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Engine Performances of Lean Iso-Octane Mixtures in a Glow Plug Heated Sub-Chamber SI Engine

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Abstract

The overreliance on fossil fuels to generate energy is not sustainable because of their carbon emissions that are harming our environment. To substitute the fossil fuels with a more sustainable options, alternative fuels, such as carbon-free ammonia has been gaining world-wide attention. To allow the application of ammonia in internal combustion engines, its performance as an engine fuel need to be investigated. Ammonia as fuel has some shortcomings that can be outlined as slow combustion rate and corrosion due to the generation of hydrogen which makes it difficult to utilize in conventional internal combustion engines. In this study, an engine equipped with sub-chamber feature was used to overcome slow combustion rate of lean-burn condition of iso-octane/air mixture. Iso-octane was chosen as the fuel specifically since in lean-burn conditions, where the excess air ratio is near 1.8, its laminar burning velocity is similar to that of ammonia. The study was conducted using a single cylinder modified diesel engine which features spark plug and glow plug in a sub-chamber. The investigations varied the engine speeds (1000 and 1500 RPMs), glow plug voltages (6 V and 10 V), excess air ratios (1.4 to 1.8), and ignition timings (362 °CA to 365 °CA). The results suggested improved engine performances with a lower excess air ratio and higher glow plug voltage due to more complete and stable combustion. By increasing the engine speed, the lean burn limit was extended as seen from the improved engine performances. Because of the sub-chamber feature, advancing the ignition timing, with respect to the after top dead centre, resulted in lower engine performances. Larger excess air ratio was found to increase the sensitivity of the engine performances with the ignition timing. The brake mean effective pressure for all conditions has a coefficient of variation of less than 5%, indicating stable combustion. The results suggested that the current setup can be used to investigate ammonia blended fuel and direct ammonia combustion in future works.

Keywords: Ammonia; Glow plug; Iso-octane; Lean burn; Spark Ignition; Sub-chamber

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1. Introduction

Most of the energy currently produced is derived from burning hydrocarbon fossil fuels that generate carbon by-products such as carbon dioxide (CO_2). These carbon by-products are also categorized as greenhouse gases that are negatively affecting the environment and intensify the effect of climate change [1], [2]. With concern towards the carbon emissions and climate change due to the overreliance on fossil fuels, more sustainable fuels that have low to zero-carbon net emissions have been proposed as alternative sources of energy [3], [4]. The fuel alternatives include natural gas and its derivatives which are fossil fuels with the lowest carbon emissions [5], [6], biofuel [7], [8], hydrogen [9], and ammonia [10]. Ammonia, in particular, has an excellent potential to substitute fossil fuel as it is carbon-free hydrogen carrying fuel with good energy density and has the potential to be produced sustainably [11], [12]. Ammonia is preferable than pure hydrogen to decarbonise the energy sector since hydrogen requires a more complicated supply chain and storage. Ammonia has been utilized in the agriculture industry as fertilizer for almost 100 years, in which, current technology allows its storage and transportation to be much cheaper and easier. Additionally, in terms of energy density, liquid ammonia contains 15.6 MJ/L of energy, whereas liquid hydrogen has only 9.1 MJ/L at cryogenic temperature, which is around 40% less than ammonia [13], [14]. Because of these potentials, ammonia has gained popularity and recent studies have been dedicated to enabling its application in internal combustion engines (ICEs). By not having the need of converting ammonia back to hydrogen for energy source, the additional potential to increase the overall efficiency for energy production [15]. Nevertheless, there are some shortcomings that hinder the study and application of ammonia in ICEs, namely its toxicity and corrosive natures [16], narrow flammability limit [10], high auto-ignition temperature [14], low laminar burning velocity and calorific value [10], and large NO_x emissions [17].

Owing to those shortcomings, it is difficult to directly use ammonia in ICEs, as it usually resulted in poor engine performances. The difficulty and poor performances were also observed when investigating the ammonia combustion in laboratory settings. Nevertheless, several studies have been conducted to investigate ammonia combustion and methods have been devised to address the issue. The solutions include blending ammonia with other fuels and upgrading the engine setup [13], [18]. Frigo and Gentili [19] studied stoichiometry ammonia/hydrogen performance in a spark-ignition (SI) engine. Their results showed that a certain minimum hydrogen ratio is needed to maintain the coefficient of variation (COV) of the indicated mean effective pressure (IMEP) less than 10% for stable ammonia-hydrogen combustion. They found that, compared to gasoline, ammonia blended with the minimum hydrogen amount has lower brake thermal efficiency, brake power, and net heat release than gasoline. Further exploring the potential of ammonia in ICEs, Lhuillier et al. [20] investigated engine performance of premixed ammonia/air and ammonia/hydrogen/air mixtures. They found that in a modern SI engine, combusting ammonia only requires small to no upgrade. However, to achieve similar performance as conventional fuel, a hydrogen blending of 20% in the fuel is required. From the analysis of the fuel mean effective pressure and IMEP, they suggested that increasing the intake pressure through supercharging ammonia engine should help improve ammonia combustion.

Since it is challenging to conduct a direct ammonia combustion study, particularly with its poor performance, toxicity, and corrosiveness, the present work proposed another alternative to study ammonia combustion. In this study, iso-octane fuel was ignited at extreme conditions, i.e. very lean mixtures, to achieve similar combustion characteristics as ammonia and emulate its combustion behaviour to a degree. At atmospheric conditions, the ammonia/air mixture has a maximum laminar burning velocity of around 7 cm/s [10], [14]. Another fuel that can reach approximately similar laminar burning velocity at lean condition is iso-octane/air mixtures. The experimental laminar burning velocity of iso-octane/air mixture is 14.8 cm/s at an equivalence ratio of 0.7 (excess air ratio of 1.43) [21] and numerically approximated to be ~10 cm/s at an equivalence ratio of 0.6 (excess air ratio of 1.67) [22]. It is reasonable to assume that at leaner mixtures, the laminar burning velocity of iso-octane/air mixture is around 7 cm/s which warrant its usage as an alternative to study ammonia in ICEs.

Several studies have investigated lean burn engine performances, motivated by its low combustion temperature that gives better specific heat ratio, fuel efficiency, emissions, and lower cooling and pump losses [23], [24]. The preceding gasoline lean burn investigation conducted by Ichiyanagi et al. [23] using a glow plug to heat the sub-chamber of SI engine have built a good foundation for the present study. The preceding work found improved performances through glow plug usage, and that maximum brake torque occurred in ignition timing after top dead centre (ATDC) and advanced with increased excess air ratio. Ratnak et al. [24] experimentally and numerically investigated the engine performances of blended iso-octane/n-heptane with primary reference fuel of 90. The study was conducted up to an excess air ratio of 1.6 in a SI engine under 4000 RPM. They found increased thermal efficiency, however, reduced IMEP with a higher excess air ratio. They attributed the higher thermal efficiency with the advancement of the spark ignition timing due to the lower temperature of lean flames. It resulted in lower heat losses to the wall, resulting in larger specific heat ratio. Serras-Pereira et al. [25] studied the IMEP and COV of the IMEP for iso-octane compared with different fuels with an excess air ratio of 1.0 and 1.2 using a direct injection SI research engine. By employing a single injection strategy, they found that lean iso-octane has reduced IMEP and increased COV of the IMEP compared to stoichiometry condition. The increase of COV of the IMEP from stoichiometry to lean mixtures in iso-octane is much larger than the other fuels they investigated, going as high as above 10-20%.

With the motivation to improve the understanding of ammonia combustion as a solution to decarbonise the energy sector, the present work investigated the characteristics and engine performance of lean-burn conditions of iso-octane/air mixtures (excess air ratio up to 1.8). This unconventional approach is chosen on the basis that lean iso-octane/air mixtures have similar laminar burning velocity as of ammonia. Unlike the preceding lean burn study that used gasoline as fuel [23], the present work also included an additional variable, engine speed, in the investigation to extend the understanding of lean burn engine performances. The parameters investigated include the brake torque, brake mean effective pressure (BMEP), the COV of the BMEP, and the brake thermal efficiency. The present work is part of a three-year plan to develop an engine that can be started with single ammonia fuel. The realisation of direct ammonia combustion engine is necessary to help in the effort to decarbonise the energy sector and prevent further environmental damage and climate change. The result of the present work will add additional insight for future studies to develop a suitable engine for direct ammonia combustion.

2. Method

In this study, the engine performances and combustion characteristics of lean iso-octane/air mixtures were investigated. The investigation used an experimental diesel engine with high compression ratio (CR) of 17.7 – almost two times higher than general SI engine, equipped with a sub-chamber for diffusion combustion. A spark plug and a glow plug (NGK-SRM) was instrumented in the sub-chamber as auxiliary units to initiate the combustion process for lean mixtures. The concept for this experimental engine setup was to use iso-octane/air mixture and set the ignition timing to ATDC in order to enable the diffusion combustion more effectively from the sub-chamber to the main chamber. The characteristics of the iso-octane fuel are given in Table 1 [26]. Engine specifications and the schematic view of the experimental setup are given in Table 2 and Figure 1, respectively. It should be noted that 0 °CA is set as the beginning of the intake stroke where the piston is at TDC. Thus, -30 °CA for injection timing corresponds to the end of the compression stroke of the previous engine cycle. Details on the combustion concept and experiment setup are available in the previous work [23].

The main differences of the present work with the preceding one [23] are in the fuel used and the experimental conditions investigated. The present study was conducted under two sets of conditions. In the first set of experiments, ignition timing remained constant while the glow plug voltage, the excess air ratio, and the engine speed were varied. For the second set of experiments, the glow plug voltage and engine speed were kept constant, while the ignition timing and excess air ratio (equivalence ratio) were varied. The first and second sets of the experiment are summarized in Tables 3 and 4, respectively. As shown in Table 3, ignition timing was set to 365 °CA while glow plug voltages were set from 6 V to 10 V and excess air ratios were changed from 1.4 to 1.7. In preliminary cases, at stoichiometric conditions (λ=1) abnormal combustion results were observed, causing in knocking phenomenon to occur due to the high compression ratio (CR=17.7) characteristic of this experimental engine. That is why the ignition timing was set to ATDC. Thus, the standard operating conditions for this experimental setup were investigated with the conditions that were created in Tables 3 and 4.

Table 1. Iso-octane fuel characteristics [26]

Fuel Properties	Iso-Octane
Density [g/cm³]	0.7476
Octane [RON]	100
Energy content [MJ/kg]	42.28
Flame velocity [m/s]	0.38
Boiling Point [°C]	99
Stoichiometric AFR	14.22

Table 2. Engine specifications

Engine model	YANMAR TF 120V - E
Engine type	Horizontal single cylinder diesel
Valve mechanism	Overhead valve
Ignition method	Spark ignition
Fuel supply	Port injection
Standard injection timing (°CA)	-30
Sub chamber	Spherical swirl with glow plug
Type of aspiration	Natural aspiration
Bore x stroke (mm)	92 x 96
Compression ratio	17.7
Total displacement (cc)	638
Sub-chamber displacement (cc)	23.5 (3.7% of total displacement)
Valves per cylinder (intake/exhaust)	1/1
Max speed (RPM)	2400
Cooling system	Water cooling with heat exchanger
Chamber orifice cross-sectional area (mm²)	Single orifice, 52.6

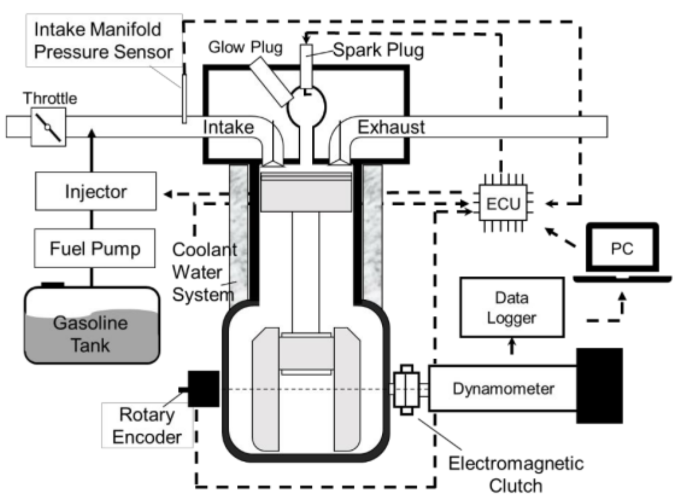


Figure 1. Schematic of the experiment setup.

Table 3. Conditions for the first set of the experiments

Engine speed (RPM)	Glow plug voltage (volt)	Excess air ratio (-)	Ignition timing (°CA)
1000	6	1.4	365
1000	6	1.6	365
1000	6	1.7	365
1000	10	1.4	365
1000	10	1.6	365
1000	10	1.7	365
1500	6	1.4	365
1500	6	1.6	365
1500	6	1.7	365
1500	10	1.4	365
1500	10	1.6	365
1500	10	1.7	365

Table 4. Conditions for the second set of the experiments

Engine speed (RPM)	Glow plug voltage (volt)	Excess air ratio (-)	Ignition timing (°CA)
1000	10	1.6	365
1000	10	1.7	365
1000	10	1.8	365
1000	10	1.6	364
1000	10	1.7	364
1000	10	1.8	364
1000	10	1.6	363
1000	10	1.7	363
1000	10	1.8	363
1000	10	1.6	362
1000	10	1.7	362
1000	10	1.8	362

In all conditions, the intake manifold pressure was set to 99 kPa (abs), the intake air temperature was 20 °C, and the coolant temperature was set to 70 °C. Intake manifold pressure was kept constant at 99 kPa (abs) by adjusting the throttle valve angle manually for different engine speeds. The intake manifold pressure was used by the manifold absolute pressure sensor which is connected to the engine control unit (ECU, INFINITY SERIES7) to control the injected fuel amount. ECU used in this study was a speed-density type, which uses the engine speed, intake air density to control the fuel amount from in-house build "Fuel Map" tables in the ECU. Fuel Map tables were prepared to create a relation between intake manifold pressure, engine speed and air excess ratio. In-line with this, ignition timing was set accurately by using ECU, which controlled the ignition timing using the rotary encoder (720 pulses/cycle) and cam sensor (1 pulse/cycle) to determine the crank angle and TDC angle. The coolant temperature and intake temperature were regulated using temperature controller connected to the coolant heat exchanger. An electromagnetic clutch that is connected to the dynamometer was used to help maintain a constant engine speed. In ensuring the accuracy of the measurements, all equipment and sensors were calibrated before the experiments.

The brake torque, BMEP, the COV of the BMEP, and the brake thermal efficiency were measured to understand the engine performances. The brake torque was measured at a resolution of 200 ms using an eddy current dynamometer connected to an electromagnetic clutch. BMEP was calculated using the obtained brake torque by employing Equation (1), where $BMEP$ is the brake mean effective pressure, n_r is the number of revolutions per cycle, which is two for four-stroke engines, T is the brake torque, and V_d is the displacement volume.

$$BMEP = \frac{2\pi\, n_r\, T}{V_d} \tag{1}$$

COV of the BMEP was calculated by employing Equation (2) to assess the instability of the measured BMEP. COV_{BMEP} is the COV of the BMEP, σ_{BMEP} is the standard deviation of the BMEP, and $\bar{X}_{BMEP}$ is the average instantaneous BMEP. In this study, 5% was set as the threshold for an acceptable COV of the BMEP. Beyond 5%, the combustion can be considered as unstable. There are previous studies that have used threshold for COV of 10% [19], [27]-[29] or a more stringent threshold of 5% [20], [30]. For the present study, lean burn combustion conditions were achieved COV_{BMEP} less than 5%, which proved to be appropriate and in-line with the literature.

$$COV_{BMEP} = \frac{\sigma_{BMEP}}{\bar{X}_{BMEP}} \tag{2}$$

The brake thermal efficiency was calculated by employing Equation (3), where η_{th} is the brake thermal efficiency, N is the engine speed, T is the brake torque, H is the lower heating value (LHV), V_f is the fuel flow rate, and ρ_f is the fuel density.

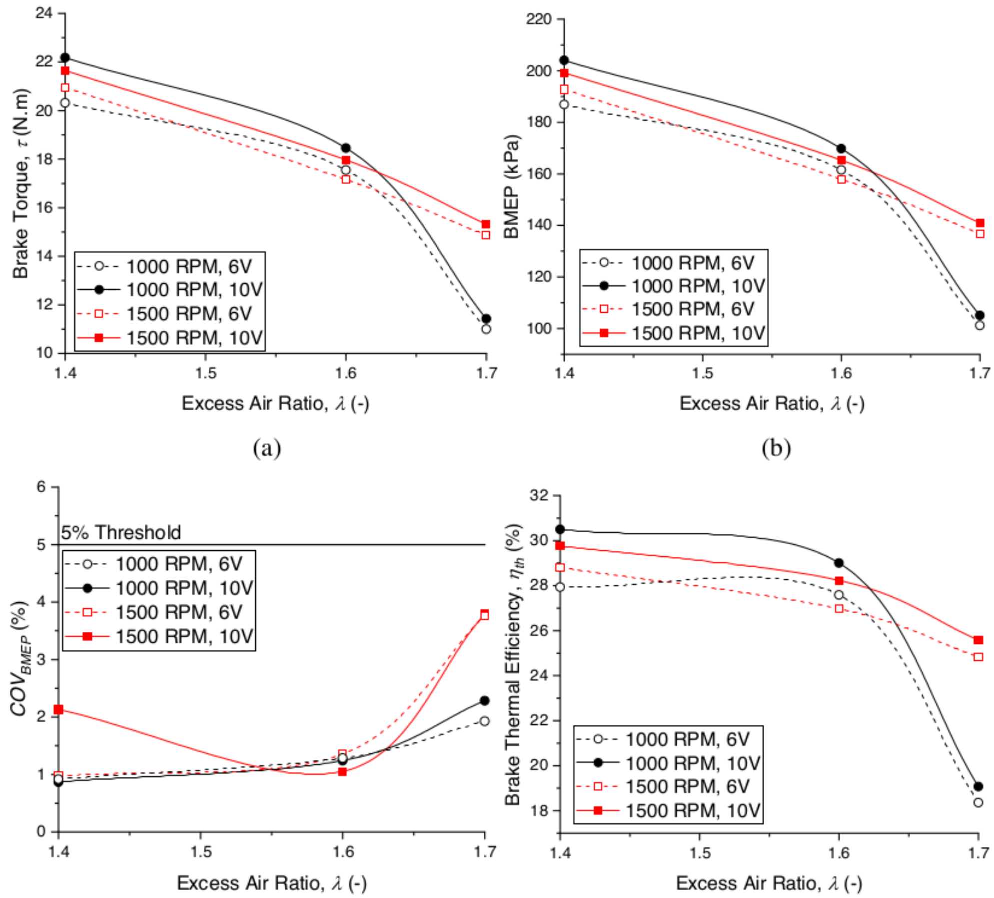
$$\eta_{th} = \frac{2\pi\, N\, T}{H\, V_f\, \rho_f} \tag{3}$$

3. Result and Discussion

3.1. Engine performances of lean iso-octane/air mixtures for varying engine speeds, glow plug voltages, and excess air ratios (The first set of the experiments)

The results for the first set of the experiments are given in Figures 2(a-d). Figures 2(a) and 2(b) show the brake torque and BMEP, respectively. The brake torque and BMEP have a similar trend since they are proportional to one another, as shown in Equation (1). The brake torque and BMEP decreased with increased excess air ratio for all engine speeds and glow plug voltages investigated. This is expected as leaner mixtures are less stable and likely to have incomplete combustion that reduces the brake torque. Looking at the effect of the engine speed, a significant decrease of brake torque and BMEP was observed from an excess air ratio of 1.6 to 1.7 for an engine speed of 1000 RPM. At a similar excess air ratio with an engine speed of 1500 RPM, the brake torque and BMEP decreased, albeit not as monumental. It suggested that engines operated at a lower speed have a smaller lean burn limit, and the performance worsen as it reached the limit. Observing the effect of glow plug voltage shows that higher voltage increased the brake torque and BMEP of the engine. The increased voltage enhanced the effectiveness of the glow plug to heat the sub-chamber, which can be explained by a chain effect. With the improved heating effectiveness, the mixture temperature in the sub-chamber was increased, which also resulted in higher combustion velocities and faster combustion duration [31], [32], [33]. Higher combustion velocity improved the degree of constant volume combustion which also enabled more complete combustion of the fuel. More complete combustion results in two main aftermaths. First, an increase in torque was achieved with higher combustion velocity due to higher sub-chamber gas temperature, thus BMEP and brake thermal efficiency were also increased. Secondly, with close to complete combustion, lower COV_{BMEP} can be achieved as it eliminates the probability of unstable combustion.

The results for COV of the BMEP are given in Figure 2(c). For all conditions, the COV_{BMEP} were within the 5% threshold, suggesting stable operations. With increased excess air ratio, the COV_{BMEP} increased since the combustion reached closer to the lean burn limit. An exception to the trend was observed for a mixture with an excess air ratio of 1.4 under 1500 RPM and glow plug voltage of 10 V. The COV_{BMEP} for this condition is higher compared to the other conditions with an excess air ratio of 1.4, albeit still within the threshold. One possible reason for this exception is that the high glow plug voltage and high engine speed resulted in high initial mixture temperature. Combined with the low excess air ratio, the mixture tends to self-ignite and destabilise the combustion, increasing the COV_{BMEP}.



(c) (d)

Figure 2. Engine performances of lean iso-octane/air mixtures for the first set of experiment. The investigated parameters include (a) brake torque, (b) BMEP, (c) COV of the BMEP, and (d) brake thermal efficiency.

Observing the change of glow plug voltage from 6 V to 10 V shows no significant difference in COV_{BMEP}. This is an indication that glow plug voltage is already creating the necessary conditions to have a consistent combustion occurrence. Thus, the insignificant differences in the COV_{BMEP} between the voltages in the present study can be related to the stable combustion on all air excess ratios investigated. At a higher excess air ratio that is closer to the lean burn limit, the combustion becomes more unstable and the difference in the COV_{BMEP} between voltages became more apparent.

A shift in the engine speed did not dramatically alter the COV_{BMEP} for excess air ratios of 1.4 and 1.6 (excluding the exception). However, for an excess air ratio of 1.7, a mixture combusted at a lower engine speed has less COV_{BMEP}. It contrasts with the previous assessment, which suggests a better lean burn limit and stable combustion with higher engine speed. Nevertheless, the combustions were stable for all conditions (within the 5% threshold), and future works should be performed to confirm the relationship between COV_{BMEP} and engine speed. It is possible that when the investigated excess air ratios and engine speeds were expanded, the overall trend will be in line with the earlier assessment.

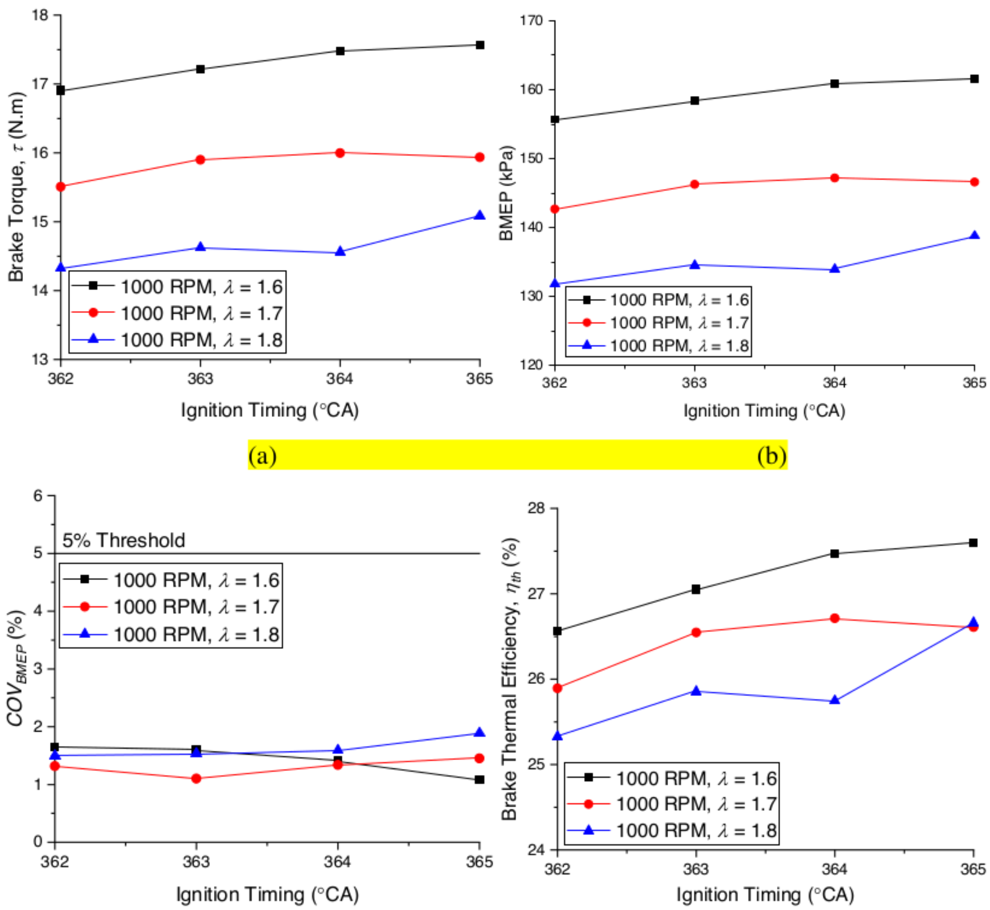
In terms of brake thermal efficiency, as given in Figure 2(d), the results suggested that increased excess air ratio tended to diminish the efficiency. For engine speed of 1000 RPM, a significant drop was observed when reaching an excess air ratio of 1.7, owing to the decreased brake torque. Under similar change in excess air ratio, the engine that was operated at 1500 RPM did not experience a significant drop in brake thermal efficiency, albeit still decreasing. Larger glow plug voltage is shown to improve the brake thermal efficiency. The improvement originated from the more complete combustion with higher glow plug voltage that increased the brake torque, as previously discussed. As seen in Equation (3), brake torque is proportional to the brake thermal efficiency; increased brake torque brought larger engine output and resulted in the increase of the brake thermal efficiency.

3.2. Engine performances of lean iso-octane/air mixtures for varying excess air ratios and ignition timings (The second set of the experiments)

The results for the second set of the experiments are shown in Figures 3(a-d). For these figures, the horizontal axis corresponds to the ignition timing (°CA) instead of the excess air ratio. It was changed for clarity since ignition timing has more variety than the excess air ratio for the second set of experiments. Figures 3(a) and 3(b) show the brake torque and BMEP of the engine, respectively. The results suggested that advanced ignition timing ATDC tended to decrease the brake torque and BMEP, within the present experimental condition, which contrasts with the common trend observed in the conventional ICEs. This phenomenon is related with the sub-chamber feature implemented in the current experimental engine setup where high pressure loss occurs at the orifice between the sub-chamber and main chamber [23], [34]. The high CR, 17.7, of the experimental engine causes difficulty for the ignited iso-octane/air mixture in the sub-chamber to propagate into the main chamber during the compression stroke. When the ignition occurs during ATDC, as the piston starts to move downwards, the pressure in the main chamber reduces and enables faster propagation of the flame from the sub-chamber to the main chamber. This also results in higher pressure applied on the piston, causing an increase in brake torque, BMEP and brake thermal efficiency. As the ignition timing was advanced (from 365 °CA to 362 °CA), brake torque, BMEP and brake thermal efficiency were decreased. This is an indication of the slower and less effective flame transition with lower pressure applied to the piston. Similar to the first set of experiments, it shows that a higher excess air ratio was found to reduce the brake torque. It should be noted that mixtures with an excess air ratio of 1.8 had a more dramatic decrease of brake torque and BMEP from 365 °CA to 364 °CA. It suggested that, at a higher excess air ratio, the engine performance is more susceptible to the change in ignition timing as the combustion is less stable.

The COV of the BMEP, as shown in Figure 3(c), showed a small decrease as the ignition timing ATDC advanced from 365 °CA to 362 °CA. However, COV_{BMEP} are all under the 5% threshold which did not influence the operation stability immensely. Similar trend with higher decrease in COV were also obtained in a previous study [34], as the ignition timing ATDC advanced towards TDC. In this study, for 365 °CA, the COV_{BMEP} has a similar trend to the first set of the experiments where a higher excess air ratio resulted in a larger COV_{BMEP}. However, that trend does not apply to other ignition timings. At a more advanced ignition timing, the results suggested a non-monotonic trend between excess air ratio and COV_{BMEP}. The trend can be attributed to the less ideal condition for the combustion with advanced ignition timing, as previously explained. Nevertheless, all the COV_{BMEP} measured are close to one another and are less than 5%.

As shown in Figure 3(d), advanced ignition timing ATDC reduced the efficiency due to the lower brake torque. Similar to the first set of experiments, the brake thermal efficiency decreased with a higher excess air ratio. An exception was observed in the ignition timing of 365 °CA for a mixture with an excess air ratio of 1.8. At this condition, the brake thermal efficiency is close to the one with the excess air ratio of 1.7 and abruptly decreased with a more advanced ignition timing. It can be attributed to the large torque at 365 °CA compared to the other ignition timings, as previously discussed, and the low flame temperature for excess air ratio of 1.8. One explanation can be that the lower flame temperature brought lower heat loss and combined with the large torque at that ignition timing, resulted in high thermal efficiency.



(c) (d)

Figure 3. Engine performances of lean iso-octane/air mixtures for the second set of experiment. The investigated parameters include (a) brake torque, (b) BMEP, (c) COV of the BMEP, and (d) brake thermal efficiency.

4. Conclusion

Engine performance studies for lean iso-octane/air mixtures as an approximation for ammonia/air mixtures have been conducted. Two sets of conditions were investigated to study and analyse the effect of various parameters on engine performances. Results from the first set of the experiments found better engine performance with a lower excess air ratio. It can be attributed to the more complete combustion that brings higher engine output and stability with lower excess air ratio. Lower engine speed has a narrower window for lean burn limit, as observed from the abrupt drop in the brake torque, BMEP, and brake thermal efficiency from excess air ratio of 1.6 to 1.7 under 1000 RPM. Increasing the glow plug voltage from 6 V to 10 V resulted in better engine performance due to a more complete combustion from the increased mixture temperature. For the first set of the experiments, the best engine performance was found in combustion with excess air ratio of 1.4, glow plug voltage of 10 V, and engine speed of 1000 RPM. Under those condition, the torque reached 22.18 N.m, BMEP reached 204.04 kPa, COV of the BMEP reached 0.87%, and the brake thermal efficiency reached 30.5%.

The second set of experiments' results suggested a reduced engine performance with the advancement in the ignition timing ATDC. The lower performance has to do with the sub-chamber setup that favour combustion at a delayed ignition timing after top dead centre. At higher excess air ratio, the changes in ignition timing have more significant effect on the engine performances. Ignition timing was found to have a small effect on the COV of the BMEP. For the second set of the experiments, the best performance was found with excess air ratio of 1.6, and ignition timing of 365 °CA. Under those conditions, the torque reached 17.56 N.m, BMEP reached 161.55 kPa, the COV of the BMEP reached 1.08%, and the brake thermal efficiency reached 27.6%. In both experiments, there were exceptions from the trend observed, and possible reasons for those exceptions have been provided in the discussion (Section 3).

All conditions investigated indicated COV of the BMEP less than 5%, suggesting that the combustions were stable despite the lean iso-octane/air mixtures studied (up to excess air ratio of 1.8). It supports the suitability of the present setup, after a slight adjustment, to investigate ammonia which has poor combustion characteristics. The subsequent work will build from the present results by investigating the engine performance of ammonia blended with other fuels and eventually direct ammonia combustion in ICEs.

5. Author's declaration

Authors' contributions and responsibilities

- [√] The authors made substantial contributions to the conception and design of the study.
- [√] The authors took responsibility for data analysis, interpretation, and discussion of results.
- [√] The authors read and approved the final manuscript.

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Availability of data and materials

- [√] All data are available from the authors.

Competing interests

- [√] The authors declare no competing interest.

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7. References

[1] R. Rosid, B. Sudarmanta, L. Atmaja, and S. Özer, "An Experimental Study of the Addition of Air Mass Flow Rate Using a 30% Emulsion-Fueled Diesel Engine at High Load," *Automotive Experiences*, vol. 3, no. 2, pp. 41–46, 2020, doi: 10.31603/ae.v3i2.3618.

[2] E. Yilmaz, T. Suzuki, K. Ito, G. J. Gotama, W. Anggono, and M. Ichiyanagi, "Analysis of the Spray Characteristics of Water and Water/Glycerin Mixtures using an Interferometric Laser Imaging for Droplet Sizing Technique," *International Journal of Technology*, vol. 12, no. 1, pp. 101–112, 2021, doi: 10.14716/ijtech.v12i1.4188.

[3] W. Anggono, A. Hayakawa, E. C. Okafor, G. J. Gotama, and S. Wongso, "Laminar Burning Velocity and Markstein Length of CH_4/CO_2/Air Premixed Flames at Various

Equivalence Ratios and CO2 Concentrations Under Elevated Pressure," *Combustion Science and Technology*, vol. 00, no. 00, pp. 1–20, 2020, doi: 10.1080/00102202.2020.1737032.

[4] A. C. Arifin, A. Aminudin, and R. M. Putra, "Diesel-biodiesel blend on engine performance: an experimental study," *Automotive Experiences*, vol. 2, no. 3, pp. 91–96, 2019, doi: 10.31603/ae.v2i3.2995.

[5] B. C. Purnomo and N. Widodo, "Torque and power characteristics of single piston lpg-fueled engines on variations of ignition timing," *Automotive Experiences*, vol. 2, no. 1, pp. 22–27, 2019, doi: 10.31603/ae.v2i1.2632.

[6] V. Esfahanian, M. M. Salahi, A. Gharehghani, and M. Mirsalim, "Extending the lean operating range of a premixed charged compression ignition natural gas engine using a pre-chamber," *Energy*, vol. 119, pp. 1181–1194, 2017, doi: 10.1016/j.energy.2016.11.071.

[7] E. Marlina, M. Basjir, M. Ichiyanagi, T. Suzuki, G. J. Gotama, and W. Anggono, "The role of eucalyptus oil in crude palm oil as biodiesel fuel," *Automotive Experiences*, vol. 3, no. 1, pp. 33–38, 2020, doi: 10.31603/ae.v3i1.3257.

[8] M. Wahyu, H. Rahmat, and G. J. Gotama, "Effect of Cassava Biogasoline on Fuel Consumption and CO Exhaust Emissions," *Automotive Experiences*, vol. 2, no. 3, pp. 97–103, 2019, doi: 10.31603/ae.v2i3.3004.

[9] M. Aziz, A. TriWijayanta, and A. B. D. Nandiyanto, "Ammonia as effective hydrogen storage: A review on production, storage and utilization," *Energies*, vol. 13, no. 12, pp. 1–25, 2020, doi: 10.3390/en13123062.

[10] A. Hayakawa, T. Goto, R. Mimoto, Y. Arakawa, T. Kudo, and H. Kobayashi, "Laminar burning velocity and Markstein length of ammonia/air premixed flames at various pressures," *Fuel*, vol. 159, pp. 98–106, 2015, doi: 10.1016/j.fuel.2015.06.070.

[11] A. Goldmann, W. Sauter, M. Oettinger, T. Kluge, U. Schröder, J. R. Seume, J. Friedrichs, and F. Dinkelacker, "A study on electrofuels in aviation," *Energies*, vol. 11, no. 2, 2018, doi: 10.3390/en11020392.

[12] A. Valera-Medina, S. Morris, J. Runyon, D. G. Pugh, R. Marsh, P. Beasley, and T. Hughes, "Ammonia, Methane and Hydrogen for Gas Turbines," *Energy Procedia*, vol. 75, pp. 118–123, 2015, doi: 10.1016/j.egypro.2015.07.205.

[13] A. Valera-Medina, H. Xiao, M. Owen-Jones, W. I. F. David, and P. J. Bowen, "Ammonia

for power," *Progress in Energy and Combustion Science*, vol. 69, pp. 63–102, 2018, doi: 10.1016/j.pecs.2018.07.001.

[14] H. Kobayashi, A. Hayakawa, K. D. K. A. Somarathne, and E. C. Okafor, "Science and technology of ammonia combustion," *Proceedings of the Combustion Institute*, vol. 37, no. 1, pp. 109–133, 2019, doi: 10.1016/j.proci.2018.09.029.

[15] M. Chiong, C.T. Chong, J. Ng, S. Mashruk, W.W.F. Chong, N.A. Samiran, G.R. Mong, and A. Valera-Medina, "Advancements of combustion technologies in the ammonia-fuelled engines," *Energy Conversion and Management*, vol. 244, no. 114460, 2021, doi: 10.1016/j.enconman.2021.114460.

[16] J. H. Lee, S. I. Lee, and O. C. Kwon, "Effects of ammonia substitution on hydrogen/air flame propagation and emissions," *International Journal of Hydrogen Energy*, vol. 35, no. 20, pp. 11332–11341, Oct. 2010, doi: 10.1016/j.ijhydene.2010.07.104.

[17] A. Hayakawa, Y. Hirano, E. C. Okafor, H. Yamashita, T. Kudo, and H. Kobayashi, "Experimental and numerical study of product gas characteristics of ammonia/air premixed laminar flames stabilized in a stagnation flow," *Proceedings of the Combustion Institute*, vol. 38, no. 2, pp. 2409–2417, 2021, doi: 10.1016/j.proci.2020.07.030.

[18] H. Lesmana, Z. Zhang, X. Li, M. Zhu, W. Xu, and D. Zhang, "NH3 as a transport fuel in internal combustion engines: A technical review," *Journal of Energy Resources Technology*, vol. 141, no. 7, 2019, doi: 10.1115/1.4042915.

[19] S. Frigo and R. Gentili, "Analysis of the behaviour of a 4-stroke SI engine fuelled with ammonia and hydrogen," *International Journal of Hydrogen Energy*, vol. 38, no. 3, pp. 1607–1615, 2013, doi: 10.1016/j.ijhydene.2012.10.114.

[20] C. Lhuillier, P. Brequigny, F. Contino, and C. Mounaïm-Rousselle, "Experimental study on ammonia/hydrogen/air combustion in spark ignition engine conditions," *Fuel*, vol. 269, no. 117448, 2020, doi: 10.1016/j.fuel.2020.117448.

[21] X. Han, Z. Wang, Y. He, S. Wang, Y. Liu, and A. A. Konnov, "Temperature dependence of the laminar burning velocity for n-heptane and iso-octane/air flames," *Fuel*, vol. 276, no. 118007, 2020, doi: 10.1016/j.fuel.2020.118007.

[22] S. Ratnak, J. Kusaka, and Y. Daisho, "Experiments and Simulations of a Lean-Boost Spark Ignition Engine for Thermal Efficiency Improvement," *SAE International Journal of Engines*, vol. 9, no. 1, pp. 379–396, 2016.

[23] M. Ichiyanagi, Y. Kang, B. Guo, R. Saito, K. Kajiki, E. Yilmaz, and T. Suzuki, "Improvement of Fuel Consumption for SI Engines by Combining with Glow Plug Heated Sub-Chamber and Lean Burn," *SAE Technical Paper*, no. 2020-32-2310, 2020, doi: 10.4271/2020-32-2310.

[24] S. Ratnak, J. Kusaka, Y. Daisho, K. Yoshimura, and K. Nakama, "Thermal efficiency improvement of a lean-boosted spark ignition engine by multidimensional simulation with detailed chemical kinetics," *International Journal of Automotive Engineering*, vol. 6, no. 4, pp. 97–104, 2015, doi: 10.20485/jsaeijae.6.4_97.

[25] J. Serras-Pereira, P. G. Aleiferis, and D. Richardson, "An analysis of the combustion behavior of ethanol, butanol, iso-octane, gasoline, and methane in a direct-injection spark-ignition research engine," *Combustion Science and Technology*, vol. 185, no. 3, pp. 484–513, 2013, doi: 10.1080/00102202.2012.728650.

[26] Japanese Standards Association (JSA), "JIS K 2202:2012 - Motor Gasoline," *Japanese Industrial Standards*, 2012.

[27] M. Comotti and S. Frigo, "Hydrogen generation system for ammonia-hydrogen fuelled internal combustion engines," *International Journal of Hydrogen Energy*, vol. 40, no. 33, pp. 10673–10686, 2015, doi: 10.1016/j.ijhydene.2015.06.080.

[28] J. Kim, K. M. Chun, S. Song, H. Baek, and S. W. Lee, "The effects of hydrogen on the combustion, performance and emissions of a turbo gasoline direct-injection engine with exhaust gas recirculation," *International Journal of Hydrogen Energy*, vol. 42, no. 39, pp. 25074–25087, 2017, doi: 10.1016/j.ijhydene.2017.08.097.

[29] J. Vancoillie, J. Demuynck, L. Sileghem, M.V.D. Ginste, S. Verhelst, L. Brabant, and L.V. Hoorebeke, "The potential of methanol as a fuel for flex-fuel and dedicated spark-ignition engines," *Applied Energy*, vol. 102, pp. 140–149, 2013, doi: 10.1016/j.apenergy.2012.05.065.

[30] X. Yu, Z. Guo, L. He, W. Dong, P. Sun, Y. Du, Z. Li, H. Yang, S. Wang, and H. Wu, "Experimental study on lean-burn characteristics of an SI engine with hydrogen/gasoline combined injection and EGR," *International Journal of Hydrogen Energy*, vol. 44, no. 26, pp. 13988–13998, 2019, doi: 10.1016/j.ijhydene.2019.03.236.

[31] S.S. Chung, J.K. Yeom, J.S. Park, "Scavenging a sub-chamber type CNG fueled engine". *International Journal of Automotive Technology*, vol. 9, pp. 123–128, 2008,

doi:10.1007/s12239-008-0016-7.

[32] C.E.C. Alvarez, G.E. Couto, V.R. Roso, A.B. Thiriet, and R.M. Valle, " A review of prechamber ignition systems as lean combustion technology for SI engines," *Applied Thermal Engineering*, vol. 128, pp. 107-120, 2018, doi: 10.1016/j.applthermaleng.2017.08.118.

[33] Y. Nada, Y. Kidoguchi, Y. Yamashita, R. Furukawa, R. Kaya, H. Nakano, and S. Kobayashi, "Effects of Sub-Chamber Configuration on Heat Release Rate in a Constant Volume Chamber simulating Lean-burn Natural Gas Engines," *SAE International Journal of Advances and Current Practices in Mobility*, vol. 2, no. 2, pp. 1032-1040, 2020.

[34] M.P. Bunce, N.D. Peters, S.K. Pothuraju Subramanyam, and H.R. Blaxill, "Assessing the low load challenge for jet ignition engine operation", in *Proceedings of the International Conference on Internal Combustion Engines and Powertrain Systems for Future Transport* (ICEPSFT 2019), 1st edition, London, United Kingdom, CRC Press, 2020.

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