Abstract. The stringent emissions and needs to increase fuel efficiency makes controlled auto-ignition (CAI) based combustion an attractive alternative for the new combustion system. However, the combustion control is the main obstacles in its development. Reactivity controlled compression ignition (RCCI) that employs two fuels with significantly different in reactivity proven to be able to control the combustion. The RCCI concept applied in a constant volume chamber fueled with direct injected diesel and compressed natural gas (CNG) was tested. The mixture composition is varied from 0 – 100% diesel/CNG at lambda 1 with main data collection is pressure profile and combustion images. The results show that diesel-CNG mixture significantly shows better combustion compared to diesel only. It is found that CNG is delaying the diesel combustion and at the same time assisting in diesel distribution inside the chamber. This combination creates a multipoint ignition of diesel throughout the chamber that generates very fast heat release rate and higher maximum pressure. Furthermore, lighter yellow color of the flame indicates lower soot production in compared with diesel combustion.

1. Introduction
Stringent emissions regulations and a significant increase of fuel price highly affecting the growth rate of automotive technology development with the objective of reducing fuel consumption and improving engine efficiency. Controlled auto-ignition (CAI) based combustion system such as homogeneous charge compression ignition (HCCI), stratified charge combustion ignition (SCCI), and premixed charge compression ignition (PCCI) are the recent engine development with high efficiency, low emissions and fuel consumption.

In the effort of finding the effective method of controlling the combustion process, dual fuel or later known as reactivity charge compression ignition (RCCI) is found to be able to tailor the combustion process and phasing [1]. RCCI is a combination of the two fuels with significant difference in reactivity, high reactivity and low reactivity fuels. Various fuel combinations had been tested such as diesel-methane [2], diesel-gasoline [3, 4] and heptane-methane [5].

Originally, it was started with the combination of diesel and CNG where diesel fuel is used as pilot igniter for CNG. While, CNG selection as the combination of diesel is due to its low carbon ratio as well as its high octane number. It was proven that this combination can reduce the unburned hydrocarbon and nitric oxide emissions. Furthermore, it was stated that the methane addition significantly affect the intensity and spreading of the flame during the
combustion, especially with the suitable in-cylinder bulk flow motion. Furthermore, diesel-CNG combination is able to significantly reduce the soot and NOx emissions [6].

The interaction between methane and diesel was described by Carlucci, Laforgia [7] and Carlucci, De Risi [8]. Methane addition in the intake port is significantly affect the intensity and spreading of the flame during the combustion process of the dual fuel thus increase the combustion efficiency. As the results, hydrocarbon and NOx emission generated from this fuel combination is significantly lower compared to diesel. These earlier research have proven the ability of dual fuel RCCI fuel combination method in increasing the performance and reducing the emission of the diesel engine. However, the fundamental interactions between the two fuels have not been explained. It is necessary to improve the understanding on the interaction between the two fuels in order to improve the efficiency as well as opening the possibilities for other types of fuel combination.

The earlier diesel-CNG RCCI introduced CNG at the intake manifold while diesel is directly injected into the combustion chamber. This method is found to be advantageous because this setup does not require significant modification to the engine. However, it gives a limitation on the control parameter to the diesel injection parameters such as injection pressure and multiple injection system. Previous research stated that the combustion results from the dual fuel combination also affected by the bulk in-cylinder flow motion [7]. It is known that the cylinder bulk motion have significant effect on the fuel mixing process which also maybe the cause of the variation in the combustion process of the dual fuel.

In order to gain more control in fuel delivery method and fuel-air mixing variation, dual-direct injection method is proposed in this research. The freedom to control the injection strategies for both fuels, will give further advantages in shaping the combustion process of RCCI and further improve the combustion performance as well as the operating range of the CAI based engine. This study focuses on the combustion properties of direct injected diesel, and directly injected CNG mixture in the constant volume chamber (CVC) at elevated temperature. This method isolates the mixture distribution affecting parameters to the injection strategy which excluding the bulk in-cylinder flow. Furthermore, the mixture composition effect to the combustion output of the mixture will be discussed further.

2. Experimental Setup
The study performs 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 purity 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.
In the experiment, three fuel mixtures were tested, Diesel-CNG and heptane-CNG. The composition was varied from 10-100% Liquid fuel/CNG. The combustion data for these mixtures were obtained for lambda 1.

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.

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               |

The CNG injector was using 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.
Lambda was generated by calculating the stoichiometric reaction between the fuels and oxygen.

\[ x \text{C}_{10}\text{H}_{22} + (1 - x)\text{CH}_4 + a(O_2 + 3.76\text{N}_2) \leftrightarrow b\text{CO}_2 + c \text{H}_2\text{O} \]

Lambda resulted from the above equation for each mixture is depicted in Figure 3. It ranges from 17.8 to 16.6.

![Figure 3. Lambda for various mixture compositions.](image)

The required fuel amount at constant volume (0.000492 m³) was determined and translated to the injector opening by dividing the total fuel required with the injector delivery rate.

3. Results And Discussion

Various compositions of diesel and CNG ranges from 0 to 100% diesel/CNG percentage were tested. It is found that there is a lowest limit for diesel/CNG composition percentage in order for the combustion to occur. 50% diesel/CNG shows the lowest composition limits for the mixture to combust in this experiment as shown in Figure 4. The inexistence of combustion for lower diesel percentage may be caused by the dominant CNG properties that have very low reactivity with high auto-ignition temperature and very high octane number that suppressed the diesel combustion.

This diesel-CNG trend has a similar pattern to the simulation done by Zoldak, Sobiesiak [1] that shows increasing maximum pressure with additional CNG in the mixture. The main reason for this behavior is the unique interaction between diesel and CNG. Diesel combustion categorized as diffusive where the combustion occurs during the injection period. CNG, on the other hand, have very low reactivity that makes it difficult to combust. Diesel as the source of ignition for CNG creates a favorable condition for CNG to combust yet CNG is suppressing the combustion of diesel to the point where diesel droplet has been distributed all over the chamber. The phenomena happen in such ways that distributed source of ignition occurs inside the chamber to ignite CNG and starts the flame propagation process similar to the spark ignition combustion.

This interaction also caused faster combustion rate with a shorter duration as shown in the heat release graph in Figure 5 where the maximum pressure increased from 0.02 kJ/s to 0.1 kJ/s, and the combustion duration reduced from 1.5 s to 0.9 s. Furthermore, Figure 5 also shows the significance of CNG in diesel combustion. 10% CNG composition in the mixture is able to improve the HRR twice of the single diesel combustion. However, diesel on the other hand
shows second pressure peak at 90 ms after the combustion starts. This is caused by the combustion of unburned diesel at the center of the chamber as shown in Figure 6 as the yellow bright point while the earlier flame shows darker flame that indicates the final stage of the combustion process.

![Figure 4](image)

**Figure 4.** Combustion properties of Diesel-CNG at lambda 1.

![Figure 5](image)

**Figure 5.** Heat release rate profile for various mixture of diesel-CNG combustion at lambda 1.

However, the combustion limitation occurs at the point where diesel combustion could not create the suitable environment for CNG to combust which is shown by the decreasing rate of the combustion at 50-50 diesel-CNG composition.
Figure 7 also shows that CNG injection creates distributed hotspot along the diesel injection axis. It is marked by the bright spots along the axis. These scattered hotspots could increase the heat release rate of the mixture up to four times faster and significantly shorter duration compared to the single fuel (diesel). In addition, the flame at the final stage of the combustion for 100% diesel shows darker yellow color that indicates potentially high soot concentration in the exhaust. The DCNG mixture, on the other hand, shows bright yellow flame during the combustion process and subtle percentage of the darker flame on the final stage of the combustion. This behavior align with the previous literature involving diesel and CNG mixture that stated that diesel-CNG mixture combination is able to drastically reduce the soot emission in diesel engine.

4. Conclusions
In this paper, diesel and CNG mixture combustion behavior is analyzed. The addition of CNG in diesel can increase the combustion output of the mixture. It generates higher maximum pressure, faster heat release rate, and shorter combustion duration. The minimum mixture composition is at 50% diesel/CNG that is caused by the low reactivity of CNG that suppresses the diesel combustion.

The main reason for the increased combustion output is the multi ignition point generated with CNG injection. CNG is suppressing the diesel combustion and delayed the timing until the diesel is distributed throughout the chamber and create a multipoint ignition.
The flame image shows that the combustion of diesel-CNG mixture is better than diesel combustion shown by bright yellow flame throughout the combustion process while diesel shows darker yellow flame color. The flame color also indicates the probabilities of soot generation where darker flame has larger probabilities to generate more soot emissions. Further experiment on the engine need to be done in order to verify the combustion characteristics of diesel-CNG mixture combination. Furthermore, dual fuel direct injection system concept need to be tested in the actual engine in order to prove its capabilities in controlling CAI based engine technology.

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