An experimental investigation on single cylinder RCCI engine fuelled with diesel/petrol

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Abstract. The objective of this research paper is to investigate the combustion and emission characteristics by developing a clean combustion phenomenon, with an improvement in efficiency in an internal combustion engine. Most of the commercial transportation is through the CI (Compressed Ignition) engine and these engines creates relatively high emission in the form of Oxides of Nitrogen (NOx) and Particulate Matter (PM). With an increase in fuel prices and emission norms globally, thus demands a clean combustion from IC engine. In order to overcome the above stated problems associated, a step ahead is taken by the use of Reactivity Controlled Combustion Ignition concept (RCCI). As per the experiment conducted RCCI is capable of achieving high thermal efficiency and low NOx and PM emissions. In this experiment a light-duty single-cylinder diesel engine is modified to run an RCCI mode using diesel and petrol as a fuel. The reduction and increase in efficiency and emissions has been obtained by carrying out a slight modification in the intake named as Port Fuel Injector (PFI) for using the Low Reactive Fuel (LRF). The engine speed is kept constant by varying the Start of Injection (SOI). The PFI injector is being run by using an Arduino setup, where the LRF injection will be monitored and controlled by the Arduino. Load is applied using an eddy current dynamometer. The experiment is run with two combinations fuels such diesel and diesel-petrol.

1. Introduction

In the olden days, people used carts and horses to travel, which were later replaced by combustion engines, which uses fuel chemical energy and converts into mechanical energy. The compression ignition (CI) engine reigns supreme than all the engines till now due to its higher fuel efficiency. However, these engines cause high NOx and soot emissions which are harmful to environment. Even though there are aftertreatment devices like DPF (Diesel Particulate Filters) and SCR (Selective Catalytic Reduction) which helps control the pollutions, which also increases fuel consumption in the vehicles. These aftertreatment processes are costly and are also durable to certain time period [1-12].

In order to create an engine within the emissions norms with the increase in the engine efficiency researchers are going towards the dual fuel technology. HCCI (Homogeneous Charged Compression Ignition), PCCI (Premixed Charged Compression Ignition) and RCCI (Reactivity Controlled Compression Ignition) are the dual fuel concepts which helps in reducing the NOx and soot emissions, thereby increasing the engine efficiency. In CI engine the easy way to achieve less NOx is by HCCI concept. The HCCI mode of combustion with the diesel/petrol has the best results. However,
controlling the ignition timing and the rate of heat release is very difficult in this mode of combustion. RCCI concept has very high efficiency and to reduce the pollution emitted into the atmosphere. RCCI engine uses two fuel with different reactivity to make complete and proper combustion to reduce the NOx, which is usually created during very high temperatures and pressure. The different reactivity fuel used here is High Reactivity Fuel (HRF), which is usually diesel and Low Reactivity Fuel (LRF) where petrol is taken. Here the HRF acts as fuel igniter, and LRF acts as fuel, which is used to run the engine [13-20].

Charitha et al. [21] conducted an experiment with a modified diesel engine to run the RCCI setup with diesel and cottonseed oil. Initially, the light-duty diesel engine was modified to run the RCCI setup, and the injection was controlled by using a different control unit, which controls both the HRF and LRF injection. NOx, HC, and Smoke concentration were 30% decreased at full load condition with 30% cottonseed oil. The HRF and LRF ratio determines how the combustion takes place inside the cylinder. Jia et al. [22] have conducted an investigational study on an engine fueled with natural gas-diesel dual-fuel RCCI mode. In their experiment, two different compression ratios, namely 14 and 17, and a split injection strategy for injection for diesel. EGR used at 42%-50% on CA50 in order to reduce the UHC. Low NOx and soot emission are formed at both the CR, but there is more UHC released. Comparing both the compression ratio, the emissions are much lower in CR14 than in CR17. Even though they are using EGR still, there are more UHC, but these UHC can be controlled by using after treatment process. Klos et al [23] investigated the combustion instability of NOx trade-off in the RCCI engine. Here both the experiment and simulation in CHEMKIN were done on 1.9L modified diesel to run RCCI setup with gasoline/diesel as fuel. From the experiment, it was found that if the SOI timing is between -30 to -20 ATDC to produce two separate combustions. CFD simulation with ignition delay calculation shows that late injection timings have regions of very short ignition delay. By retarding injection timing, there are variations in CA50, and IMEP (Indicated Mean Effective Pressure). Late SOI timings have increased in NOx emission. Li et al. [24] did a parametric study and optimization of the RCCI engine fueled by methanol and diesel. The study was carried out on all the strategies of RCCI. By using the multidimensional model and NSGA-II, the test is carried out in the CHEMKIN. The test results showed that the methanol fraction and SOI affects NOx and soot emissions. Increasing the initial temperature and decreasing the EGR creates high Ringing Intensity (RI). The fuel spray distribution is affected by the nature of the fuel, initial temperature, and SOI. Based on the study of methanol fraction at 66.5% is good for achieving fuel economy and emissions for the RCCI concept. Li et al. [25, 26] did a numerical study on the combustion and emission on the RCCI engine. CHEMKIN was used here to do the numerical analysis between methanol and diesel as fuel. The advanced SOI also contributes to improving the fuel economy and helps in avoiding knocking. Splitter et al. [27] studied the effect of compression ratio and piston geometry on RCCI load limits and efficiency.

From the above literature review, it was decided to do the study on RCCI mode of combustion by modifying the VCR engine to suit for RCCI mode. The compression ratio will be set at 17.5, and the stock piston will be used. The injection of the PFI injector are going to be controlled by the Arduino programming whereas, the diesel SOI is varied from 23⁰ to 20⁰ before TDC. The fuels to be used are diesel (HRF) and 96 octane petrol (LRF). The main objective of the project is to investigate the performance, combustion, and emission characteristics of RCCI mode in the modified engine with diesel and petrol.

2. Selection of fuel

The fuels used for the study of RCCI mode are:

- HRF – diesel
- LRF – petrol
The fuel properties of diesel and petrol, which are used for this experiment, are shown in Table 1. In this experiment, a high-octane petrol is used in order to reduce knocking and get proper combustion. Since the methanol and ethanol are good oxidizer agents and will get oxidized easily.

### Table 1. Fuel properties of diesel and petrol

| Property                          | Diesel          | Petrol          |
|----------------------------------|-----------------|-----------------|
| Molecular formula                | C12- c25        | C4-c12          |
| Density (kg/m³)                  | 810-890         | 682             |
| Kinematic viscosity(mm²/s)       | 4.842           | 0.44            |
| Cetane number                    | 40-55           | 17              |
| Octane number                    | 20-30           | 80-99           |
| Stoichiometric air/fuel ratio    | 14.3            | 17              |
| LHV(MJ/Kg)                       | 42.3            | 42.4            |
| Latent heat                      | 0.23-0.60       | 380-550         |
| Auto ignition temp               | 210-250         | 310             |
| Flash point                      | 65-68           | -45 to -38      |
| Boiling point                    | 180-340         | 78              |

3. Experimental setup and procedure

3.1. Experimental setup

A single-cylinder, direct injection, water-cooled engine is modified to satisfy the experimental requirement for the current work, as shown in figure 1, and Table 2 shows the engine specification and Table 3 shows the PFI injector specification. An electronic PFI system is used to inject petrol during the intake process through the inlet manifold to get a homogeneous charge. The injector of the PFI system is mounted close to the inlet valve to get better vaporization of petrol. The PFI system works on 4bar injection pressure and is fixed/injects fuel at -15° before TDC during the suction stroke, which is electronically controlled by using an Arduino, which controls the injection timing and injection pulse width. A Kirloskar DI system is used for diesel injection into the cylinder where the ignition timing is varied from -23° to -20° before TDC. The engine operation loads are given by the eddy current dynamometer. The photographic view of the engine setup is shown in the figure 2.

### Table 2. engine specification

| Type                   | 1-cylinder water cooled engine |
|------------------------|--------------------------------|
| Make                   | Kirloskar                      |
| Number of cylinders    | 1                              |
| Number of valves       | 4                              |
| Bore(mm)               | 87.5                           |
| Stroke(mm)             | 110                            |
| Orifice diameter(mm)   | 20                             |
| Connecting rod(mm)     | 234                            |
| Dynamometer arm length(mm) | 185                         |
| Power(kw)              | 3.5                            |
| Speed(rpm)             | 1500                           |
| Compression ratio      | 12:1 to 18:1                   |
| Injection point variation | 0° to 25° BTDC                |
Table 3. PFI injector specification

| Fuel pressure | Number of holes |
|---------------|----------------|
| 4 to 5 bar    | 4              |

![Figure 1: RCCI Engine Setup](image)

3.2. Programming

Arduino programming is used here to run the LRF to the VCR engine. A block diagram of the working is shown in figure 2. Arduino here acts a Control Unit for the LRF fuel system. Arduino is connected with the injector and proximity sensor. The proximity sensor is mounted near the camshaft of the engine and whenever the bolt on the camshaft comes in contact with the proximity sensor, the sensor sends a signal to the arduino. The arduino then sends a signal to the injector to spray. Since we need a fine spray the injector is made to open only for 20-30 ms whenever it receives a signal to fire. There is pressure sensor attached to the LRF fuel line to monitor the fuel pressure. This pressure sensor returns the fuel back to the fuel tank through the pressure relief valve when the is more than 40psi. figure 3 shows the circuit diagram.

![Figure 2: Block diagram of arduino setup](image)
4. RESULTS AND DISCUSSION

4.1. Engine performance

4.1.1. Brake thermal efficiency

The variation of brake thermal efficiency with load for diesel and RCCI mode is shown in figure 4. It is seen that the brake thermal efficiency increases as the load increases. It is found that the RCCI mode produces higher BTE than convectional diesel mode. It is evident from the graph that in RCCI mode due to the combination of two fuels blend, there is complete combustion inside the cylinder. At peak load, the RCCI is at 38.78%, and diesel is at 35.39%. The BTE of RCCI mode is 9.57% higher than that of diesel at full load conditions. The higher increase of BTE in RCCI mode is due to the reduced heat loss at lower combustion temperature in RCCI combustion mode.

![Figure 3. circuit diagram of arduino board](image)

**Figure 3.** circuit diagram of arduino board

![Figure 4. BTE vs load](image)

**Figure 4.** BTE vs load

4.1.2. Break specific fuel consumption

The variation between the RCCI and diesel is shown in figure 5. The BSFC for RCCI is shown to be increased than the diesel. The increase in fuel consumption is due to the fact that the PFI is being used only at 15% in which case the engine uses lots of fuel. The peak value of both the diesel and RCCI is 0.6 and 0.74, respectively. The BSFC of RCCI is 23.3% higher than the diesel.
4.2. Emission characteristics

4.2.1. Oxides of Nitrogen

The variation of oxides of nitrogen between the RCCI and diesel is shown in figure 6. It can be seen from the graph that RCCI is lower than diesel. The formation of NOX mainly depends on the oxygen concentration, time of reaction and temperature of combustion during the combustion process. The graph shows that as the load increases, the NOx increases due to high cylinder pressure. The lower NOx is found using RCCI combustion which resulted in lower temperature during combustion. At peak load, the NOx formed in RCCI and diesel are 497 ppm and 857 ppm. The RCCI is 41% lower than that of diesel.

4.2.2. Carbon mono Oxide emission

The variation of Carbon mono oxide between the diesel and RCCI mode is shown in figure 7. CO emission is influenced by many parameters such as fuel injection pressure, fuel injection timing, quality of the air-fuel mixture, engine speed, and load. The carbon mono oxide emission is higher in RCCI than diesel as the load increases. The formation of CO emission from the engine with diesel and dual fuel operation depends on the oxygen concentration and in-cylinder temperature during combustion. The peak load of diesel and RCCI is found to be 0.21ppm and 0.27ppm. RCCI is 38%
higher than diesel. The increase in CO can be observed with reduced in-cylinder temperature in RCCI combustion mode. The reduction in reaction rate is observed as the combustion chamber in-cylinder temperature causing increased CO emission and unburnt hydrocarbons in RCCI mode. The resulting increase in CO emission from the RCCI mode is also due to the PFI fuel trapped in the crevices while combustion.

![Figure 7. CO vs load](image)

### 4.2.3. Hydro Carbon emission

The variation between the RCCI and diesel mode is shown in figure 8. It was found out that the RCCI mode released more hydrocarbon emission than that of diesel mode of combustion. The HC emissions are maybe of fuel particles stuck in the crevices. In addition to this, the literature section shows us that the modified piston with the crevice will help in fuel to flow, which helps better combustion. At the peak load, the RCCI and diesel exhibited HC emission of 50ppm and 36ppm respectively. RCCI is 38% higher than diesel.

![Figure 8. HC vs load](image)

### 4.2.4. Smoke

The smoke emission depends on fuel density, viscosity, and fuel droplet size. Smoke emission was found higher for RCCI mode than diesel as shown in figure 9. It was noted during the testing the indication of black smoke, which is because of the increase of UHC and CO created by the incomplete combustion in RCCI mode. The smoke opacity increases for both diesel as RCCI as the load increases.
At peak load, the opacity of diesel and RCCI mode are 37.4 and 80.7. The RCCI mode is 53.65% higher than diesel.

5. CONCLUSIONS

Based on the experimental work, the following conclusions were made:

- It is noted that the brake thermal efficiency of RCCI increases as the load increases. The peak load of RCCI and diesel are found to be 38.78% and 35.39%. the difference between the two modes is almost 9.57%.
- The peak value of BSFC in both the diesel and RCCI is 0.6 and 0.74, respectively. The BSFC of RCCI is 23.3% higher than the diesel. This loss of fuel can be resolved by increasing the PFI fuel quantity to 55% and by the use of EGR, which helps in reducing the fuel consumption and reduces the UHC.
- At peak load, the NOx formed in RCCI and diesel are found as 497 ppm and 857 ppm respectively. The RCCI is 41% lower than that of diesel.
- The carbon mono oxide emission is higher in RCCI than diesel as the load increases. The peak load of diesel and RCCI is found to be 0.21ppm and 0.27ppm. RCCI is 38% higher than diesel.
- It was found out that the RCCI mode released more hydrocarbon emission than that of diesel mode of combustion. At the peak load, the RCCI and diesel are at 50ppm and 36ppm. RCCI is 38% higher than diesel.
- The smoke opacity increases for both diesel and RCCI as the load increases. At peak load, the opacity of diesel and RCCI mode are 37.4 and 80.7. The RCCI mode is 53.65% higher than diesel.

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