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Diesel/CNG Mixture Autoignition Control Using Fuel Composition and Injection Gap

Firmansyah *, A. Rashid A. Aziz †, Morgan Raymond Heikal † and Ezrann Z. Zainal A. †

Centre for Automotive Research and Electric Mobility, Universiti Teknologi Petronas, Bota 32610, Perak, Malaysia; rashid@utp.edu.my (A.R.A.A.); morgan.heikal@utp.edu.my (M.R.H.); ezrann.zainal@utp.edu.my (E.Z.Z.A.)

* Correspondence: firmansyah@utp.edu.my; Tel.: +60-5-368-8102

† These authors contributed equally to this work.

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Abstract: Combustion phasing is the main obstacle to the development of controlled auto-ignition based (CAI) engines to achieve low emissions and low fuel consumption operation. Fuel combinations with substantial differences in reactivity, such as diesel/compressed natural gas (CNG), show desirable combustion outputs and demonstrate great possibility in controlling the combustion. This paper discusses a control method for diesel/CNG mixture combustion with a variation of fuel composition and fuel stratification levels. The experiments were carried out in a constant volume combustion chamber with both fuels directly injected into the chamber. The mixture composition was varied from 0 to 100% CNG/diesel at lambda 1 while the fuel stratification level was controlled by the injection phasing between the two fuels, with gaps between injections ranging from 0 to 20 ms. The results demonstrated the suppressing effect of CNG on the diesel combustion, especially at the early combustion stages. However, CNG significantly enhanced the combustion performance of the diesel in the later stages. Injection gaps, on the other hand, showed particular behavior depending on mixture composition. Injection gaps show less effect on combustion phasing but a significant effect on the combustion output for higher diesel percentage (≥70%), while it is contradictive for lower diesel percentage (<70%).

Keywords: diesel/CNG; fuel composition; injection gap

1. Introduction

Stringent emission regulations and significant increases in fuel prices are influencing the growth of automotive technology developments with the objectives of reducing fuel consumption and improving engine efficiency. Controlled auto-ignition based combustion systems, such as homogeneous charge compression ignition (HCCI) [1,2], stratified charge combustion ignition (SCCI) [3], premixed charge compression ignition (PCCI) [4], and reactive charge compression ignition (RCCI) [5] are the recent engine developments promising high efficiency, low emissions, and low fuel consumption.

Amongst the above strategies of the autoignition based combustion system, RCCI is the most recent development in the effort to control the combustion and extend its operating range. RCCI relies on substantial differences in the reactivity of the involved fuels. The most common combination in RCCI is diesel-gasoline [6,7] as these fuels are the primary fuels in the automotive industry. The previous research outlined that fuel composition is the most influential parameter of the combustion performance. The fuel composition variation determines the global reactivity index that can be ascertained by the mixture's octane number [8]. The global reactivity of the mixture is higher with higher gasoline percentage in the mixture, thus the combustion requires longer delays to increase the local reactivity. Longer ignition delays allow a significant rate of heat to be transferred to the walls, which reduces the maximum peak of heat release from the combustion process. As a result, the combustion duration is shorter, and the NO_x and soot emissions are lower.

Another important parameter affecting autoignition is the fuel stratification. Fuel stratification as a means of controlling homogeneous charge combustion has been studied extensively. It started with the implementation of gasoline direct injection (GDI) in a diesel engine to achieve HCCI combustion [9]. It was found that the combustion efficiency increased with the increased level of stratification. However, high stratification levels generated high NO_x and reduced the combustion efficiency. Further investigations on the effect of stratification were carried out in a single cylinder engine with two GDI injectors [10], and it was found that stratification significantly increased the indicated mean effective pressure (IMEP) and emissions, especially at the lean limits but the effect was limited to the rich limits due to the high rate of pressure rise, CO, and NO_x. Because of this potential, further investigations were carried out using two-stage fuels (high reactive fuels) [11]. Stratification was proved to reduce the pressure rise rate, but it was very sensitive to the local equivalence ratio. Following this direction, implementations of fuel stratification to control HCCI combustion were tested on various fuels (Dimethyl Ether (DME) [12] and heptane [13]), with turbocharging [14] and exhaust gas recirculation [15].

The literature shows great possibilities of using the fuel stratification level as a possible means of controlling HCCI combustion. In the RCCI combustion systems, the effect of fuel stratification that later translates into a gradient of local reactivity index was demonstrated by Li et al. [16]. The fuel reactivity gradient was shown to retard the ignition timing, ease the heat release, and pressure rise rates. Slower formation of CH_2O and OH radicals during the high-temperature reaction were the main reasons for the mentioned performance of high reactivity gradient mixtures.

Most of the RCCI experiments were carried out with port fuel injection and direct injection combinations where the low reactive fuel was injected into the port, while the high reactive fuel was injected directly into the cylinder [17–19]. This method is limited as the variation of the local reactivity depends only on the high reactive fuel distribution, which in turn determines the local reactive index value. Due to this limitation, the reactivity variation is limited to a small window of crank angles as the common injection window of the high reactive fuel is realized at the near top dead center. This condition limits the operating range of RCCI to medium load and medium speed cases because of the very small window available at high-load and high-speed conditions. Other researchers tested multiple injections of the high reactive fuel in order to modify the stratification level inside of the chamber and to overcome this limitation [20]. This resulted in a high combustion temperature, high local reactivity index, and increased the thermal efficiency, which then increased soot and NO_x emissions. Further efforts to control soot and NO_x emissions by varying the injection timing as well as the number of multiple injections have shown drawbacks with unacceptable levels of carbon monoxide and hydrocarbon emissions.

Therefore, the dual direct injection method is proposed in order to utilize these reactivity indices in the combustion chamber. The dual direct injection (DDI) method is a viable tool to control the stratification levels, thus controlling the reactivity index in the chamber especially the local reactivity index. DDI can also suppress the peak pressure rise rate and increase thermal efficiency up to 48.7% with very low NO_x, HC, and soot emissions [21]. The dynamics between two injection events control the level of mixture stratification and hence affect the local reactivity index. The results of DDI simulation show that DDI has the potential to control the RCCI combustion strategy. The previous experiment in DDI was done with the combination of gasoline and diesel [22–25], while the combination of diesel and compressed natural gas (CNG) have not been investigated despite this combination being widely investigated in the RCCI engine investigation using the port and direct fuel injection combination. Therefore, this report is focusing on the combination of diesel/CNG mixture using the dual direct injection method. Furthermore, it is also shows the interaction between the liquid and gaseous fuel in the chamber in the RCCI combustion method that has not been reported.

Controlling the autoignition by varying the mixture composition and increasing the gradient of the local reactivity index with a reasonable global reaction index is a promising possibility in achieving an optimized combustion system. In order to achieve these objectives, an investigation of the fuel combination diesel-natural gas that has significant differences of octane numbers, 25 and 120, respectively, was carried out and reported in this paper. Furthermore, the effects of fuel compositions and the gaps between injections of the fuels were investigated in order to gain a comprehensive understanding of this method of controlling the autoignition process.

2. Materials and Methods

The study performs an extended experimental investigation on the auto-ignition behavior of dual fuel (Diesel-CNG) in a constant volume combustion chamber (Figure 1). A probe heater is used to increase the temperature inside the combustion chamber. Heater temperature is set at 800 °C in order to get a stable auto-ignition from the mixture of combustion chamber pressure equal to atmospheric. Furthermore, oxygen with a purity of 99.5% is used as the replacement of air in order to reduce the complexity of the reaction and to increase the auto-ignition occurrence probabilities. Diesel-CNG mixture was tested. Two parameters were tested, fuel compositions and injection gaps. The composition was varied from 10 to 100% diesel/CNG. Furthermore, the injection gaps between the fuels were varied between 0 and 20 ms with an increment of 5. The combustion data for these mixtures were obtained for lambda 1.

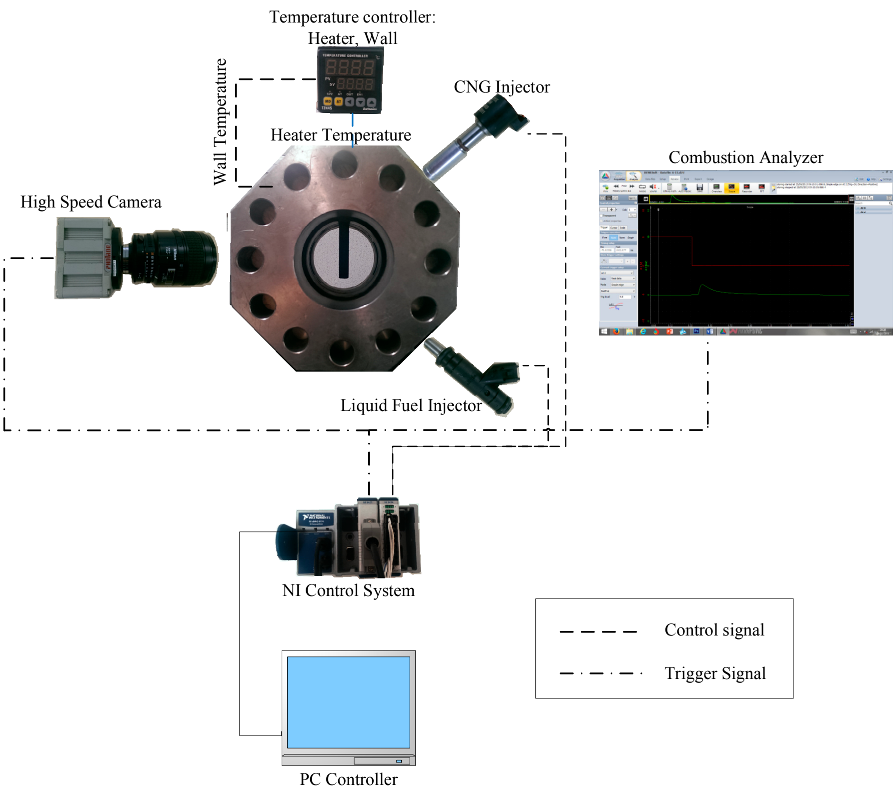


Figure 1. Fuel injector, heater arrangement and experimental schematic in the Constant volume chamber (CVC).

The injector used is Siemens Deka 4 with 3 bars injection pressure and 4.3 g/s delivery rate (manufacturer specification and fueled with gasoline). Due to density variations of the fuels, the calibration process is carried out in the ambient condition for each file to measure the actual delivery rate of the injector. The calibration results are shown in Table 1. The CNG injector was using a low-pressure CNG injector from Orbital with 7.2 g/s at injection pressure 7.5 bars. The injectors were placed 90° relative to each other and both are directly injected into the combustion chamber (Figure 1). Figure 2 depicted the stoichiometric values for various compositions of diesel/CNG. The oxygen/fuel ratio ranges from 16.6 to 17.8 for 10–100% diesel/CNG. The lambda values were maintained at 1 by injected the required fuels amount (diesel and CNG) at its stoichiometric values described in Figure 2.

The required fuel amount at a constant volume (0.000492 m^3) was determined and translated to the injector opening by dividing the total fuel required with the injector delivery rate.

Table 1. Injector delivery rate for each fuel.

Fuels	Injector Delivery Rate (g/s)
Diesel	4.2 @ 3 bar
CNG	7.2 @ 7.5 bar

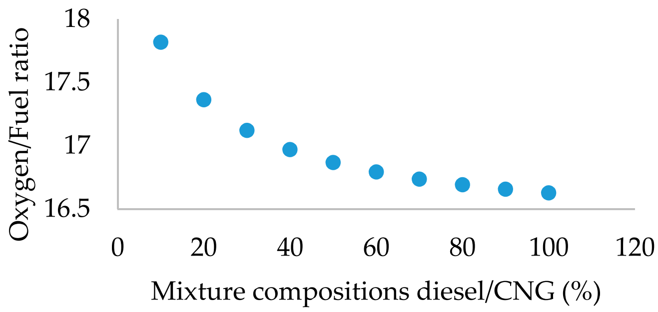


Figure 2. Lambda for various mixture compositions.

The total heat released (THR) is a summation of heat release rate (kJ/s) through the duration of the combustion process, from start to finish.

3. Results

The autoignition characteristics of the diesel-CNG mixture and the effect of fuel compositions and injection gaps as means to control the combustion process of RCCI concept are presented in the following discussions.

3.1. Effect of Fuel Composition

Fuel composition is the most influential parameter on the combustion behavior of RCCI strategy as shown in Figure 3.

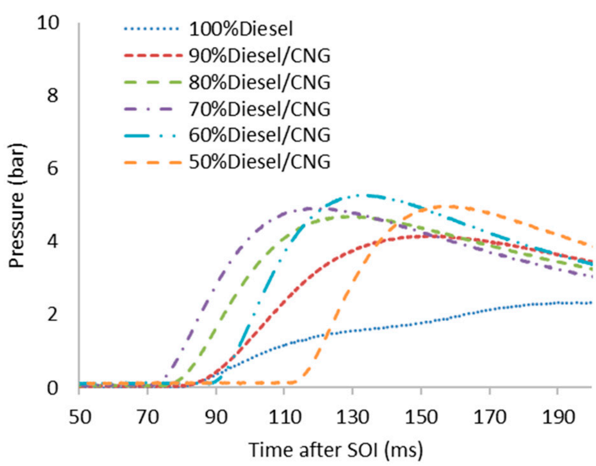
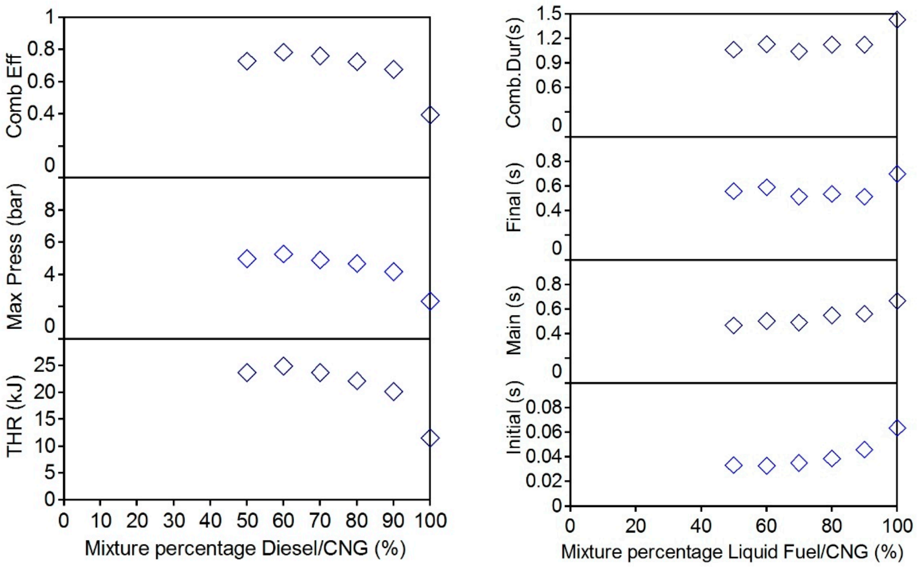


Figure 3. Pressure profile for various mixture compositions of d gap.

As can be seen from the results, reducing the percentage of diesel from 100% to 70% progressively reduced the ignition delay. This is thought to be due to the reduced time required for a flammable mixture to be realized in the chamber as the reduced amount of diesel in the mixture required less time for evaporation and mixing with the oxygen. As the diesel proportion was reduced further to 60% and 50%, this trend was reversed. Conjecture was made stating that this is due to the fact that the low reactivity of the CNG has the greater influence on the overall mixture flammability. However, once the flame started the combustion duration decreased with the increase in the percentage of the CNG in the mixture as a result of the higher degree of premixing. The changes in the trend are clearly shown in Figure 4, which shows the combustion performance for different fuel compositions at a zero injection gap. It can be clearly seen that increasing the CNG percentage enhanced the combustion performance by up to 40% CNG in the mixture where the shortest combustion duration and the highest combustion efficiency were achieved. This enhanced combustion performance of 60/40 composition is thought to be due to the combination of the shorter time required for diesel vaporization (less fuel amount) and the high initial heat release rate producing sufficient amount of energy to initiate the CNG combustion.



(**a**) (**b**)

Figure 4. Combustion performance for various diesel/compressed natural gas (CNG) compositions at 0 ms injection gap (**a**) combustion performance; (**b**) combustion phasing.

As the percentage of the CNG in the composition increased to 50%, this trend started to reverse as the CNG reduced the global reactivity index and suppressed the combustion of diesel resulting in increased combustion delay and a reduced initial rate of heat release. As the CNG percentage increased further, the combustion could not be achieved in the current experiment, as the CNG was dominant and could not be autoignited.

Figure 5 shows high-speed images of the burning in the chamber for both the pure diesel and 60/40% diesel/CNG mixture. As can be seen, the diesel combustion exhibited the expected diffusion flame characteristics. The images also showed that the increased ignition delay in the case of the diesel/CNG mixture resulted in multiple ignition sites as the proportion of the premixed diesel combustion increased.

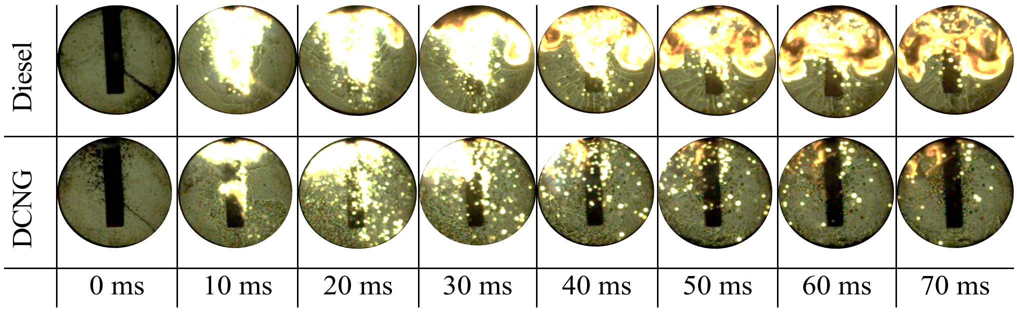


Figure 5. Diesel and 60/40 diesel/CNG mixture combustion sequence.

3.2. Effect of Injection Gaps

In order to vary the mixture distribution inside of the chamber and hence the gradient of local reactivity, the gap between the CNG start of injection and that of the diesel was varied from 0 to 20 ms in increments of 5 ms, as shown in Figure 6. The diesel was injected first as the pilot igniter, and CNG followed according to the gap setting.

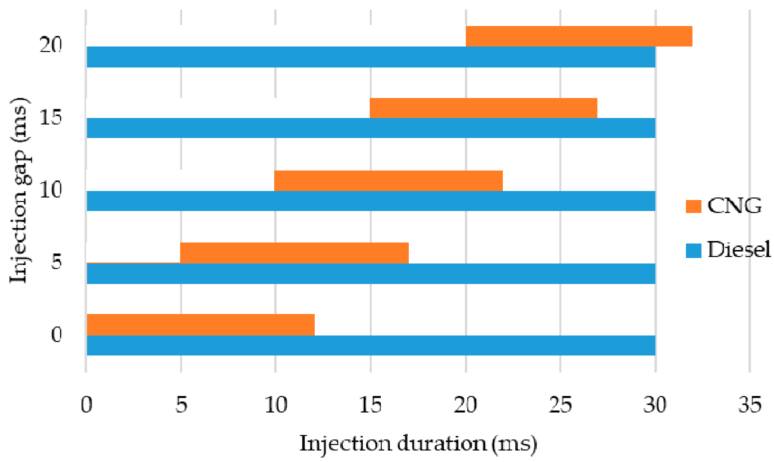


Figure 6. Injection timing illustration for 60/40 diesel/CNG composition.

As can be seen from Figure 7, the 0 ms injection gap showed higher stratification levels of the diesel droplet distribution while the 20 ms injection gap showed a more homogeneous mixture.

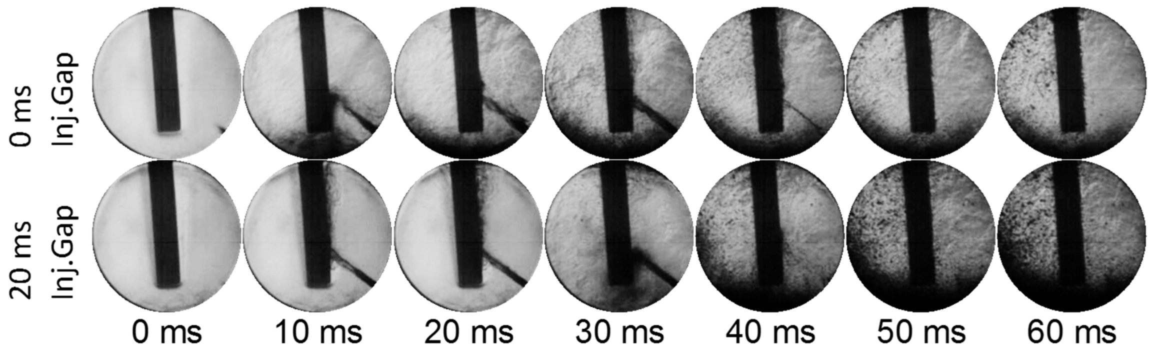


Figure 7. Mixture distribution for 0 ms and 20 ms injection gaps for 60/40 diesel/CNG composition.

The images show that the diesel fuel droplets (dark color) are concentrated at the bottom of the chamber for 0 ms injection gap, but are more uniformly distributed in the chamber in the case of the

20 ms injection gap. The diesel was injected for 30 ms, and the CNG was injected for 12 ms to achieve 60/40 diesel/CNG fuel composition. It should be pointed out that the injection gap is between the start of injection of the two fuels.

The mixture distribution differences between the injection gaps can be explained as follows. In the case of the 0 ms injection gap, both of the fuels were injected at the same time. Therefore, the velocity vector in the first 12 ms of the injection period was dominated by the CNG jet due to its high velocity. The diesel droplets were forced to the bottom of the chamber during this period. After the end of the CNG injection, diesel was still being injected and hence was directed to the upper region of the chamber as it was no longer affected by the CNG jet. Although the established in-cylinder flow due to CNG injection continued to assist in the mixing, it had little effect on the diesel jet, and hence the diesel droplets mainly moved downward to the bottom of the chamber due to gravity.

However, in the case of the 20 ms injection gap, diesel was injected towards the upper region of the chamber in the first 20 ms undisturbed as no CNG was being injected during this period. During the CNG injection, the earlier diesel distribution was then disrupted and mixed with the CNG and oxygen inside the chamber resulting in a more homogeneous mixture compared to the 0 ms case.

The above-mentioned fuel distributions, in turn, influenced the combustion performance, as shown in Figure 8.

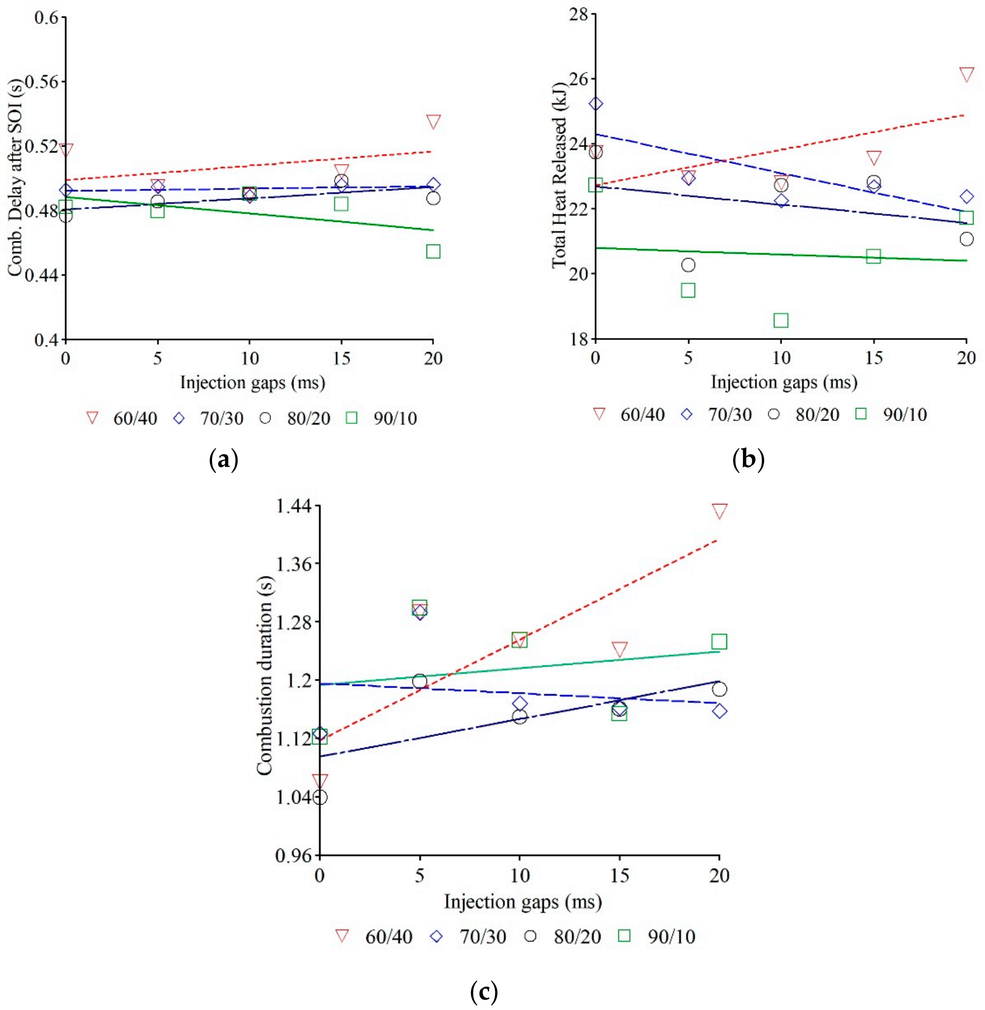


Figure 8. Effect of injection gaps to the combustion delay for various mixture compositions (**a**); total heat released (**b**) and combustion duration (**c**) on various mixtures of diesel/CNG.

Changes in the trends of combustion phasing and performance were identified between the 60/40 and 70/30 diesel/CNG compositions. As shown in Figure 8a, the combustion delay for 60/40 composition increased with increased injection gaps, but decreased for 70/30, 80/20, and 90/10 mixture. Similar behavior was also shown with THR in Figure 8b where the higher injection gap increased the THR for 60/40 and decreased it for the other compositions. On the other hand, longer injection gaps significantly increased the combustion duration (Figure 8c) for 60/40 from 1.12 s to 1.44 s, and its effect reduced as the diesel composition increased to the almost similar duration for the 90/10 composition for all of the injection gaps. The reason for these behaviors is thought to be due to the mixture distribution in the chamber being different for the different compositions. In the 90/10 composition, for example, CNG injection had less effect on the variation of the diesel distribution as the CNG injection duration was very short, 3 ms, and diesel injection was very long, 46 ms. This condition created a 'diesel-like' combustion performance regardless of the injection gap.

The effects of the injection gap on the combustion phasing are shown in Figure 9a for a 60% mixture. The duration of the initial combustion phase is largely unaffected by the injection gap, suggesting that this stage is mainly influenced by the combustion of the diesel fuel (low-temperature reaction). On the other hand, the duration of the main and final combustion stages shows a marked increase with the increase in the injection gap. This is thought to be due to the dominance of the CNG combustion (high-temperature reaction) at these stages. These increases in the combustion durations are a direct result of the low flame propagation speed of the CNG. This effect was more evident in the final stages of combustion as the diesel fuel was probably fully consumed during the initial and main combustion stages.

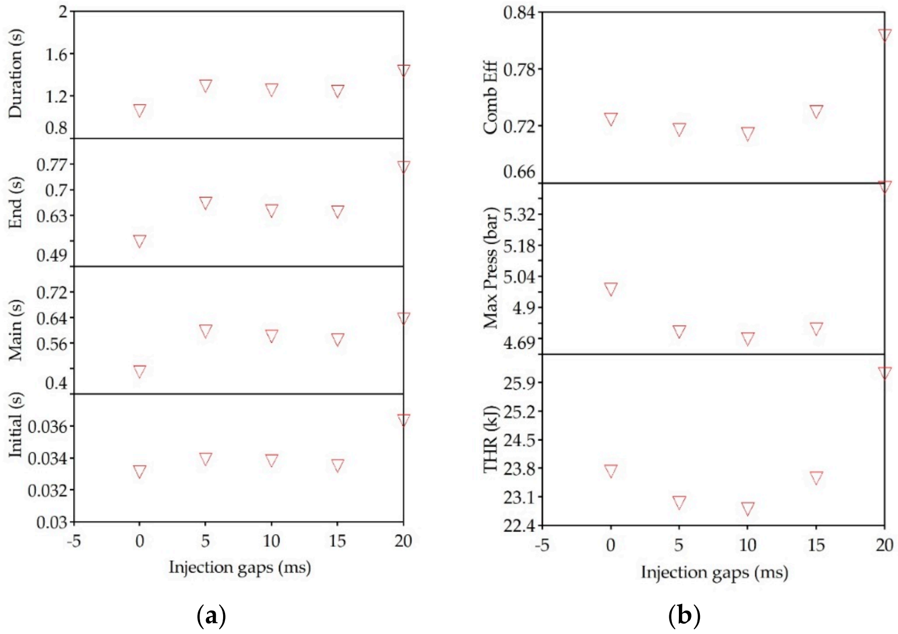


Figure 9. Combustion performance of diesel/CNG for various injection gaps for 60/40 Diesel/CNG. (**a**) Combustion phasing; (**b**) Combustion performance.

The effects of these changes in the combustion phasing on the integral combustion parameters are shown in Figure 9b. It is surprising to see that, despite the effect of the injection gap on the combustion phasing, the integral parameters are only slightly affected. This suggests that the overall increase in the combustion period with the increase in the combustion gap is not enough to influence the combustion behavior. Nevertheless, there was a small increase in all of the parameters shown with the increase in the injection gap.

The trends are at variance between 60/40 and 70/30 mixtures, as shown in Figure 10. 70/30 mixture behaves in the transition between the high stratified combustion and homogeneous mixture combustion. The combustion stages are less sensitive to the injection gap variations or in this case the mixture stratification level except for the initial combustion stage. At the initial stage, the combustion duration is longer as the injection gap increases. At the initial stage, 0 ms injection gap have more distributed droplet due to assistance from CNG injection momentum. As the diesel droplets are distributed, it attains a rapid vaporization rate, thus creating a favorable environment for the combustion to start. Therefore, the combustion delay and initial stage of combustion for 0 ms injection gap are shorter than 20 ms injection gap. As the combustion proceeds, the mixture characteristics for 40 ms and above shows almost a similar distribution, as shown in Figure 11, which might be the main reason for the subsequent combustion stages became insensitive to the injection gap variation.

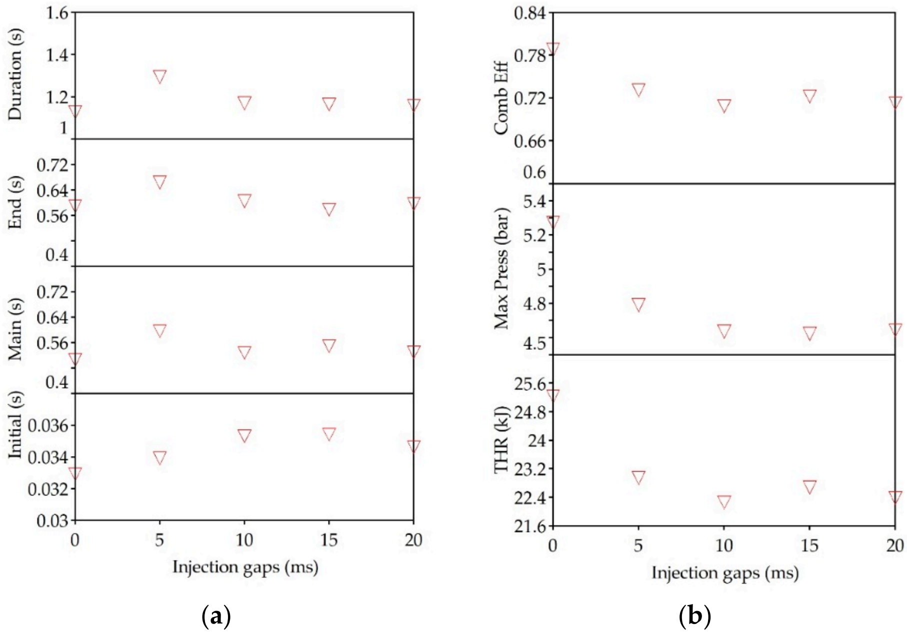


Figure 10. Combustion performance of diesel/CNG for various injection gaps for 70/30 Diesel/CNG (**a**) Combustion phasing; (**b**) Combustion performance.

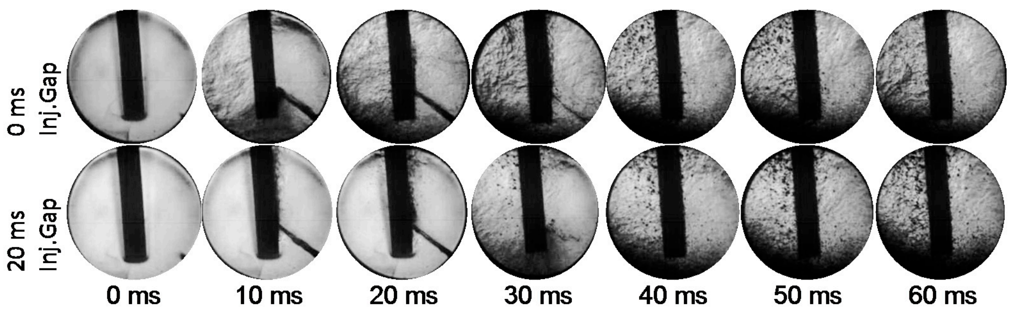


Figure 11. Mixture distribution for 0 ms and 20 ms injection gaps for 70/30 diesel/CNG composition.

In contrary with the 60/40 mixture, 70/30 mixture integral combustion parameters show a significant difference. The combustion efficiency, maximum pressure, and THR decrease with longer injection gap. These trends are closing into the 90/10, diesel rich mixture. The mixture distribution is more stratified because of the CNG amount that assisting the mixture is reducing at a higher diesel percentage, thus the combustion behavior moves toward the highly stratified mixture.

The data shows that the injection gap can shape the heat release rate in dual fuel combustion. However, this effect is reduced as the diesel percentage in the mixture increases.

4. Discussion

The fuel composition is showing dominant influence in the combustion of diesel/CNG mixtures. The combustion duration increased as the diesel composition increased, which is primarily caused by the diesel combustion that occurred during injection period. The addition of CNG in the mixture improved the air-fuel mixing, as well as reducing the global reactivity of the mixture, thus suppressing the combustion process of diesel. It produces shorter combustion duration yet a longer combustion delay. Nevertheless, the CNG addition improved the combustion output shown by higher combustion efficiency, maximum pressure, and total heat released. The combustion of diesel/CNG mixture is evenly distributed through the chamber while the combustion of diesel is focused around the injection path. These flame characteristics showed that diesel/CNG has potential in reducing soot emissions and improving the combustion performance. The data shows that 60/40 have the optimum mixture with the highest combustion efficiency, maximum pressure and THR, and the shortest combustion duration. This combination will improve the overall output from the combustion.

The injection gap, on the other hand, shows the diverse effect of the combustion phasing and combustion output. A high percentage of diesel (≥70%) will create a highly stratified mixture because of the lesser CNG injection that assists the mixing. As the effect, the injection gap shows less effect to the combustion phasing, but it does affect the combustion output. It indicates that 0 ms injection gap have a shorter delay and higher combustion efficiency. While for the lower diesel percentage (<70%), CNG significantly affects the mixture distribution that makes the injection gap able to create a different mixture distribution. Thus, it is able to influence the combustion phasing without affecting the combustion output. Longer injection gaps produce a longer combustion duration, especially at the main and final combustion stage.

The results show that CNG injection event was creating a various diesel stratification level across the chamber and create a variation of local reactivity index. Hence, it determines the combustion behavior of the mixture.

5. Conclusions

An investigation of the effect of fuel composition and the gap between the injections of diesel and CNG mixtures in a constant volume chamber was carried out. The aim of this study was to assess the use of these variables as a means of controlling the combustion process of these mixtures. There are few conclusions can be drawn from the results.

(1) The results showed that the fuel composition had a significant impact on the global reactivity index that later affect the combustion performance with higher pressure and THR, shorter duration, and higher combustion efficiency as compared to diesel combustion.
(2) The combustion performance deteriorated with higher CNG percentages in the mixture because of the low reactivity of CNG.
(3) 60/40 diesel/CNG composition shows the best output when compared to other mixture compositions as it produces higher combustion output and shorter combustion duration, even though it shows long combustion delay.
(4) The primary reason for the diesel/CNG mixture better combustion output is the distributed diesel droplet caused by CNG injection that became multiple ignition points that significantly shortened the combustion duration.
(5) The gap between the injections of the diesel and the CNG was found to have a diverse effect relative to the mixture compositions.

(6) For high diesel percentage, the injection gaps show less effect to the combustion phasing, yet it has a significant effect on the combustion output. The combustion efficiency is reduced, and the combustion delay is longer with the increase of injection gap.
(7) In contrary, for the lower diesel percentage, injection gaps show a significant effect on the combustion phasing with a longer injection gap having longer combustion duration. Despite its effect on the combustion phasing, injection gap shows less effect on the combustion output.
(8) Mixture composition and injection gap are capable of controlling the combustion output and phasing as it generally creating various global and local reactivity index.

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Conflicts of Interest: The authors declare no conflict of interest.

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