Comparative study of gas-to-liquid fuel, B5 diesel and their blends with respect to fuel properties, engine performance and exhaust emissions


Gas-to-liquid (GTL) fuel is regarded as a promising alternative diesel fuel. It can be used either directly as a diesel fuel or in blends with petroleum-derived diesel or biodiesel. This study investigated the fuel properties, engine performance and exhaust emissions of B5 diesel, GTL fuel and their blends. The main fuel properties of the blended fuels showed a linear variation with the fraction of GTL fuel in the blend. The density and viscosity of the blends decreased with the addition of GTL fuel, but the flash point, cetane number and calorific value increased. The engine performance test results showed an average increase in power of 1.15–5.18%, but a lower brake-specific fuel consumption (1.11–5.58%) for GTL fuel and its blends compared with B5 diesel alone. The emission analysis results showed that the GTL fuel and its blends had a slight reduction in NOx emissions (2.33–11.3%) and a significant reduction in CO (6.92–21.52%), hydrocarbon (8.62–31.76%) and smoke (12.2–48.88%) emissions compared with B5 diesel. These indicate the potential for the application of B5 diesel–GTL blends.

1 Introduction

There has been much recent interest in the use of alternative liquid fuels for transportation. This interest has resulted from worldwide economic growth, concerns about energy security, volatility in fuel prices and the need for renewable fuels as supplies of fossil fuels decline. Targets to improve air quality and to diversify energy resources have also intensified research into suitable alternative fuels for use in internal combustion engines. Gas-to-liquid (GTL) fuel has been highlighted as a clean alternative fuel.1,2 GTL fuel is synthesized from natural gas and the current worldwide reserves of natural gas are sufficient for sustained production. GTL fuel can be synthesized in a number of ways, including the methane-reforming process, Fischer–Tropsch synthesis and hydrocracking.2 The Fischer–Tropsch synthesis converts a mixture of carbon monoxide and hydrogen into various liquid hydrocarbons using suitable catalysts.4

GTL fuel has a number of beneficial properties, such as a high cetane number (CN), almost zero sulfur, and negligible amounts of aromatic and hetero-atomic species such as sulfur and nitrogen.3 A higher CN leads to improved combustion with lower emissions of CO, hydrocarbons (HCs) and particulate matter.3,6 NOx emissions can also be reduced by increasing the exhaust gas recirculation ratio up to a certain level without a significant penalty in the form of smoke emissions.7 GTL fuel is therefore regarded as a potential alternative fuel with lower exhaust emissions without requiring any major engine modifications or resulting in a significant loss in efficiency.

Several studies have been carried out on the applications of GTL fuel. Oguma et al.4 conducted a comparative study of GTL fuel and diesel in a four-stroke, single-cylinder, naturally aspirated direct-injection diesel engine. They observed a slightly lower brake thermal efficiency (BTE) for GTL fuel than for diesel, but a number of emission parameters, including CO, NOx, HCs and soot, were lower for the GTL fuel than for diesel. Similar research was conducted by Wang et al.8 using a Euro III common rail heavy-duty unmodified diesel engine. The result showed similar values of power, torque and brake-specific fuel consumption (BSFC) for the two fuels, but a significant reduction in NOx, CO and HCs for the GTL fuel. Wu et al.9 investigated GTL fuel and conventional diesel blends in a six-cylinder turbocharged direct-injection compression ignition engine under various load and speed conditions. The results showed improvements not only in the BTE and BSFC, but also a simultaneous reduction in CO, HCs, soot and NOx emissions. Ng et al.10 and Schaberg et al.12 used ultra-low sulfur diesel and EN590 diesel with GTL fuel in diesel-fueled passenger cars and observed a good reduction in exhaust emissions. Moon et al.11 tested GTL–biodiesel blends in a 2.0 L, four-cylinder turbocharged diesel engine under several steady-state engine operating conditions to investigate the emission characteristics. The results showed a reduction in CO and HC emissions, but an...
increase in NO\textsubscript{x} emissions of about 12%. Lapuerta et al.\textsuperscript{13} also investigated the emission characteristics of GTL–biodiesel blends in a four-cylinder, four-stroke, turbocharged, intercooled, direct-injection diesel engine. Lower CO, HC and NO\textsubscript{x} emissions were found for GTL fuel than for diesel, but GTL–biodiesel blends had higher NO\textsubscript{x} emissions than biodiesel alone.

Based on these research works, it can be seen that GTL fuel can be blended with conventional petroleum-derived diesel and biodiesel. As a result of the excellent fuel properties of GTL fuel, the properties of these blends may show significant improvements over the pure petroleum-derived diesel and biodiesel fuels. In the work reported here, we investigated the blending of GTL fuel with commercially available B5 diesel. B5 diesel is a blend of 5% trans-esterified palm biodiesel and 95% fossil fuel diesel and is used for transportation in Malaysia.\textsuperscript{14} Despite several studies on GTL blends with diesel and other fuels, GTL–B5 diesel blends have not yet been investigated with respect to their engine performance and exhaust emission characteristics. The presence of GTL fuel in a blend with B5 diesel may improve fuel properties such as density, viscosity, the calorific value and the CN, perhaps improving the performance and emission features of commercial B5 diesel used in Malaysia. This paper reports a comparative analysis in the context of the fuel properties, engine performance and exhaust emission characteristics of GTL fuel, B5 diesel and their blends.

2 Experimental methods

2.1. Fuel blend preparation and analysis of properties

B5 diesel was mixed with GTL fuel with the aim of improving the fuel properties, engine performance and emission characteristics. The two fuels were mixed to obtain blends containing 20, 30 and 50% GTL fuel by volume in B5 diesel; these mixes were designated G20, G30 and G50, respectively. Neat GTL fuel was designated as G100. Calculated volumes of B5 diesel and GTL fuel were placed in a sealed magnetic stirrer and then in a shaker. Each fuel blend sample was stirred at 4000 rev min\textsuperscript{-1} for 20 min and the stirred blend was then placed in the digital shaker for a further 20 min at 400 rev min\textsuperscript{-1}. The blended sample was removed from the shaker and observed for 12 h to ensure that no phase separation occurred. Details of the apparatus used for the fuel property analysis and the experimental results are shown in Tables 1 and 2, respectively.

2.2. Engine test rig

A single-cylinder, direct-injection, water-cooled diesel engine was used for the experimental investigation. Fig. 1 shows a schematic diagram of the test engine set-up and its association with the control and measurement modules, which were used to analyze the performance and emission characteristics of the test fuel samples. Two fuel tanks were assembled in the test bed. One tank was used for the diesel fuel and the other was used for the test fuels. No special modification was required for the test engine to operate with GTL fuel. Table 3 gives the specifications of the test engine and the experimental conditions. The initial engine run was performed with diesel before starting the tests with B5 diesel, followed by the G100, G20, G30 and G50 blends. The operations were carried out at the same injection timing for all the fuels tested. The engine performance and emission tests were performed at full load and within the speed range 1200–2400 rev min\textsuperscript{-1} at an interval of 200 rev min\textsuperscript{-1}. All the tests were performed under steady-state conditions with adequately warmed exhaust gases and water coolant temperatures. To maintain accuracy, each test point was iterated three times to obtain an average reading. In addition, each test data series (i.e. the test points with identical fuel samples at different engine speeds) were recorded on the same day to minimize day-to-day variations in the experimental results. Although the experimental results were not consistently reproducible from day to day, the trends presented were consistent throughout and are in good agreement with data from the same test performed on a different day. The performance test was controlled by Dynomax-2000 software using a laptop interfaced with the engine test bed.

Table 1 Equipment for fuel property testing

<table>
<thead>
<tr>
<th>Property measured</th>
<th>Equipment</th>
<th>Manufacturer</th>
<th>Standard method</th>
<th>ASTM D6751 limit</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic viscosity</td>
<td>SVM 3000-automatic</td>
<td>Anton Paar, UK</td>
<td>D445</td>
<td>1.9–6.0</td>
<td>±0.35%</td>
</tr>
<tr>
<td>Density</td>
<td>SVM 3000-automatic</td>
<td>Anton Paar, UK</td>
<td>Not specified</td>
<td>±0.1 kg m\textsuperscript{-3}</td>
<td></td>
</tr>
<tr>
<td>Flash point</td>
<td>Pensky–Martens flash point, automatic</td>
<td>Normalab, France</td>
<td>D93</td>
<td>130 min</td>
<td>±0.1 °C</td>
</tr>
<tr>
<td>Calorific value</td>
<td>C2000 basic calorimeter, automatic</td>
<td>IKA, UK</td>
<td>D240</td>
<td>Not specified</td>
<td>±0.1% of reading</td>
</tr>
</tbody>
</table>

Table 2 Fuel properties tested

<table>
<thead>
<tr>
<th>Property</th>
<th>Diesel</th>
<th>GTL fuel</th>
<th>G20 blend</th>
<th>G30 blend</th>
<th>G50 blend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density@40 °C (g cm\textsuperscript{-3})</td>
<td>0.8328</td>
<td>0.7619</td>
<td>0.8178</td>
<td>0.8056</td>
<td>0.7922</td>
</tr>
<tr>
<td>Kinematic viscosity@40 °C (mm\textsuperscript{2} s\textsuperscript{-1})</td>
<td>3.4626</td>
<td>2.7417</td>
<td>3.2761</td>
<td>3.2462</td>
<td>3.1253</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>77.5</td>
<td>103.5</td>
<td>83.5</td>
<td>85.5</td>
<td>88.5</td>
</tr>
<tr>
<td>Calorific value (MJ kg\textsuperscript{-1})</td>
<td>44.664</td>
<td>46.785</td>
<td>45.026</td>
<td>45.152</td>
<td>45.834</td>
</tr>
<tr>
<td>Cetane no.</td>
<td>55</td>
<td>75</td>
<td>65</td>
<td>68</td>
<td>70</td>
</tr>
</tbody>
</table>
An AVL DICOM 4000 gas analyzer was used to measure the concentration of CO, HC and NOₓ in exhaust emissions. The opacity for smoke measurements was measured using an AVL DiSmoke 4000 analyzer. All emissions were measured during steady-state operation of the engine. Table 4 gives the measurement range resolution and accuracy of both instruments.

### 3 Results and discussion

#### 3.1 Fuel property analysis

Fuel property analysis was carried out as a part of the investigation to predict the quality of several fuel blends before the engine test. The blended fuels showed improved fuel properties with the addition of GTL fuel to the blend. B5 diesel has a higher viscosity and density than fossil fuel diesel. GTL fuel had about 20.8% lower kinematic viscosity than B5 diesel and a density about 8.5% lower. A high density of any fuel yields a higher viscosity, which has a significant influence on the efficiency of spray atomization, resulting in poorer combustion with higher exhaust emissions. Hence the blends of B5 diesel and GTL fuel had both a lower density and a lower kinematic viscosity, which may have advantages for fuel spray atomization. GTL fuel, with a high paraffinic content, has a much higher CN than other compression ignition engine fuels, which offers the benefits of a better combustion performance. B5–GTL blends also showed a higher CN than B5 diesel alone and this corresponded to the ratio of the volume of GTL fuel in the blends. About 98 vol% of GTL fuel consists of paraffins and 2% of olefins, with a hydrocarbon range from C₈ to C₂₄. Previous studies have shown that the contents of n-paraffin iso-paraffin and aromatic molecules in high CN GTL fuel are approximately in the range 82–84 wt%, 16–18 wt% and 0.1–0.3 vol%, respectively. Highly paraffinic GTL fuels may have poor cold-flow properties, which may be of concern in countries with severe winter conditions. Some studies have reported higher CP and cold filter plugging point values in GTL fuel than in diesel and biodiesel. Other studies have shown that the cold-flow properties of GTL fuel were improved when it was blended with diesel and biodiesel. Several cold-flow improver additives (polymers containing an α-olefin, a vinyl ester and an ester of an α,β-unsaturated carboxylic acid in copolymerized form) have been proposed and further research in this field (e.g. fraction replacement) is being conducted by several research...
institutes and GTL producers. GTL fuel has a flash point about 22°C higher than B5 diesel and this also affects the flash point of the blends, which showed a linear relation with the increase in the percentage of GTL fuel in the blends. A higher flash point means that the fuel is safer to handle and store and prevents unexpected ignition during combustion. GTL fuel showed about a 4.75% higher calorific value than B5 diesel. Blends of GTL–B5 diesel showed a higher calorific value as the GTL fuel fraction in the blends increased. This is regarded as an improvement because a higher calorific value of any fuel is desirable because it favors the release of heat during combustion and improves the engine performance.

3.2. Engine performance test

3.2.1. Engine power output. Fig. 2 compares the power outputs of the test engine fueled with B5, GTL fuel and their blends. For all the tested fuels, the power output increased slightly as the speed increased. Although the engine was unmodified, the GTL fuel and the blends showed slightly improved power outputs than B5 diesel alone. The maximum power was achieved by all the tested fuels at 2200 rev min⁻¹. On average, G100 showed about 5.48% higher power than B5 diesel. G20, G30 and G50 had average power outputs about 2.27 and 3.81% higher than diesel, respectively. It is obvious that the addition of GTL fuel to the blends boosted the power output of the blended fuels. As B5 diesel itself is a blend of biodiesel and fossil fuel diesel, the viscosity of B5 diesel is higher than diesel. In contrast, the inherent lower density and viscosity of GTL fuel lowered the viscosity of the blends. The improvement in the density and viscosity of the blends improved the atomization process during combustion, yielding improved combustion, and is also reflected in the slight improvement in power output.¹⁸ The higher calorific value of GTL fuel also boosted the power output when using G100, G20, G30 and G50 blends.

3.2.2. Brake-specific fuel consumption and brake-specific energy consumption. Fig. 3 shows the effect of GTL–B5 diesel blends on the BSFC with variations in engine speed. The BSFC of a compression ignition engine depends on the volumetric fuel injection system and fuel properties such as the density, viscosity and calorific value. In this experiment, the BSFC was calculated from the fuel flow-rate generated from the digital fuel flow meter, output power and the density of the fuel samples. It was observed that all of the blended fuels improved the BSFC compared with B5 diesel. At 2200 rev min⁻¹, all the fuels had their lowest BSFC. On average, G100 showed about a 5.58% lower BSFC than B5 diesel. G20, G30 and G50 had average BSFC values about 1.11, 2.21 and 3.95% lower than diesel, respectively. This improvement in BSFC for GTL fuel and its blends can be explained in terms of common combustion phenomena and fuel properties. As the fuels were delivered to the test engine on a fixed volumetric basis, the amount of fuel injected in a single stroke was the same for all the fuels tested. Hence the fuels such as GTL fuel and its blends, which have higher calorific values, required a comparatively small amount of fuel per stroke to produce the same power as the B5 diesel alone.⁷,²³ The combustion performance of GTL fuel and its blends demonstrated that lower in-cylinder pressures and a lower rate of pressure increase help to compensate for the mechanical losses and lead towards better combustion.²⁴

Table 4  Specification of exhaust gas analyzer

<table>
<thead>
<tr>
<th>Method</th>
<th>Measured component</th>
<th>Range</th>
<th>Resolution</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVL DICOM 4000 5-gas analyzer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-dispersive infrared</td>
<td>CO</td>
<td>0.10 vol%</td>
<td>0.01 vol%</td>
<td>±0.2</td>
</tr>
<tr>
<td>Non-dispersive infrared</td>
<td>Unburned HC</td>
<td>0–20 000 ppm vol.</td>
<td>1 ppm</td>
<td>±0.5</td>
</tr>
<tr>
<td>Electrochemical</td>
<td>NOₓ</td>
<td>0–5000 ppm vol.</td>
<td>1 ppm</td>
<td>±0.4</td>
</tr>
<tr>
<td>Smoke opacimeter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photodiode detector</td>
<td>Opacity (%)</td>
<td>0–100%</td>
<td>0.10%</td>
<td>±0.1</td>
</tr>
</tbody>
</table>

Fig. 2  Variation in power output with engine speed at full load for the tested fuels.

Fig. 3  Variation in BSFC with engine speed at full load for all tested fuels.

44532 | RSC Adv., 2014, 4, 44529–44536

This journal is © The Royal Society of Chemistry 2014
Another performance parameter is the brake-specific energy consumption (BSEC). The BSEC is used to compare the performance of fuels with different calorific values. The BSEC can be defined as the product of the BSFC and the calorific value of the fuel. It indicates the amount of energy consumed to produce a unit output of power in one hour. In general, the value of the BSEC decreases in line with an increase in energy consumption efficiency. Fig. 4 shows the effect on the BSEC of GTL–B5 diesel blends with variations in engine speed. As with the BSFC, B5 diesel had a higher BSEC value than the other test fuels. All the fuels had their lowest BSFC at 2200 rev min⁻¹. On average, the G100 blend showed about a 2.35% lower BSEC value than B5 diesel. G20, G30 and G50 had lower average BSEC values than diesel of about 1.01, 1.27 and 1.81%, respectively.

3.2.3. Brake thermal efficiency. Engine BTE is regarded as a significant performance parameter and can be measured by the product of the mechanical efficiency and the net indicated thermal efficiency. As a result of the effect of various loss mechanisms, such as combustion inefficiency, heat transfer and mechanical friction, the BTE of a real operating diesel cycle is usually <50% and often far less than this value.¹³ In this study, the BTE was calculated by eqn (1), where \( \eta_{\text{bt}} \) is the BTE (%), \( f_c \) is the BSFC (g kW⁻¹ h⁻¹) and \( H_v \) is the heating value of the fuel (MJ kg⁻¹).

\[
\eta_{\text{bt}} = \left( \frac{3.6 \times 10^3}{f_c \times H_v} \right) \times 100\%
\]  

Fig. 5 shows the relationship between BTE and speed for the GTL fuel, B5 diesel and blended fuels. As expected, all the tested fuels showed a higher BTE under medium speed conditions compared with operation at lower speeds. A simple reason behind this trend is that a lower fuel consumption, on a relative basis, is required to overcome the mechanical losses associated with the engine at medium to higher speeds than at lower speeds. An in-depth analysis of the reverse trends observed at low and at medium speed engine conditions showed two competing effects. At the top dead center, a higher level of spontaneous premixing occurs, which induces a faster rate of combustion.²⁴ This yields a reduction in compression work while increasing the expansion work, resulting in a superior BTE for GTL fuel compared with B5 diesel.

There is no significant difference between the BTE of all the fuels. The BTE was marginally higher for the GTL fuel than for the other fuels. This trend is also supported by previous studies.¹⁰,²³ All the fuels had a maximum BTE at 2200 rev min⁻¹. On average, G100 showed about a 1.76% higher BTE than B5 diesel. G20, G30 and G50 had higher average BTE values than diesel of about 0.45, 0.98 and 1.32%, respectively.

In the context of energy saving and efficient energy use, this improved BTE of the synthetic fuels is a significant advantage. In addition, the higher BTE is beneficial to the automobile manufacturer as an improved BTE widens the range of opportunities to comply with strict pollutant regulations and after-treatment system requirements by modification of the injection parameters.

3.3. Exhaust emission tests

3.3.1. CO emission. The formation of a rich combustion mixture as a result of a lower air-fuel proportion is the main reason for the emission of CO. Flame quenching inside the over-lean region and in the wall impingement quenching region also favors the formation of CO. A higher CO content in emission gases is an indicator of incomplete combustion. The presence of more stable aromatic hydrocarbons is responsible for the formation of more CO as a result of the excess amount of total HCs.

Fig. 6 shows the variations in the CO emissions for B5 diesel, GTL fuel and their blends at various engine speed ratings. All of the tested fuels had higher emissions at lower speeds than at
higher speeds. On average, GTL fuel had the most reduced CO emissions of about 21.52% compared with B5 diesel. The GTL–B5 diesel blends also showed a reduction in CO emissions. On average, the G20, G30 and G50 blends showed reductions of 6.92, 8.99 and 12.62%, respectively, compared with B5 diesel. It is obvious that the presence of GTL fuel in the blends caused a reduction in CO emissions. This can be explained by the fuel properties and combustion phenomena. One of the prime reasons behind the formation of CO is the rich combustion due to low air–fuel ratios. Flame quenching in the over-lean zone and in the wall impingement quenching zone are also responsible for CO emissions. GTL fuel has a good thermal efficiency, which increases the air–fuel ratio. Certain characteristics of GTL fuel, such as a higher H/C ratio, a higher CN and a very low aromatic content also improve combustion, which favors the reduction of CO emissions. The higher CN of GTL fuel shortens the ignition delay that prevents fewer over-lean zones. The lower distillation temperature of the GTL fuel induces rapid vaporization, which reduces the probability of flame quenching and ensures lower CO emissions.

3.3.2. HC emissions. Fig. 7 shows the variations in HC emissions for B5 diesel, GTL and their blends at various engine speeds. All of the fuels produce low HC emissions with increases in speed. GTL fuel and its blends showed significantly lower emissions than B5 diesel alone. On average, G100 has 31.76% less HC emissions than B5 diesel. G20, G30 and G50 showed an average reduction of 8.62, 10.91 and 16.81%, respectively, compared with B5 diesel. The main reasons for the formation of HC emissions in combustion ignition engines are an over-lean fuel mixture (too high an air–fuel ratio) throughout the ignition delay period, improper mixing of fuel adjacent to the spray core at the time of combustion and, in particular, wall quenching of the flame due to the impingement of fuel spray on the peripheral areas of the combustion chamber. As for the CO emissions, the reduction in HC emissions can be explained in terms of the fuel properties and combustion phenomena of the GTL fuel. The higher CN of the GTL fuel shortens the ignition delay, which prevents the formation of over-lean regions. The lower distillation temperature of the GTL fuel ensures a correct pace for evaporation and mixing with air to produce a more effective combustible charge, which results in less unburned HCs in the exhaust emissions.

3.3.3. NOx emissions. NOx formation in combustion ignition engines can be described in the context of the Zeldovich mechanism. During combustion, the higher temperatures disengage the molecular bonds of nitrogen, which then takes part in a series of reactions with oxygen, resulting in thermal NOx. NOx formation in the flame front and in the post-flame gases depends on the oxygen content, the in-cylinder temperature and the residence time.

Fig. 8 shows a relation between NOx emissions and engine speed for B5 diesel, GTL fuel and the blends at a full engine load with variations in speed. Overall, NOx emissions are fairly high in the low to mid-speed range, but decrease at higher speeds. This trend can be explained by the longer time required for combustion when the engine speed decreases. On average, G100 showed about an 11.3% reduction in NOx emissions compared with the B5 diesel. The addition of GTL fuel to the blends contributes to a greater reduction in NOx emissions than for the reference B5 diesel fuel throughout the test speed range. G20, G30 and G50 showed an average reduction of 2.33, 4.095 and 4.85%, respectively, when compared with B5 diesel.

The reasons behind the decrease in NOx emissions can be explained by the influence of the fuel properties on combustion and exhaust emissions. The higher CN of the GTL fuel induces a shorter ignition delay, followed by a lower pre-mixed charge, which results in lower combustion temperatures and pressures. It leads to the formation of less NOx by the temperature-dependent thermal NOx formation mechanism in the cylinder. The significantly lower aromatic content of the GTL fuel maintains a lower local adiabatic flame temperature, which also assists in the reduction in NOx emissions.

3.3.4. Smoke emissions. Smoke is an undesirable by-product of combustion in compression ignition engines and is primarily produced through the incomplete combustion of the hydrocarbon fuel. Smoke from the engine exhaust tailpipe is usually in the form of dark black smoke. Soot formation in exhaust gases can be identified by the “smoke opacity” term which can also be used to forecast the tendency to form soot during the combustion of any test fuel. The composition of the smoke is governed by the type of fuel and the operating conditions of the engine. We measured the variation in smoke opacity for all test fuels. Fig. 9 shows the smoke opacity values of...
the B5 diesel, GTL fuel and blended fuels with respect to the engine speed. The GTL blended fuels showed a similar trend, but lower values, than the baseline diesel fuel throughout the speed range. Compared with diesel, an average reduction in smoke emission was observed for the G100, G50, G30 and G20 fuels of about 48.88, 29.51, 17.08 and 12.20%, respectively. This reduction in smoke emission, which is in agreement with that reported previously,\textsuperscript{13,24} can be explained by the combined effect of the absence of aromatic compounds (regarded as soot predecessors), a low sulfur content and a higher hydrogen to carbon ratio of the GTL fuel.

4 Uncertainty analysis

Uncertainty analysis was used to validate the accuracy of the experimental results. The percentage uncertainty of measured emission quantities, such as CO, HC, NO\textsubscript{x} and smoke, were calculated using the percentage uncertainties of the various instruments used in the experiments. It was observed that the experimental emission results of all the sample fuels were within the accepted range. Table 5 illustrates a sample calculation of uncertainty analysis for the NO\textsubscript{x} emissions of B5-diesel.

5 Conclusion

In this study, GTL fuel and B5 diesel were investigated in terms of fuel properties, engine performance and exhaust emissions. The influence of GTL fuel in the three blends of B5 diesel was also analyzed on the basis of these parameters. The outcome of the investigation can be summarized as follows:

- GTL fuel has superior fuel properties to B5 diesel. The fuel properties of the GTL–B5 diesel blends showed a linear variation with the fraction of GTL in the blends and showed an improvement in fuel properties compared with B5 diesel. These properties had a significant influence on the engine performance and emission tests.
- GTL fuel can be used in unmodified diesel engines. The result of the engine test with the G100 blend showed engine performance and exhaust emission characteristics better than those obtained with B5 diesel.
- In the engine performance test, all the examined parameters showed an improvement for the G100 blend compared with B5 diesel. On average, the G100 blend showed an improvement in power, the BTE, the BSFC and the BSEC of about 5.48, 1.76, 5.58 and 2.33%, respectively, compared with B5 diesel.
- Exhaust emission experiments showed an overall significant reduction for the G100 blend compared with B5 diesel. On average, G100 showed a reduction in CO, HC, NO\textsubscript{x} and smoke emissions of approximately 21.52, 31.76, 11.3 and 48.88%, respectively, compared with B5 diesel.
- All the performance and exhaust emission parameters showed improvements with an increased quantity of GTL fuel in the GTL–B5 diesel blends. On average, the blends showed an increased power (1.72–3.42%) and BTE (1.68–3.5%), but a decreased BSFC (5.96–8.95%) and BSEC (5.2–6.54%) compared with B5 diesel.
- In the emission test, the GTL–B5 diesel blends had lower emissions, such as CO (6.92–12.62%), HC (8.62–16.81%), NO\textsubscript{x} (2.33–4.85%) and smoke (12.2–29.51%) compared with B5 diesel.
- Of all the blends, G50 showed noticeably improved performances and emissions compared with G30 and G20.

An in-depth analysis of the outcomes of this investigation has increased the possibility of commercial applications for the

Table 5 Uncertainty analysis of the experimental data (sample calculation)

<table>
<thead>
<tr>
<th>Speed (rev min\textsuperscript{-1})</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Maximum/minimum value</th>
<th>Analyser accuracy +1 ppm</th>
<th>Average ppm</th>
<th>Uncertainty level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>548</td>
<td>550</td>
<td>551</td>
<td>551</td>
<td>548</td>
<td>549.5</td>
<td>0.45</td>
</tr>
<tr>
<td>1400</td>
<td>520</td>
<td>521</td>
<td>522</td>
<td>522</td>
<td>520</td>
<td>521</td>
<td>0.38</td>
</tr>
<tr>
<td>1600</td>
<td>501</td>
<td>501</td>
<td>503</td>
<td>503</td>
<td>501</td>
<td>502</td>
<td>0.4</td>
</tr>
<tr>
<td>1800</td>
<td>434</td>
<td>435</td>
<td>436</td>
<td>436</td>
<td>434</td>
<td>435</td>
<td>0.46</td>
</tr>
<tr>
<td>2000</td>
<td>412</td>
<td>412</td>
<td>410</td>
<td>412</td>
<td>410</td>
<td>411</td>
<td>0.49</td>
</tr>
<tr>
<td>2200</td>
<td>394</td>
<td>394</td>
<td>392</td>
<td>394</td>
<td>392</td>
<td>393</td>
<td>0.51</td>
</tr>
<tr>
<td>2400</td>
<td>362</td>
<td>362</td>
<td>360</td>
<td>362</td>
<td>360</td>
<td>361</td>
<td>0.55</td>
</tr>
<tr>
<td>Overall uncertainty level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.46 (%)</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9 Variation in smoke opacity with engine speed at full load for all the tested fuels.
GTL–B5 diesel blends. These fuel blends may meet future strict emission regulations and also provide the better engine performance required by automobile manufacturers.

Acknowledgements

The authors would like to appreciate University of Malaya for financial support through High Impact Research grant titled: “Clean Diesel Technology for Military and Civilian Transport Vehicles” having grant number UM.C/HIR/MOHE/ENG/07 and also a research grant with grant number RP016-2012E.

References