Measurements of Laminar Flame Speeds of Alternative Liquid Fuel Blends

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1 Introduction

In the past 20 years, there has been a great deal of research and efforts that have been done to minimize the environmental damages due to global warming. Human activities like excessive use of fossil fuels can promote global warming and accelerate the climate change in a destructive way and there is a need to control it [1]. In addition, the tough legislations in the European Union and the USA, in particular, to reduce emissions have forced many industries to look into alternative fuels with less emission production. One such alternative fuel that has gained much interest recently is the Gas-To-Liquid (GTL) fuel. Currently, Qatar is the largest producer and exporter of GTL products, with a production rate of 175,000 barrels per day of GTL-diesel fuel [2]. The GTL fuels have not replaced yet the conventional fuels fully but they are in use in blended forms in a number of combustion applications, mainly internal combustion engines (ICEs). This instils a responsibility on the researchers to find out the optimum conditions and characteristics of GTL blended fuels, and to examine their suitability for using in ICEs.

A recent detailed review paper [3] conducts a detailed analysis of GTL fuel blends with conventional diesel by studying the fuel characteristics, combustion behaviour, and its effect on engine performance and emissions. The paper concludes by reviewing various studies of GTL fuel blends that the GTL fuel can be safely regarded as a cleaner fuel with much reduced emissions and greenhouse gases. Moreover, the same work established that the power of a diesel engine increases about 1% to 5% when used with GTL, which was related to the higher calorific value of GTL compared with diesel fuel [3]. It is obvious that GTL fuel and its blends can provide a solution for the high emissions level of diesel engines. However, detailed combustion characteristic investigations are required before using this new alternative fuel widely in engines.

Laminar Flame Speed, S_N, is a very important fundamental characteristic of any fuel that can give information about the atomization, reactivity, diffusivity, and exothermicity. In addition, investigating S_N of this new fuel is critical in predicting the performance of fuel in gas turbines and ICEs. S_N depends on many parameters including the fuel composition. There have been many experimental techniques developed for the measurements of S_N of fuel-air mixtures. Andrews and Bradly, has done a critical review about the

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effectiveness and shortcomings of many of these experimental techniques [4]. They have divided these methods into two types; constant pressure and constant volume test rigs. This classification is based on the ability of the test rig to accommodate various ranges of initial pressures and temperatures. The constant pressure methods are conducted mostly at the atmospheric pressure and constant temperature. On the other hand, the constant volume methods, commonly known as combustion bombs, can be used at a variety of initial temperatures and initial pressures [5]. In this work, a cylindrical combustion bomb is utilized for the measurements of GTL fuel blends at various equivalence ratios and initial temperatures.

Bradley and Mitcheson [6] have established a universal equation can be used to find the flame speed in relation to pressure increase (dP/dt). This equation is given as:

$$dP/dt=(3S_L \rho_u)/(R_S \rho_i)\,(P_e-P_i)\,[1-(P_i/P)^{(1/\gamma_u)}\,\{(P_e-P)/P_e-P_i\}]^{(2/3)} \qquad (1)$$

Here, ρu is the density unburnt mixture

γu is the specific heat ratio of unburned mixture

P is the pressure at the time of combustion

Pe is the equilibrium pressure

Pi is the initial pressure

This equation and several other numerical models employing pressure data for the calculation of laminar flame speeds have been used in many investigations such as those of [7-10]. In the present work, the laminar flame speed is calculated from the pressure raise versus time record as proposed by Lewis and Von Elbe [11], as shown in Table 1. These set of equations have been used successfully to calculate S_N of Jojoba Methyl Ester (JME) biofuel from pressure data measured inside the combustion bomb [12].

The majority of previous investigations have focused of measuring S_N of a single fuel-air mixture and few works have considered fuel blends. A research work had been done by Huzayyin et. Al [13], for the measurement of laminar flame speed of LPG-air and Propane-Air mixtures using a combustion bomb. They used a cylindrical combustion bomb made up of thick steel that can hold and internal pressure of up to 90 MPa. The end covers of the cylinder has a 30mm diameter quartz glass window as a viewing port. At the time of combustion, a pressure transducer is used to measure the pressure versus time signal and this data is used to calculate the flame speed of the mixture.

Another work conducted using a similar test rig is by Bradley et. Al [14], where they used a spherical steel bomb with 150 mm diameter glass windows for measuring the laminar flame characteristics of ethanol and air mixtures. This test rig has also been used previously for the measurement of S_N of iso-octane blends by [15]. This experiment was conducted by heating the bomb to 395 K by a 6000 Watts electric heater. There were four electric motor fans installed directly to the bomb for proper mixing of the mixture. In addition, the fans can facilitate the mixture in evaporating completely because this will increase the heat transfer from the coils. A syringe and needle valve is used to inject the fuel inside the bomb. The mixture was ignited by using automotive ignition coil spark system. The pressure map was recorded using a pressure transducer and flame images were taken by schlieren cine photography. The flame radius obtained from high speed imaging were plotted against time to get the flame speed. The measured SN by both devices were in excellent agreement, which proves the accuracy of using the pressure data in getting S_N of any fuel-air mixture.

When two or more fuels are blended together, the combustion characteristics of the blended fuel are expected to be different from those of each fuel due to change of the blended fuel compositions. A recent work has been done by Ibrahim and Ahmed [16] utilizing the test rig of [17] concluded that the laminar flame speeds of the blended mixtures of LPG and methane with air are higher than their individual flame speeds at same test conditions. This finding was attributed to the change in the production and consumption rate of the molar fraction of H, O, OH and CH3 radicals in the reaction zone due to the high flame temperatures when adding LPG. Similar observations have been found when the SN of blended palm methyl esters (PME) and diesel fuels have been measured [18]. It has been reported that there is a decrease in SN in the lean side and increase on the rich side of the blended fuel-air mixture compared with those of diesel fuel. This also was explained by the lower flame temperatures of the PME blends, as they can somehow offset by the higher reactivity of the oxygen containing mixtures [18].

It is clear from above that it is necessary to understand the combustion characteristics, especially S_N, of blended fuels before using them in existing engines. Therefore, there is a need to investigate S_N of GTL fuel blended with conventional diesel as a promised alternative fuel for diesel engines. Laminar flame speeds of GTL fuel blends have not been investigated thoroughly yet and there is a considerable lack of information in this area. The present work aims to measure the laminar flame speeds of GTL-diesel fuel blends over a wide range of equivalence ratios and initial temperatures using a specially designed state of the art cylindrical combustion.

2 Experimental Methods

Figure 1 shows the schematic diagram of the cylindrical combustion bomb test rig with the measuring devices. The test rig consists of a steel shell of 400 mm internal diameter, 5mm thickness and a length of 650 mm. It has four internal temperature controlled heating coils with 2.1 kW each, which is capable of reaching a maximum temperature 450°C in less than 40 minutes. The bomb is equipped with three orthogonal quartz glass windows each one with 150 mm diamter, three ports, PCB Piezotronics pressure transducer, lambda (O_2) sensor and thermocouples. The lambda (O_2) sensor is IMR (Model IMR 1000) capable of measuring O2 percentage (0-21%) with an accuracy of +/- 0.2%. The pressure transducer has a range of 7 bar and an operating temperature up to 343°C. The output pressure response from this sensor is 10 pC/psi, which is then converted by an In-Line Charge Converter (Model 422E35), also from PCB Piezotronics. The inline charge amplifier converts the signal with a gain of 0.99 mV/pC. Therefore, the final calibration factor used for converting the transducer signal to pressure was 6.238 mV/psi.

The bomb is also equipped with four custom made fans mounted at 90° angle from each other. The blades of the fan were bent at 60° angle to ensure proper mixing of the air-fuel mixture, due to high flow velocity from the fans, and adequate turbulence intensities if used for turbulent flame speed measurements in the future. For the fan shaft sealing, a novel design was introduced using graphite packing surrounding the fan-motor shaft to ensure that there is no air leakage from the shaft area of the fans.

The spark ignition system used to ignite the mixture consists of a new automotive ignition coil and a capacitive circuit that used AC mains and operated by a 500W dimmer switch. The spark ignition system also includes high-tension cables, 440V and 3.5µF capacitor, and stainless steel electrodes with a gap of 3mm, which is kept constant throughout all experiments. This ignition system produces continuous sparks with about 20 kV voltage and 200 mA current, which were enough to ignite the flammable mixture at any conditions under investigation.

An air supply system and a vacuum system are connected to the bomb. The vacuum system uses a Leybold Trivac Rotary Vacuum Pump D8A w/ Marathon Electric Motor 3/4HP, 1725RPM. The pressure transducer is connected to a GW-Instek digital storage oscilloscope with 150 MHz sampling rate and data acquisition system. The air compressor is used to clean the bomb from any residual gases after the experiments, while the vacuum pump is used to evacuate the bomb before and after experiment. In addition, the air-fuel supply line is wrapped with electric heating wires to ensure that no fuel condensation takes place during injection.

The four internal electric heaters are used to maintain the temperature inside the bomb at the desired values, which are monitored by a K-type thermocouple. This thermocouple is located in the middle of the bomb, as shown in Fig. 1, as close as possible from the spark location. Finally, for visualization proposes of ignition and flame propagation, a high-sensitivity high-resolution Canon digital camera with videography resolution 1920 x 1080 pixel and 30 fps shutter speed has been used. The basic properties of fuels tested in this project are shown in Table 2.

3 Results and Discussion

A. Flame visualization experiment

Although this research relies on the pressure signal for flame speed measurements, the developed test rig has three quarts windows to allow for high-speed flame imaging for the measurements and visualizations of the flame propagation. A direct visualization of the ignition and subsequent flame propagation of the stoichiometric GTL fuel-air mixture inside the bomb was conducted. Fig. 2 shows sequence of photos for the spark ignition and the flame spreading of GTL fuel ignited at an initial temperature of 180°C. The time difference between each of these photos is 33 ms. The first four images show, after the spark, a blue-coloured flame spreading evenly towards the surface of the chamber. It takes about 99 ms for the flame front to pass the optical window (image no. 3). From image no. 5, it can be observed that when the flame reaches the cylinder walls, the residual fuel droplets are burnt, which appears in image sequence number 7 and 8. This flame visualization verifies that the desired conditions for proper mixing and spreading of flame have been met inside the bomb. This also verifies that the flame is spreading evenly from the centre of the bomb towards the walls.

B. Flame speed-measuring technique

Three categories of results were obtained; i.e. test runs using 100% conventional diesel fuel, 100% GTL-diesel fuel, and a 50%-50% blend for conventional diesel and GTL-diesel by volume. These measurements have been done at ambient initial pressure, 190°C initial temperature and a wide range of equivalence ratios. In addition, measuring the flame speeds of the above fuels at different initial temperatures have considered as well. The first set of results for conventional diesel was used and compared with literature to validate the accuracy of the experimental procedure. The initial temperature of the test rig was kept at 190°C. The amount of fuel injected in the test rig was approximately 6.5mL, to aim at getting an equivalence ratio equals 1.0. The voltage (mV) signal captured by the oscilloscope is saved in the CSV format. The pressure is calculated by converting the signal (mV) from the oscilloscope into pressure using the calibration data of the pressure sensor. Using this calibration factor, the CSV data file obtained from pressure sensor for the full range of signal is converted into pressure. Note that the original voltage signal was slightly noisy. Therefore, the curve is made smooth by applying signal conditioning techniques like; normalization and upper envelope extraction, as shown in Fig. 3. Similar plots of pressure raise signals with time are used to obtain the peak pressure in every case under investigations, which in this case, Fig. 3, is about 3.35 bar. Then, the pressure data are used in the equations of Table 1 to obtain the laminar flame speed at different equivalence ratios at which the ignition took place.

The mixture strength measured by the lambda sensor is then recorded. It has been observed that the reading of the oxygen percentage after injecting the fuel is about 19.8% O_2. This means that total volume of air in bomb is shared with some volume of fuel evaporated inside the bomb after injection. Moreover, we cannot rely completely on the volume of fuel injected for equivalence ratio calculation (6.5mL in this case), as not all the injected fuel is evaporated due to the fact that some fuel is trapped in the fuel injection lines or near the crevices of the bomb. Therefore, the actual mass of air and fuel has to be calculated based on lambda sensor reading, which gave an equivalence ratio of 1.0. This shows that the mixture is at stoichiometric conditions. An MS Excel calculator is developed which can be used to find out the equivalence ratios for different initial conditions in each experimental trial.

The pressure data obtained from the pressure sensor is used for flame speed calculation. As mentioned earlier, S_N is calculated from the pressure versus time record as proposed by [11], as shown in Table 1. The values for the parameters mentioned in the model were taken by direct measurements from the instruments installed on the bomb. An MS Excel calculator was developed which uses the initial conditions as well as final conditions of the test which were specific for each test run. The laminar flame speed is then obtained as a result of the test runs with conventional diesel fuel, where plotted against the equivalence ratio of the mixture. The present results were compared with Ref. [18] as they have used the diesel fuel of same properties as the one used in this project. The values from, the previous research and current work, for S_N were plotted against a range of equivalence ratios, as shown in Fig4.

It can be observed from Fig. 4 that the trend of S_N follows the standard as S_N increases from equivalence ratio of 0.7 and peaks at 1.1. Then, S_N starts to decrease gradually towards the rich side. It can be noted form the figure that the values of flame speed of [18] are slightly higher than the values obtained in the present work. This could be because of two reasons. First, the testing environment are not exactly the same in both cases. The present test rig can be different in the many forms like; volume of bomb, number of crevices, actual temperature of air inside the bomb, as well as other testing environment such as air humidity. Second, the initial temperature of the test mentioned in the previous work was 196.85^{o}C, whereas the tests conducted in this work are at 190^{o}C. The value of S_N depends mainly on the value of initial temperature, as mentioned in the literature [12] which shows that S_N decreases as the initial temperature decreases. This could be the main factor why the values in this project are slightly lower than the previous research work. It can be observed that the maximum difference between the values of both works is about 4 cm/s, which gives an error of approximately 5%. This value is acceptable in the experimental work apart from the two reasons mentioned earlier.

C. Effect of equivalence ratio variation on the S_N of GTL fuel

The equivalence ratio calculations were similar in most respects as the H/C ratio for GTL and diesel fuel were approximately the same [3], as shown in Table 2 earlier. The S_N calculations were also the same, as they rely on the pressure signal. It is important to highlight here that igniting the mixtures of GTL fuel was much easier than that of the conventional diesel. In addition, the ignition probability at the lean equivalence ratios with GTL was higher than that of diesel fuel. This could be due to the fact that the GTL fuel starts boiling from 160^{o}C, while conventional diesel starts boiling after 190^{o}C. This could have accounted for less effect of wall cooling at the time of fuel injection. In addition, unlike the conventional diesel, it was noted that the exhaust gases after evacuating the bomb were colourless with GTL fuel. This could be because of close to zero Sulphur content in the clean GTL fuel.

After investigating the pure GTL fuel, the investigation was further enriched by studying the trends for blended fuels. This is because most of the industry is using GTL blended with the conventional fuels. The idea is to have the positive characteristics of new fuel along with the economy of using the conventional fuel combined together to give optimum fuel blend. Therefore, the blended fuel investigated was GTL fuel mixed with conventional diesel in 50%-50% proportions by volume. After preparing the blended fuel, the rest of experimental test runs were conducted in the same way as the conventional diesel and GTL-Diesel tests. It was observed that the blended fuel mixtures in some trials were harder to ignite at 190^{o}C, similar to what was experienced in the experimental runs with conventional diesel. However, in some trials, the blended fuel ignited in the first attempt. This could be due to the fuel separation in the blended fuel, which may result in irregular ignition behaviour. To overcome this problem, the blended fuel was prepared just before the experiments without leaving any time for separation. It should be mentioned that the separation behaviour of the GTL when blends with conventional diesel is an interesting topic that worth further investigation. Moreover, the exhaust smoke observed with the blended fuel was not as black as the conventional diesel, but it was light grey in colour.

After carrying out individual tests and analysing the recorded values, a comparison between the three tested fuels; i.e. conventional diesel, GTL-Diesel, and 50-50 blend, is necessary in order to establish some relationships and to see the trends.The first comparison made was for the equivalence ratio versus S_N for the three test fuels. This is very important study as this gives an idea about the combustion characteristics of each fuel and the one giving the highest flame speed at certain mixture conditions.

As seen in Fig. 5, the pure GTL fuel has the highest flame speed as compared to conventional diesel and 50-50 blend, near and at stoichiometric conditions ($\phi = 1$). The flame speed of pure GTL fuel peaks to 88.3 cm/s at an equivalence ratio of 1.1. As the equivalence ratio of mixture gets away from the stoichiometric conditions towards the lean side, the S_N of the GTL gets slightly lower than the conventional diesel to about 55 cm/s at $\phi = 0.8$ in comparison with 60 cm/s for the later one. Similar behaviour can be observed in rich mixtures $\phi > 1.2$, as S_N of conventional diesel becomes slightly higher that of GTL. The high S_N of the GTL over a wide range of ϕ from 0.9 to 1.2 could be the result of its higher calorific value as compared with both fuels. This high calorific value increases the flame temperature, which results of increasing S_N. It is not clear from the current study why S_N of GTL gets lower than that of diesel fuel close to the lean and rich limits, which required further investigations with laser diagnostics to study the reaction rate of the flame front at these conditions.

The behaviours of 50-50 blend is quite interesting when compared with both pure fuels. At lean equivalence ratios; i.e. $\phi < 0.9$, it starts with the lowest flame speed and stays low until it approximately equalizes with the conventional diesel at equivalence ratio of 1.0. At 1.1, the flame speed is only 2-3 cm/s higher than the conventional diesel. Then, the flame speed again drops lower than both fuels. From this, it can be concluded that the blended fuel is exhibiting lower flame speed than both pure fuels away from stoichiometric conditions. Near stoichiometric conditions, the blended fuel has slightly higher S_N than that of conventional diesel. This proves the conclusion made before that the combustion characteristics of the blended fuel can be completely different from those of pure fuels [16]. In the present work, S_N of the blended fuel is sometimes lower than both GTL and diesel fuels such as the cases at $\phi = 0.8$ and $\phi = 1.3$.

D. Effect of the initial temperature variation on S_N

The second comparison between the three tested fuels is investigating the effect of initial temperature variation on the flame speed. The equivalence ratio for this study was kept constant at ϕ =1.0, while the fuel was ignited at three initial temperatures, i.e. 190ºC, 220ºC and 250ºC, all at ambient pressure. Fig**.** 6 shows the effect of the increase in initial temperature on laminar flame speed of the three fuels; conventional diesel, GTL and blended fuel.

It can be observed from Fig. 6 that the S_N is increasing almost linearly with the increase in initial temperature of the mixture for all the three tested fuels. This linearity behaviour has been observed before in similar investigations [12]. For GTL, S_N reaches about 87.5 cm/s at T_i = 220°C and 94.2 cm/s at T_i = 250°C. These values are higher than those of diesel and blended fuel at the corresponding temperatures. It is interesting to note that the increase in S_N of the blended fuel is not matching that of the GTL and diesel fuels. S_N of the blended fuel reaches 89.7 cm/s at T_i = 250°C, which is lower than those of both GTL and diesel fuels at the same temperature; 94.2 and 91 cm/s, respectively. It is known that at high temperatures, the rate of reaction is increased resulting in higher flame speeds. However, for some reason, S_N of the blended fuel slows down at higher temperatures comparing with those of pure fuels. It has also been observed that the ignition probability of igniting all mixtures increases with the increased in T_i, and all the ignition attempts were successful from the first trial, as the mixture was at higher temperature and easier to ignite.

4 Conclusions

In this work, the laminar flame speed of GTL fuel and its 50%-50% blend with conventional diesel have been investigated in a cylindrical bomb capable of measuring S_N, at different initial temperatures and equivalence ratios. S_N was measured by analysing the pressure signals inside the bomb after combustion. It was found that pure GTL-Diesel has the highest flame speed near stoichiometric conditions. However, at lean and rich mixtures, the flame speed of GTL get slightly lower than conventional diesel. The blended fuel has a lower S_N at lean and rich mixture conditions than those of other fuels. Studying effect of increasing the initial temperature of the mixture on flame speed revealed that S_N of the three tested fuels increases with the increase in initial temperature of the mixture almost linearly. However, the blended fuel has the lowest S_N at high temperature.

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References

1. Radhi, H., 2009. Evaluating the potential impact of global warming on the UAE residential buildings - A contribution to reduce the CO2 emissions. *Building and environment,* 44(12), pp. 2451-2462.
2. IQ OG, 2012. *Gas to liquids-6 ground-breaking GTL,* s.l.: s.n.
3. Sajjad, H. et al., 2014. Engine combustion, performance and emission characteristics of gas to liquid (GTL) fuels and its blends with diesel and bio-diesel. *Renewable and Sustainable Energy Reviews,* Volume 30, pp. 961-986.
4. Andrews, G. & Bradley, D., 1972. *Determination of burning velocities: A critical review.* s.l.: American Elsevier Publishing Company, Inc.
5. Parsinejad, F., Arcari, C. & Merghalchi, H., 2006. Flame Structure and Burning Speed of JP-10 Air Mixtures. *Combustion Science and Technology,* Volume 178, pp. 975-1000.
6. Bradley, D. & Mitcheson, A., 1976. Mathematical solutions for explosions in spherical vessels. *Combustion and Flame,* Volume 26, pp. 201-217.
7. Dahoe, A., Zevenbergen , J., Lemkowitz , S. & Scarlett, B., 1996. Dust explosion in spherical vessels: the role of flame thickness in the validity of the cube-root law. *Journal of Loss Prevent Process Industries,* 9(1), pp. 33-44.
8. Rallis , C., Garforth , A. & Steinz , J., 1965. Laminar burning velocity of acetylene–air mixtures by the constant volume method: dependence on mixture composition, pressure and temperature. *Combustion and Flame,* Volume 9, pp. 354-356.
9. Babkin, V. & Kononenko, Y., 1967. Equations for determining normal flame velocity in a constant-volume spherical bomb. *Combustion and Flame,* 3(2), pp. 268-275.
10. Metghalchi , M. & Keck, J., 1982. Burning velocities of mixtures of air with methanol, isooctane, and indolene at high pressure and temperature. *Combustion and Flame,* Volume 48, pp. 191-210.
11. Lewis, B. & Von Elbe, G., 1987. *Combustion, Flames and Explosions of Gases.* 3rd ed. s.l.:Academic Press.
12. Radwan, M., Ismail, M., Elfeky, S. & Abu-Elyazeed, O., 2006. Jojoba methyl ester as a diesel fuel substitute: Preparation and characterization. *Applied Thermal Engineering,* Volume 27, pp. 314-322.
13. Huzayyin, A., Moneib, H., Shehatta, M. & Attia, A., 2008. Laminar burning velocity and explosion index of LPG–air and propane–air mixtures. *Fuel,* 87(1), pp. 39-57.
14. Bradley, D., Lawes, M. & Mansour, M., 2009. Explosion bomb measurements of ethanol–air laminar gaseous flame characteristics at pressures up to 1.4MPa. *Combustion and Flame,* 156(7), pp. 1462-1470.
15. Bradley, D. et al., 1998. The Measurement of Laminar Burning Velocities and Markstein Numbers for Iso-octane–Air and Iso-octane–n-Heptane–Air Mixtures at Elevated Temperatures and Pressures in an Explosion Bomb. *Combustion and Flame,* 115(2), pp. 126-144.
16. Ibrahim, A. S. & Ahmed, S. F., 2015. Measurements of laminar flame speeds of alternative gaseious fuel mixtures. *ASME Journal of Energy Resources Technology,* 137(3), pp. 032209-1.
17. Ahmed, S., Kasti, K., Khalid, B. & Olba, M., 2012. *Turbulent and Laminar Burning Velocity Measurements of New Alternative Fuels,* Doha: QNRF-UREP 12-021-2-006.

18. Chong, C.T., and Hochgreb, S., 2011. Measurements of laminar flame speeds of liquid fuels: Jet-A1, diesel, palm methyl esters and blends using particle imaging velocimetry (PIV). *Proceedings of the Combustion Institute* 33, pp. 979–986

Table 1. Equations used for flame speed calculation [11]

Main Equation	$\mathbf{S_N = (dr_i/d_t)\ (r_i/r_b)^\wedge 2\ (P_i/P)^\wedge(1/y_u)}$
Sub Eq (i)	$dr_i/d_t = (R/3(P_e\text{-}P_i))[(P\text{-}P_i)/(P_e\text{-}P_i)]^{\wedge(2/3)}\ (d_p/d_t)$
Sub Eq (ii)	$r_i = R\ [(P\text{-}P_i/(P_e\text{-}P_i)]^{\wedge(1/3)}$
Sub Eq (iii)	$r_b = R\ [1\text{-}(P_i/P)(T_u/T_i)(P_e\text{-}P)/(P_e\text{-}P_i)]$
Sub Eq (iv)	$(T_u/T_i) = (P/P_i)^\wedge(1/y_u)$

Table 2. Properties of fuels used

Properties	Diesel	GTL Diesel	50-50 Blend
H/C Ratio	2.125	2.1-2.15	2.1-2.125
Approx. Formula	$C_{16}H_{34}$	$C_{16}H_{34}$	$C_{16}H_{34}$
Density at 15°C (kg/m^3)	830	770	792
Boiling Range (°C)	190-360	160 - 360	165 - 360
Flash Point (°C)	55	77	71
Centane No.	55	75	64
Calorific Value (MJ/kg)	42.9	49.3	46.2

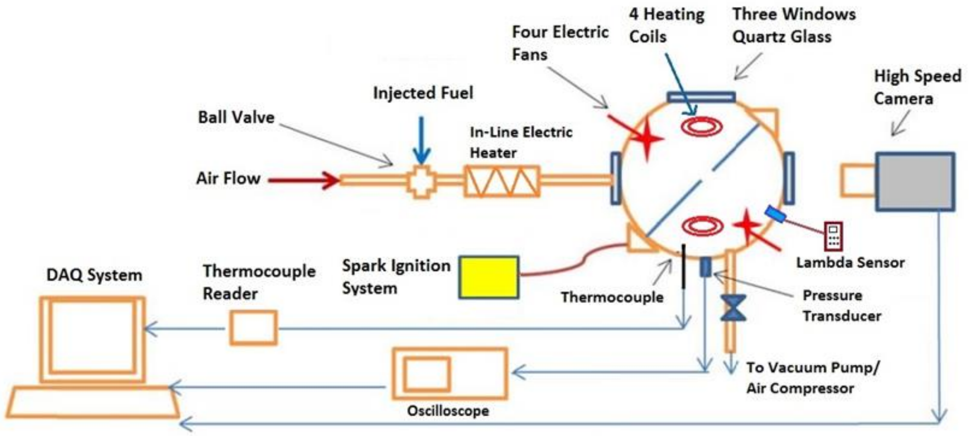

Fig. 1. Schematic diagram of the cylindrical bomb test rig.

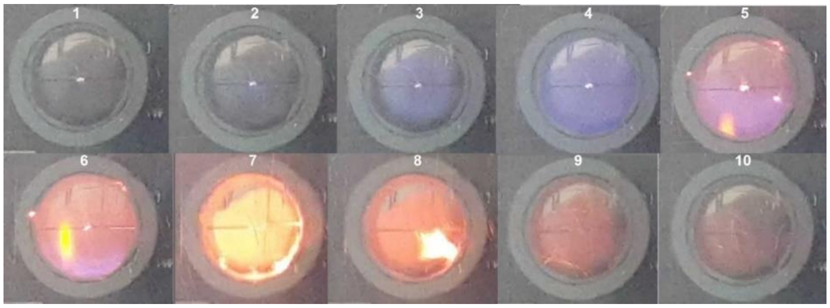

Fig. 2 – Visualization of ignition and flame propagation of GTL fuel-air mixture at ϕ = 1 and T_i = 180°C. Time difference between images is 33 ms.

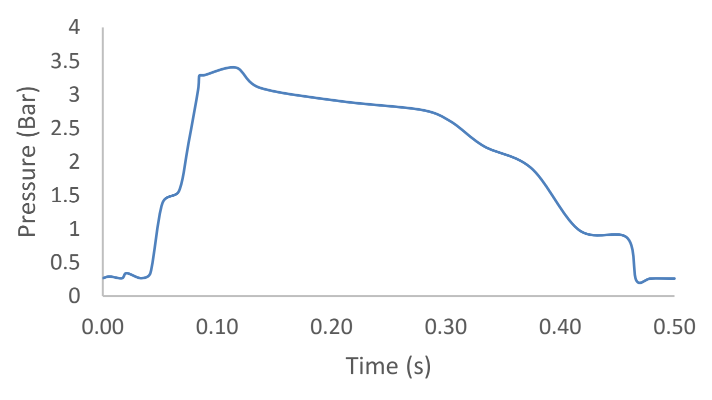

Fig. 3 A typical signal of pressure raise vs. time of diesel ignition at T_i =180°C and ϕ = 1.

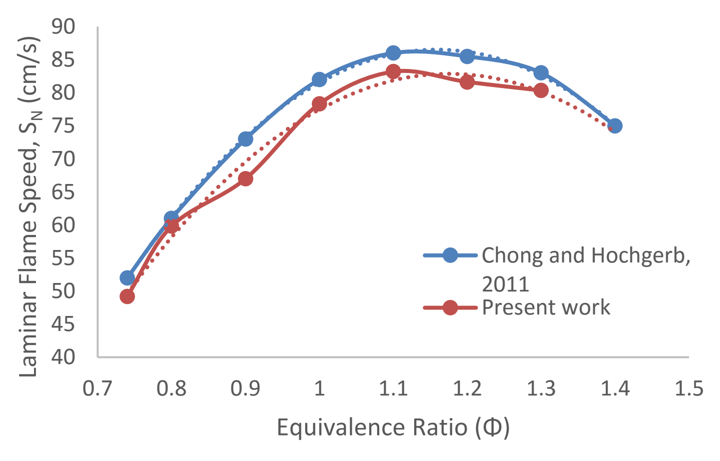

Fig. 4. A comparison of S_N of a diesel fuel between the present work and those of [18].

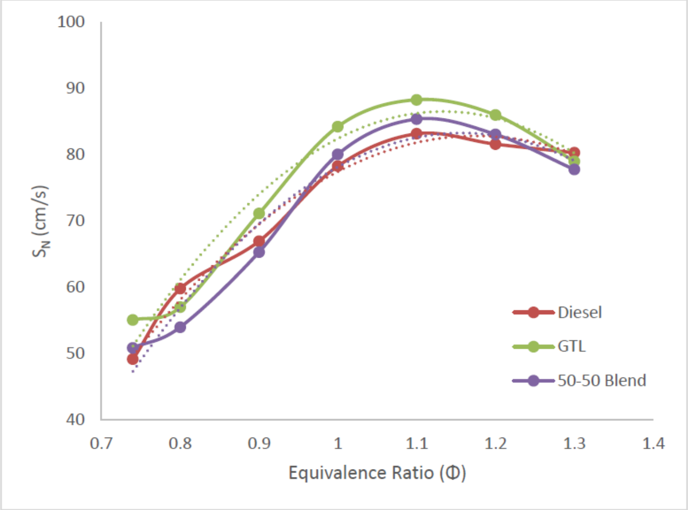

Fig. 5. S_N of GTL, conventional diesel, and 50-50 blend as a function of ϕ. T_i =190°C.

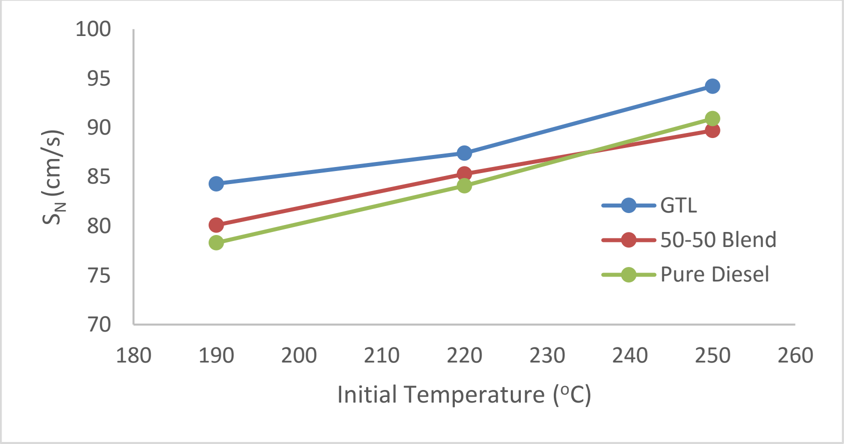

Fig. 6. Effect of changing initial temperature on the S_N of GTL, diesel and 50-50 blend. ϕ = 1.0.