Performance and emission characteristics of biogas-bio diesel fuelled RCCI engine at various butanol-gasoline injection timings

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Abstract. Energy, a basic need of human life, has been playing significant role behind many technological developments. Most of the world's commercial energy requirements are fulfilled by using fossil fuels. Combustion of fossil fuels releases toxic gases which in further turns as a source of pollution for the environment, globally. The present research work focused on minimizing the emissions that emerges during combustion in an IC engine through Reactivity Controlled Compression Ignition (RCCI) mode. The performance and emission characteristics of a single-cylinder CI engine are analyzed with 3 different fuels; biodiesel, butanol-gasoline (1:4 ratio), and biogas. The operational loads taken for the present study falls in the range from 5 N-m to 20 N-m at the engine speed of 1800 RPM. The influence of biogas on the emission characteristics is exclusively carried out with two different flow rates; 12lpm and 16lpm. The injection timings for butanol-gasoline blend are varied from 0 to 8ms. Fuel properties such as Viscosity, Vapor pressure, Density, Cloud point, Pour point, and Flashpoint are estimated. Engine parameters such as Brake Thermal Efficiency (BTE), Volumetric Efficiency (VE), HC, CO, NOx and smoke emissions, Peak pressure, Heat Release Rate (HRR), Ignition Delay, are analyzed. It is observed from the experiments that increasing injection time of pilot fuel increases the HC and CO emissions; reduces the NOx emissions; decreases the smoke level with increase in biogas flow rate; and decreases the BTE, VE, and HRR

Keywords: RCCI, Biodiesel, Biogas, HC Emissions, Brake Thermal Efficiency.

1. Introduction
The automobile industry dominates the mechanical world for the past century. Nevertheless, it also pollutes the atmosphere by burning fossil fuel. Stringent regulations imposed on emissions from automobiles necessitate the sector to progress towards alternate option in place of fossil fuels. Alternative fuels are found to be a promising solution to retrofit the fossil fuel applications. However, the working methodology and process controls must be clearly defined to work with alternative fuels in conventional IC engines. IC engines under new modes of combustion such as HCCI and RCCI are witnessed to produce low emissions with enhanced brake thermal efficiency (BTE). Reactivity Controlled Compression Ignition (RCCI) is commonly known for its dual-fuel mechanism in which highly reactive fuel is injected into the cylinder and low reactive fuel is injected through intake manifold. Established methods in literature show that varying fuel flow rates, injector timings, adjusting low and high reactive fuels, start of ignition (SOI) of the high reactive fuels and multiple injection methods are proved to be effective in augmenting the IC engine combustion performance [1-3]. Oxygenated biofuels and alcohol fuels such as biodiesel [4-6] and butanol [9] are focused because of their renewability and superiority on reducing soot emission under a high EGR rate. Biodiesel, a kind of fuel extracted from long-chain fatty acid esters of animals and plants is superior in reducing the soot emissions under high EGR rate, yet it influences combustion timing and possibly increases NOx emission [4-6]. Extensive research towards biofuels yielded to materialize the usage of ethanol and n-butanol as a partial substitute for diesel. Beside high octane number, n-butanol possesses lower
volatility, hydrophilicity, higher energy density and safety over ethanol. Butanol, when blended properly with gasoline provides optimum viscosity that has no influence on port timing. Biodiesel/ethanol mixtures showed good potential in emissions control whereas biodiesel/n-butanol mixtures are proved to have better thermal efficiency under RCCI operation modes [7 & 8]. Biogas, another kind of fuel with low reactivity, provides better mixing ability, renewability and clean combustion. It is produced by anaerobic digestion of organic substances like cow dung, kitchen waste, and agricultural waste. Zunqing Zheng, [10] performed an experimental study on combustion and emission of dual fuelled RCCI engine with three low reactivity oxygenated biofuels. n-butanol, 2, 5-dimethylfuran (DMF), and ethanol. The fuels are injected through the port injection method. Injection time was varied to study the combustion and emission levels in an Inline 4-stroked diesel engine at 1500 rev/min. The change in trends of combustion and emissions are similar for three RCCI modes. Biodiesel/ethanol reduces NOx and soot emissions concurrently (soot<0.3 FSN and NOx<1.5 g/kWh at SOI of 8 CA ATDC) and biodiesel/n-butanol exhibits the highest ITE of 47.5% and proves many advantages on improving the thermal efficiency of RCCI combustion. Haifeng Liu,[11] performed research on the effect of port injecting hydrous ethanol and studied their combustion and emission characteristics in dual-fuelled RCCI engine and proved that combustion efficiency decreases with the fall in ethanol purity. NOx and soot emissions are decreased by 79% and 50% under low load conditions. But in high load conditions, the reduction in NOx and soot emission was 72% and 27%. The thermal efficiency of 55% can be obtained at engine loads from 5 – 17 bars IMEP. D.Z.Zhou, [12] conducted a numerical study on the RCCI engine which is fuelled by Biodiesel and Methanol. Engine loads are varied at 10%, 50%, and 100% and methanol mass fraction rose from 0%-80% with an interval of 20%. Heat release rate under 10% load condition, decreases with an increase in methanol mass fraction; under 50% load condition, it increases with the increase in methanol mass fraction from 0% to 60% and decreases from 60% to 80%; under 100% load condition. Ignition timing decreases with an increase in a mass fraction at all three loads.

Numerous researchers concentrated on Ethanol as low reactive fuels due to its high octane number and good volatility. Studies focusing on different reactivity fuels to reduce the emissions under RCCI mode of combustion are found limited. Biogas was not used as a primary fuel. Henceforth, this work is set to investigate RCCI mode of combustion by varying the flow rate and injection timings of the highly reactive and low reactive fuels for optimizing the emissions. Biogas along with mixture of butanol-gasoline are selected as port injection low reactivity fuels and biodiesel as direct injection high reactivity fuel.

2. Experimental Setup and Methodology

2.1. Engine and fuel

A single cylinder four stroke compression ignition engine manufactured by Kirloskar Pvt. Ltd, with some internal changes made (an additional injector was fitted near the inlet manifold), has been used during the experiment. The specifications of the engine are given in Table 1. Figure 1 shows the experimental setup of our study. In the experiment, B20 biodiesel, Butanol gasoline mixture and biogas are used as fuels. B20 biodiesel (Primary high reactive fuel) was prepared by mixing 20 % biodiesel and 80% conventional diesel. On the other hand, Butanol-Gasoline mixture fuel (secondary low reactive fuel) was prepared by mixing n-butanol and Gasoline in the ratio of 1:4. Due the constrain in obtaining natural bio gas, a mixture of CH4 and CO2 in the ratio of 3:2 was used. Table 2 shows all the basic properties of the fuels used in our study. Since the fuel is blended specifically to our need, the properties of the fuel are analyzed dedicated to this study.
Table 1. Specifications of Engine.

| FACTOR                          | SPECIFICATION                                                                 |
|--------------------------------|-------------------------------------------------------------------------------|
| Engine Type                    | Vertical, Single Cylinder, water-Cooled (STD As Per AV1XL Engine), Four Stroke Cycle, water-Cooled, Compression Ignition Diesel Engine. |
| Engine weight (kg)             | 90                                                                            |
| Physical dimensions of bare engine (mm) | 438 X 429 X 620                                                                |
| Maximum speed (rpm)            | 2200                                                                          |
| Bore [mm]                      | 87.5                                                                          |
| Stroke [mm]                    | 80                                                                            |
| Specific Fuel Consumption (gm/hp-hr) | 175 + 5%                                                                    |
| Compression ratio [–]          | 17 : 1                                                                        |
| /Cubic Capacity (Ltr)          | 0.485                                                                         |

Table 2. Fuel Properties

| Property                      | B-20 Biodiesel | Gasoline-butanol mixture |
|-------------------------------|----------------|----------------------------|
| Density (kg/m3)               | 845.4          | 752                        |
| Kinematic Viscosity (mm2/s)   | 4.32 @ 400C    | 0.95 @ 300C                |
| Flash point (0C)              | 80             | 26                         |
| Fire point (0C)               | 91             | 26                         |
| Cloud point (0C)              | 6              | -23                        |
| Pour point (0C)               | -6             | -28                        |
| Vapour pressure               | -              | 42mbar @ 250C              |
| Calorific Value (kJ/kg)       | 39,312         | 42,520                     |

Figure 1. Experimental Setup
2.2. Methodology
A small cylinder containing B20 Biodiesel was connected to the direct injection port via a plastic pipeline. The injector externally fitted was used to inject the butanol and gasoline mixture fuel. Bio gas being the gaseous fuel, was injected in the air intake port. All the test conditions of the experiment are mentioned in Table 3. The engine was operated at a running condition of 1500-1800 rpm. A dynamometer was fitted to the crankshaft, so that the load given to the engine can be varied, from 5N-m till 20N-m in steps of 5N-m, for each biogas flow rate and secondary injector port timings.

Two cylinders with CH4 and CO2, were connected to a thermal mass flow rate meter manufactured by Bronk Horst with an operating range of 0.5 to 25 lpm each, so that the bio gas flow rate can be controlled. The mass flow rate of CH4 and CO2 was set to 7.2lpm and 4.8lpm respectively for a biogas flow rate of 12lpm. For a flow rate of 16lpm of biogas, the mass flow rate was set to 9.6lpm and 6.4lpm for CH4 and CO2 respectively. In order to adjust the injector port timings, the secondary fuel’s pipe has been governed by a pressure gauge (6125C11) at the initial stage and an Arduino based Injection Timing Controller (Arduino UNOR3) at the manifold in order to manage the three different timings (0ms, 4ms, 8ms).

To study the combustion characteristics like peak pressure, peak pressure rise rate, HRR (heat release rate), a piezo electric pressure transducer (Kistler make) was fitted to the engine. This pressure transducer was integrated to an angle encoder (Kubler 8,5020) with 10CA resolution and charge amplifier which was further connected to a Data Acquisition System (NIUSB6341) with 500 kHz frequency rate manufactured by the national instrument company. All these data obtained is stored to a computer in the form of graphs. Thus, from these data, the values of Peak pressure, location of peak pressure, maximum rate of pressure rise, CA50 (Crank angle at 50% of maximum pressure), CA90 (crank angle at 90% of maximum pressure) are found. These values were used to calculate the value of Maximum HRR value.

After the completion of the power stroke, exhaust gases like NOX, CO, CO2, HC, O2 and smoke are released from the exhaust. In order to study the amount of exhaust gases emitted (emission characteristics), AVL444NDI exhaust gas concentration analyser is used. But to find out the quantity of smoke emitted, a separate smoke meter (AVL4373) is used. Thus, the concentration of exhaust gases and smoke emitted was determined.

| Table 3. Test Conditions |
|--------------------------|
| Factors                  | Value          |
| Engine speed (r/min)     | 1500-1800      |
| Load (N-m)               | 5, 10, 15,20   |
| Biogas flow rate (lpm)   | 12, 16         |
| Injector Port timings (ms) | 0, 4, 8       |

3. Results and Discussion
A Comparative study has been conducted by dividing the results in to 3 subdivisions, First the Combustion Characteristics of the fuel from the data collected, followed by Performance and emission characteristics which is been explored to study and compare it with the conventional diesel fuel. Tests were conducted at 4 different loads by varying injector timings and flow rates.

3.1. Combustion characteristics
3.1.1. Maximum Pressure
Figure 2 is graphically showing the maximum pressure values for the variation of load, injector timings and biogas flow rate. Maximum pressure increases with load at 0 ms.and 4 ms injector timings for both biogas flow rates, whereas at 8 ms the trend is very different compared to 0 and 4 ms cases.
It is also observed from the graph that for 8ms butanol gasoline injection timing, the peak pressure attained is very low. This shows that more amount of low reactive fuel aids in improper combustion of biogas, leading to the reduction in peak pressure with increase butanol gasoline injection timing.

![Figure 2. Maximum pressure for Constant Biogas flow rate at 12kg/s and 16kg/s](image)

3.1.2. **Maximum Heat Release Rate**

Figure 3 shows the variation of heat release rate with load for biogas flow rates of 12 lpm and 16 lpm respectively. It can be observed that the heat release rate increases with the applied load at all injector timings and biogas flow rates. The heat release rate variation corresponding to 12 lpm biogas flow rate and 0 ms injector timings is similar to that of 16 lpm biogas flow rate and 4 ms injector timings.

![Figure 3. Maximum Heat Release Rate for Constant Biogas flow rate at 12kg/s and 16kg/s](image)

3.1.3. **Ignition Delay**

Figure 4, denotes the values of ignition delay against various loads at the biogas flow rate of 12 lpm, at different injector timings of 0, 4, and 8 ms and also denotes the ignition delay at a flow rate of 16 lpm. The graph shows a decreasing trend in ignition delay at 8ms injector timing at 16 lpm flow rates. At 0 ms injector timing the ignition delay increases from a load of 5 N-m and reaches a maximum value at 15 N-m and then decreases for both flow rates. At 4ms ignition delay decreases eventually at 12 lpm whereas a slight variation is seen at 16 lpm.
3.2. **Performance characteristics**

3.2.1. Brake Thermal Efficiency

Figure 5 graphically shows brake thermal efficiency values for various loads, biogas flow rates and injection timings. The efficiency values with respect to load for conventional diesel engine is also indicated.

At biogas flow rates of 12lpm and 16lpm, the brake thermal efficiency reduces with increasing injection timings and increases with increasing in load values. The maximum efficiency recorded in the present experiment is 31.40% and 30.65% at 12lpm and 16 lpm flow rates respectively. But diesel shows higher efficiency of 32.75% at 20N-m load due to its rich fuel mixture.

3.2.2. Volumetric Efficiency

Volumetric efficiency values are graphically shown in Figure 6 respectively. The experimental results showed that the volumetric efficiency increases with increase in injection timings under all loads at 12lpm. The maximum efficiency value noted is 82.1%. At 16 lpm of biogas flow rate, maximum efficiency of 81.01% is obtained at 0ms with 20 N-m load. Diesel fuel records the maximum efficiency of 92.69%.
3.3. Emission characteristics

3.3.1. CO Emission
Figure 7 gives the CO emissions with load for different biogas flow rates and butanol-gasoline injection timings along with the emission values for conventional diesel mode. Normally the emission of CO is due to many factors such as incomplete combustion, delayed combustion and so on. In 12lpm biogas flow rate case, there is a steady increase in the CO emission with increase in butanol-gasoline injection timing. But, the 16lpm biogas flow rate case, shows a different trend compared to 12lpm case, except 0ms butanol-gasoline. The overall CO percentage is maintained less than 0.3 percentage even for higher loads.

3.3.2. NOx Emission
NOx emission values are shown in the Figure 8. The results indicate a gradual increase in NOX emissions with application of load for both flow rates. The NOx emission increases with injector timings at 5N-m load. However, the NOx emission reversed to decreasing order with respect to injector timings as the applied load is increased. It is observed that the addition of butanol-gasoline mixture reduces NOx emission. It is observed that NOx emission is less compared to conventional diesel fuel which is due to low temperature of combustion.
3.3.3. Smoke Emission
Smoke emission values are shown in the Figure 9. The amount of smoke emitted with respect to the load applied, for the cases 12 lpm and 16 lpm biogas flow rates and conventional diesel mode are given in the Figs 16 and 17 respectively. In general, the smoke (i) decreases up to 15 N-m load (ii) increases beyond 15N-m load. The overall observation shows that the fuel with 16lpm biogas flow rate + 8ms butanol-gasoline injector timings is recommendable consequent to constancy in smoke emission with applied load.

3.3.4. HC Emission
Figure 10 shows the variation hydrocarbon emission with applied load. At 12lpm of biogas flow rate, the HC count increases with respect to injector timings from 0 ms to 8 ms, whereas it decreases for increase in load. At 16 lpm, 0 ms and 8 ms follow similar HC emission trend with 12 lpm flow rate.
4. Conclusion

Previous investigations conducted by researchers focused on ethanol and other alcohol fuels as a prime substitute for diesel to improve emission and performance characteristics[13-17]. However RCCI method does not show any insolubility issues when two different fuel are mixed. An experimental study on RCCI operation is carried out in a single-cylinder four-stroke engine to study the combustion, emission and performance characteristic by using a Biodiesel as high reactive and mixture of butanol-gasoline and biogas as low reactive fuel. Combustion and emission characteristics were studied under different conditions varying biogas flow rate, injector timing, and load. The conclusion can be summarized by comparing the results with diesel fuel are as follows,

- Brake thermal Efficiency and Volumetric Efficiency are high at low flow rate of biogas. The maximum thermal efficiency and Volumetric efficiency is noted as 31.40% and 82.1% at 12lpm of biogas. It increases with an increase in injection timings and loads applied. In case of Diesel fuel the maximum brake thermal efficiency and Volumetric is recorded as 32.75% and 82.11% at 20 N-m respectively.

- The CO emission is lower for 16 lpm biogas flow rate with 4ms butanol-gasoline pulsed injection. But, it gives higher NOx value. At high flow rate of low reactive fuel, CO shows similar levels when compared with Diesel.

- Ignition delay increases with the advance of load on the engine which can be controlled by increasing the flow rate of less reactive fuel. At 0 ms, secondary fuel flow rate increases rapidly, whereas at 4ms, it decreases comparatively and at 8ms rate of flow it falls steadily. While operating with Diesel fuel the ignition delay increases with the increase in load.

- Maximum heat release rate increases with advancing the load on the engine and it can be decreased by increasing the secondary fuel flow rate. The trend in Maximum heat release rate concerning diesel is not uniform. It decreases till 15 N-m and rises in 20 N-m.

- Smoke level shows a decreasing pattern till 15 N-m but increases at 20 N-m for all injector timings. Diesel constantly increases its smoke levels as load increases. Diesel shows better smoke results compared with butanol-gasoline and biogas mixture.

- NOx emission increases with the addition of loads at all flow rates. The trend in NOx emission concerning injection timings is not uniform. But when compared to Diesel has higher NOx emission but trend in fuels are similar.
Based on this study, the fuel with 16lpm biogas flow rate and 8ms butanol-gasoline pulsed injection performs good with lower ignition delay, higher HRR, lower HC, lower NOx emission and lower smoke with reasonably good performance features.

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