Influence of injection pressure on performance and emission characteristics of single cylinder RCCI engine fuelled with ethanol gasoline and diesel biodiesel blends.

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Abstract. Reactivity controlled compression ignition (RCCI) has great potential for a simultaneous reduction in Nitrogen oxides (NOx) and particulate matter (PM) with increase in thermal efficiency. In this experimentation, an attempt is made to investigate the effect of injection pressure on the performance emission and combustion characteristics of single cylinder RCCI engine. Literature reveals that injection pressure has a great influence on the quality of charge preparation, fuel stratification, and incylinder reactivity. Suitably modified engine was operated for 0 to 12 kg loads, for 400 to 700 injection pressure. The blend of ethanol gasoline E20 used as a low reactivity fuel and blend of diesel jatropha biodiesel B20 used as a high reactivity fuel. Experimental results showed that increase in injection pressure enhances the degree of charge homogeneity, reduces the combustion duration, and provides higher rate of energy release. For 12 kg load and 700 bar injection pressure, it is observed that 5% rise in thermal efficiency, 27% reduction in smoke opacity, 2% reduction in HC, 4% reduction in CO and 20% rise in NOx as compared to 400 bar injection pressure.

1. Introduction

Energy consumption of the world continuously increases as a result of a higher rate of economic growth through industrialization, enhancement of living standards, and increasing population. The majority of the energy can be fulfilled with the help of internal combustion engines operated on fossil fuel. In comparison with SI engines, CI engines are more popular because of higher energy conversion efficiency, nearly zero throttling losses, reliability, durability, and overall leaner operation.[1] The important issues related to these CI engines are PM and NOx emissions which are very harmful to human health and environmental pollution.[2] There is a trade off relationship between the NOx and PM.[3] It is a very challenging task to the simultaneous reduction of NOx and PM without affecting thermal efficiency. The strategies like an early injection of the fuel reduce the PM but increase the NOx and the strategies like exhaust gas recirculation (EGR) and late injection reduce the NOx but increases the PM. The low temperature combustion strategy has great capacity to reduce the NOx and PM simultaneously without affecting the thermal efficiency of the engine.[4][5][6]

There are different low temperature combustion strategies invented by the researchers like HCCI(Homogeneous Charge Compression Ignition), PCCI (premixed charge compression ignition),PPCI (partial premixed charge compression) etc[7][5] RCCI is the most promising one in which the fuel having high octane number referred as low reactivity fuel (LRF) injected through the port and high reactivity fuel (HRF) like diesel directly injected into the combustion chamber with single, double injections to maintain the reactivity gradient to control the combustion duration and high temperature heat release which produces ultra low NOx and soot emission without affecting the thermal efficiency.[2] The reactivity gradient and mixture stratification greatly influenced by the
various parameters like ratio of LRF to HRF, fuel properties, no of pulses, the mass of the fuel in each pulse, etc. The injection pressure of the HRF is one of them. There are two aspects of the injection pressure one is, if the injection pressure is high, as a result of higher rate of vaporization the mixture becomes homogenous and the other hand if the particle size reduces the inertia of the particles reduces and reduces the penetration lengthwise. For the same amount of fuel, if injection pressure is high then the duration of injection reduces.[8] Basically, rapid combustion rates are the function of higher injection pressure, which contributes the increasing cylinder gas temperature at higher level. Initially while stating the combustion, the spray was confined to a very small area at injection location. After that it get spread out over the entire combustion chamber. The utilization of the cylinder surface is not so effective which leads to affect the combustion process and resulted into the lower heat to work conversion process. Therefore there were further reduction in torque and power. Nazemi et al[9] experimentally proved that as the pressure increases, weak auto ignition occurs at the piston bowl area which reduces the HRR with retardation of combustion phasing by. HC, CO, Soot increases as a result of low combustion chamber temperature while reduction in the NOx.

As an effective control on the mixture preparation, combustion event and duration and ease of multifueling RCCI has great potential to adopt the bio fuels as blend with conventional diesel fuel or gasoline. As a sustainable fuel, biofuels like ethanol and biodiesels have a great capacity to reduce the harmful emissions as well as an alternative option as a fuel for the IC engines, as a result of scarcity of petroleum products and their increasing prices. Some biodiesels having lower viscosity and lower cetane number can be directly used as a fuel for CI engines but some biodiesels blended with conventional diesel fuel as practical constraints.[4] Biodiesel can be manufactured locally, there should not require any refining process, less cost of transformation so they are energy efficient, cheaper than the petroleum products, farmers can produce on a farm also and up to B20 there should not any requirement of the modifications in the existing engine.[10] In comparison with diesel biodiesel have a higher cetane number, greater lubricity and low sulphur content. [11] There are a variety of biodiesel are available and they can be produced from different feedstocks, Jatropha biodiesel most attractive alternative fuel for diesel fuel. The oil content jatropha seeds as well as oxidation stability of jatropha biodiesel is more than the soyabeans and palm and very good low temperature characteristics.[12]

In this experimentation the blends of ethanol and gasoline are used as port injection fuel since the blending of small amount of ethanol in gasoline increases the octane rating of the mixture and which helps in the increasing reactivity gradient in the combustion chamber. The lower propensity of ethanol increases auto ignition leads to increases the operating limit of the engine as well as higher oxygen content helps to reduce the HC emission.[13] The main objective of this investigation is to find out the effect of variation in injection pressure and their detailed analysis for RCCI operation with blends of gasoline ethanol as a LRF and blends of jatropha biodiesel and diesel as a HRF. The uniqueness of this investigation is that the effects of all parameters were investigated for the various loading conditions.

2. Methodology
2.1. Test setup and related facilities
A single cylinder, naturally aspirated, medium duty stationery diesel engine is used for the experimentation with suitable modifications. The specifications of the test engine are given in table 1. The photographic view of actual experimental setup is shown in figure 1. The engine was coupled to an eddy current dynamometer for load measurement. Controlled unit is provided for the loading and unloading of the engine. The blends of ethanol- gasoline fuel E20 have been injected through the port as a high reactivity fuel. A separate ECU is connected to control the rate of HRF. The blend of the diesel- jatropha biodiesel B20 used as a high reactivity fuel and injected directly into the combustion chamber through the common rail system.

Direct injection of high reactivity fuel B20 and their controls like injection pressure, amount of fuel in each pulse, no of pulses, injection timing etc has been controlled using the NiRa i7 open
The electronic control unit (ECU) which receives inputs through the different sensors like cam, crank, manifold absolute pressure (MAP), mass air flow, oil temperature sensors and rail pressure located in test setup.

Table 1. Test Engine Specification

| model and make of the engine | TVI Kirloskar, |
|------------------------------|----------------|
| General details              | 4 stroke, CI constant speed, water cooled |
| No. of cylinders             | 1              |
| Stroke                       | 110 mm         |
| Bore                         | 87.5 mm        |
| Swept volume                 | 661 cc         |
| Compression ratio            | 17.5:1         |
| Rated Output                 | 5.2 kW at 1500 rpm |
| Injection Nozzle             | 3 holes        |
| Fuel injection pressure      | 205 bar        |

Table 2. Specification smoke meter

| Measurement Range    | Opacity          |
|----------------------|------------------|
|                      | 0-100%           |
| Resolution           | Opacity          |
|                      | 0.1%             |
|                      | absorption       |
|                      | 0.01m-1          |
| Accuracy             | Better than ±0.03 of measured values |
| Operating Temperature| 5 -50°C          |
| Linerity check       | 50% of measurement range (automatic) |
| Measurement Length   | 0.43mm ± 0.005mm |
Table 3. Specification of five gas analyzer

| Measurement Data | Measurement | Resolution |
|------------------|-------------|------------|
| CO               | 0-15%Vol    | 0.001 % Vol|
| HC               | 0-2000 ppm Vol | 1ppm/10ppm |
|                 | (0-2000ppm) (>2000ppm) |
| CO₂              | 0-20%Vol    | 0.1 % Vol  |
| O₂               | 0-25%Vol    | 0.01 % Vol |
| NOx              | 0-5000 ppm Vol | 1 ppm Vol |
| Engine Speed     | 400-6000rpm | 1 rpm      |
| Oil Temperature  | 0°C -125°C  | 1°C        |
| Lambda           | 0-9.9999    | 0.001      |

2.2 Fuels used

In this experimentation the fuels, diesel, gasoline and ethanol has been procured from the local petrol pump and market while the jatropha biodiesel prepared inhouse with the transesterification process. The photographic view of transesterification process is as shown in figure 2. The ethanol used in this experimentation having purity about 99.99%. The blends of fuel E20 and B20 were prepared on the volume basis. The mechanical stirrers used for mixing the fuels as shown in figure 3. The detailed properties of the blends used are shown in table 4.

Table 4. Properties of test fuels

| Fuel                | Calorific value (KJ/kg) | Density (kg/m³) |
|---------------------|-------------------------|-----------------|
| Gasoline            | 44500                   | 730             |
| Diesel              | 42500                   | 830             |
| Ethanol             | 26200                   | 785             |
| Jatropha Biodiesel  | 39500                   | 880             |
| E20                 | 40840                   | 741             |
| B10                 | 42200                   | 835             |

Figure 2. Preparation of the biodiesel
2.3 Modification in the existing test setup
The RCCI operation required minimum two fuels, so separate tank was provided for E20 fuel. As fuel injection is concerned, high pressure common rail system was provided for direct injection of high reactivity fuel and modified port fuel injection system is provided for the LRF with solenoid operated fuel injector. The modifications carried out in the existing set up are as shown in figure 4.

3. Result and discussion
The experimentation was carried out at constant speed about 1500 rpm for 0 to 12 Kg load condition with increments by 4 Kg. The direct injection of HRF was splitted into pilot injection and main injection. The base line operating conditions are shown in table 5 In this experimentation the injection pressure varied from 400 to 700 bar by using open ECU Nira i7.
Table 5. Baseline operating condition

| Parameter                  | Value      |
|----------------------------|------------|
| Injection pressure (PFI)   | 4 bar      |
| Injection pressure (DI)    | 500 bar    |
| Pilot injection timing     | 25 deg btdc|
| Pilot injection mass       | 40%        |
| LRF to HRF ratio           | 60:40      |
| Main injection angle       | 16 deg btdc|
| Inlet air temperature      | 45°C       |

3.1 NOx emission

The effect of variation of injection pressure on NOx emission shown in figure 5. Increase in injection pressure reduces the size of injected fuel droplets and increase the fuel vaporization rate results in the higher pressure rise rate[14]. It enhances the stratification of the charge and increases the combustion chamber temperature, which increases the NOx. About 21% increases in NOx observed for 700 bar for 12 kg loading condition as compared to 400 bar pressure.

![Figure 5. Effect of injection pressure on NOx emission](image)

3.2 HC emission

![Figure 6. Effect of injection pressure on HC emission](image)

Basically in case of RCCI combustion LRF is injection too early in the compression stroke, during
compression, the charge get trapped in the crevice zones of the combustion chamber.

The lower incylinder temperature and trapped charge increases the HC emission at the lower load. The effect of variation of injection pressure on HC emissions are shown in figure 6. For the 12kg load and 400 bar injection pressure it is observed that there is HC emission is higher as compared to 700 bar. For all injection pressures as a load increases there is drastic reduction in the HC emission as an effect of enhancement of the combustion process as an effect of increasing temperature, higher degree of atomisation as well as oxygenated fuel combination. [15] For 700 bar injection pressure and 12 Kg load, slight reduction about 4% in HC emission were observed compared to 400 bar.

3.3 Smoke opacity

The effect of variation of injection pressure on CO emission as shown in figure 7. Since the fuel combination used is E20-B20, the viscosity and density of the B20 is higher, for proper mixing of the fuel it is essential to improve the atomization process.[15] As the pressure increases due to reduction in particle size, rate of vaporization increases which leads to improve the combustion process ultimately results in the reduction of smoke opacity. As compared to 400 bar pressure and 12 kg loading condition, 27% reduction has been observed for 700 bar.

![Figure 7. Effect of injection pressure on smoke opacity](image)

3.4 CO emission

![Figure 8. Effect of injection pressure on CO emission](image)
The effects of variation of injection pressure on CO emission as shown in figure 8. The CO emission is less for no loading condition as a result of lower oxidation rate of CO. As the load increases, increasing oxidation rate decreases the CO %. For 12 kg loading condition, and 700 bar injection pressure reduction in CO by 4% as compared to 400 bar.

3.5 Brake thermal efficiency
The effects of variation of injection pressure on brake thermal efficiency are as shown in figure 9. As the injection pressure increases, as an effect of shorter combustion duration, higher heat energy release rate, advanced combustion phasing there is increase in brake thermal efficiency for 12 kg loading condition and 700 injection pressure 5 % rise in thermal efficiency has been observed as compared to 400 bar injection pressure.

![Figure 9: Effect of injection pressure on brake thermal efficiency](image)

3.6 Cylinder pressure and rate of pressure rise

![Figure 10: Pressure Vs Crank angle for 12 kg loading condition](image)
The phases mixture preparation processes degree of atomization, vaporization greatly influence by the injection pressure. [15][16] As the injection pressure increases the rate of vaporization of the fuel also increases and increases the degree of homogeneity of the mixture.[8] The size of the fuel particles reduces as the injection pressure increases and they losses their inertia and unable to penetrate the compressed air fuel mixture of HRF, which results slow penetration of the flame. But in case of moderate injection pressure the fuel particle size is high enough are more flexible to mixture with the mixture.

Combustion process and incylinder pressure greatly influences by these factors. Figure 10 shows pressure Vs crank angle diagram for 12 kg loading condition. It is observed that for 700 injection pressure the start of combustion (SOC) slightly advanced. As the injection pressure varies from 400 to 700 bar, there is increase in the combustion pressure developed observed in the combustion chamber. This is a result of higher degree of charge homogeneity of the mixture.[14] Figure 11 shows effect rate of pressure rise Vs crank angle, it was observed that, there is increase in rate of pressure rise has been observed for 700 bar pressure.

4. Conclusion
Critical analysis of effect of injection pressure on performance, emission and combustion characteristics of the engine for RCCI operation of E20- B20 fuel combination were carried out in this experimentation. The conclusions of these experimentations are as follows

- Fuel injection pressure is one of the most important factor in RCCI combustion process which affects on the atomization, combustion phasing, and combustion duration, start of combustion which affects on emission as well as performance of the engine.
- For 12 kg loading condition, as compared to 400 bar injection pressure, 20% rise in the NOx formation, 4% reduction in the HC emission, 2% reduction in CO emission were observed.
- Increase in thermal efficiency by 5% for 12 kg load for 700 bar pressure in comparison with 400 bar.
- For 700 bar injection pressure, smoke opacity as been reduced for all loading condition. As compared to 400 bar injection pressure, 27% reduction in smoke opacity was observed for 12 kg loading condition and 700 bar injection pressure.
• The fuel properties like viscosity and density as well as fuel ratio also plays an important role in the rate of vaporization, and atomization which is closely associated with the emission formation.

• For given set of baseline configuration of operating parameter for 12 kg loading condition by considering minimum NOx and smoke opacity, 600 bar pressure is most efficient.

5. References

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