A Review on Performance, Emission and Combustion Characteristics of Biodiesel Blends in a Diesel Engine with Varying Injection Pressures

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Abstract- Rapid industrialisation and urbanisation have led to extremely high demand for petroleum fuels like petrol, diesel. This has resulted in high uncontrolled emissions leading to extensive damage to the environment. The need to investigate alternative fuels which are less polluting is profound today. While more expensive alternative technologies like battery driven technologies, solar cars are not yet feasible for mass production, efforts to improve existing feasible technologies is necessary. The need of the hour is further optimisation of available parameters like biodiesel blends, injection pressures and other nozzle parameters.

Biodiesels are methyl or ethyl ester of fatty acids produced from animal fat and vegetable oils. It can be used in completely pure form or blended with diesel before use. Due to its properties being similar to diesel, little or no engine modification is used. It also provides for easy storage and use. The benefits are many fold with significant reduction in emissions of unburnt hydrocarbons, Particulate matter and Carbon monoxide. Improving emission characteristics of exiting diesel engines can also be done by optimising injection pressures. Fuel injection pressure plays a huge role in combustion characteristics directly influencing emission and performance. The review paper focusses on the use of biodiesel blends and variation of injection pressures in diesel engines and their impact on the performance characteristics and emissions of the engine.

Keywords Performance, Emissions, Fuel Injection Pressure, Biodiesel

1. Introduction

In today’s world, climate change poses a great threat towards the future generations and the sustainability of the planet is under question. A roadmap for a sustainable future requires pollution to be controlled. This has led to extensive research in the field of renewable energy, green engineering, green products and industrial ecology. Emissions from automobiles contribute to pollution to a great extent. Vehicles running on diesel are preferred nowadays due to their superior mileage and robust nature. They are known for their high thermal efficiency and reduced CO2 emissions. However, these benefits are associated with higher emissions of NOx, unburnt HC, PM and CO.

Variants of biodiesel such as Karanja, Jatropha and their blends with baseline diesel have been investigated for studying combustion, emission and spray characteristics. Several researchers have explored the possibility of using biodiesel blends in existing diesel engines by comparing engine performance, emission data and spray development. Engine output parameters such as NOx, PM, unburnt HC, BSFC have been experimentally calculated for cost and performance viability in modern automobiles. Biodiesels have improved emission characteristics (unburnt HC, CO, particulates, sulphates) while producing slightly higher NOX values. However the major problem with biodiesel is its higher cost of production, lower energy content and slightly lower fuel economy. Biodiesel has a higher viscosity, lower volatility compared to baseline diesel.

Research has also focussed on employing higher FIPs to improve emission and performance of modern diesel engines. In this review paper, we aim to study the existing research on diesel engine performance and emissions. We also aim to study the spray pattern formation, combustion phenomenon and emission characteristics with respect to parameters such as FIP and various blends of Biodiesel.

Table 1. Abbreviations used in review

B5, B10, B20, B100	5%, 10%, 20%, 100% blend of biodiesel in diesel by volume
FIP	Fuel Injection Pressure
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
BSEC	Brake Specific Energy Consumption
PM	Particulate Matter
UBHC	Unburnt Hydrocarbons
NOx	Oxides of Nitrogen
WCO	Waste Cooking Oil
DEE	Diethyl Ether

2. Bio-diesels

With fossil fuel reserves gradually depleting, Biodiesels have been the focus of extensive research in recent years. The methyl or ethyl ester of fatty acids, biodiesel is produced from vegetable oils and animal fats. It can be used itself as a standalone fuel or can be blended with mineral diesel to form blends of different concentrations. [1] Various blends of Biodiesel involving Karanja Oil, Jatropha Oil, Methyl Ester, Ethanol, Palm Oil and Cooking Oil Biodiesel, Tung Biodiesel, Linseed Oil Methyl Esters have been investigated. Biodiesels, conventionally were found to reduce substantially lower emissions of carbon monoxide, unburnt hydrocarbons and particulate matter than mineral diesel as they are derived from oils and fats of renewable biological sources. [1] Due to their high oxygen content and higher specific gravity when compared to diesel were found to have lower heat value on weight basis. [2] Vegetable oils are associated with high viscosity due to the their large molecular weight and structural complexity. [1]Thermal efficiency of an engine operating on biodiesels when compared to diesel was observed to improve. BSFC of biodiesels are more than diesel due to the lower calorific value when compared to diesel. [3] Jatropha biodiesel blends were found to exhibit similar characteristics which were in accordance with the research reviewed.

2.1. *Emissions for different biodiesel blends*

Notable differences were observed in the emission characteristics between biodiesel (a commercial biodiesel derived from rapeseed oil) and normal diesel. [4] The HC emissions were lower for biodiesel owing to higher oxygen content and the NOx emissions were less owing to a lower flame temperature. These results were attributed to the physical properties of biodiesel such as a higher density, viscosity, surface tension and boiling point. [5] The effect of FIP for Diesel and Linseed Oil Methyl ester diesel blends (B10, B20, B40 and B60) was that the amount of CO_2 emission is proportional to the amount of fuel burnt and hence on the engine load. Higher FIP leads to better mixing and hence lower unburnt HC. [6] It was noted that biodiesel led to increased fuel consumption due to lower energy content and high viscosity. This might be mitigated at higher FIPs at the cost of higher NOx emissions. It is possible to decrease Biodiesel fuel consumption through increasing FIP and not exceed NOx emission. [7] It was noted that all blends of Karanja and Jatropha (10%, 20% and 30%) showed higher NOx levels compared to baseline diesel. On the contrary, CO emissions were reduced. Better combustion ensured lower HC emissions. Similarly smoke is lower for biodiesel blends. The commonly observed effect of biodiesel was an average 15% increase in NOx, and around 50% drop in CO. [8] It is possible to decrease Biodiesel fuel consumption through increasing FIP and not exceed NOx emission. During the whole range of experimentation, the NOx emissions were found to be higher than diesel. Emissions like HC, CO and smoke density on the other hand, were found to be reduced when compared to diesel. [9] A contradicting research showed little to no difference of NOx emissions when the engine was run on Jatropha- diesel blends and pure diesel at low to medium loads. It concluded that NOx emissions are not majorly affected by biodiesel concentrations at medium to high engine loads. [10] Another research reported that compared to B0, NOx levels was 4.2% lower (B10), 0.8% higher (B20) and 12.2% higher (B10–0). At low speed ranges, CO levels were in the decreasing order: B100, B20, B10 and B0. The trend reversed at medium and high speed ranges. Overall, CO emissions were 85.5% higher for B100, 41.4% higher for B20, 20.7% higher for B10 over diesel mostly due to poor cold warm-up. HC emissions followed similar emission trend as CO.

[11] Addition of Jatropha has been observed to improve the solubility of ethanol in Diesel, thereby increasing oxygen content. A significant reduction in smoke was observed for blends, possibly due to higher oxygen content in ethanol blends, especially at higher engine loads. Low viscosity and higher oxygen content in ethanol blends however led to an overall increase in NOx emission at all loads and engine speeds. NOx emissions however decreased with increase in engine speed for all blends. CO emissions increased compared to diesel due to lower in-cylinder temperature and longer ignition delay. Better combustion due to high oxygen gives rise to higher combustion temperature leading to higher NOx levels. [3] A blend of 5% ethanol and 95% Jatropha methyl ester proved to increase oxygen content by up to 12% by mass causing a reduction in emission level of CO and CO_2. [12] HC, CO and PM emissions dropped drastically with an increase in percentage of biodiesel in the blend of the fuel whereas NOx emissions increased slightly. Results from the use of B20 were compared with other types of biodiesel, namely, soy, rapeseed, tallow and yellow grease. Rapeseed oil showed to have almost 20%, 17%, 7% and 2% reduction in level of HC, CO, PM and NOx emissions respectively compared to B20. Biodiesel was found to have the best effects on a medium load vehicle. [13] With an injection timing of 21deg BTDC and an FIP of 220 bar, results were very close to those in the case of the diesel engine for A20 fuel. At high pressure, better mixing resulted in reduced HC, CO and smoke intensity. However, NOx emissions increased due to improved combustion conditions. [7] Higher cetane numbers and latent heat of vaporisation of Diethyl Ether resulted in shorter ignition delay as well as lower in-cylinder temperatures for the biodiesel bends resulting in 15% NOx reduction for the 20% blend of Thevetia Peruviana biodiesel. However, HC emissions increased upon addition of Diethyl Ether (DEE). [2] Blends of Jatropha Methyl Ester and ethanol showed lower CO and HC Emissions compared to diesel. HC emissions were found to be least for 100% Jatropha Methyl Ester possibly due to high oxygen content. Consequently, NOx emissions were found to increase with increase in Jatropha Methyl Ester concentration.

The Count Mean Diameter [14] for Karanja blend Biodiesel was lower than diesel. The 10% blend showed lowest total particulate number which increased with higher blends. [15] There is no significant difference in soot concentration of flame for diesel, palm oil biodiesel (BDFp) and cooked oil biodiesel (BDFc) at 1000 bar. It dropped drastically to an insignificant value for BDFp and BDFc, unlike diesel at 2000 and 3000 bar. [16] Use of biodiesel in older vehicles (equipped with DOC) lowered CO and PM emissions due to presence of oxygen in biodiesel molecules. NOx already high remained stable. For newer vehicles (equipped with DPC+DPF/ Urea-SCR), very low levels of CO was observed. NOx levels increased with higher blending. [5] Retardation of timing led to higher CO, lower smoke and similar HC levels. Advancement of injection timing however led to higher CO and smoke but lower NOx. The 15% blend for Tung Biodiesel had improved performance and exhaust emissions. The CO, HC, Smoke emissions were lower for higher FIPs while NOx levels went up. [17] NOx emissions showed a dual trend, decreasing at low to medium speeds and reversing at high speeds for 5% and 10% blends.

2.2. Ignition delay

Biodiesel and its blends are commonly found to have a shorter ignition delay compared to baseline diesel. [6] In spite of a lower calorific value, lower volatility and higher viscosity, biodiesels have a higher cetane number. Higher FIP leads to better atomisation and air fuel mixture preparation. [15] Ignition delay depends on the cetane number (Diesel=58, BDFp (Palm Oil biodiesel) =64.6, BDFc (Cooked Oil Biodiesel) =51). While BDFp has the shortest ignition delay, BDFc has a shorter ignition delay compared to diesel in spite of a lower cetane number. The ignition delay value falls drastically for 2000 and 3000 bar for BDFc and BDFp while the reduction is considerably less for diesel. [15] Use of Diethyl Ether has been shown to lower ignition delay by virtue of higher cetane number. [18] A minimum ignition delay period of 12.4° crank angle was observed for a blend of 40% Waste Cooking oil (WCO) methyl ester, 10 % ethanol and 50 % diesel which is comparable to diesel. [3] Prolonged combustion and a longer ignition delay is a direct result of increased oxygen content. A higher cetane number also contributes to a longer ignition delay. [19] The fuel line pressure and injection spray patterns of a four stroke CI engine fuelled with diesel and dimethyl ether showed that injection occurred later in case of DME (Dimethyl Ether) due to lower bulk modulus, leading to delayed ignition. When DME was injected, the sprays spread widely having a shorter penetration. [20] Canola Oil Methyl Ester (COME) and blends B0, B5, B20, B50 and B100 at 180, 200, 220 and 240 bar FIP were investigated using engine loads: 25 kPa and 50 kPa BMEP.

Biodiesel and its blends showed shorter IDs because of the higher cetane number. Consequently, lower fuel burning in the pre-ignition burning phase led to lower pressure rise rates and peak cylinder gas pressures for biodiesel. ID values decreased with increase in FIP. The ignition delay was also found to be lower at higher load for all FIPs for all blends including B0. The premixed ignition phase was longer for B0 due to higher ID.

2.3. *Performance for different biodiesel blends*

Biodiesels were found from studies to have nearly similar values of cetane number, energy density and heat of vaporisation to diesel. The lower BTE of both Karanja and Jatropha blends could be due to [7] lower calorific value and high viscosity leading to poor atomisation. [11] BTE is slightly improved for Jatropha blends at high load, due to better mixing, higher oxygen content. However it is lower at low loads for high ethanol blends. [2] Jatropha-Ethanol blends showed higher BTE compared to diesel with the 20% blend of Ethanol in Jatropha methyl ester showing a 12.1% improvement compared to diesel. BSEC values were highest for 100% Jatropha methyl ester.

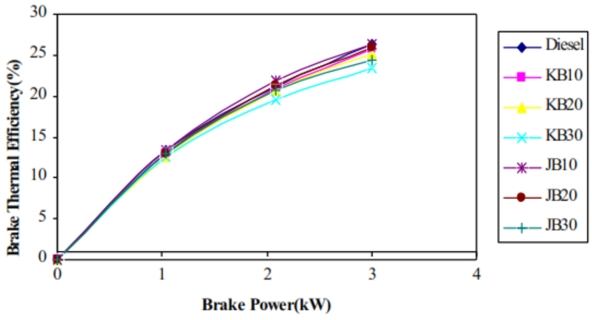

Fig. 1. Variation of BTE for blends of Karanja and Jatropha [7]

BSFC increased at low loads, while decreasing at high loads. [3] The use of ethanol decreases the calorific value of the fuel, thus improving combustion with higher heat release. BSFC as well as BTE increases due to increased oxygen content. [21] DEE blends of biodiesel significantly reduced viscosity and improved atomisation. This resulted in higher BTE for the blends of Thevetia Peruviana biodiesel, and achieved maximum BTE for the 20% blend. [22] Higher FIP increased atomisation but lower penetration generating faster combustion rates for all blends of Linseed Oil Methyl ester diesel (B10, B20, B40 and B60). B60 has the highest brake power at low and high FIP. BSFC is higher at higher FIPs due to lower brake efficiency. [20] The maximum cylinder pressure, which depends on the initial combustion rates is higher for diesel at all loads, and slightly increased with increase in FIPs. The diffusion phase was higher for COME. Lower LHV of COME reduces the Rate of Heat Release which also reduces with blend amount of COME. At 200 bar, BSFC values ranged from 376, 380, 385, 395 and 419 g / kWh for B0, B5. B20. B50, B100 and the trend applies for all FIPs and loads. BSFC also reduced with increase in FIP. BTE increased for all blends at all FIP indicating the trend. Overall, increased FIP led to lower BSFC, BSEC and higher BTE. [5] BTE was maximum at standard injection timing, due to higher power and lower fuel consumption.

[4] The biodiesel (a commercial biodiesel derived from rapeseed oil) had a longer spray tip penetration and almost half the spray angle of diesel. These results were attributed to the physical properties of biodiesel such as a higher density, viscosity, surface tension and boiling point. [23] Amongst biodiesels, Karanja and Jatropha had longer spray tip penetration and narrower spray angle than WCO. Baseline diesel had a shorter penetration and faster vaporisation. In the non-evaporating test (800 bar, 300K, 30 bar ambient pressure), spray tip penetration was 40%, 18% and 9% greater for Karanja, Jatropha and WCO compared to diesel. Biodiesels exhibited slightly narrower cone angles compared to baseline diesel.

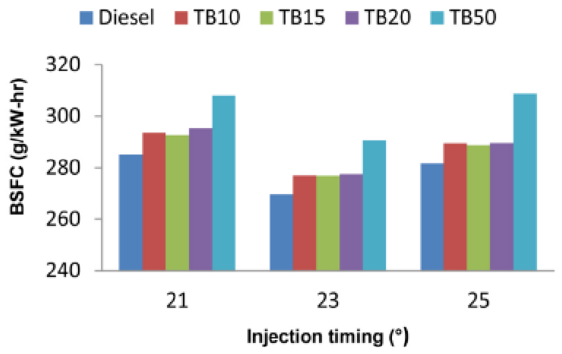

Fig. 2. BSFC values for Diesel and biodiesel blends at Various Injection Timing [5]

Equivalence ratio along spray is an indicator for combustion and emission characteristics. It showed a decreasing trend along the spray, with biodiesels showing a 10% lower equivalence ratio. In the evaporating condition (800 bar, 804K, 41.7 bar ambient pressure), penetration length was shorter and spray was narrower. Spray area was least for diesel because of rapid vaporisation. Spray tip penetration was 125%, 118% and 30% greater for Karanja, Jatropha and WCO compared to diesel. Biodiesels hence exhibit poorer spray characteristics, but has a slightly lower air-fuel mixture indicating lower soot emissions. [24] The fuel spray characteristics of dimethyl ether (DME) was compared with that of diesel in a constant volume vessel. Spray tip penetration and cone angle were observed to be longer and narrower at atmospheric pressure. Intermittent DME spray was observed at FIPs of 25MPa and 40 MPa, regardless of chamber pressure. [17] Use of ethanol blended biodiesel resulted in higher BSFC compared to diesel. Addition of cetane improvers such as DTBP had a satisfactory improvement in performance.

3. Fuel Injection Pressure (FIP)

3.1. Spray penetration

FIP has a great impact on spray pattern and its flow characteristics. [25] The atomization structure at various FIPs, ambient pressures for a constant injection time for a common-rail diesel injector has been investigated using the phase Doppler particle analyser (PDPA) system and a spray visualization system. The PDPA system was used to investigate the Sauter mean diameter (SMD) size. It was observed that the spray tip penetration is more for a higher FIP. With an increase in ambient pressure, the spray tip penetration decreases. The SMD was found to be higher for a higher ambient pressure which means atomization decreases with increase in ambient pressure. [26] The experimental results showed that the spray jet has stronger penetration momentum at higher pressures (200 MPa to 400 MPa). Due to increased air resistance with increasing FIP, the penetration spacing diminished and the difference was found to gradually increase over time. A two stage velocity distribution presented a reduced effect of FIP on velocity values from 21% to 14.8%. A two mode leading edge shock wave was observed consisting of spherical shock wave and oblique shock wave with junction points. With increase of the FIP, there is a limitation of the number of junction points.

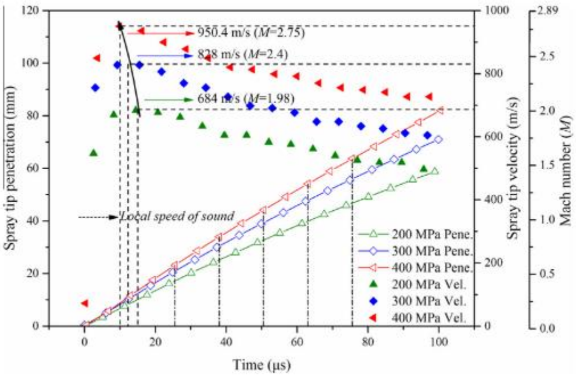

Fig. 3. Evolution of Spray tip penetration (mm) at 200-400 bar FIP [26]

The study and optimization of fuel spray penetration is very important because a large penetration leads to wall wetting whereas a small penetration leads to improper mixing of fuel, both cases reducing fuel efficiency. [27] The increase in in-cylinder pressure decreases penetration length whereas the increase in FIP increases penetration length. An increase in number of holes of the nozzle decreased the penetration length. [28] The diesel fuel flow and spray characteristics over a wide fuel temperature range were studied using a common rail system and constant volume combustion chamber (CVCC) to help solve the cold start issue. The fuel temperature was controlled between 243K and 313K. Fuel injection quantity was found to decrease with a decrease in temperature. As the fuel temperature decreased, the start of injection was retarded and end of injection was advanced which led to reduction of injection duration. Fuel spray penetration was found to increase and spray angle was found to decrease with cold fuel due to interaction with surrounding gas and diminished fuel evaporation.

Attempts have been made to form a flow model of fuel using fluid dynamics. [29] The modelling of the diesel spray was done into two regions: the main region (steady flow) and front region. Equation of propagation of the spray tip was formulated and compared with experimental data obtained from a Common Rail Direct Injection (CRDI) nozzle. An assumption in the model is that the distance between the fronts of the penetrating spray is so far from the nozzle that the details of flow near nozzle have no influence on the penetration process. Experimentally, the CRDI with nozzle inner diameter 0.190mm was used with FIP's of 300, 500, 700, 1000 and 1350 bar. The shock wave propagation in ambient air was accounted for, with the model predicting velocity of the spray tip during the preliminary stages of penetration. The predictions of the far-field spray penetration model were found to agree well with the experimental data with the temporal dependence of the penetration length being highlighted. [30] An attempt had been made in reducing the complexities of fluid modelling by proposing a unified model that took into consideration 3 flow regimes: Stokes, Allen and Newton. An analytical result is derived via the variational iteration method (VIM). The unified model thus developed leading to significant time saving. Ignition delay has also been studied independently. [31] At higher FIP, the ignition delay reduced from 11.5 ms to 7 ms at 40 bar cylinder pressure in a constant volume combustion chamber. It was noted that the rate of heat release increased with higher FIP. [32] The above results were supported with better emission results at higher FIPs. [14] It was observed that spray tip penetration increased by nearly 13 mm after 1.0 ms from SOI at 1000 bar compared to 300 bar FIP (~46% increase). At the same time, spray tip penetration reduced remarkably on increasing ambient cylinder pressure from 20 bar to 40 bar. The spray area of diesel increased with higher FIP while it decreased with increase in ambient cylinder pressure. The average size of particles represented by Count Mean Diameter (CMD) decreased with higher FIP for all fuels.

3.2. Emissions

FIP has a profound impact on emission levels of fuels in diesel engines. [33] Superior combustion characteristics were observed at the lower pressure (500 bar). At higher FIP (1000 bar), knocking was observed. Cylinder pressure and ROHR (rate of heat release) was found to be higher for lower FIPs. However, BTE was found to decrease with increase in FIP. At lower FIPs, engine performance was found to be superior with lower BSFC. Lower emissions of CO, HC, CO_2 and NOx was observed at lower FIP. These emission characteristics can be further improved by advancing the SOI (Start of injection). PM concentration was found to increase with the increase in engine load. However increasing the FIP reduced the particulate concentration at all engine loads.

Studies have been made on various technologies like EGR (Exhaust gas recirculation) and HCCI (Homogeneous Charge Compression Ignition). [34] The effect of variation of FIP was investigated with and without EGR. A common rail direct injection V6 diesel engine was used. The experiments showed that the performance and emissions of the engine at higher pressure injection were improved when compared to lower pressure injection for both EGR ON and EGR OFF cases. Increase of FIP up to a certain optimum value can lower emissions of HC, PM and CO. It was observed that a combination of higher FIP and EGR produced lower nitrogen oxides (NOx) and fuel use with less smoke. An increase in pressure from 300 bar to 700 bar resulted in major improvements in engine performance and emissions. At higher FIP and EGR OFF, a decrease in HC and CO emissions was observed. However, NO_X emissions increased. Hence a combination of high FIP and EGR ON is required. Another work using EGR has been done where [35] high FIPs for heavy duty engines were used for 2 test driving cycles: A50 (Cruise Condition) -1250 rpm, 195 N-m and C100 (Rated engine power condition) -1800 rpm, 280 N-m. In A50, higher FIP did not improve the emissions-efficiency trade-off. However, higher rail pressures are optimised by calibrating it with lower EGR rates, retarded injection timings. For the C50 cycle, retarded injection timing results in lower EGR requirement and improvement of fuel economy. For moderate NOx emissions (3-5 g/kW-hr), moderate FIP (1500 bar) is sufficient.

[36] The rate of increase of FIP and fuel injection quantity in the initial duration of injection was correlated with the NOX emissions. Concave profile cam was found to be better than the tangential profile in improving the trade-off between NOX emissions and PM. It was found that PM emissions were 20% lower in case of concave profile cam even when the NOx emissions were almost same. [37] The strategy for achieving higher power density using electronic high FIP fuel unit was evaluated. As fuel rail pressure is increased, the indicated mean effective pressure (IMEP) values was higher at an A/F ratio of 20:1 compared to 30:1. With increase in inlet air temperature, IMEP values decreased.

HCCI has two main disadvantages- a small power range and higher emission levels of CO and HC than normal SI engines. [38] The shortcomings of the HCCI can be overcome by adapting to a hybrid technique of having a narrow angle low FIP (90 degrees and 10 MPa) in the first stage of injection followed by a high pressure conventional injection angle (150 MPa and 127 degrees) which prevents the formation of fuel rich localities in the ignition chamber preventing knocking as well as increasing the range of operation of the HCCI technique. Efforts have been made to study the cause and impact of deposits in engines. [39] A review of known fuel degradation mechanisms suggested that high FIP and high shear environments should be examined as the primary causes for increased deposit formation. The EN15751 test method was used which involved oxidative stress and detection of fuel oxidation by a physical method. The impacts of hydrodesulphurization on fuel composition and deposit formations due to a number of reactions were considered.

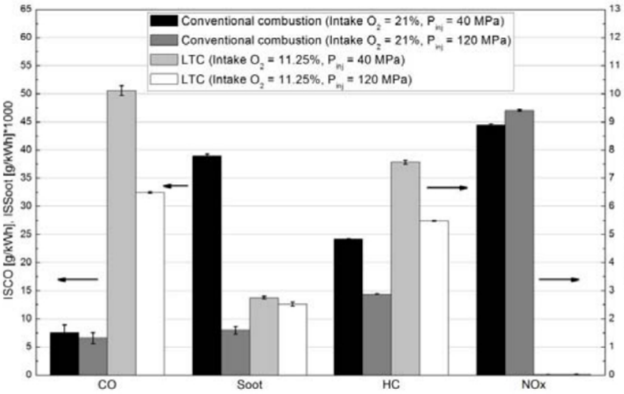

Fig. 4. Effect of FIP on exhaust emissions of a 5-cylinder CRDI diesel [40]

[40] A higher FIP leads to lower ignition delay and combustion duration. It also resulted in improved atomization and enhanced evaporation of fuel droplets. A higher FIP also resulted in lower CO, HC emissions and soot. It was also effective due to higher combustion efficiency and fuel conversion efficiency.

Conclusion

From the array of research work that has been reviewed, it can be safely accepted that injection pressure is directly proportional to the degree of atomisation which in turn increases the fuel efficiency due to better combustion. However, NOx emissions increase due to a higher combustion temperature. Injection pressure also influences the spray tip penetration, with penetration increasing with an increase in injection pressure. Research has been done on various blends of biodiesel. Jatropha as well as ethanol has been extensively used in biodiesel blends which reduced the CO, PM and unburnt HC levels in the emission. Jatropha has been identified as an important component in forming biodiesel blends owing to its cheap cultivation and thus, easy availability in abundance. Ethanol diesel blends up to 20% have been found to run smoothly without any engine modifications. Exhaust gas temperatures and lubricant temperatures have been observed to be lower for ethanol-diesel blends than pure diesel. Considerable reduction of NOx and CO emissions have been observed while using ethanol-diesel blends. In conclusion, in cohesion with the main motive of finding ways of reducing emission levels without sacrificing on engine performance, the combination of Jatropha and ethanol as a biodiesel blend has not been investigated to a great extent. Thus, some investigation in this regard with the support of the vast work done in the field of injection pressure and nozzle geometry can be used to achieve the dream of a greener tomorrow.

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