The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2022

Volume 21, Pages 525-540

IConTES 2022: International Conference on Technology, Engineering and Science

# Investigation on the RCCI Engine on Performance and Emission

**Ahmad Fitri YUSOP**
Universiti Malaysia Pahang

**Mohamad Adzuan AZIZ**
Universiti Malaysia Pahang

**Mohd Adnin HAMIDI**
Universiti Malaysia Pahang

**Daing Mohamad Nafiz DAING IDRIS**
Universiti Malaysia Pahang

**Ummi Hafsah ZAIDI**
Universiti Malaysia Pahang

**Abstract**: RCCI engine is among the most promising combustion technology for the upcoming generation of heavy-duty motors. In RCCI mode combustion, different combinations of low reactivity fuels (LRF) and high reactivity fuels (HRF) such as PRF-Diesel, can be used to achieve a chemical reaction or reactivity stratification in the engine combustion chamber. The high reactivity fuel (HRF) which is diesel will be injected in the direct fuel injection and the low reactivity fuel (LRF) which is Primary Reference Fuel (PRF) will be injected in port fuel injection. Combustion in the engine combustion chamber will convert the chemical energy of fuels to heat that can be used directly or further converted to mechanical energy. Internal combustion engine outputs mechanical power by extracting energy in fuels via combustion reaction in the cylinders. Fuels are burned in the combustion chambers to generate high temperature and high-pressure gas which delivers power to the piston. RCCI had a low performance at high engine speed due to its high tendency on knocking and high pressure rise rate. Therefore, this study investigates the effect of the fuel stratification on the RCCI combustion and it's extended to the interaction of high and low reactive fuels, PRF and diesel in the RCCI combustion system. Modified engine was tested for engine performance. The change in BSFC, Power and Torque are observed at all loads and speeds with different PRF percentages. For emissions, this RCCI engine was said to produces extremely low in nitrogen oxide. On a regular diesel engine, these kinds of pollutants cause problems. The cool burning, on the other hand, does not emit nitrogen oxide when using an RCCI engine. Aside from that, because the RCCI engine uses less diesel fuel, the diesel fuel has more time to mix in the cylinder.

**Keywords:** RCCI engine, Performance, Emission, Engine speed, Engine load

## Introduction

Homogeneous-charge compression ignition (HCCI) engines are said to have higher thermal efficiency and lower pollutant emissions than conventional diesel and gasoline engines over the last two decades The reactivity-controlled compression ignition (RCCI) mode has been developed and extensively explored to achieve ultra-high efficiency and near-zero emissions in an internal combustion engine. The reactivity-controlled combustion ignition is achieved by producing reactivity stratification in the cylinder by using two fuels with different cetane numbers. The low reactivity (low cetane number) fuel is premixed with air before being charged into the cylinder via the intake manifold; the high reactivity (high cetane number) fuel is then injected into the charged mixture via a direct injector. With that, the reactivity stratification is created (Reitz & Duraisamy, 2015). According to earlier research, the LRF should contribute as the majority of total injected fuel in order to create a highly efficient RCCI operation with minimal emissions, while the HRF is used to initiate the combustion process. Furthermore, HRF plays an important role in in-cylinder reactivity stratification because HRF injection settings are one of the most important parameters for the combustion process development. The RCCI concept has recently been demonstrated in a variety of engine platforms, including single-cylinder, multi-cylinder, heavy-duty, medium-duty, and light-duty diesel engines with low, medium, and high compression ratios (CR). These studies show that, under stationary circumstances, RCCI can produce lower NOx emissions, as well as ultra-low soot emissions. Despite this, RCCI has a number of issues, including excessive unburned HC and CO emissions during low engine load operation, as well as excessive maximum pressure rise rates (MPRR) and in-cylinder maximum pressure peaks (Pmax) at high loads. These two constraints limit the RCCI's operating range to medium loads, making it unsuitable for use in real engines situations. As a result, the large number of operating conditions within the RCCI range produced after the gear shifting optimization is predicted to result in a significant reduction in aftertreatment requirement (Benajes et al., 2018). Kokjohn et al., in particular, studied at the combustion characteristics of diesel low temperature combustion (LTC), ethanol-diesel RCCI, and E85-diesel RCCI combustion numerically. The consumption of high reactive diesel and low reactive E85 in E85-diesel RCCI combustion was found to be staged combustion, with E85 not being used until the gradual shift of diesel consumption to the second stage ignition (Benajes et al., 2018).

RCCI combustion is a dual-fuel technique that takes advantage of the benefits of employing different reactivity fuels. High-reactivity fuels, such as diesel, are injected directly into the chamber, whereas low-reactivity fuels, such as gasoline, are delivered through the intake ports. These engines feature more effective combustion phasing control and operate better at higher loads (Kahnooji & Yazdani, 2021). The overall combustion of RCCI cases occurs earlier and its mean heat release rate (HRR) is more evenly distributed over time than that of the corresponding SCCI cases in the low and intermediate-temperature regimes. This is due to the fact that within the negative temperature coefficient (NTC) zone, PRF number stratification, PRF', is governing and the different level of temperature, T', has a small effect on overall combustion. The difference between RCCI and SCCI combustion becomes negligible in the high-temperature regime, however, because the ignition of the PRF/air mixture is mainly sensitive to T' rather than PRF' and different level of equivalence ratio, phi'(Luong et al., 2017). Chemical kinetics, which is known to be heavily impacted by mixture pressure, influences the RCCI strategy. When diesel is introduced into a homogenous gasoline/air combination, the local PRF number in the cylinder is reduced, resulting in an increase in local reactivity (Han et al., 2018).

Studies on dual combustion of gasoline and hybrid powertrains have shown that lower maximum ICE outputs result in reduced NOx and soot emissions (García et al., 2020). The narrow angle direct injection technique was used in a study on homogenous charging compression ignition engine features powered by biofuels to create practically zero percentiles of nitrogen oxides and high output power particle emissions, torque at part load conditions (Saiteja & Ashok, 2021). Additionally, a strain gauge cell was used in a performance and operating cost study to compute the brake power of the dynamometer in the dual-mode RCCI diesel-natural gas and diesel combustion engines (Ansari et al., 2018). Further studies on the technique for injecting and changing a single-cylinder diesel engine's combustion chamber have shown that if engine injection properties are improved so that the new swirl bowls produce the same amount of power, NOx emissions may also be reduced (Sener et al., 2020). In order to keep CA10 constant, the SOI should be advanced by increasing load. The reason for this is that the local equivalence ratio will increase by enhancing load; therefore, injection should be start earlier to more homogenize the mixture. This dual stage HTHR qualifies for lower engine noise and higher engine torque operation due to increased fuel injection (Pan et al., 2020). Additionally, studies on natural gas diesel injection techniques with dual fuel compression premixed ignition combustion in low load conditions have demonstrated that great fuel economy and torque of diesel engines are accomplished (Park et al., 2019). In addition, a study on energy's dual-combustion exergy testing for oxygenated biofuels found that the essential elements in increasing an engine's torque output—which in turn enhanced brake power—were lessened pumping effort, lessened compression work, and improved expansion processes (Rangasamy et al., 2020). Additionally, according to research on combustion, performance, and emission characteristics, CI engines are more widely used in a variety of economic sectors, such as transportation, agriculture, and construction, because they offer better power/driving output, durability, and dependability due to their higher BTE braking efficiency (Singh et al., 2020). In the meantime, data from the study on air intake method for low HC and CO emissions in dual fuel premixed (Shim et al., 2018) shows that the engine's maximum torque is at 1400 rpm. Additionally, research on the combustion of dual fuel diesel and natural gas at low loads shows that, even with changes in NG quantity after other burning limitations are established (W. Li et al., 2016), the test setup parameter remains constant with engine speed and torque output. Furthermore, research into the emissions and performance of dual direct injection hydrogen-diesel engines set their engine at a constant speed of 2000 rpm, which is the speed at which the production engine achieves its maximum torque output. Before more data is collected, research into comparisons between dual combustion of pure diesel and diesel methanol sets the engine torque parameters at 440N.m and 220N.m.

Exhaust Gas Temperature (EGT) and Brake Specific Fuel Consumption (BSFC) are lower in RCCI mode as compared to CDC (Charitha et al., 2019). The fuels with S=5 and S=8 exhibit a minor increase in BSFC values for dual mode with differing octane numbers seen under low load situations because of the early combustion start, which releases more energy during the compression stroke and reduces cycle efficiency (García et al., 2019). In addition, the performance of the RCCI with diesel demonstrates that the inclusion of biodiesels results in a higher fuel demand to provide a similar engine output due to the fuel's reduced heat content (Charitha et al., 2019). Additionally, a study of fuel on RCCI demonstrates the effects of RON of PI fuels and CN of DI fuels on the indicated fuel consumption (ISFC) under various premixed ratios and reveals that the ISFC of the majority of fuel combinations was higher than the DICI mode, primarily because of the insufficient combustion of port injection fuel and the delayed combustion phase. Additionally, research on methanol and the extra air/fuel ratio reveals that during lean burn conditions, the equivalent BSFC decreased (L. Wang et al., 2019).

According to a performance study of hydrogen diesel, the temperature of the exhaust gas as it travels through the turbocharger drops by roughly 45 K (Liu et al., 2021). Additionally, research on oxidation catalysts indicates that keeping the exhaust gas temperature below 150 °C helps to increase HC adsorption (Piqueras et al., 2019). Additionally, research on diesel-natural gas indicates that the highest EGT is 480 °C (Ansari et al., 2018). The exhaust temperatures of this dual-fuel strategy were greater, according to a research of dual fuel in full operational map (Raza et al., 2019). The hotter combustion processes also produced reduced CO and unburned HC emissions as well as greater exhaust gas temperatures, according to a research of ethanol/diesel (Pedrozo, May, Lanzanova, et al., 2016). Additionally, according to a study on the optimization of performance and operating costs for a dual mode diesel-natural gas RCCI and diesel combustion engine, Diesel-NG fuel blends are used more and more in RCCI internal combustion engines due to their high Brake Thermal Efficiency (BTE), low NOx and PM emissions, and relatively low Exhaust Gas Temperature (EGT). In this configuration, the EGT was predicted using data from the RCCI exhaust gas temperature after the turbine (Ansari et al., 2018). On the other hand, research on the impact of equivalence ratio on the combustion and emissions of a dual-fuel natural gas engine ignited with diesel claimed that the high equivalence ratio in dual-fuel ignition mode is responsible for the increased exhaust gas temperature and decreased combustion duration. Additionally, it is claimed that the high equivalence ratio combustion has a higher cylinder average temperature than the lean burn combustion, in which the temperature of the exhaust gas is elevated as a result of a reduction in air mass. It is further claimed that regardless of strategy variations such nozzle specifications, an increase in equivalent ratio can be used to obtain the highest heat release rate, an increase in exhaust gas temperature, and a shorter combustion time. Additionally, the findings showed that an increase in EGT causes CO emissions to rise noticeably when the equivalency ratio exceeds 0.95 (Salahi et al., 2017). The reactivity-controlled compression ignition (RCCI) mode has been developed and extensively explored to achieve ultra-high efficiency and near-zero emissions in an internal combustion engine. They determined that the fuel reactivity gradient was the main parameter in the RCCI mode combustion process and emission product control after examining the fuel mixing process.

Researchers have devoted a lot of time and attention into studying fuel injection parameters in order to improve efficiency and reduce emissions. Premixed fuel ratio, injection pressure, direct-injected fuel spray angle, and SOI (start of injection) timing, among other injection parameters, are all related to an engine's injection method (J. Li et al., 2018). According to the study, for moderate-to-high loads, a gasoline/diesel dual-fuel RCCI regime may achieve ultra-low NOx and soot emissions as well as high thermal efficiency, but diesel low temperature combustion (LTC) with single-shot fuel injection is more suitable for low-load operations (Y. Wang, Yao, et al., 2016). Pressure and temperature are reduced, and combustion phasing is delayed, when engine speed is increased at three different piston bowl profiles. Higher engine speeds not only allow for fewer chemical reactions, resulting in more incomplete combustion, but they also allow for less heat transmission, potentially leading to higher in-cylinder temperatures (Kakaee et al., 2016). It has been demonstrated that an optimised mid-speed RCCI engine with a compression rate of 15.2 may achieve gross indicated efficiencies of 52 percent while maintaining the benefits of a high blend rate (over 90 percent) and achieving $NO_x$, CH4, and CO emissions below the strict Stage V standard (Mikulski et al., 2019). The RCCI engine with a pre-chamber experiences a completely full combustion process during the fuel mixtures with a greater equivalence ratio, which resulting in high combustion efficiency, nearly to no UHC emission, and low CO emissions. However, at high load conditions, substantial levels of NO are produced due to high temperatures. While flame propagation does not occur adequately during the fuel mixtures with low equivalence ratios. The RCCI engine with a pre-chamber encounters incomplete combustion, resulting in lower combustion efficiency and higher UHC and CO emissions (Salahi et al., 2017). In addition, study on performance of RCCI shows that the $CO_2$ emissions indicate an increase for RCCI at higher engine loads (Reitz & Duraisamy, 2015). With the introduction of COME, there was a simultaneous reduction in NOx and smoke emissions. Unburnt hydrocarbons (UHC) dropped at lower percentages of COME and increased at higher percentages of COME, while $CO_2$ emissions fell marginally (Charitha et al., 2019). The $CO_2$ content in the intake and exhaust was used to compute the EGR rate. Furthermore, as CA10 decreased, more combustion took place towards the top dead centre. Less fuel accumulates on the cylinder head in the case of 30% biodiesel in the first pulse. As a result, the rate of evaporative fuel consumption (EFC) is faster than the case with 70% in the first pulse. When it comes to the effect of fraction in the first pulse, the NO emissions decrease as the fraction in the first pulse increases. Fuel deposition in the squish zone is severe when more fuel is delivered through the first pulse (J. Li et al., 2018).

The RCCI combustion strategy's major purpose is to decrease emissions, particularly $NO_x$ and soot, by managing in-cylinder reactions through low temperature and lean combustion (Kakoee et al., 2020). RCCI combustion can operate at a wide range of engine loads (4.6–14.6 bar) with near-zero NOx and soot levels (meet regulation standards), a low pressure rise rate and ringing intensity, and a high indicated efficiency (J. Li et al., 2017). Over a wide engine IMEP range of 4 bar to 14.5 bar using gasoline and diesel fuels, RCCI results revealed high thermal efficiency and also very low $NO_x$ and soot emissions. $NO_x$ emissions and combustion noise were reduced as low as possible by adopting Exhaust Gas Recirculation (EGR) during high load operating conditions. However, owing of the PPRR constraint and EGR rate requirements, extending to loads over 14.5 bar IMEP with gasoline/diesel has been challenging (Nazemi & Shahbakhti, 2016). A lower amount of $NO_x$ and higher soot emissions can be obtained through the longer diffusion combustion resulted from shorter mixing interval. Higher injection pressure increased diesel atomisation and resulted in a more uniform charge, causing the SOC to be delayed. This resulted in a faster combustion process, increased PRR, and increased $NO_x$ emissions (Pedrozo, May, Dalla Nora, et al., 2016). The use of E85 as the LRF allows the RCCI operating zone to be extended, resulting in a larger ultra-low NOx region but higher HC and CO levels in the RCCI zone. RCCI soot levels are lower with E85 than with gasoline (Benajes et al., 2018). In comparison to gasoline and natural gas, alcoholic fuels have a higher heat of vaporisation. This ability to absorb heat during evaporation might result in a cooling effect, lowering the temperature of the charged mixture. The reduction in temperature has the ability to lower $NO_x$ production (J. Li et al., 2017).

Furthermore, as IMEP (load) increases, HC and CO emissions decrease dramatically for methanol combustion. With a higher IMEP (load), more turbulence and warmer in-cylinder temperatures can lessen the problem of unburned methanol, lowering HC emissions dramatically (Dong et al., 2020). According to experimental results of RCCI engine with variable percentages of Bio-Diesel (COME) ranging from 10% to 30% at various engine loads, the reduced percentages of COME result in lower HC emissions, with a maximum reduction of roughly 33% at 15% of COME. While, the higher percentages of COME result in higher HC emissions (Charitha et al., 2019). Another study found that when the 2-butanol/diesel is used in RCCI combustion mode, the HC emissions released are much higher compare to the Conventional Combustion Mode (CCM) under various engine loads. The decreased in combustion temperature, which results in poor combustion, and the 2-butanol trapped in crevices throughout the combustion process could be the main causes of this outcome (Pan et al., 2017). At moderate engine speeds, high thermal and combustion efficiency can be attained with relatively low CO and HC emissions and low fuel consumption. When compared to the cases where EGR was not used, less CO and HC emissions were released, implying that further fuel consumption improvements could be achieved. This is due to the adoption of EGR, which causes a longer ignition delay (Y. Wang, Zhu, et al., 2016).

## Experimental Setup

### Flowchart

Figure. 1 demonstrates the working process of the experiment. The experiment starts with Literature Review on related past researches journal of RCCI Engine. The best fuels are then determined to be used in this research. The different types of Primary Reference Fuel (PRF) used are PRF20, PRF40, and PRF60. PRF uses iso-octane and n-heptane for fuel blending. For PRF20, it means the fuel blending is 20% of iso-octane and n-heptane, while PRF40 means 40% iso-octane, 60% n-heptane and 40% iso-octane, 60% n-heptane for PRF60. Diesel was chosen in this experiment due to its high cetane number. The ease at which diesel fuel ignites, influences engine starting and combustion roughness. The higher the cetane rating, the shorter the lag time between the time the fuel enters the combustion chamber and the time it begins to burn. For each PRF value, various engine speed at 900, 1200, 1500, 1800, 2100 rpm and various engine loads at 0%, 20%, 40%, 60% by using PRF 20%, 40%, 60% are used to investigated the performance, and emission of RCCI Engine. The experiment continues step by step until the desired data are obtained. All results will be recorded and transfer into graphs.

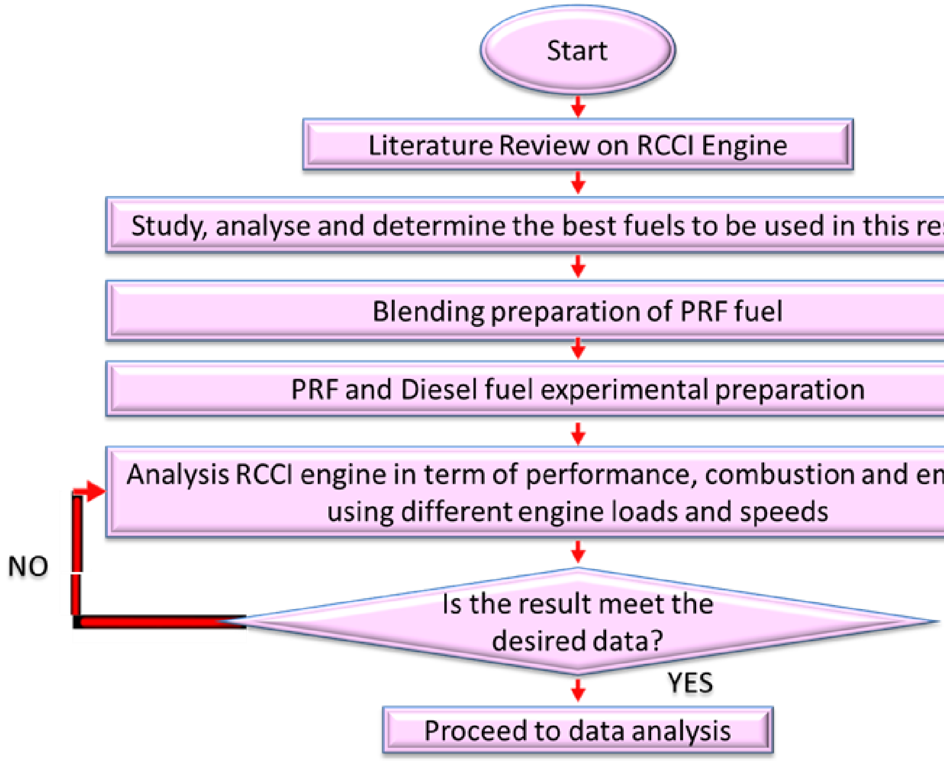


Figure 1. Project flowchart

**Engine Modification**

The diesel engine used to conduct the experiment and run the sample fuels is YANMAR Model TF120-M, a single cylinder diesel engine with 2400RPM and 12HP, water cooled, 4 cycle diesel engine with direct injection (DI) and natural aspirated engine. YANMAR TF120-M is manufactured by Yanmar Co.Ltd. The engine swept volume is 638cm3 with bore × stroke of 92 × 96 mm.

The experiment will be started by using diesel in normal engine mode at engine speed 900rpm, 1200rpm, 1500rpm, 1800rpm, and 2100rpm with various engine loads at 0%, 20%, 40% and 60%. The experiment then will be continued by using PRF20 in RCCI engine mode. Two beakers will be filled with PRF20 and diesel respectively. In this study, both beakers serve as fuel tanks. Low reactivity fuel (PRF) is used at the port injection system while pure diesel is used at direct injection system. The two fuel tanks will be placed on separate weighing scales to determine the weight losses, which corresponds to fuel consumption. The engine switch will be turned on to start the engine power. Measure the engine performance first if the engine has been running for 15 minutes or has reached an oil temperature of 600C in order to ensure the engine reaches an appropriate operating condition. The selected engine performances parameters to be measured are torque, exhaust gas temperature, and power. It is also necessary to ensure that all computers are turned on and that all software is connected to the computer for data collection. The experiment will be repeated with different PRF values of PRF40 and PRF60 at five different rpm which is 900, 1200, 1500, 1800, 2100 rpm with four different stages of load which is 0%, 20%, 40% and 60% at TPS 0% and 15%. All data is checked and recorded.

The engine was modified to run the engine in a dual fuel injection. The change is made to the injection system at the port and dynamometer. To establish the RCCI engine mode, the diesel engine must be transformed from single fuel injection to dual fuel injection, which includes direct injection and port injection. Low reactivity fuel, which is the variable PRF values in this research is used at the port injection while pure diesel is used at direct injection as high reactivity fuel. Further details of the engine specifications used in this research can be obtained from Table 1.

Table 1. Engine specifications

| Model | Yanmar Model TF120M |
|---|---|
| Type | Horizontal single-cylinder 4-stroke diesel engine |
| Bore (mm) | 92 |
| Stroke (mm) | 96 |
| Displace volume ($cm^3$) | 638 |
| Compression ratio | 17.7:1 |
| Continuous rating output | 10.5 HP @ 2400 rpm |
| Maximum rating output | 12.0 HP @ 2400 rpm |
| Fuel injection type | Direct Injection |
| Injection timing | $17^o$ BTDC |
| Max power | 7.7 kW @ 2400 rpm |
| Max torque | 161 Nm @ 4500 rpm |
| Cooling system | Water-radiation |
| Fuel tank capacity | 11L |

**Experimental Software**

KANE LIVE displays "real time" readings for HC, CO, CO2, NOx, and O2 emission. All data is viewable digitally in computer, allowing for easy tracking of parameters as they change over speeds and loads. The standard file for importing and exporting data, a.CSV file, can be used to save and keep all the live data in the computer. DynoMonV4 is used to measure the performance of the RCCI engine. The performance parameters measured by the engine speeds and loads in this experiment are torque, power, Brake Specific Fuel Consumption and Exhaust Gas Temperature. Standard factors like RPM, Coolant temperature, load, MAP, and MAF can be modified by TunerStudio MS Lite filtering data to fit your configuration or preferences. The calibration settings of the controller are being changed. You can use it to record runtime data and capture it. Offline tuning, loading and saving tune files, and basic data logging are among the functions offered. Picolog6 is used to measure the temperature of the engine such as intake temperature, engine oil temperature and exhaust temperature.

KANE AUTOplus Gas Analyser, which is handheld and portable, is used to measure combustion characteristics of CO, HC, CO2, O2, and NOx. It is connected to KANELIVE software and the software will display the results of gas emissions. A weighing balance is an instrument that is used to measure the weight of the fuel decrement for the combustion process in this experiment. The additional dynamometer connected to the diesel engine is employed for measuring force, torque, and power. The power produced by the engine, motor or other rotating prime mover can be calculated by simultaneously measuring torque and rotational speed (RPM). The dynamometer used in this experiment act as load in a real-world vehicle. It can be adjusted to increase or reduce the load during the experiment. The dynamometer is also connected to the diesel engine to measure the torque, power and force.

**Fuel Preparation**

The RCCI engine mode used two types of fuel which are Low Reactivity Fuel (LRF) and High Reactivity Fuel (HRF). In this experiment, pure diesel (B0) that was injected by direct injection was employed as the high reactivity fuel (HRF), while Primary Reference Fuel (PRF 20, 40, 60), which were injected using a port injection technique employed as the low reactivity fuel in this experiment. Additionally, as the pure diesel is supplied to the direct injection system, it requires no blending process. The volume of each n-heptane and iso-octane used in this experiment are tabulated in Table 2 below.

Heptane, commonly known as n-heptane, is an important component of gasoline and has the chemical formula of H3C(CH2)5CH3 or C7H16 (petrol). When used as a test fuel component in anti-knock test engines, a fuel that is 100% heptane corresponds to the zero point on the octane rating scale. The percentage of iso-octane in heptane, which is stated on gasoline (petrol) pumps around the world, is the octane number, which relates to the antiknock qualities of a comparative mixture of heptane and isooctane. Table 3 shows N-heptane properties. Isooctane is an alkane composed of pentane with two methyl substituents at position 2 and one methyl substituent at position 4 as illustrated in Table 4. It acts as a fuel additive, a nonpolar solvent, and a nephrotoxin. It is a volatile organic substance and an alkane.

Table 2. Fuel matrices

| Fuel mixture (500ml each blend) | | |
|---|---|---|
| Primary reference fuel | n-heptane | iso-octane |
| PRF20 | 80% | 20% |
| PRF40 | 60% | 40% |
| PRF60 | 40% | 60% |

Table 3. N-heptane properties

| n-heptane properties | |
|---|---|
| Properties | Description |
| IUPAC Name | heptene@Dipropylmethane |
| Molecular formula | C7H16 |
| Molecular Weight | 100.2 |
| Physical Description | -clear colourless liquid<br>-petroleum-like odor<br>-Flash point 25°F<br>-Less dense than water<br>- insoluble in water<br>- Vapours heavier than air |
| Boiling Point | 98.5 °C |
| Melting Point | -90.6 |
| Autoignition Temperature | 433 °F (285 °C) |
| Experimental Properties | It is a lighter component in gasoline, burns more explosively, causing engine pre-ignition (knocking) in its pure form, as opposed to octane isomers, which burn more slowly and give less knocking. |

Table 4. Iso-octane properties

| Iso-octane properties | |
|---|---|
| Properties | Description |
| IUPAC Name | 2,2,4-trimethylpentane |
| Molecular formula | C8H18 |
| Molecular Weight | 114.23 |
| Physical Description | -clear colourless liquid<br>-petroleum-like odor<br>-Less dense than water<br>- insoluble in water<br>- Vapours are heavier than air |
| Boiling Point | 99.2 °C |
| Melting Point | -107.3 |
| Autoignition Temperature | 784 °F (418 °C) |
| Experimental Properties | Less than 32 Saybolt universal second<br>Antiknock octane number 100; dipole moment: 0 |
| Usage | 2,2,4-Trimethylpentane is used in determining octane numbers of fuels, in spectrophotometric analysis, as a solvent and thinner, and in organic syntheses. |

The process of blending the PRF20, PRF40 and PRF60 involved in this experiment is the mixing of two types of fuels in a beaker which are iso-octane and n-heptane. Pure isooctane (2, 2, 4-trimethylpentane) has been assigned an octane number of 100 because of its excellent antiknock properties and n-heptane is assigned an octane number of zero because of its propensity to auto-ignite easily. Therefore, a 80:20, 60:40 and 40:60 blending ratio of iso-octane and n-heptane respectively are used to prepare the PRF20, PRF40 and PRF60 in this experiment. The fuel blending requires stirring process for 15 minutes with 500rpm by using IKA RW20 Digital

Overhead Stirrer. After the fuel blending process is completed, the blended fuel will be kept for at least 2 hours before can be used for the experiment.

## Result and Discussion

This experiment investigates the the effect of blending Diesel-PRF in RCCI engine mode on torque, power, exhaust gas temperature (EGT), and gas emissions. The experiment was conducted under the determined operational conditions. This chapter explains the engine results for the throttle positioning sensor (TPS) 0% and 15%.

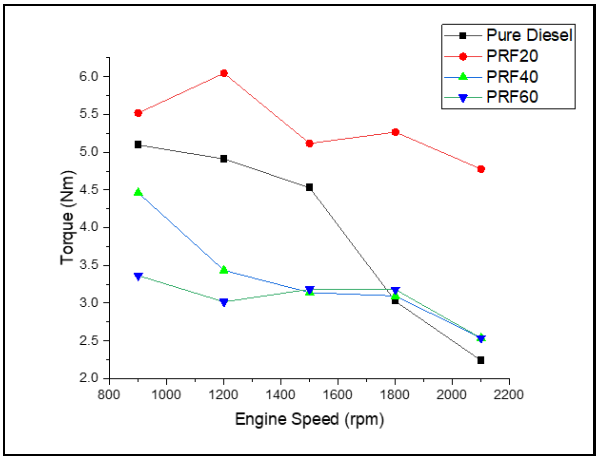


Figure 2. Torque at 0% Load

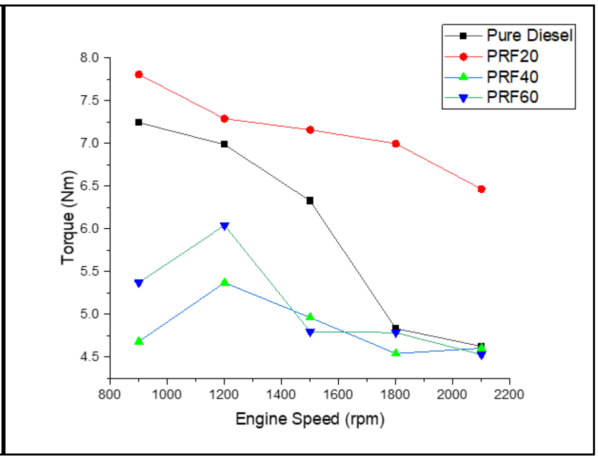


Figure 3. Torque at 20% Load

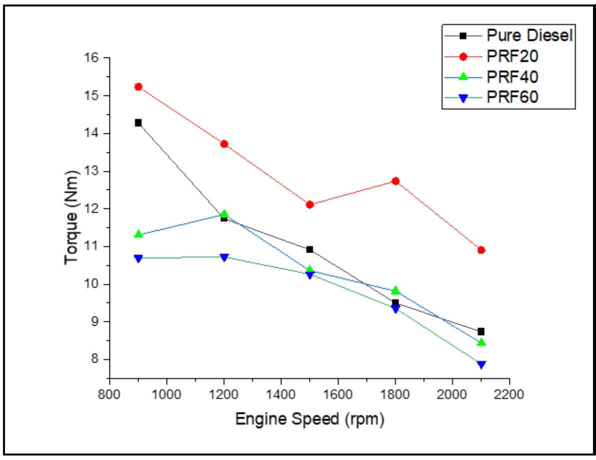


Figure 4. Torque at 40% Load

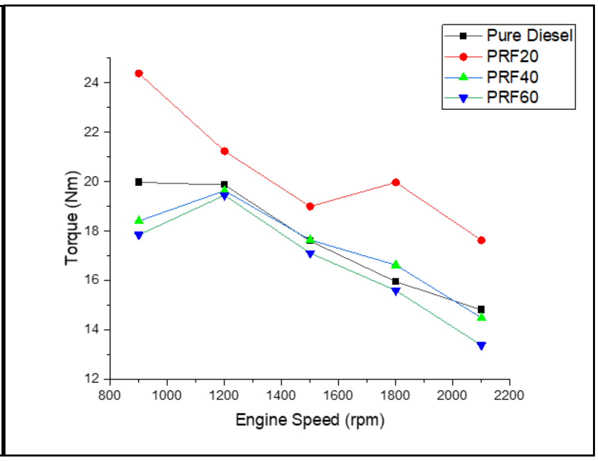


Figure 5. Torque at 60% Load

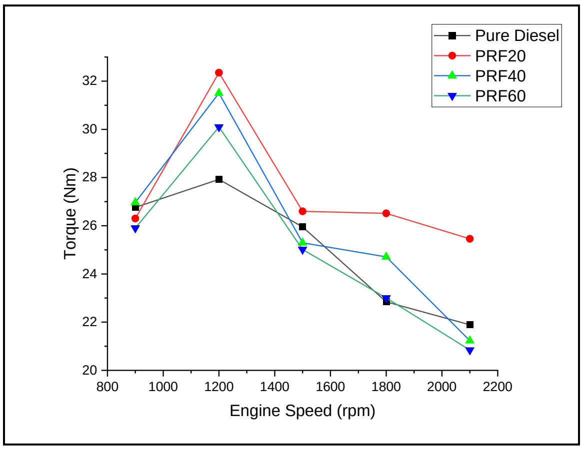


Figure 6. Torque at 80% Load

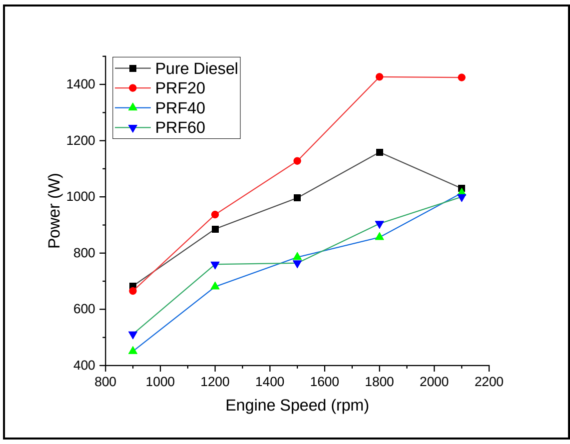


Figure 7. Power at 0% load

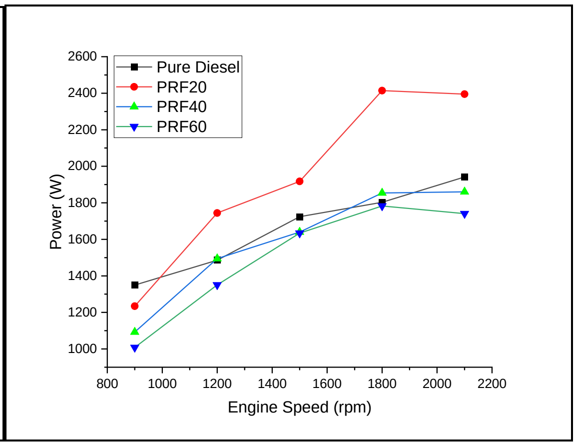


Figure 8. Power at 20% load

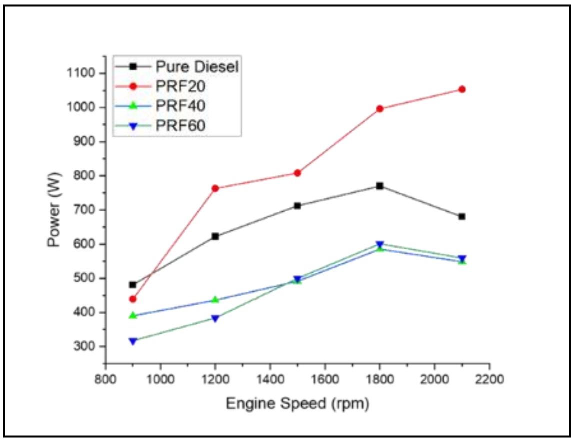


Figure 9. Power at 40% load

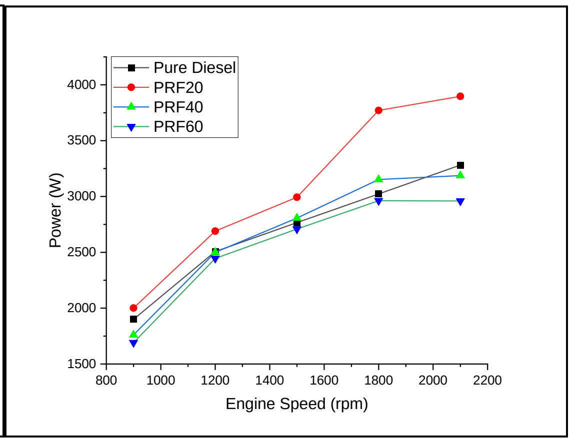


Figure 10. Power at 60% load

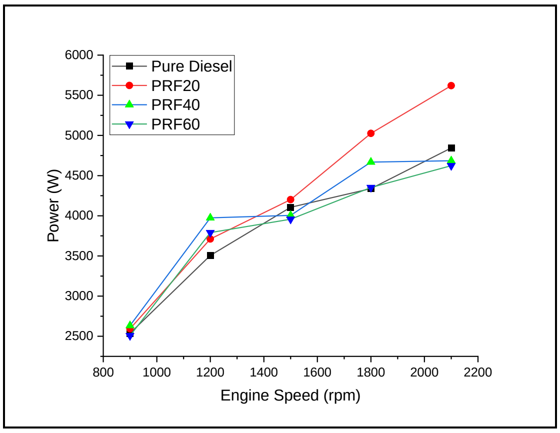


Figure 11. Power at 80% load

Figures 2-6 show the result of the torque output with five different loads for 0 % 15 throttle positioning sensors (TPS). Torque decreases with increased engine speed and load. The torque increases with increase load is because as the load increases, the engine will increase its speed resulting the torque to decrease. The torque graph shows increasing trend with increase the various of load test. Moreover, more air and diesel were injected for the engine to stay at each rpm which provide more chemical energy burnt is convert into kinetic energy which means the torque produces of the engine will also increase. Additionally, the torque illustrates a significant decrease trend with 15% throttle positioning sensor's opening. This is due to the fact that a lower temperature combustion process is the only way to fulfil the LTC's goal of improved emission efficiency. Because not all of the fuel is burned during LTC, a rich mixture is used to accomplish low temperature combustion, which results in a low temperature. The pressure in the cylinder is lower than other advanced combustion strategies because of the low temperature at which combustion is accomplished and the amount of unburned fuel that is still present in the cylinder, which results in reduced torque output from the engine.

When more PRF fuel is pumped into the RCCI engine mode, the mixture becomes richer. Rich mixture causes the fuel to remain unburned, which causes the mixture's temperature to slightly decrease. Therefore, the lower the temperature, the lower the torque output as the combustion's low temperature also causes a drop in cylinder pressure. When low reactivity fuel is not injected in the RCCI engine, the cylinder temperature is at its ideal level or is not low as the low reactivity fuel is injected. Because of this, under these conditions, the pressure and complete combustion produced by the temperature and the lack of a rich mixture, respectively, deliver the higher torque output.

Figures 7-11 show result of power output with five different loads with five different loads and five different loads for 0% and 15% throttle positioning sensors (TPS). Power increase as the engine speed and load increases. The power increase with increase load is because from the beginning torque is always increase with increasing load. Since power and torque are directly proportional, the power is also increase with increase in engine load. The power also increased with the increasing the amount of rpm. This is because more air and fuel caused more energy to be released, thus the engine provides more power to the vehicle. Additionally, as the quantity of the throttle positioning sensor is increased, the power value output decreases. This happens as a result of the injection of low reactivity fuel into the combustion chamber. The low temperature of the combustion techniques is utilised to minimise the potential value production of the emissions because the LTC's major goal is to reduce emissions. Since power and torque are directly inversely correlated, as the throttle positioning sensor that controls the amount of low reactivity fuel increases, power will also decrease. The lower temperature of the combustion caused low torque because there is still unburned fuel in the cylinder.

Highest engine speed combines with only high reactivity create much higher temperature and pressure thus there is no unburnt fuel left in the cylinder which create the most power value ouput. The higher load also makes the torque and power increase since the torque and power are directly proportional. This is because the low temperature combustion left the unburnt fuel in the cylinder hence not all the fuel is burn to make the temperature higher. Plus, with the low load and low rpm make the torque available at this point is not higher enough to make greater power output. Hence, the load, rpm and the amount of tps opening is directly proportional to the power output is produced.

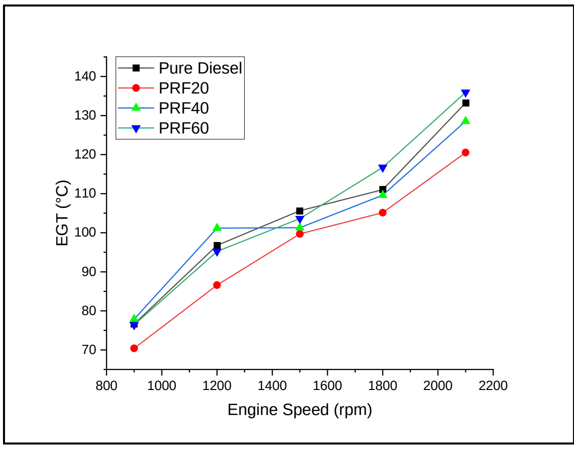


Figure 12. EGT at 0% Load

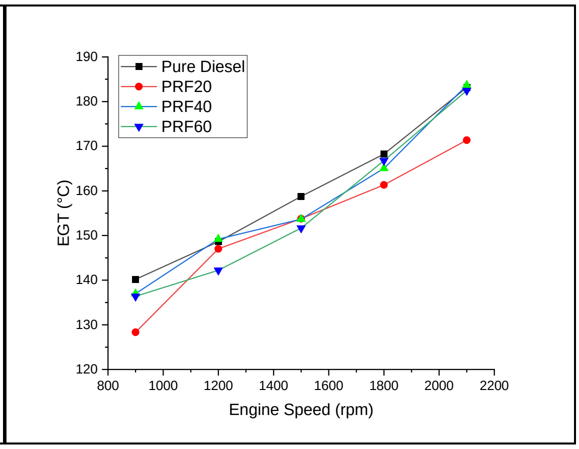


Figure 13. EGT at 20% Load

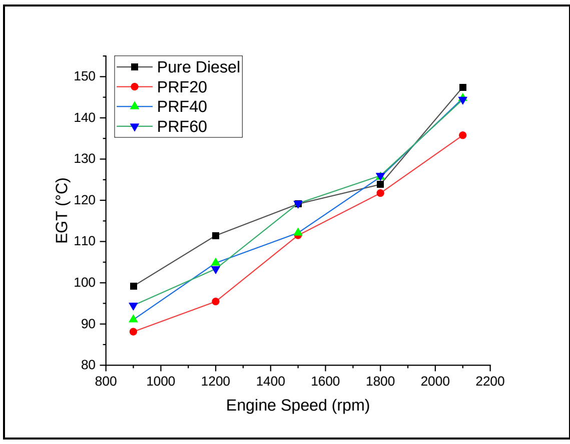


Figure 14. EGT at 40% Load

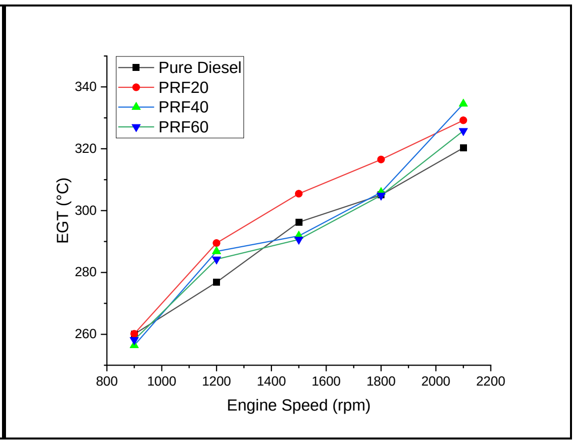


Figure 15. EGT at 60% Load

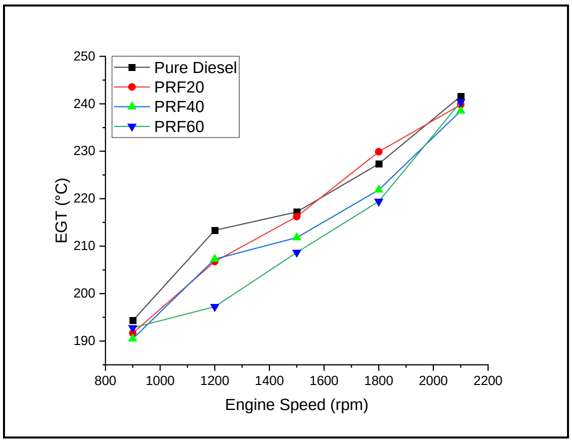


Figure 16. EGT at 60% Load

Figures 12-16 show the result of the Exhaust Gas Temperature with five different loads for various throttle positioning sensor (TPS). EGT is increase with increase engine speed and load. The EGT increase when the engine speed increase is because more air and fuel is injected in the combustion cylinder hence increase the combustion temperature thus make the EGT is also increase. EGT and engine is directly proportional. In addition, EGT is also increase with increase the engine load. This is because, the torque increase with load increase. Torque is increase due to engine speed is slow down hence pressure and temperature is increase too. Hence, the EGT will increase by the load. EGT and engine load is also directly proportional.  Another than that, EGT will decrease with increase in Throttle Positioning Sensor (TPS). This is because a rich fuel mixture by opening a TPS will left the unburnt fuel in the cylinder. Hence, the combustion temperature is low because of the unburnt fuel thus lower the EGT value. The EGT and the TPS is inversely proportional.

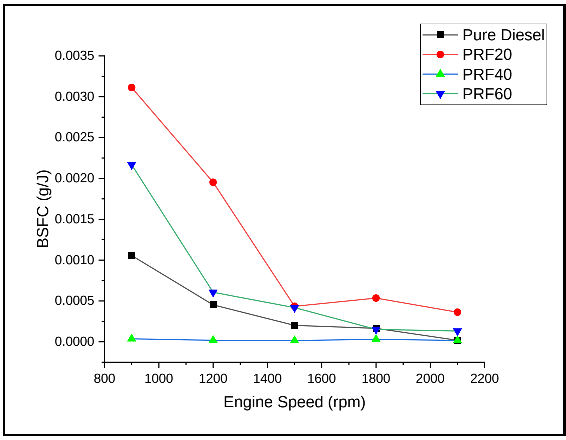


Figure 17. BSFC at 0% Load

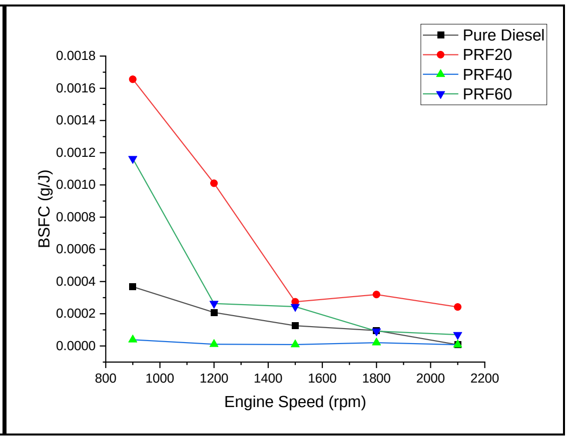


Figure 18. BSFC at 20% Load

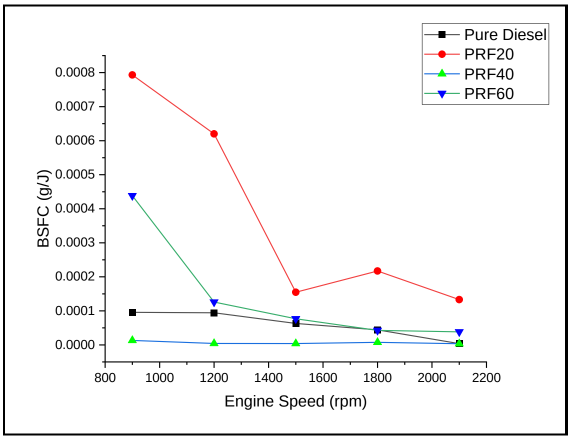


Figure 19. BSFC at 40% Load

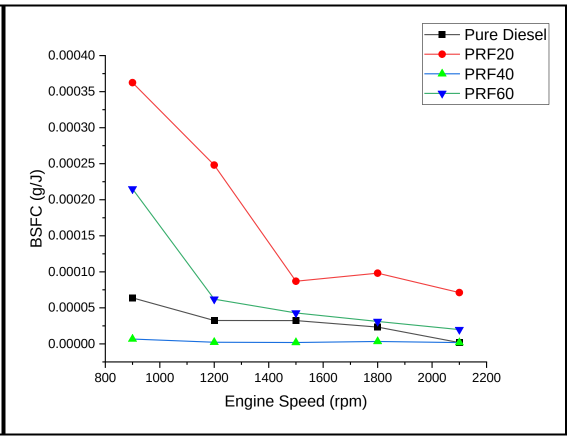


Figure 20. BSFC at 60% Load

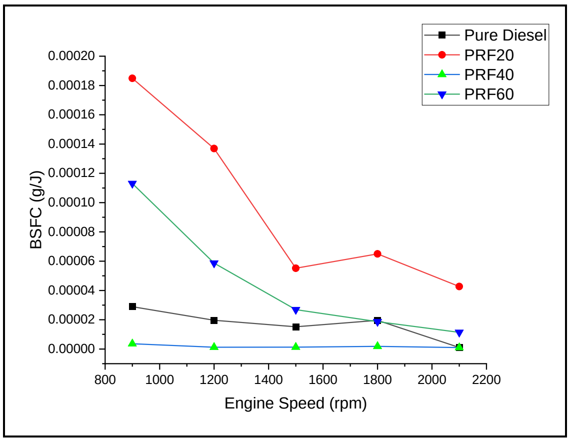


Figure 21. BSFC at 80% Load

Without the presence of the low reactivity fuel, the temperature of the combustion cylinder is higher since there is no unburnt fuel left. Moreover, the highest load is also contributed to the maximum EGT value output created. This is because, the higher the engine load, the higher the torque value to the engine. Pressure and temperature always directly proportional to the torque value. Hence, at the highest torque occur, the temperature is always the highest at the circumstances. Plus, the EGT output is also depends on the engine speed. This is because, the higher the engine speed, the higher the amount of air and fuel is injected in the cylinder create more pressure and temperature. But it is vice versa when the low reactivity fuel is start to inject because the combustion is richer hence the temperature will decrease. It only applicable at tps 0% or only high reactivity fuel is running.

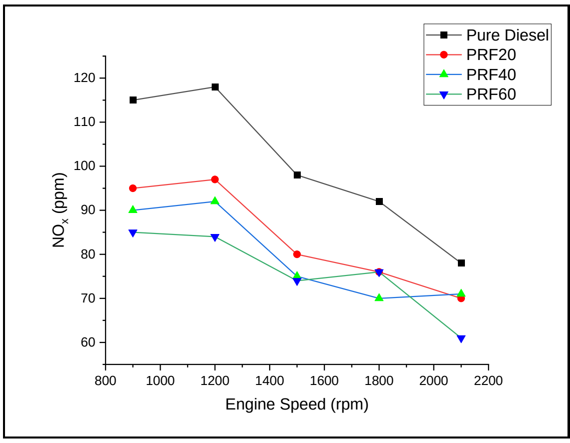


Figure 22. NOx at 0% Load

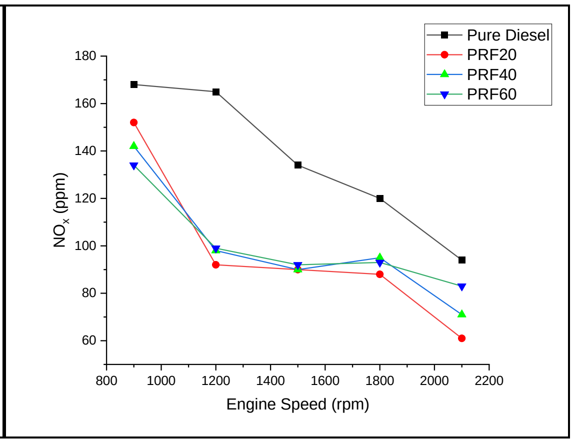


Figure 23. NOx at 20% Load

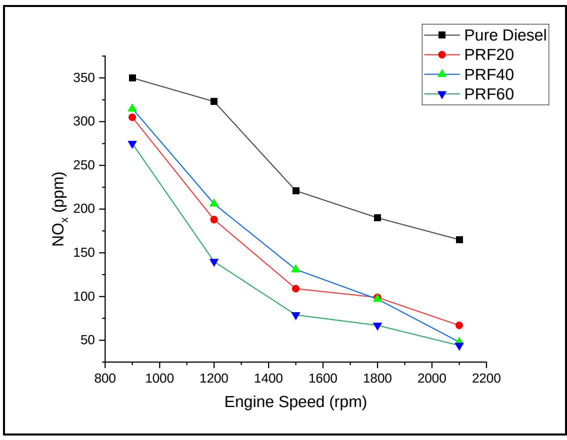


Figure 24. NOx at 40% Load

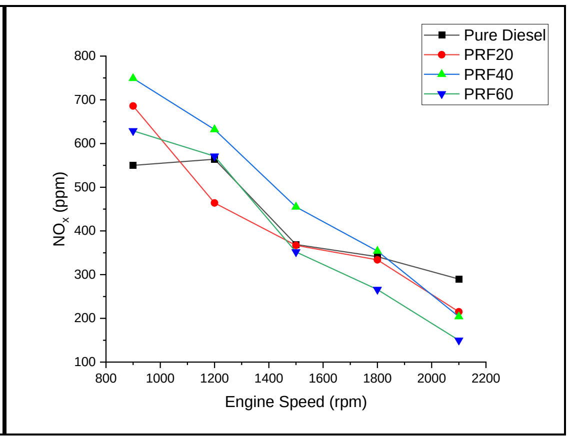


Figure 25. NOx at 60% Load

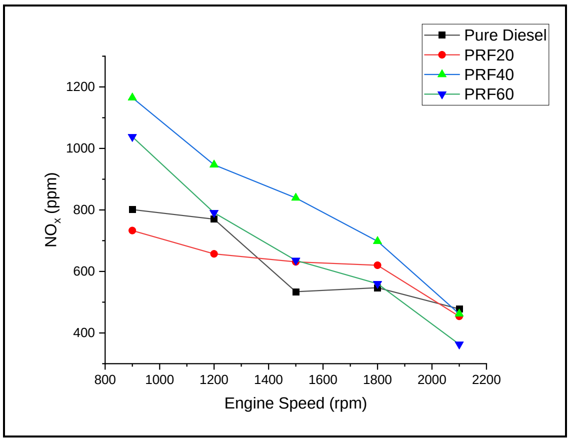


Figure 26. NOx at 80% Load

Figure 17-21 show BSFC result with five different loads for various throttle positioning sensor (TPS). The BSFC was found to decrease with increase in load and speeds for all tested fuels at 0% and 15% TPS. This is due to the higher percentage increase in brake power with load as compared to the increase in fuel consumption. The main reason for reduction in BSFC with load is the conversion efficiency of the fuel. At higher loads, the turbulence and in-cylinder temperature inside the combustion chamber will be high which helps in the atomization and proper mixing of fuel resulting in higher combustion efficiency. Other than that, the engine will be running with richer air fuel ratio at lower loads compared to full load condition. However, if a constant speed engine is used, then BSFC will be affected by the torque speed characteristics. Low BSFC values are obviously desirable.

Figures 22-26 show result of NOx emission with five different loads and five different loads for 0% and 15% throttle positioning sensors (TPS). NOx emission increase as the engine load increases and decreases as the engine speed increase. Another advantage of this engine is its emissions, which are extremely low in nitrogen oxide and particulate matter, such as soot. On a regular diesel engine, these kinds of pollutants cause problems. The cool burning, on the other hand, does not emit nitrogen oxide when using an RCCI engine. As the engine speed increases, the RCCI engine uses less diesel fuel, therefore it allows the diesel fuel to have more time to mix. The majority of diesel fuel is well blended and does not produce particulate matter. As a result, particulate matter and nitrogen oxide levels are extremely low in this engine, and it is super-efficient, up to 10-15% more efficient than a standard diesel engine. This is mainly as a result of having lower combustion temperature and because of the less heat transfer within the cylinder. Other possible assumption is it could be due to the higher latent heat of vaporization of PRF, which leads to reduction in the combustion gas temperature thereby reducing the NOx emissions.

## Conclusion

This paper provides a brief summary of the project and a list of recommendations that can be used in future research. The application of the RCCI engine has been investigated to increase the capacity of the modified diesel engine to operate with port injection system. In order to investigate whether diesel engines can be made to burn more efficiently and perform better than other conventional engines, the application of the RCCI engine has also been investigated experimentally with the PRF20, PRF40 and PRF60. Regarding the consequences of the dual injection system or RCCI utilised in diesel engines in terms of performance and gas emissions, new information is created. This experiment involved creating a PRF20, PRF40 and PRF60 fuel by blending iso-octane by 20%, 40% and 60% and n-heptane by 80%, 60% and 40% in order to carry out the research.

Engine performance in terms of torque, power, BSFC and exhaust gas temperature are measured in this project. While the exhaust gas temperature was manually retrieved using PICOLOG software, the raw data for torque and power were collected from Focus Applied Technologies' software. According to the results, engine speed and load both enhance the power value. However, due to the LTC strategy implemented during the RCCI engine mode combustion, there is a considerable reduction in torque when operating in the RCCI mode as opposed to merely running pure diesel or tps0. The torque value kept decreasing from low to highest rpm but increasing as engine load increases. The lowest torque value is recorded at 2100rpm at tps 0% with load 0%. Due to the low temperature in the cylinder caused by the rich mixture in RCCI mode, the engine is unable to completely burn the mixture, which reduces the torque produced. The power value follows the same pattern. It is impacted by the torque as well. The power is significantly reduced compared to simply when pure diesel is operating because of the LTC effect encouraged by RCCI. The EGT data demonstrates that when the RCCI mode is operating, the temperature was lower than when simply pure diesel was operating. NOx, was analyzed in this project. NOx emissions increased as the engine load increased but decreased as the engine speeds increased.

## Recommendations

While the exhaust gas temperature is decreasing, the recommendation of this RCCI mode combustion strategy may be useful to reduce emissions. However, due to the low temperature combustion provided when running the RCCI mode, the performance in terms of torque and power is not really improved. To further enhance engine performance and reduced the gas emissions in this project, new strategies can be implemented.

## Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

## Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Technology, Engineering and Science ( www.icontes.net ) held in Antalya/Turkey on November 16-19, 2022.

*The authors would like to thank the Ministry of Higher Education for providing fi-nancial support under Research Acculturation of Early Career Researchers No. RACER/1/2019/TK03/UMP/1 and University Malaysia Pahang for laboratory facilities as well as additional financial support under Internal Research grant RDU192605.

## References

Ansari, E., Shahbakhti, M., & Naber, J. (2018). Optimization of performance and operational cost for a dual mode diesel-natural gas RCCI and diesel combustion engine. *Applied Energy*, *231*(September), 549–561. https://doi.org/10.1016/j.apenergy.2018.09.040

Benajes, J., García, A., Monsalve-Serrano, J., & Lago Sari, R. (2018). Fuel consumption and engine-out emissions estimations of a light-duty engine running in dual-mode RCCI/CDC with different fuels and driving cycles. *Energy*, *157*, 19–30. https://doi.org/10.1016/j.energy.2018.05.144

Charitha, V., Thirumalini, S., Prasad, M., & Srihari, S. (2019). Investigation on performance and emissions of RCCI dual fuel combustion on diesel - bio diesel in a light duty engine. *Renewable Energy*, *134*(x), 1081–1088. https://doi.org/10.1016/j.renene.2018.09.048

Dong, Y., Kaario, O., Hassan, G., Ranta, O., Larmi, M., & Johansson, B. (2020). High-pressure direct injection of methanol and pilot diesel: A non-premixed dual-fuel engine concept. *Fuel*, *277*(April), 117932. https://doi.org/10.1016/j.fuel.2020.117932

García, A., Monsalve-Serrano, J., Martinez-Boggio, S., Gaillard, P., Poussin, O., & Amer, A. A. (2020). Dual fuel combustion and hybrid electric powertrains as potential solution to achieve 2025 emissions targets in medium duty trucks sector. *Energy Conversion and Management*, *224*(June), 113320. https://doi.org/10.1016/j.enconman.2020.113320

García, A., Monsalve-Serrano, J., Villalta, D., & Sari, R. (2019). Fuel sensitivity effects on dual-mode dual-fuel combustion operation for different octane numbers. *Energy Conversion and Management*, *201*(October). https://doi.org/10.1016/j.enconman.2019.112137

Han, W., Li, B., Pan, S., Lu, Y., & Li, X. (2018). Combined effect of inlet pressure, total cycle energy, and start of injection on low load reactivity controlled compression ignition combustion and emission characteristics in a multi-cylinder heavy-duty engine fueled with gasoline/diesel. *Energy*, *165*, 846–858. https://doi.org/10.1016/j.energy.2018.10.029

Kahnooji, M., & Yazdani, K. (2021). The effect of direct water injection on a diesel-gasoline reactivity controlled compression ignition engine. *Fuel*, *285*(September 2020). https://doi.org/10.1016/j.fuel.2020.119109

Kakaee, A. H., Nasiri-Toosi, A., Partovi, B., & Paykani, A. (2016). Effects of piston bowl geometry on combustion and emissions characteristics of a natural gas/diesel RCCI engine. *Applied Thermal Engineering*, *102*, 1462–1472. https://doi.org/10.1016/j.applthermaleng.2016.03.162

Kakoee, A., Bakhshan, Y., Barbier, A., Bares, P., & Guardiola, C. (2020). Modeling combustion timing in an RCCI engine by means of a control oriented model. *Control Engineering Practice*, *97*(February). https://doi.org/10.1016/j.conengprac.2020.104321

Li, J., Ling, X., Liu, D., Yang, W., & Zhou, D. (2018). Numerical study on double injection techniques in a gasoline and biodiesel fueled RCCI (reactivity controlled compression ignition) engine. *Applied Energy*, *211*(August 2017), 382–392. https://doi.org/10.1016/j.apenergy.2017.11.062

Li, J., Yang, W., & Zhou, D. (2017). Review on the management of RCCI engines. *Renewable and Sustainable Energy Reviews*, *69*(November 2016), 65–79. https://doi.org/10.1016/j.rser.2016.11.159

Li, W., Liu, Z., & Wang, Z. (2016). Experimental and theoretical analysis of the combustion process at low loads of a diesel natural gas dual-fuel engine. *Energy*, *94*, 728–741. https://doi.org/10.1016/j.energy.2015.11.052

Liu, X., Srna, A., Yip, H. L., Kook, S., Chan, Q. N., & Hawkes, E. R. (2021). Performance and emissions of hydrogen-diesel dual direct injection (H2DDI) in a single-cylinder compression-ignition engine. *International Journal of Hydrogen Energy*, *46*(1), 1302–1314. https://doi.org/10.1016/j.ijhydene.2020.10.006

Luong, M. B., Yu, G. H., Chung, S. H., & Yoo, C. S. (2017). Ignition of a lean PRF/air mixture under RCCI/SCCI conditions: A comparative DNS study. *Proceedings of the Combustion Institute*, *36*(3), 3623–3631. https://doi.org/10.1016/j.proci.2016.08.038

Mikulski, M., Ramesh, S., & Bekdemir, C. (2019). Reactivity Controlled Compression Ignition for clean and efficient ship propulsion. *Energy*, *182*, 1173–1192. https://doi.org/10.1016/j.energy.2019.06.091

Nazemi, M., & Shahbakhti, M. (2016). Modeling and analysis of fuel injection parameters for combustion and performance of an RCCI engine. *Applied Energy*, *165*, 135–150. https://doi.org/10.1016/j.apenergy.2015.11.093

Pan, S., Li, X., Han, W., & Huang, Y. (2017). An experimental investigation on multi-cylinder RCCI engine fueled with 2-butanol/diesel. *Energy Conversion and Management*, *154*(August), 92–101. https://doi.org/10.1016/j.enconman.2017.10.047

Pan, S., Liu, X., Cai, K., Li, X., Han, W., & Li, B. (2020). Experimental study on combustion and emission characteristics of iso-butanol/diesel and gasoline/diesel RCCI in a heavy-duty engine under low loads. *Fuel*, *261*(August 2019). https://doi.org/10.1016/j.fuel.2019.116434

Park, H., Shim, E., & Bae, C. (2019). Injection strategy in natural gas–diesel dual-fuel premixed charge compression ıgnition combustion under low load conditions. *Engineering*, *5*(3), 548–557. https://doi.org/10.1016/j.eng.2019.03.005

Pedrozo, V. B., May, I., Dalla Nora, M., Cairns, A., & Zhao, H. (2016). Experimental analysis of ethanol dual-fuel combustion in a heavy-duty diesel engine: An optimisation at low load. *Applied Energy*, *165*, 166–182. https://doi.org/10.1016/j.apenergy.2015.12.052

Pedrozo, V. B., May, I., Lanzanova, T. D. M., & Zhao, H. (2016). Potential of internal EGR and throttled operation for low load extension of ethanol-diesel dual-fuel reactivity controlled compression ignition combustion on a heavy-duty engine. *Fuel*, *179*, 391–405. https://doi.org/10.1016/j.fuel.2016.03.090

Piqueras, P., García, A., Monsalve-Serrano, J., & Ruiz, M. J. (2019). Performance of a diesel oxidation catalyst under diesel-gasoline reactivity controlled compression ignition combustion conditions. *Energy Conversion and Management*, *196*(May), 18–31. https://doi.org/10.1016/j.enconman.2019.05.111

Rangasamy, M., Duraisamy, G., & Govindan, N. (2020). A comprehensive parametric, energy and exergy analysis for oxygenated biofuels based dual-fuel combustion in an automotive light duty diesel engine. *Fuel*, *277*(November 2019), 118167. https://doi.org/10.1016/j.fuel.2020.118167

Raza, M., Wang, H., & Yao, M. (2019). Numerical investigation of reactivity controlled compression ignition (RCCI) using different multi-component surrogate combinations of diesel and gasoline. *Applied Energy*, *242*(March), 462–479. https://doi.org/10.1016/j.apenergy.2019.03.115

Reitz, R. D., & Duraisamy, G. (2015). Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines. *Progress in Energy and Combustion Science*, *46*, 12–71. https://doi.org/10.1016/j.pecs.2014.05.003

Saiteja, P., & Ashok, B. (2021). A critical insight review on homogeneous charge compression ignition engine characteristics powered by biofuels. *Fuel*, *285*(September 2020), 119202. https://doi.org/10.1016/j.fuel.2020.119202

Salahi, M. M., Esfahanian, V., Gharehghani, A., & Mirsalim, M. (2017). Investigating the reactivity controlled compression ignition (RCCI) combustion strategy in a natural gas/diesel fueled engine with a pre-chamber. *Energy Conversion and Management*, *132*, 40–53. https://doi.org/10.1016/j.enconman.2016.11.019

Sener, R., Yangaz, M. U., & Gul, M. Z. (2020). Effects of injection strategy and combustion chamber modification on a single-cylinder diesel engine. *Fuel*, *266*(January), 117122. https://doi.org/10.1016/j.fuel.2020.117122

Shim, E., Park, H., & Bae, C. (2018). Intake air strategy for low HC and CO emissions in dual-fuel (CNG-diesel) premixed charge compression ignition engine. *Applied Energy*, *225*(May), 1068–1077. https://doi.org/10.1016/j.apenergy.2018.05.060

Singh, A. P., Kumar, V., & Agarwal, A. K. (2020). Evaluation of comparative engine combustion, performance and emission characteristics of low temperature combustion (PCCI and RCCI) modes. *Applied Energy*, *278*(July). https://doi.org/10.1016/j.apenergy.2020.115644

Wang, L., Chen, Z., Zhang, T., & Zeng, K. (2019). Effect of excess air/fuel ratio and methanol addition on the performance, emissions, and combustion characteristics of a natural gas/methanol dual-fuel engine. *Fuel*, *255*(May), 115799. https://doi.org/10.1016/j.fuel.2019.115799

Wang, Y., Yao, M., Li, T., Zhang, W., & Zheng, Z. (2016). A parametric study for enabling reactivity controlled compression ignition (RCCI) operation in diesel engines at various engine loads. *Applied Energy*, *175*, 389–402. https://doi.org/10.1016/j.apenergy.2016.04.095

Wang, Y., Zhu, Z. W., Yao, M., Li, T., Zhang, W., & Zheng, Z. (2016). An investigation into the RCCI engine operation under low load and its achievable operational range at different engine speeds. *Energy Conversion and Management*, *124*, 399–413. https://doi.org/10.1016/j.enconman.2016.07.026

## Author Information

**Ahmad Fitri Yusop**
Universiti Malaysia Pahang,
26600, Pekan, Pahang, Malaysia
Contact e-mail: *fitriy@ump.edu.my*

**Mohamad Adzuan Aziz**
Universiti Malaysia Pahang,
26600, Pekan, Pahang, Malaysia

**Mohd Adnin Hamidi**
Universiti Malaysia Pahang,
26600, Pekan, Pahang, Malaysia

**Daing Mohamad Nafiz Daing Idris**
Universiti Malaysia Pahang,
26600, Pekan, Pahang, Malaysia

**Ummi Hafsah Zaidi**
Universiti Malaysia Pahang,
26600, Pekan, Pahang, Malaysia

**To cite this article:**

Yusop, A.F., Aziz, M.A., Hamidi, M.A., Daing Idris, D.M.N., & Zaidi, U.H. (2022). Investigation on the RCCI engine on performance and emission. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 21*, 525-540.