fuel was analyzed by GC-MS (gas chromatography-mass spectrometry) and showed the carbon distribution of 8-20. Selected physical properties such as density and distillation were measured. The GTL fuel was blended with standard fossil diesel fuel by ratios of diesel/GTL: 100/0, 70/30, 50/50, 30/70 and 0/100. The engine was equipped with a pressure transducer and crank angle encoder in one of its cylinders. The properties of ignition delay and maximum in-cylinder pressure were studied as a function of fraction of the GTL fuel. Particle emissions were measured using DMS500 particle size instrument at both upstream (engine out) and downstream of the DPF (DPF out) for particle number concentrations and size distribution from 5 nm to 1000 nm. The results show that total particle number concentrations were significantly reduced with the increase of GTL fuel fractions. The particle number emissions reduction was captured both from nucleation and agglomeration mode particles. The significant reduction in particle emissions were due to the chemical composition of the GTL fuel, dominantly alkanes without aromatics, which leads to more complete combustion. The ignition delays were reduced with the increasing of blending ratio of the GTL and GTL blends also showed shorter combustion duration when compared to diesel fuel at low engine power test conditions.

Introduction

Diesel engines have advantages of higher thermal efficiency, better fuel economy and lower CO_2 emissions compared to SI engines. However, the diesel-gate scandal seriously damaged the reputation of diesel engines and sales of diesel cars plummeted. Since the diesel gate event occurred at the end of 2015, the diesel registration dropped dramatically by 47% as shown in figure 1. [1] On the other hand, diesel engines are still the dominant power source for heavy duty vehicles and machines. It is therefore imperative to control and reduce emissions from diesel engines. Apart from efforts on the improvement of engine design and exhaust aftertreatment systems, use of clean or low emission fuels is an important approach for reducing emissions.

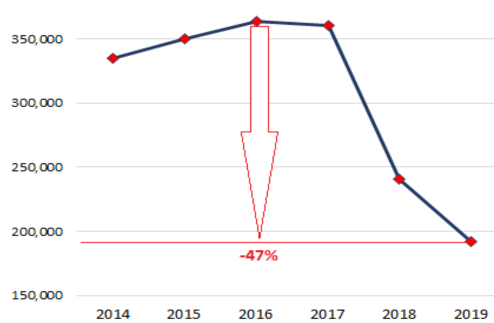

Figure 1. UK diesel registration since 2014.

The gas to liquid (GTL) fuel can be one possible solution. The chemical composition of GTL fuel is nearly all paraffinic. Compared to diesel, the GTL fuel has hardly any aromatics and only normal-paraffins and iso-paraffins hydrocarbons. This gives GTL fuel higher cetane number values, allowing for the GTL fuel to burn faster and cleaner than conventional diesel fuels. [2]

The production of GTL fuel is based on the technology developed in the 1920s, named as Fischer-Tropsch process which allows for carbon monoxide and hydrogen gas to be converted to liquid hydrocarbons. [3] [4] First, the synthesis gas was produced from natural gas by partial oxidation. Then, CO and H_2 acquired would be converted to liquid hydrocarbons using Fischer-Tropsch process. Finally, the liquid generated would be treated with hydrocracking processed to fractionate its chemical bonds and to achieve high quality paraffinic liquid fuel which can be used in diesel engine. [5]

The characteristics of high CN and aromatics free of the GTL fuel, imparts the GTL fuel potentials to reduce emissions. Kitano, K's, reported a 26% reduction of particle matter emissions by the GTL fuel compared to diesel on the application of direct injection diesel engine. [6] Similar results were found by Myburgh, Ian that the GTL fuel could reduce all regulated emissions except no clear improvement on NOx emission. [7] However, according to Maly, Rudolf R, the GTL fuel can slightly reduce NOx emission when used as alternative fuels to diesel engine. On the other hand, the GTL fuel is produced from natural gas instead of crude oil, indicating the application of GTL fuel can relieve the reliance on conventional crude oil. [8]

Therefore, emissions of GTL fuels can be critical to its future application. At the same time, with consideration for the economic cost from GTL fuel production, this research aimed at investigating the influence of GTL fuel blending ratio on particle number emissions and size distributions, and efficacy of DPF. In order to find out how GTL fuel can improve the engine particle emissions at different blending situations, the fuel distillation property and composition of diesel and GTL fuel were analyzed by TGA (thermogravimetric analysis) and GC-MS in this research. The GTL fuel was blended with diesel fuel at 0%, 30%, 50%, 70% and 100% by volume. A light duty 3.0 Liter, direct injection, 4-cylinder IVECO diesel engine compliant with Euro 5 emission legislation was used under nine selected stable engine testing conditions. The particle number distribution measurements were sampled both before and after the after-treatment system using Cambustion DMS500 MKII particle size analyzer. The combustion pressure curve was analyzed using an AVL pressure transducer and an AVL crank angle encoder sensor.

Experiment

Fuel Properties

This research used the standard ultra-low sulphur diesel complying with EN590 and GTL fuel supplied by Royal Dutch Shell Plc. The fuel specification and properties of diesel and GTL fuels are shown in table 1. [5] In order to acquire the volatility property and carbon number distribution of diesel and GTL fuels, TGA and GC-MS tests were conducted for both fuels. The model of the TGA was METLLER TOLEDO with a temperature setting from 30 °C to 600 °C. The GC-MS was A SHIMADZU gas chromatograph-mass spectrometer QP-2010 SE. The database used to identify and quantify the carbon compounds is NIST 11 mass spectral database, which contained 243,893 spectra of 212,961 different chemical compounds. [9]

Table 1. The fuel specifications and properties of Diesel and GTL fuels.

Property	Unit	Diesel	GTL
Appearance at +25 °C		Clear	Clear & Bright
Cetane number		≥ 51.0	74 - 80
Density at +15 °C	kg/m^3	840	780
Total aromatics	% (m/m)	≤25	< 1.0
Polyaromatics	% (m/m)	≤ 8	< 0.1
Sulphur	wt %	≤10	0
Hydrogen	wt %	12.98	14.56
Carbon	wt %	87.02	85.44
H/C ratio		1.79	2.04
Net calorific value	MJ/Kg	42.9	44.0
FAME-content	% (V/V)	≤ 7.0	0
Flash point	°C	> 55	75.5
Ash	% (m/m)	≤ 0.01	≤ 0.01
Water	mg/kg	≤ 200	≤ 200
Total contamination	mg/kg	≤ 24	≤ 24
Viscosity at +40 °C	mm^2/s	2.00 - 4.50 (EN590)	3.20 - 3.90
Distillation 95 % (v/v)	°C	≤ 360	≤ 360
Final boiling point	°C	< 330	

Engine Setup

An IVECO 3.0 L diesel engine compliant with Euro 5 emission standard was used in this research. The engine was equipped with turbocharger, intercooler, EGR system, DOC (Diesel oxidation catalyst) and DPF (Diesel particulate filter). The main engine specifications are shown in table 2.

Table 2. Specifications of the test engine.

Engine type	Iveco FICE0481F
Cycle	Diesel 4 strokes
Supply	Turbocharged with intercooler
Number of cylinders	4 in line
Total displacement	2998 cm^3
Injection type	Direct & High-Pressure common rail
Bore	104 mm
Stroke	95.8 mm
Compression ratio	18
Injection sequence	1-3-4-2
Injection pressure (maximum)	1600 bar
Maximum torque	300 Nm
Maximum power	122 KW (calibrated for 96kW)
Turbocharger air temperature	Activates at ≥ 75 °C and deactivates at ≤ 65 °C

The engine was connected to a dynamometer allowing the engine to run at maximum torque of 238 Nm. The dynamometer was controlled by the DSG software, which is used to control the engine rpm, throttle position, and to record engine power data, emission data, and temperature data at 14 specific locations of the engine. Based on the engine and dynamometer capability, nine stable engine working conditions were selected for this research. The tested engine working conditions are shown in table 3. At each stable engine working condition, the experiment was lasted for 5 mins and all experiment were repeated for three times in order to provide the most reliable data.

In Cylinder Pressure and Crank Angle Measurement

A set of AVL system was used to acquire the pressure and crank angle data of the engine combustion. The system included four parts: AVL pressure transducer GH13G , AVL crank angle encoder 365X, AVL amplifier FLEXIFEM INDI 2CH SDC and AVL Indicom software. The AVL system was capable of measuring combustion pressure and engine speed up to respectively 250 bar and 20000 rpm. [10,11]

The AVL pressure transducer was installed in one of the four combustion cylinders, and an AVL crank angle encoder was installed on the engine. The signals received from the pressure transducer and crank angle encoder were sent to the AVL amplifier, which connected to an independent laptop installed with AVL Indicom software using ethernet cable. The AVL Indicom software provided the real time combustion pressure and crank angle data. The pressure to crank angle diagram and ignition delay analysis was based on the data from the AVL system.

Particle Number Distribution Measurement

The particle size distribution was measured using Cambustion DMS 500 MK II, which sampled engine exhaust gas both before and after the DPF system, thus allowing for the comparison analysis of particle emission before and after the DPF. The DMS 500 was connected to an independent computer using ethernet cable for controlling the DMS500 and logging the data. The measurement frequency setting of DMS 500 was 1 Hz. The measured particle diameter range is from 4.87 nm to 1000 nm, with total 38 different sizes of particles being measured in number concentrations ($\#/cm^3$). [12]

The Tests Conditions

Nine engine testing conditions were selected as shown in table 3. Three rpm settings were chosen: 1000, 1600, and 1900. 1000 rpm represented stable idle speed while 1600 and 1900 rpm were the peak torque (should be 300Nm but was 235Nm for this study due to the limit of the dynamometer) conditions. The purpose of the nine testing conditions was to cover as wide as possible engine operating ranges within allowed capability of the lab, engine and dynamometer.

Table 3. The engine testing conditions.

Stage of experiment	Engine rpm	Throttle position %	Torque Nm	Power kW
1	1000	30	125	13
2	1000	40	183	19
3	1000	50	207	22
4	1600	40	115	20
5	1600	50	157	27
6	1600	60	214	36
7	1900	50	135	27
8	1900	60	181	36
9	1900	70	233	47

Results and discussion

Fuel distillation characteristics Analysis

From the fuel specifications and property data shown in table 1, it can be found that the main difference between diesel fuel and GTL fuel is that the GTL fuel has lower density, higher cetane number, almost aromatic free. The GTL fuel has a higher hydrogen and carbon (H/C) ratio than diesel (2.04 for GTL and 1.79 for diesel). The mass based net calorific value of GTL fuel is slightly higher than diesel fuel. Based on those characteristics of GTL fuel, it can be assumed that the blended fuel and pure GTL fuel should have shorter ignition delay, and reductions in particle emissions mainly because the GTL fuel has higher cetane number value and chemically almost aromatic free. The research conducted by Oguma proved this finding as well. The engine power generated by those fuels should be very close as the calorific values are very similar. [13] This showed agreement with Soltic, P, et al's research. [14] However, still many details and other aspect of comparison need to be analysed in order to bring a more systematic conclusion. Hence, the TGA and GC-MS tests were conducted.

First, the distillation characteristics of diesel fuel and GTL fuel were investigated using TGA test, and the result is shown in figure 2. From the figure, it demonstrates that the GTL fuel has the same evaporating rate as the diesel fuel before 180 °C and then shows more lighter fractions than the diesel after 180 °C till the end. The ending temperature of GTL fuel is 270 °C, which is 20 °C earlier than that of diesel fuel. The indication is that more lighter fractions in the GTL fuel could lead to more complete fuel combustion, and thus lower particle and total hydrocarbon emissions should be expected from the GTL fuel. This explanation can be supported by the results from GC-MS test conducted in this research.

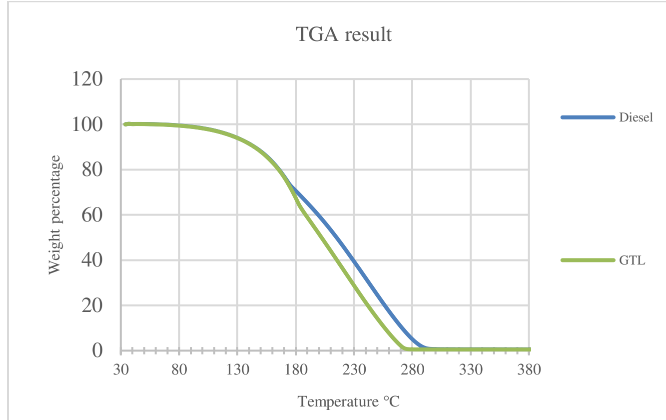

Figure 2. The TGA analysis results of diesel fuel, GTL fuel, fresh engine lube oil, and used engine lube oil.

After the TGA tests, the GC-MS tests were carried out to measure the composition and distribution of carbon chains in diesel and GTL fuels. Their respective spectra are shown in figure 3 and figure 4. It was found that the difference between GTL fuel and diesel fuel is that the GTL fuel consists of almost all straight chains or branched alkanes and in absence of aromatics. Also, GTL fuel contains more lighter fraction carbon chains than diesel fuel, particularly higher C_{10} and C_{14} fractions compared to diesel fuel. The highest intensity of $C_{19}H_{32}O_2$ detected after C20 in diesel was believed to be a biodiesel component (C19 methyl ester) contained in diesel fuel provided by the fuel manufacture.

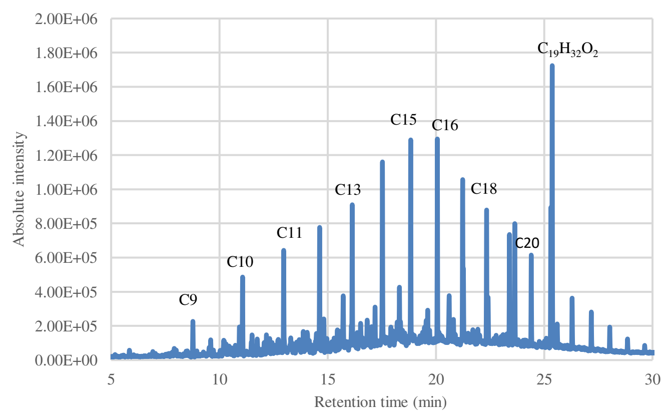

Figure 3. The carbon number distribution of diesel fuel by GC-MS analysis

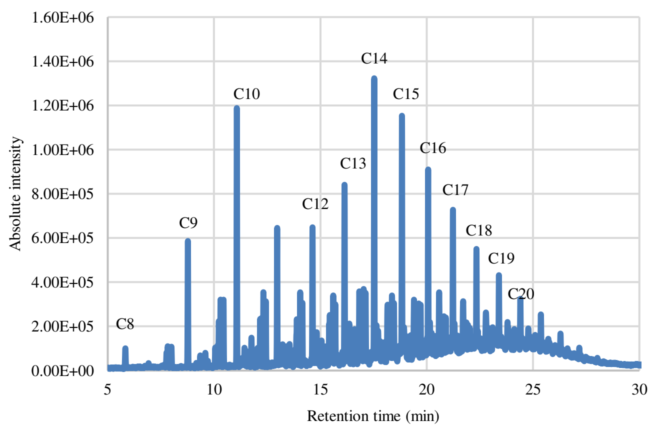

Figure 4. The carbon number distribution of GTL fuel by GC-MS analysis.

Combustion Performance

The combustion performance (pressure-crank angle) of Diesel, GTL and its blended fuels were measured by the AVL system and the results were presented in pressure to crank angle diagrams near TDC (top dead center), which allowing for the analysis of combustion pressure curve, ignition delay, multiple fuel injection.

As shown in figure 5, in the 1000 rpm, 30% throttle test condition, all fuel injections occurred 2 degrees BTDC and can be evidenced by the pressure drop caused by fuel injection. However, the pure GTL started an earlier combustion and reached a higher peak combustion pressure. The combustion duration of pure GTL was shorter and thus resulting the pressure behaved lower than any other fuels 20 degrees after the piston passed the TDC. The ignition delay of pure GTL fuel was 0.5ms at this test condition, while the rest of the fuels performed 1.5ms. This was due to the high cetane number and chemical composition-pure alkanes without aromatics. Similar research from Kidoguchi, et al also showed that fuels with higher cetane number and lower aromatics content would have shorter ignition delay and faster combustion rate. [15] Because the aromatics with ring structure require more energy to break (to be ignited). [16] This can also be supported by the work of Vandersickel et al. [17] The pressure traces before the ignition for the GTL fuels were lower than that of the diesel fuel in figures 5 and 6. This is considered due to that the turbocharging may be different between the GTL and diesel fuels when the engine was operated below 20 kW power. The pressure traces in figures 5 and 6 show that the post-combustion pressure of the GTL fuel is lower than that of the diesel fuel. This would lead to a lower boost pressure by the turbocharger and thus less intake and lower pressures before the ignition as shown in figures 5 and 6.

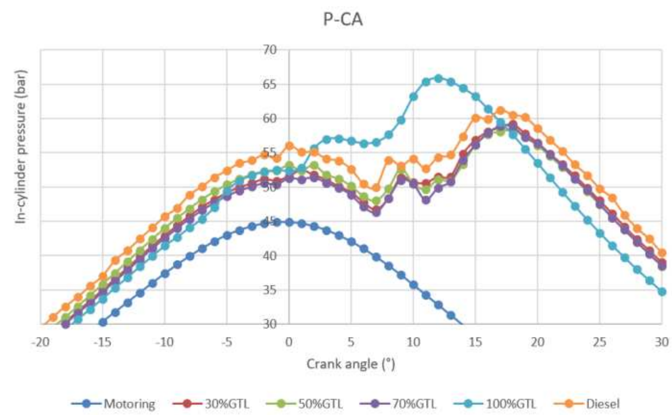

Figure 5. The pressure curve near TDC of GTL blended fuels at 1000rpm, 30% throttle, 13Kw.

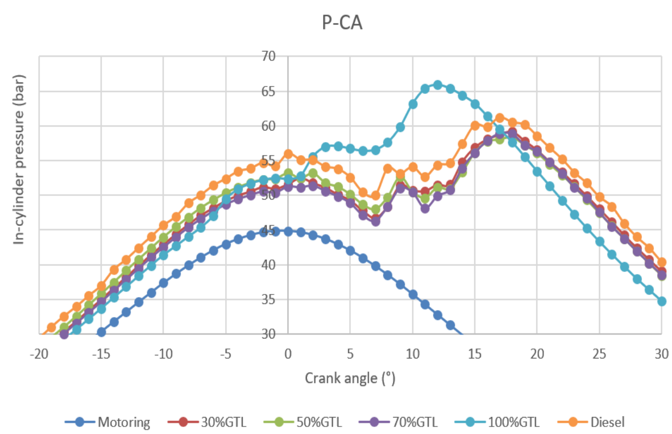

Figure 6. The pressure curve near TDC of GTL blended fuels at 1000rpm, 40% throttle, 19KW.

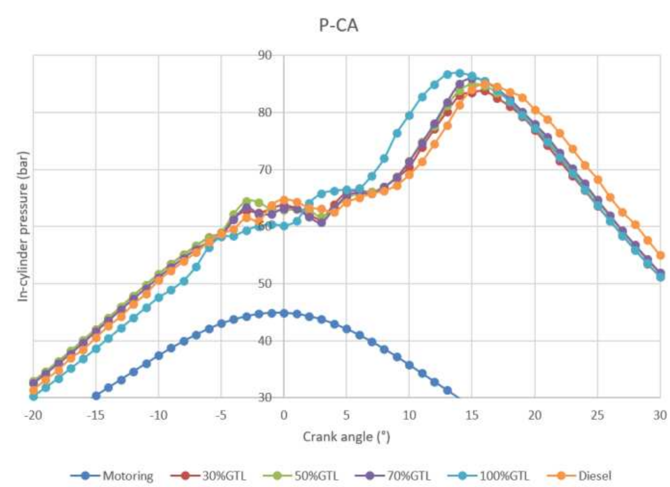

Figure 7. The pressure curve near TDC of GTL blended fuels at 1000rpm, 50% throttle, 22KW.

When the engine throttle setting was increased, it can be seen from figure 6 and 7 that the difference between pure GTL and other fuels was becoming smaller. The ignition delays of diesel and GTL blends at 40% throttle was 1.17ms, which is two times higher than the pure GTL, however when the throttle increased to 50%, the ignition delay of diesel fuel was only 0.17ms longer than GTL and its blends. From the comparison of figures 5, 6, and 7, it can be found that the P-CA is less sensitive to throttle or torque increases between fuels, for instance, at the higher power conditions, the variation between different fuels for in-cylinder pressure is smaller. In contrast, the lower the engine power settings, the more obvious the variations can be found. Therefore, it can be concluded the difference in pressure curve caused by fuel properties would be abated as the engine power increases, or the engine power settings has dominant impacts on combustion pressure.

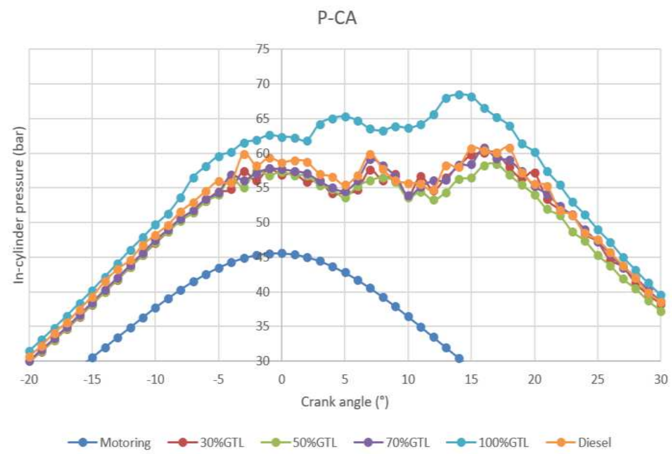

Figure 8. The pressure curve near TDC of GTL blended fuels at 1600rpm, 40% throttle, 20KW.

The results of 1600 rpm tests were presented in figures 8, 9, and 10. From figures 8 and 9, it was found that the ignition delays were becoming shorter with the blending ratio increased. This was due to the average cetane number of experimental fuels were increased with the increasing of blending ratio. In the 1600 rpm tests, the combustion process of all fuels was tended to present constant pressure combustion. Multiple fuel injections can be seen 5 degrees to 15 degrees after TDC, which is the method of how this IVECO diesel engine tried to acquire its constant pressure combustion and achieve higher thermal efficiency.

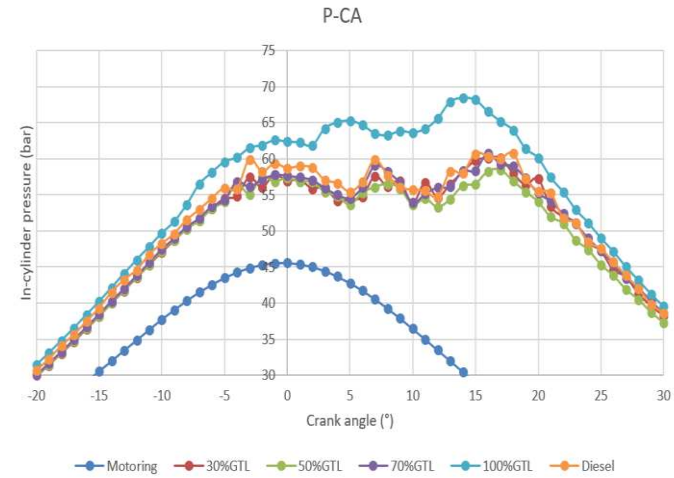

Figure 9. The pressure curve near TDC of GTL blended fuels at 1600rpm, 50% throttle, 27KW.

Another interesting finding from the 1600 rpm tests was the in-cylinder pressure would sometimes experience a sudden little rise before the start of fuel injection. This is obvious in figure 10. The pressure drops caused by fuel injection generally occurred at 8 degrees BTDC, however, all fuels experienced a pressure rise at 9 degrees BTDC from 0.5 bar to 3.9 bar. The rise is small and unlikely to be caused by pilot combustion. One explanation for this is that soon after the fuel was injected to the combustion cylinder, before the fuel started to absorb heat and lead to pressure drop, some light fractions of diesel fuel is more likely to evaporate and leading to the pressure increase. Since the evaporation of lighter fractions occurs at lower temperature than heavier fractions. [18] Once the light fractions evaporated, the liquid fuel droplet was transformed to gas, which immediately occupied the combustion cylinder and caused the in-cylinder pressure to rise. This scenario was more obvious with diesel fuel than the blended or pure GTL fuel. This can be treated as with the increasing of blend ratio, the diesel in the fuel is reducing, thus the pressure rising reaction related to diesel is becoming less obvious with the increasing of blend ratio.

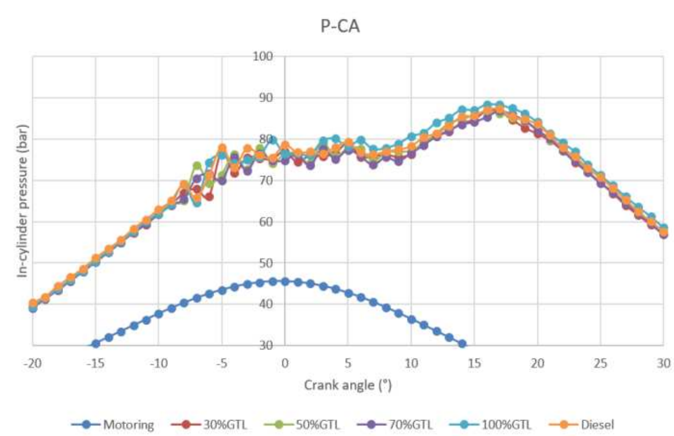

Figure 10. The pressure curve near TDC of GTL blended fuels at 1600rpm, 60% throttle, 36KW.

The results from 1900 rpm tests compromised to those previously results. However, from figures 11 to 13, it can be found that the pressure curves of all tested fuels were very close to each other. This scenario happened to 1600 rpm, 60% throttle test as well, when the engine power reached 27 KW. The engine power for 1900 rpm, 50%, 60%, and 70% throttle settings were respectively 27 KW, 36 KW, and 46 KW. Therefore, it can be concluded that when the engine power reached 27 KW and beyond, the advantage of GTL and its blends would disappear, resulting the combustion duration to be similar to diesel fuel. In the 1900 rpm tests, the multiple fuel injection strategy of the engine was more evidenced. At least five injections occurred near TDC, and this can be seen from several pressure drops near TDC for all the tested fuels. Figure 13 provides an example. This strategy helped the engine to acquire relevant stable and constant pressure combustion. As it was found from figure 11 to figure 13 that all the fuel combustion processes happened with pressure variety less than 9 bar.

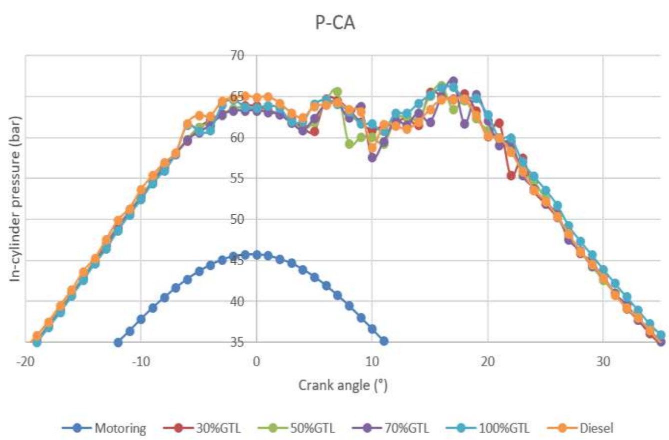

Figure 11. The pressure curve near TDC of GTL blended fuels at 1900rpm, 50% throttle, 27KW.

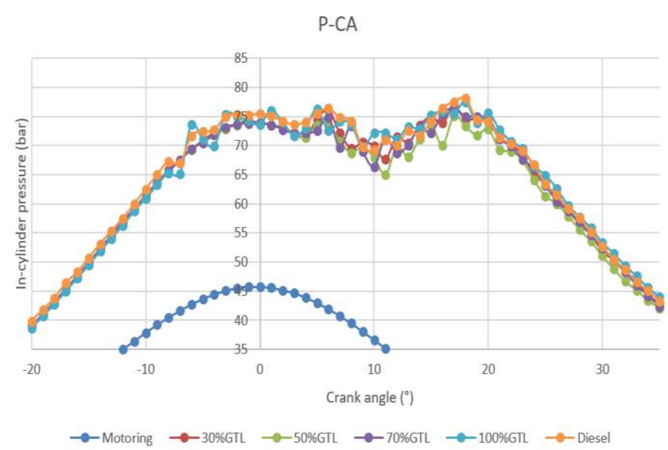

Figure 12. The pressure curve near TDC of GTL blended fuels at 1900rpm, 60% throttle, 36KW.

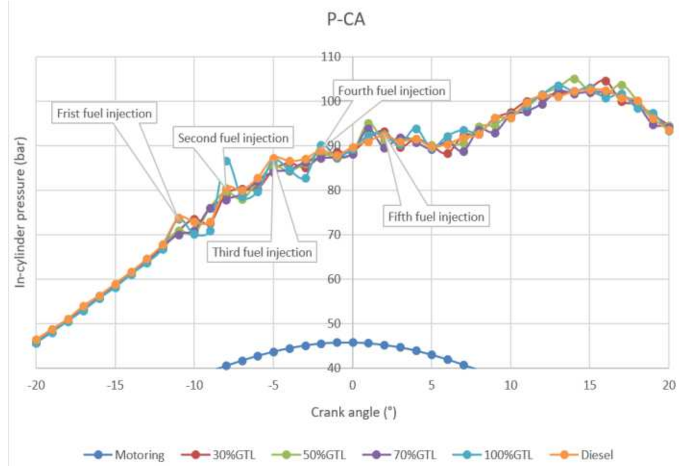

Figure 13. The pressure curve near TDC of GTL blended fuels at 1900rpm, 70% throttle, 47KW.

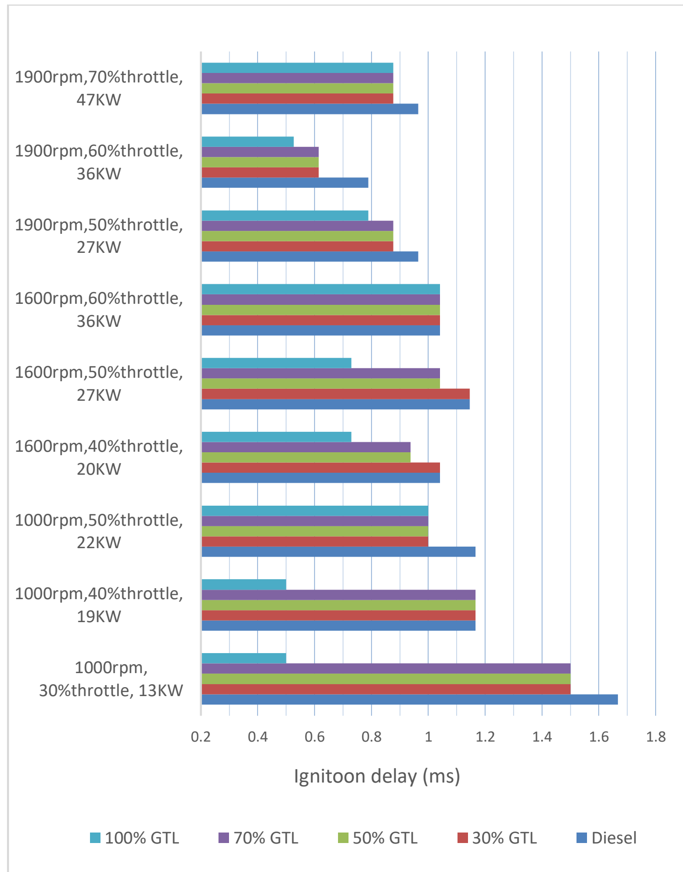

Figure 14. The ignition delay summary of all tests.

In summary, the GTL and its blends can be burned more easily and faster than diesel fuel, indicating that the particle number emission from GTL and its blends should be lower than diesel fuel because it has better combustibility. The pure GTL and its blends have a shorter combustion duration; however, this became negligible with the engine power increased higher than 27 KW. The ignition delay, as shown in figure 14, decreased with the blending ratio increased because the cetane number in the fuel was raised.

Total Particle Number Emission and DPF efficiency

The particle number emission from all tested fuels at engine out was normalized to diesel and shown in figure 15. The total PN emissions measured from engine out and DPF out are presented in figure 16 and figure 17. In general, it can be seen that the pure GTL and GTL blends can improve the PN emissions significantly both at upstream (engine out) and downstream of the aftertreatment system (DPF out). At the engine out, as shown in figures 15 and 16, the pure GTL fuel can improve the total PN productions at engine out by 27% to 53% based on different engine operating conditions. At the DPF out, the blended fuels and pure GTL fuel showed PN emissions lower than the DMS 500 MK II's lower detection limit: 2.0×10^4 in most of test conditions. Except the 30% GTL blended fuel showed some results higher than 2.0×10^4 (number/cc), but it still improved the total PN emission by at least 26%.

The reason that pure GTL fuel and it blends can improve the PN emissions effectively is due to the chemical property of the GTL fuel. According to the study by Sajjad, H et al, that the GTL fuel can reduce ultrafine nanoparticle number emission by 85.3%. [19] The GTL fuel, as discussed in the fuel property section, consisted of all straight chains and branched alkanes, which allowing it to be burned off more rapidly, more easily, and more completely. Since the particle number emission is mainly sourced from unburnt and partially burnt fuels, therefore, the aromatics free GTL can be burned more completely and consequently the GTL fuel dose have the ability to reduce PN emission. This can be proved by the PN emissions from the GTL, diesel, and GTL blended fuels. If comparing the PN emissions against the blend ratio, it can be found that the total PN emission gradually reduces with the increase of blending ratio at each specific engine operating status. Increasing the blending ratio will increase the easy-combust components in the fuels, and consequently less particle emissions will be produced. This phenomenon is more obvious from engine out PN measurement than DPF out PN emissions, because at the exhaust downstream, the highly effective DPF removed most of the particles and left particles can hardly be accurately measured by the device.

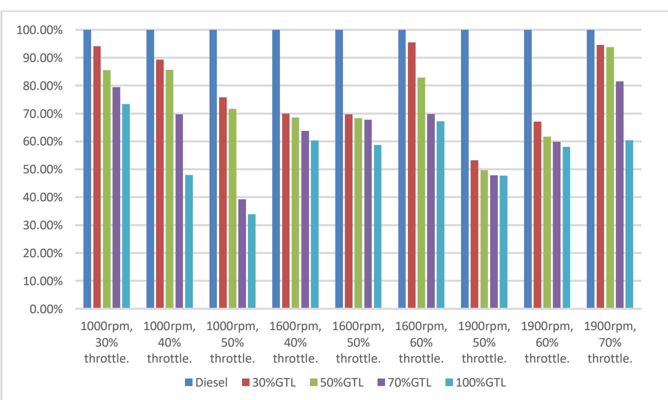

Figure 15. PN emission at engine out normalized to diesel.

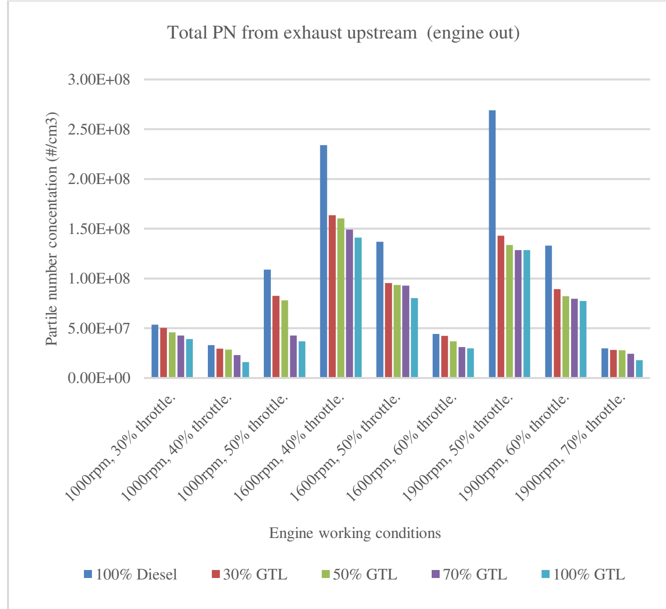

Figure 16. Total PN at engine out of GTL blended tests.

From the DPF out result, it can be found from figure 17, that only the 30% GTL blend showed similar trend as upstream at the 1600 rpm and 1900 rpm test, i.e. Particle number emissions reduced with the increasing of engine power settings. The diesel fuel only showed same findings as upstream at 1000 rpm. And the rest of the tested fuels showed undetectable PN measurement because the low PN production at engine out and the highly effective DPF. The reason that diesel fuel didn't present similar results at 1600 rpm and 1900 rpm is believed to be the DPF filtering limitation. Once the engine reaches 27 KW power condition (started from 1600rpm, 50% throttle), the diesel fuel combustion would start to generate accumulation mode particles and exceed the large particle filtration limit of the DPF, and consequently bring down the DPF efficiency. This can be proved by the results of DPF efficiency analysis.

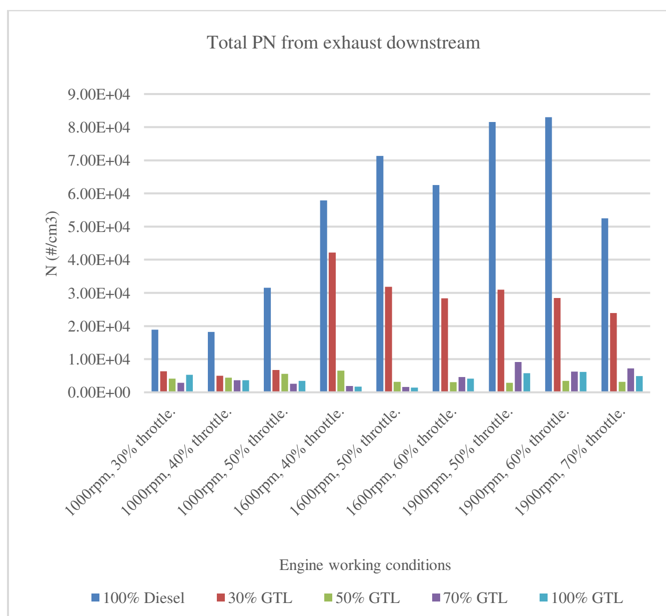

Figure 17. Total PN at DPF out of GTL blended tests.

Based on the total particle number results, the DPF efficiency can be achieved using following formula:

$$\text{DPF efficiency }\% = \frac{\text{PN upstream} - \text{PN downstream}}{\text{PN upstream}} \times 100\%$$

Equation 1

Where:

PN: Particle Number Concentration (# /cm^3)

Upstream: Measurements taken before the aftertreatment system

Downstream: Measurements taken after the aftertreatment system

From the DPF efficiency result shown in table 4, it can be seen that for all tests, the DPF achieved very high efficiencies with all above 99%. Because the total particle number measured at engine out was in the scale of 10^7 to 10^8 while the all particle number measured at DPF out was in the scale of 10^4, thus the particle number measured from DPF out is at least 1000 times lower than that from engine out. However, if taking a close look at diesel's DPF data, it can be found that when the engine power setting reached 1600 rpm, 50% (27 KW) and beyond, the DPF efficiencies of diesel fuel were all slightly lower than pure GTL fuel and GTL blended fuels. This indicates that when the engine power reached 27 kw and beyond, the diesel fuel would produce more accumulation mode particles which failed to be filtered out by the DPF because the DPF reached its filtration limit. This explains why the total particle number emissions from diesel fuel at exhaust downstream (shown in figure 5) didn't reduce with throttle increasing at engine power after 1600 rpm, 50% throttle.

Table 4. DPF efficiency of GTL blended fuel tests.

Engine working condition		DPF efficiency				
Engine rpm	Throttle%	100% Diesel	30% GTL	50% GTL	70% GTL	100% GTL
1000	30	99.9647%	99.9875%	99.9910%	99.9932%	99.9866%
	40	99.9450%	99.9832%	99.9846%	99.9842%	99.9771%
	50	99.9710%	99.9918%	99.9929%	99.9940%	99.9342%
1600	40	99.9753%	99.9742%	99.9959%	99.9987%	99.9988%
	50	99.9478%	99.9666%	99.9966%	99.9983%	99.9909%
	60	99.8591%	99.9331%	99.9917%	99.9850%	99.9315%
1900	50	99.9697%	99.9783%	99.9978%	99.9929%	99.9866%
	60	99.9377%	99.9682%	99.9958%	99.9921%	99.9762%
	70	99.8233%	99.9148%	99.9887%	99.9702%	99.9183%

Particle Size Distribution Analysis

The particle size distribution of diesel, GTL and their blends were measured at the upstream and downstream of the DPF, thus allowing the comparison across the DPF to be made. The results are provided from figure 18 to figure 35.

From the 1000 rpm engine out results, it can be observed from figure 18, figure 20 and figure 22 that some blended GTL fuels can have higher peak values of accumulation mode particles at lower power settings, but this phenomenon disappeared when the throttle settings increased to 50%. This can be caused by the relevantly low combustion temperature and poor air to fuel mixing at 30% and 40% throttle settings. The peak values of nucleation mode particles from GTL and its blends are lower than from diesel in general despite 100%, 70%, 50% GTL fuel and diesel fuel shared similar nucleation particle distribution curve at 1000 rpm, 30% throttle tests. It can also be seen from the engine out PN size distribution that the nucleation mode particles' peak values of all tested fuels ranged from 11nm to 21 nm, and the accumulation mode particles' peak values ranged from 86 nm to 365 nm. This indicates that the productions of accumulation mode particles were more sensitive to blending ratio than the nucleation mode particles, and similar findings were reported by Du's research team, that accumulation mode particles especially in diameter range around 100 nm are more sensitive to GTL blending ratios than nucleation mode particles.[20]

In general, at 1000 rpm tests, GTL and its blends showed particle number reduction in nucleation mode particles at engine out, despite that some blended fuels showed higher number emissions for accumulation particle. The total PN emissions for all tested alternative fuels were still lower than pure diesel because the GTL and it blends significantly reduced the particle production with diameter smaller than 100 nm. At the DPF out, it can be found that all blended GTL fuels and pure GTL fuel showed much lower particle emissions than diesel, and those particle number concentrations measured in were all lower than 2×10^4 (#/cm^3), which is the lower detect limits of the DMS 500.

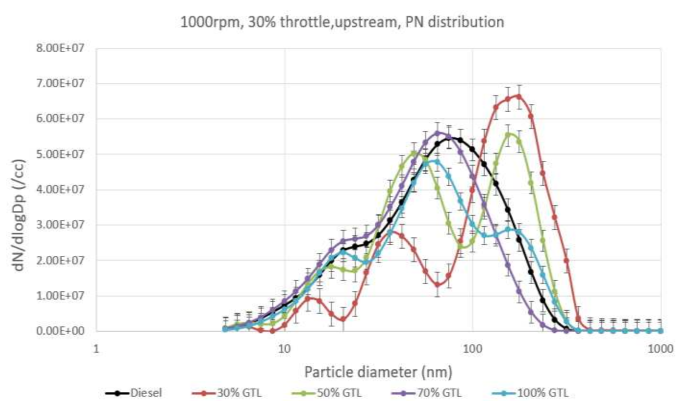

Figure 18. Particle size distribution from engine out at 1000 rpm, 30% throttle.

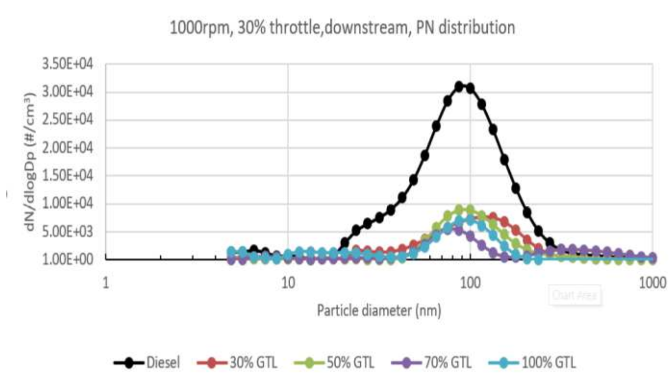

Figure 19. Particle size distribution from DPF out at 1000 rpm, 30% throttle.

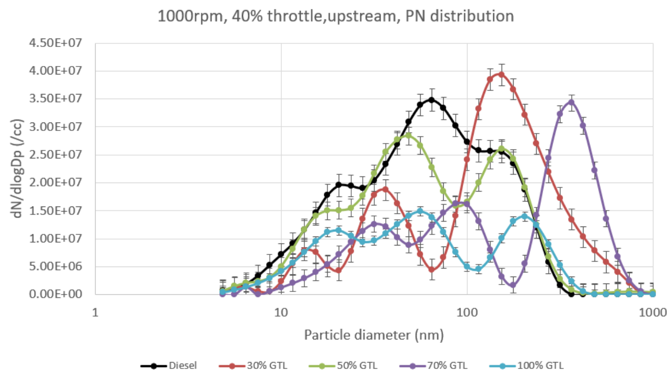

Figure 20. Particle size distribution from engine out at 1000 rpm, 40% throttle.

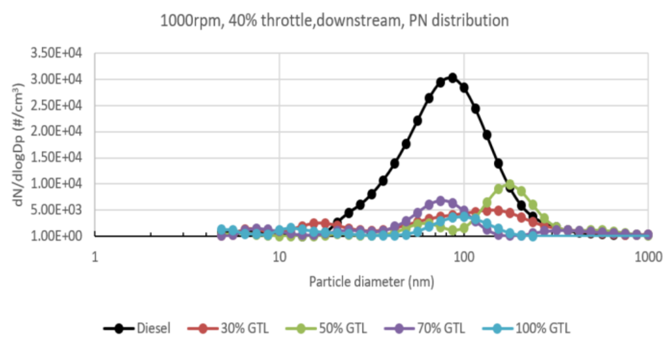

Figure 21. Particle size distribution from DPF out at 1000 rpm, 40% throttle.

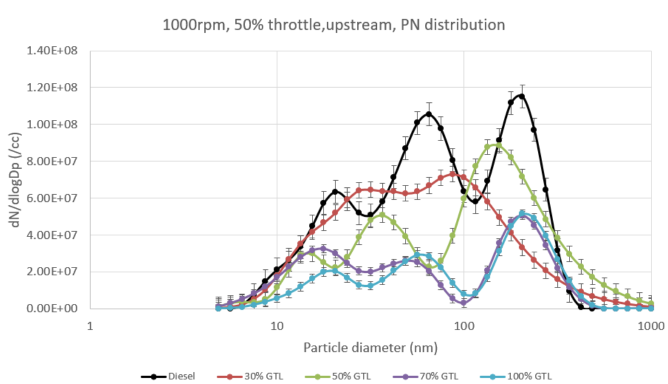

Figure 22. Particle size distribution from engine out at 1000 rpm, 50% throttle.

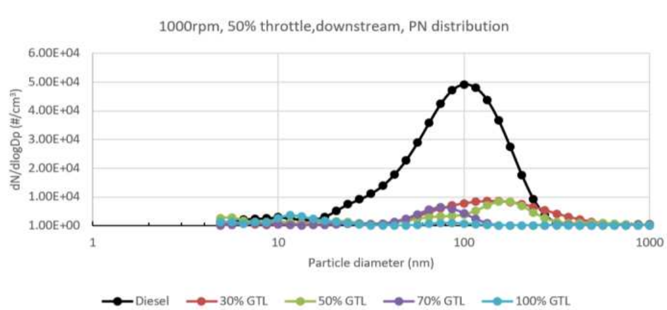

Figure 23. Particle size distribution from DPF out at 1000 rpm, 50% throttle.

When the engine rpm was increased to 1600 rpm, it can be observed from figure 24, figure 26 and figure 28 that GTL and it blends can significantly reduce the particle numbers with diameter larger than 154 nm at engine out. According to the study from Li, X et al that the GTL fuel can reduce up to 92% of accumulation mode particle number between 1400 rpm to 2200 rpm speed range. [21] The mode size for accumulation mode particles from 70% and 100% GTL fuel is between 154 nm to 205 nm, while the 30% and 50% GTL fuel had their accumulation peaks around 100 nm. It can be seen from figure 26, the mode size of accumulation mode particles increases with the blending ratio increase and this corresponds to the similar findings in figure 22, which presented the PN distribution of the 1000 rpm, 50% throttle test condition. The GTL and its blends reduced particle numbers in nucleation mode when the throttle was 40% and 50%, however with 60% throttle, the nucleation particle distributions between fuels are similar. Thus, the significant particle number reduction at 154 nm and beyond caused the PN emission reduction from GTL and its blended fuels.

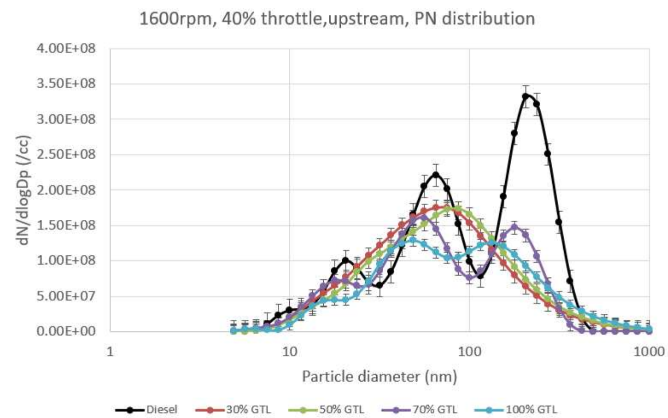

Figure 24. Particle size distribution from engine out at 1600 rpm, 40% throttle.

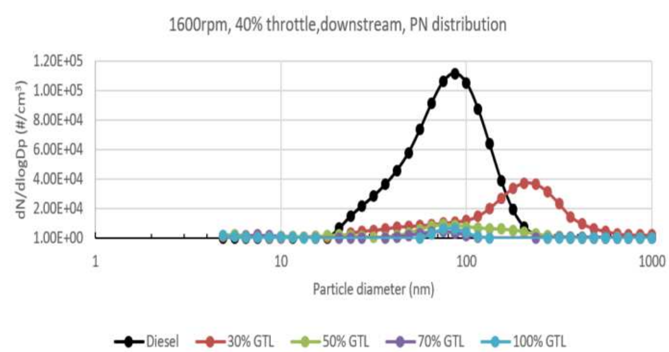

Figure 25. Particle size distribution from DPF out at 1600 rpm, 40% throttle.

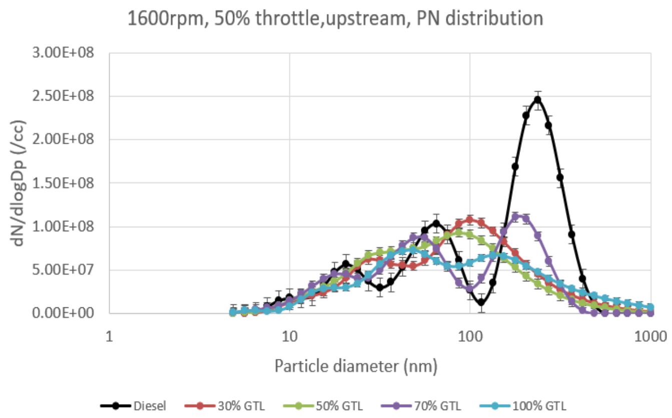

Figure 26. Particle size distribution from engine out at 1600 rpm, 50% throttle.

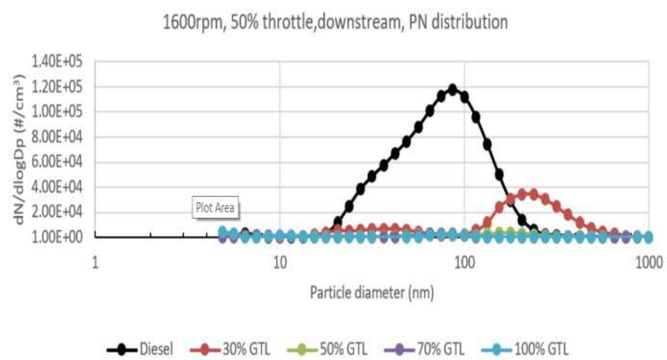

Figure 27. Particle size distribution from DPF out at 1600 rpm, 50% throttle.

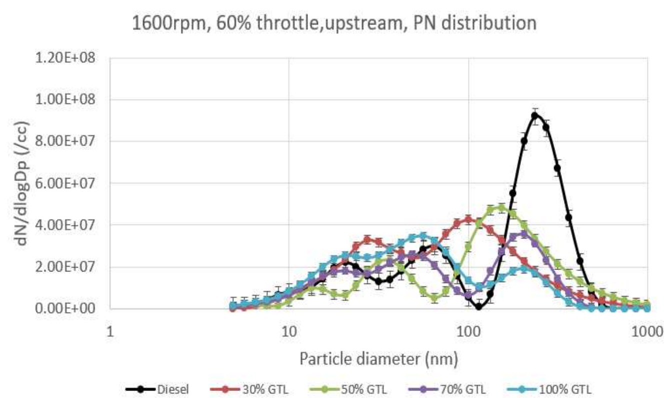

Figure 28. Particle size distribution from engine out at 1600 rpm, 60% throttle.

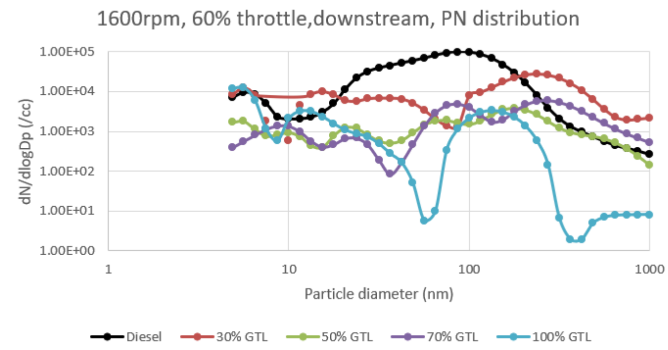

Figure 29. Particle size distribution from DPF out at 1600 rpm, 60% throttle.

From the DPF out results at 1600 rpm, the GTL and blended fuels showed almost undetectable particles, except for the 30% blended GTL fuel, which was observed to have peak values of accumulation mode particles between 205 nm to 240 nm. When looking back the 30% GTL blended fuel performance at engine out, it was found the 30% GTL fuel obtained the highest particle number production in diameter around 100 nm. Therefore, one possible explanation is that those particles with approximately 100 nm diameter generated from 30% GTL fuels were more likely to agglomerate with other Nano-particles during the exhaust gas passed through the engine exhaust aftertreatment system, and finally formed as accumulation particles with peak diameter range from 205 nm to 240 nm.

When the engine rpm increased to 1900, it can be seen from figure 30, figure 32 and figure 34 that the peak values for accumulation particles decreased as the blending ratio increased, and this is most obvious in figure 34 which is the highest engine power test condition. Particles with diameter greater than 154 nm were significantly reduced from all GTL and GTL blended fuel as in previous tests. The 30% and 50% GTL blended fuels still tended to have smaller size than 70% and 100% GTL fuel. The nucleation particle number distribution of blended fuels and pure GTL fuel are close to each other and with most of nucleation particles in diameter region from 10 nm to 31 nm. From the exhaust downstream, similar findings can be observed for 30% GTL.

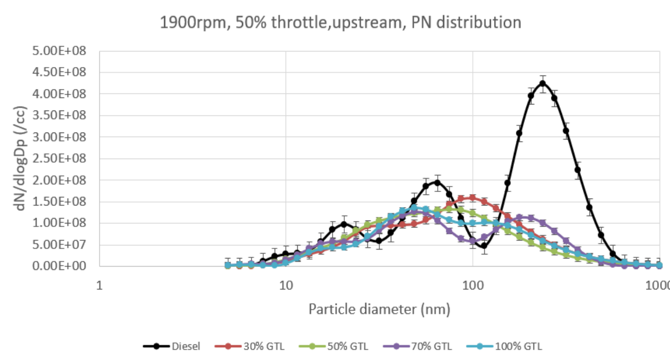

Figure 30. Particle size distribution from engine out at 1900 rpm, 50% throttle.

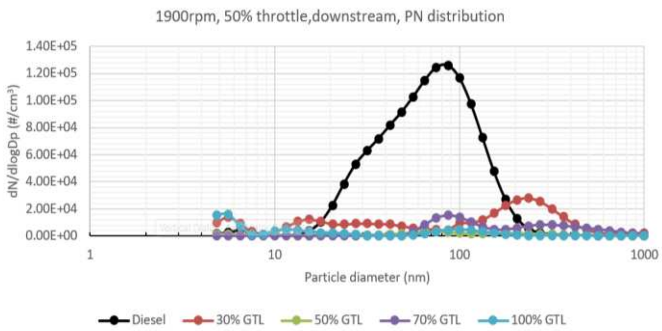

Figure 31. Particle size distribution from DPF out at 1900 rpm, 50% throttle.

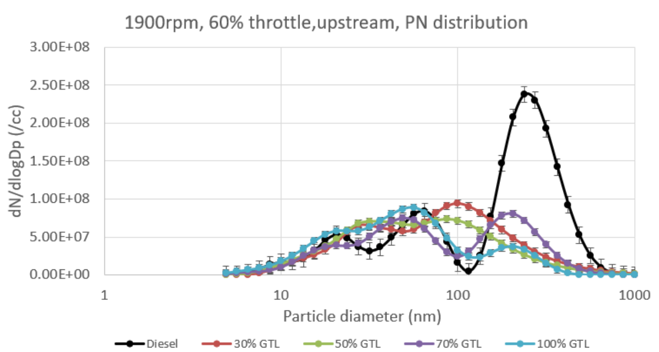

Figure 32. Particle size distribution from engine out at 1900 rpm, 60% throttle.

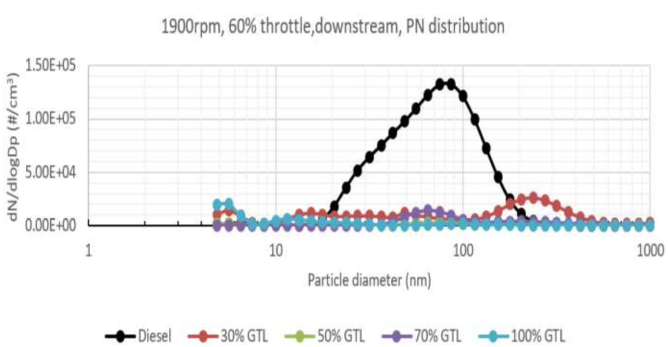

Figure 33. Particle size distribution from DPF out at 1900 rpm, 60% throttle.

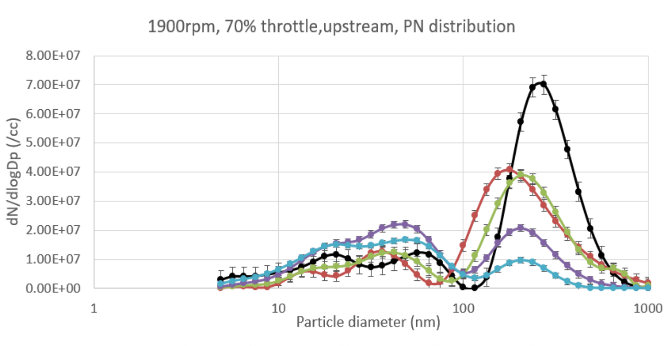

Figure 34. Particle size distribution from engine out at 1900 rpm, 70% throttle.

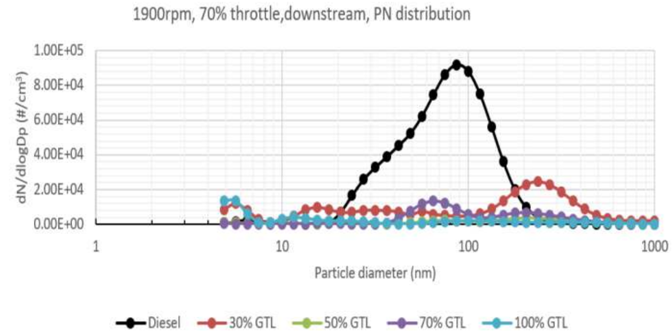

Figure 35. Particle size distribution from DPF out at 1900 rpm, 70% throttle.

In summary, the GTL and its blended fuels can significantly reduce the particle number emissions by producing much fewer accumulation mode particles with diameter greater than 154 nm at engine out. In general, the peak values for accumulation mode particles reduces with the increasing of blending ratio, indicating the more the GTL fuel blended into with diesel, the smaller the accumulation particles produced. The GTL and its blends also reduce the number of nucleation particles. However, when the engine power increased, the nucleation particle number distributions between tested fuels become similar. From the DPF out, particle number emissions are hardly to detectable from GTL and its blends due to the high efficiency of DPF and the DMS 500 detection limitation.

Summary and Conclusions

In this research, diesel fuel, GTL fuel and their blends have been tested under nine selected engine working conditions. From the comparisons in fuel property, combustion performance analysis and particle number emissions, the following conclusions can be acquired:

- The carbon number distribution of pure GTL fuel was C_9 to C_{20}, which was similar to that of pure diesel fuel. However, the GTL fuel has more lighter fractions than diesel, particularly C_{10} and C_{14}. The GTL fuel also has lower density, higher cetane number and slightly higher mass based calorific value when compared to the diesel fuel.
- The ignition delays of tested fuels were reduced when the GTL blend ratio was increased due to the fact that the cetane number was increased.
- The lighter fraction component in diesel fuel can cause in-cylinder pressure to rise suddenly before it causes pressure drop via evaporation and absorbing heat.
- Multiple fuel injections were captured in this research, demonstrating that the engine is utilizing this strategy to acquire constant pressure combustion.
- GTL fuel and its blends had shorter combustion duration than pure diesel fuel. However, this advantage became insignificant when the engine power reached 27 KW and beyond because at higher engine power test conditions,

both diesel and GTL fuels can be burned off quickly despite that the GTL fuel has better combustibility.

- GTL fuel and it blends can significantly improve the engine out PN emission by 27% to 53% , and at least 26% at DPF out. The more the GTL fuel blended into diesel fuel, the more effective the reduction of particle number emissions.

- The DPF in general showed efficiencies higher than 99% in all test conditions and left hardly any detectable particles at the downstream of the DPF. The DPF reached its filtering limitation when the engine power reaches 27 KW, when the diesel fuel combustion would start to generate accumulation mode particles.

- At the engine out, the GTL fuel can reduce nucleation mode particle number emission by up to 65% when engine power setting was low and can reduce accumulation mode particles by up to 75% when the engine power setting was high.

- At the engine out, the accumulation mode particle (ranged from 86nm to 205nm in diameter) distributions were more sensitive to blending ratio than the nucleation mode particle (ranged from 10nm to 20nm). With the increasing of blending ratio, the peak value of accumulation mode particles decreases.

Acknowledgement

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Definitions/Abbreviations

DOC	Diesel oxidation catalyst
DPF	Diesel particle filter
EGR	Exhaust gas recirculation
GC-MS	Gas chromatography-mass spectrometry
GTL	Gas to Liquid
ID	Ignition delay
PM	Particle matter
TGA	Thermogravimetric analysis

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