Investigation on Emission Characteristics of C.I Engine using Vegetable Oil with SCR Technique

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Abstract- The substitute to diesel fuels desires to be theoretically and environmentally adequate, and economically viable. Vegetable oil is one of several alternative fuels designed to extend the efficacy of petroleum, the flexibility and cleanliness of diesel engines. In this paper comparative experiments were carried out to measure the carbon monoxide, hydrocarbons, carbon dioxide and oxides of nitrogen emission level on Diesel engine with SCR technique using diesel fuel and Biodiesel blends of Jatropha, Pongamia and Neem (J20D80, P20D80 and N20D80) and the emission characteristics were analyzed. The results from the experiments prove that vegetable oil and its blends are potentially good substitute fuels for diesel engine in the near future when petroleum deposits become scarcer. The smart technologies deliver benefits to multiple interests, including an improved economy, and a positive impact on the environment and governmental policies. Continuous availability of the vegetable oils needs to be certain before embarking on the major use of it in I.C. engines. Domestically produced vegetable oil will help to reduce costly petroleum imports and the development of the vegetable oil based bio-diesel industry would strengthen the rural agricultural economy of agricultural based countries like India.

Keywords- Vegetable Oil, Biodiesel, Emissions, Catalyst, Diesel Engine.

1. Introduction

The idea of using vegetable oils instead of diesel fuel is not new and goes back to at least 1928 [2]. The concept was dropped due to cheap supply of petroleum-based fuels. The environmental concern, 1973 oil embargo and depletion of conventional sources have prompted research world-wide into alternative energy sources for internal combustion (IC) engines. Bio-fuels appear to be a potential alternative “greener” energy substitute for fossil fuels. It is renewable and available throughout the world. The sulphur content is negligibly small thus the issue of acid rain is therefore, ameliorated. The problem of using neat vegetable oils in diesel engines relates to their high viscosity. The performance of a direct injection (DI) diesel engine is affected by the spray characteristics of the fuel emerging through the injector holes [3].

Modern diesel engine injection systems have been designed to their level of performance by using diesel fuel with controlled properties. Some researchers reported that the most detrimental parameter in the use of vegetable oil as fuel is its higher viscosity [4]. Diesel engines have a vital role particularly for transportation systems. The exhaust emissions from diesel engines fueled with conventional diesel fuel have caused air pollution and global problems. There is a general agreement that biodiesel and its blends with diesel fuel can provide a substantial reduction in HC, CO, and smoke emissions with slight performance loss in diesel engine. In comparison with diesel fuel, exhaust gas analyses with biodiesel have generally resulted in an increase in NOx emissions that is dependent upon the fraction of biodiesel in the fuel blend [6-8]

1.1. Diesel Engine Emissions

Over the last 25 years or so there has been increasing public concern over the nature and composition of the combustion by-products that are emitted from engine exhaust pipes. Exhaust emissions as they are known are just the by-products of combustion of a fuel. For every 1kg of fuel burnt, there is about 1.1kg of water (as vapour/steam) and 3.2kg of carbon dioxide produced. Unfortunately we don't have 100% combustion and so there is also a small amount of products of incomplete combustion and these are carbon monoxide (denoted CO), hydrocarbons (vaporized fuel) and soot or smoke (actually hydrocarbons in a different form). In addition, the high temperatures that occur in the combustion chamber promote an unwanted reaction between nitrogen and oxygen from the air. This result in various oxides of nitrogen, commonly called NOx. There are also several minor contributors to exhaust emissions which are burnt crankcase oil and sulphur from the fuel. Both of these components will show up mostly as particulates. Oil consumption is obviously a function of engine design and amount of wear but sulphur dioxide is formed from the sulphur in the fuel. The major pollutants in diesel exhaust emissions are a direct result of the diesel combustion process itself.

1.2. Emission Reduction Techniques

There has been considerable research lately on methods for reducing emissions from diesel engines. The majority of this research has been centered on reducing emissions, which will form the basis of further discussion in the following paragraphs. Nevertheless, the methodology in reducing other forms of emissions will also be discussed. Competition by diesel engine manufacturers has meant that there are several viable solutions in reducing emissions of an engine.

The following emission control methods are applicable for diesel engines in general, regardless of the engine's application.

- Catalytic after treatment
- Injection timing retard
- Exhaust gas recirculation
- Ceramic coating
- Alternative fuels
- Engine electronic controls
- Fuel injection rate tailoring
- Variable geometry turbo charging
- Atomic oxygen after treatment

2. Biodiesel

Biodiesel is made from renewable biological sources such as vegetable oils and animal fats. Research on vegetable oils as diesel fuel was conducted at least 100 years ago but interest lagged because of cheap and plentiful supplies of petroleum fuels. Periodic increase in petroleum prices due to more demand, stringent emission norms, feared shortages of petroleum fuels due to rapid depletion and net production of carbon dioxide (CO_2) from combustion sources have rekindled interest in renewable vegetable oil fuels.

Since the oil price increased of the 1970s, various alternative fuels have been investigated with the goal of replacing conventional petroleum supplies. The initial interest was mainly one of fuel supply security, but recently more attention has been focused on the use of renewable fuels in order to reduce the net production of CO_2 from fossil fuel combustion sources. Renewable fuels like vegetable oils take away more carbon dioxide from the atmosphere during their production than is added to it by later combustion. Therefore, it alleviates the increasing carbon dioxide content of the atmosphere [5].

This intensive production and commercialization of biodiesel have raised some critical environmental concerns. Its large-scale production can lead to imbalance in the global food market by drastically increasing consumption oil prices, which mainly affect developing countries. Land availability, and in particular competition for acreage with food crops, is also considered a core limitation [9]. In order to mitigate these environmental consequences, unconventional oilseeds are being investigated as alternative feed-stocks.

The demand for energy around the world is continuously increasing, specifically in the demand for petroleum-based energy. Global warming is related with the green house gases which are mostly emitted from the combustion of petroleum fuels. To solve both the energy concern and environmental concern, the renewable energies with lower environmental pollution impact should be necessary. Nowadays several new and renewable energies have been emphasized and biomass energy is one of the renewable energies among them.

Biodiesel is described as a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats. It is oxygenated, essentially sulfur-free and biodegradable .The use of non-edible oils compared to edible oils is very significant because of the increase in demand for edible oils as food and they are too expensive as compared with diesel fuel.

Among non-edible vegetable oils the following three vegetable oils, i.e. Jatropha, Pongamia and Neem oils are showing good promise and therefore they are selected for the present study. Biodiesel is a variety of ester-based oxygenated fuels derived from natural, renewable biological sources such as vegetable oils. Its name indicates, use of this fuel in diesel engine alternate to diesel fuel. Biodiesel operates in compression ignition engines like petroleum diesel thereby requiring no essential engine modifications. Moreover it can maintain the payload capacity and range of conventional diesel. Biodiesel fuel can be made from new or used vegetable oils and animal fats. Unlike fossil diesel, pure biodiesel is biodegradable, nontoxic and essentially free of sulphur and aromatics. Biodiesel is typically made from vegetable oil though animal fat can also be used.

2.1. Advantages of Biodiesel

- Produced from sustainable / renewable biological sources
- Eco-friendly and oxygenated fuel
- Sulphur free, less CO, HC, particulate matter and aromatic compounds emissions

- Fuel properties similar to the conventional fuel
- Used in existing unmodified diesel engines
- Reduce expenditure on oil imports
- Non toxic, biodegradable and safety to handle

3. Selective Catalytic Reduction (SCR)

SCR is a technology that uses a urea-based diesel exhaust fluid (DEF) and a catalytic converter to significantly reduce oxides of nitrogen (NOx) emissions. SCR is the leading technology being used to meet the Environmental Protection Agency's 2010 Heavy-Duty Highway Engines and Vehicle emissions reduction regulations. On January 1, 2010 new federal laws took effect requiring significantly reduced amounts of NOx in diesel emissions for on road heavy duty diesel vehicles. One solution is Selective Catalytic Reduction, also known as SCR. This system utilizes urea or DEF injection, to reduce NOx levels by approximately 90%. The biggest advantage of this system is that no major redesign of an engine is required, plus no additional cooling is needed. SCR treats exhaust gas from the engine. Small quantities of diesel exhaust fluid (DEF) are injected into the exhaust before a catalyst, where it vaporizes and decomposes to form ammonia (NH_3) and carbon dioxide (CO_2). The NH_3 is then used in conjunction with the SCR catalyst and converts the NOx to harmless nitrogen (N_2) and water (H_2O).

DEF is the reactant necessary for the SCR system. It is a carefully blended aqueous urea solution of 32.5% high purity urea and 67.5% deionized water. Urea is a compound of nitrogen, produced primarily from natural gas, which turns into ammonia when heated. It is already used in a variety of industries, including as a fertilizer in agriculture. DEF is a nontoxic, nonpolluting, non-hazardous and nonflammable solution. It is stable, colorless, and meets accepted international standards for purity and composition. DEF is safe to handle and store and poses no serious risk to humans, animals, equipment or the environment when handled properly. If you know the average fuel consumption of a vehicle, you can easily calculate the amount of DEF that will be used. Heavy duty engines which use SCR receive a fuel economy improvement, up to 5%. SCR catalyst technology allows much greater NOx conversion efficiency, so the engine can be fully optimized, which contributes to this fuel economy improvement.

SCR technology is one of the most cost-effective and fuel-efficient technologies available to help reduce emissions. SCR can reduce NOx emissions up to 90 percent while simultaneously reducing HC and CO emissions by 50-90 percent, and PM emissions by 30-50 percent. SCR systems can also be combined with a diesel particulate filter to achieve even greater emission reductions for PM. SCR technology may play a key role in achieving emissions reductions that allow light-duty diesel vehicles to meet the new, lower EPA emissions regulations to be phased in through 2009 and potentially expand the diesel vehicle sales market (1).

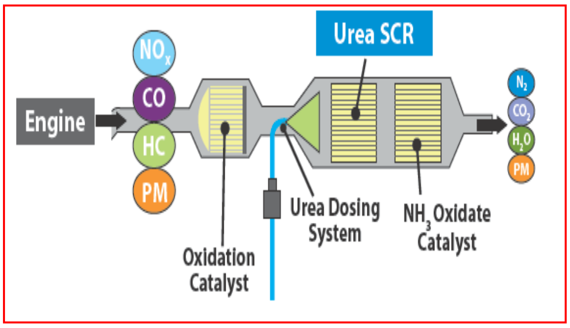

Fig 1. SCR Reaction

A number of chemical reactions occur in the ammonia SCR system, as expressed by Equations (1) to (5). All of these processes represent desirable reactions which reduce NOx to elemental nitrogen. Equation (2) represents the dominant reaction mechanism [10]. Reactions given by Equation (3) through (5) involve nitrogen dioxide reactant. The reaction path described by Equation (5) is very fast. This reaction is responsible for the promotion of low temperature SCR by NO_2 [17]. Normally, NO_2 concentrations in most flue gases, including diesel exhaust, are low. In some diesel SCR systems, NO_2 levels are purposely increased to enhance NOx conversion at low temperatures.

(1) $6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O$

(2) $4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$

(3) $6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$

(4) $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$

(5) $NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$

The SCR process requires precise control of the ammonia injection rate. An insufficient injection may result in unacceptably low NOx conversions. An injection rate which is too high results in release of undesirable ammonia to the atmosphere.

3.1. Diesel Exhaust Fluid (DEF) Consumption

As per CUMMINS Filtration, Diesel Exhaust Fluid (DEF) Consumption is expected to be approximately 2 to 3percent of fuel consumption, depending on the vehicle operation, duty cycle, geography, load ratings, etc. if we know the average fuel consumption of the engine or vehicle , we can easily calculate the DEF Consumption. The DEF dose rate will vary slightly amongst engine manufacturers [21]. Diesel Exhaust Fluid Consumption is 2 to 3percent of fuel consumption for the vehicles/ engines fitted with the electronic control module (ECM).

The Average DEF Consumption of DEF for Stationary Engines is expected to be approximately 5 to 7 percent of Fuel Consumption with ECM control. For our study and experiment, the DEF consumption comes around 10% of Fuel Consumption due to usage of simple Mechanical pump with Nozzle without ECM. With electronic control module (ECM), The DEF consumption rate will be reduced to the Standard value of 5 to 7 percent or even less.

4. Experiment Details

Fuel properties were measured before commencement of the experiments of Diesel, Jatropha, Pongamia and Neem based Biodiesel. For Pure Diesel – Specific gravity, 0.835; Calorific Value, 43500KJ/kg; For Jatropha B20 Biodiesel – Specific gravity, 0.879; Calorific Value, 43093KJ/kg; For Pongamia B20 Biodiesel – Specific gravity, 0.878; Calorific Value, 41956KJ/kg; For Neem B20 Biodiesel – Specific gravity, 0.934; Calorific Value, 39810KJ/kg.

4.1. SCR / DEF Pump

A pneumatic diaphragm type mechanical fuel pump is used to suck the liquid ammonia (SCR Fluid) from the ammonia tank and passes it to the nozzle for further injection. The pump uses a lever that rides on the inlet valve operated rocker arm finger to pump a diaphragm inside the pump up and down. This creates suction that pulls ammonia liquid into the pump, and then pushes it along. A pair of one way valves inside the pump only the ammonia liquid to move in one direction. The discharge/ output pressure of a mechanical fuel pump is quite low (4 to 10psi). The pump capacity to pump the liquid ammonia is 0.2litres/minute at 2000rpm.

Fig. 2. SCR/DEF pump

4.2. Injector

The SCR injector is an electrically operated 12V solenoid valve. The average injector duty-cycle is measured in terms of milliseconds. The average is 1.5 to 6 milliseconds. This fuel injector will be used as an injector for DEF/SCR fluid injection in the exhaust manifold to control the NOx emission. The fuel injector has 4holes in centre for injection. 3 out 4 holes were blocked to reduce the supply/injection rate of the DEF fluid.

4.3. Oxidation Catalyst/ SCR Catalyst

Cerium Oxide and Zeolite based compound coated Ceramic materials were used as catalyst for the development of Oxidation Catalyst and SCR Catalyst.

4.4. Experimental Setup

Experiments were carried out on a KIRLOSKAR Model SV1, single cylinder, four strokes, and water cooled diesel engine and the performance characteristics of the engine are evaluated in terms of brake thermal efficiency, emission characteristics in terms of smoke, HC, CO, CO_2, and NO_X. These performance, combustion and emission characteristics are compared with the results of baseline diesel engine. The HC, CO and NO_X emissions from the test engine were measured by a CRYPTON 290 SERIES EMISSION ANALYSER. Measurement of NO_X is achieved by means of a chemical sensor fitted next to the oxygen sensor. The sensor used to measure NO_X concentration is a catalyst. Sample exhaust gases taken from exhaust pipe of the test engine were passed through a filter and then entered to the NO_X analyzer. Also the smoke emission from the test engine was measured in this study. In order to measure smoke emission, an opacity (AVL make) type smoke meter was used.

Table 1. Engine Specifications

Manufacturer	Kirloskar Oil Engines Ltd
Type of Engine	Vertical, 4-Stroke cycle, Single acting, Single cylinder, High speed Compression Ignition Diesel engine
Speed	1800 rpm
Rating at 1500 rpm	5.9 kw
Compression Ratio	17.5:1
Fuel Injection Timing	27˚ BTDC
Method of Cooling	Water Cooling
Injection pressure	200 bar

Fig. 3. Experimental Setup

The test engine was started and run until achieving the stable condition. Then the engine load was increased gradually to maximum recommended value. At the same time, the dynamometer, all analyzers and meters for measurements were carried out as the recommended methods by the manufacturer's instruction manuals. The applications of loads were five levels and they were 0%, 25%, 50%, 75%, and 100% loads respectively. The engine speeds at all load levels were adjusted for constant engine speed and fixed at 1800 rpm.

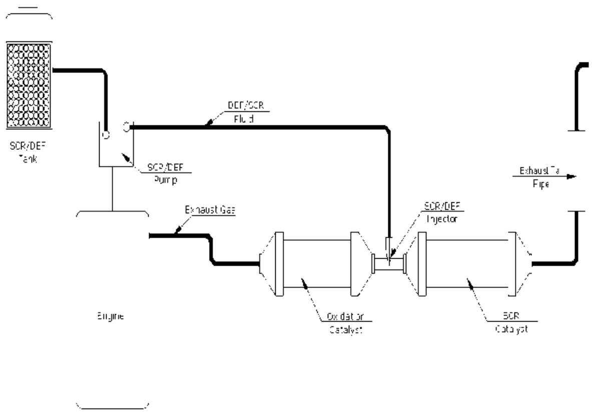

Fig. 4. Experimental Setup line diagram

In each load levels, the measurement of fuel consumption, exhaust gas temperature, fuel injection timing, crank angle, hydrocarbon (HC) emission, carbon monoxide (CO) emission, nitrogen oxides (NOx) emission, carbon dioxide emission and smoke emission were carried out and recorded the data. The same conditions, methods and procedures were used for both the experiments of biodiesel and diesel fuels. First the diesel and biodiesel blends were tested at standard engine specification that is at normal injection timing 27^0 BTDC at constant injection pressure 200bar and with a constant compression ratio 17.5.

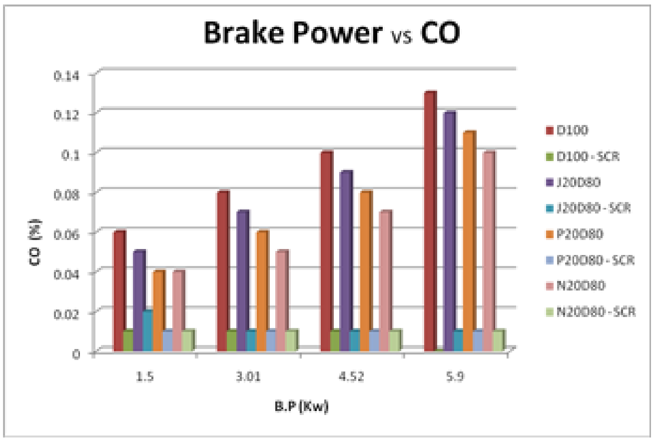

Fig. 5. Brake Power Vs CO

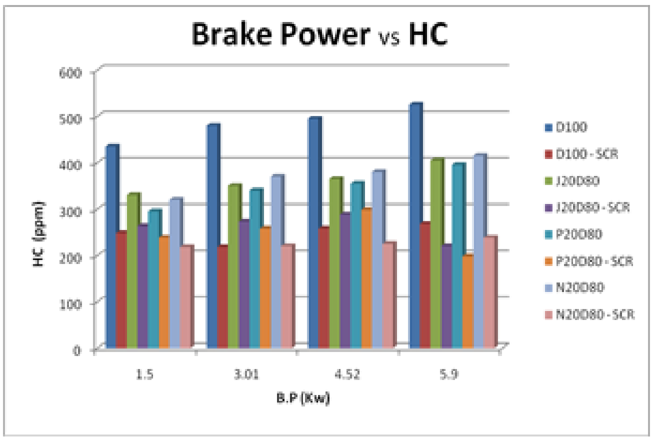

Fig. 6. Brake Power Vs HC

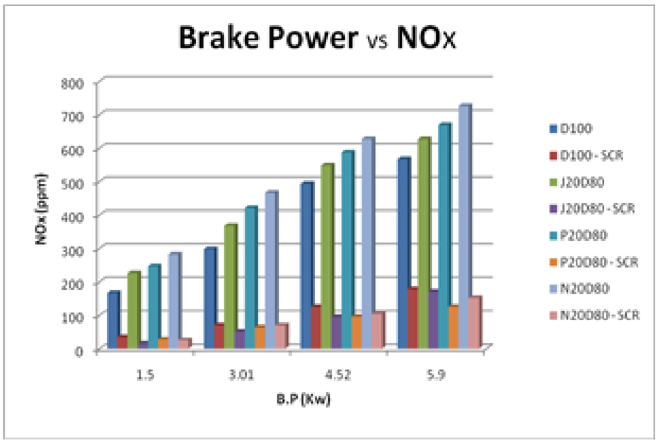

Fig. 7. Brake Power Vs NOx

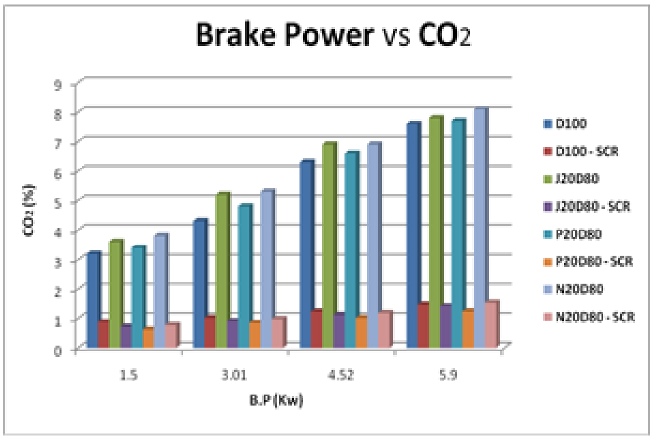

Fig. 8. Brake Power Vs CO2

5. Results and Discussion

The typical results of the present study are presented in the following section. The results presented for reduction of NOx emissions with and without the injection of diesel SCR/DEF (Ammonia) for pure diesel and biodiesel (B20).

5.1. Carbon Monoxide Emissions

Fig.5 shows the CO level for the engine working on pure diesel, biodiesel (J20, P20 and N20) respectively at standard compression ratio 17.5:1, Injection Pressure 200bar and crank angle 27^0BTDC with and without injecting the diesel SCR. From the graph, it is learnt that 100% of CO is reduced with diesel SCR, 92% of CO is reduced with J20-SCR, 91% of CO is reduced with P20- SCR and 90% of CO is reduced with N20- SCR at full load operation when comparing with SCR less injection.

5.2. Hydrocarbon Emissions

Fig.6 shows the HC level for the engine working on pure diesel, biodiesel (J20, P20 and N20) respectively at standard compression ratio 18.5:1, crank angle 27^0BTDC with and without injecting the diesel SCR. From the graph, it is learnt that 58% of HC is reduced with diesel SCR, 46% of HC is reduced with J20-SCR, 50% of HC is reduced with P20-SCR and 43% of HC is reduced with N20- SCR at full load operation when comparing with SCR less injection.

5.3. Nitrides of Oxygen Emissions

Fig.7 shows the NOx level for the engine working on pure diesel, biodiesel (J20, P20 and N20) respectively at standard compression ratio 18.5:1, crank angle 27^0BTDC with and without injecting the diesel SCR. From the graph, it is learnt that 69% of NOx is reduced with diesel SCR, 73% of NOx is reduced with J20-SCR, 81% of NOx is reduced with P20- SCR and 79% of NOx is reduced with N20- SCR at full load operation when comparing with SCR less injection.

5.4. Carbon Dioxide Emissions

Fig.8 shows the CO_2 level for the engine working on pure diesel, biodiesel (J20, P20 and N20) respectively at standard compression ratio 18.5:1, crank angle 27^0BTDC with and without injecting the diesel SCR. From the graph, it is learnt that 80% of CO_2 is reduced with diesel SCR, 82% of CO_2 is reduced with J20-SCR, 84% of CO_2 is reduced with P20-SCR and 81% of CO_2 is reduced with N20-SCR at full load operation when comparing with SCR less injection.

6. Conclusion

A variety of emission control technologies exist for controlling NOx, CO, NMHC, and PM emissions from stationary IC engines and have been in use for 10 years. Oxidation catalysts provide significant reductions in CO and HC and SCR can be used to reduce greater than 90 percent of NOx emissions from the diesel engines.

In this paper comparative experiments were carried out to measure the carbon monoxide, hydrocarbons, carbon dioxide and oxides of nitrogen emission level on SV1 KIRLOSKAR Single Cylinder Diesel engine by SCR technique using diesel fuel and Biodiesel blends of Jatropha, Pongamia and Neem (J20D80, P20D80 and N20D80). The performance and emission characteristics of diesel engine using bio-diesel were analyzed. Using biodiesel we can reduce the HC and CO level of exhaust gas emitted where as the NOx level is increasing. By injecting the DEF fluid with the help of rocker arm operated SCR pump setup, we can bring down the NOx level for pure diesel as well as for biodiesel.

It is learnt from the study that with selective catalytic reduction technique (SCR) 69 to 81percent of NOx was reduced, 43 to 58percent of HC was reduced, 90 to 100percent of CO was reduced and 80 to 84percent of CO_2 was reduced at full load operation when comparing without diesel SCR for pure diesel as well as for the biodiesel. Ceramic coatings used on the internal combustion surfaces of IC engines can improve performance, reduce emissions or allow a trade off in performance and emission levels not possible using catalyst technology itself. Used in conjunction with catalyst, ceramic coatings have allowed significant reductions in PM and NOx for heavy duty diesels while providing significant performance increases in power and torque.

From the study, it is clear that this rocker arm operated mechanical SCR pump setup is costing less when comparing with ECU based SCR setup and also effective in controlling the exhaust emissions.

References

[1] www.dieselforum.org

[2] Obert EF, Internal combustion engine and air pollution. New York: In text Educational Publishers; 1973.

[3] Heywood JB, Internal combustion engine fundamentals, New York: McGraw-Hill; 1988.

[4] Tahir AR, Lapp HM, Buchanam LC. Sunflower oil as a fuel for compression ignition Engine. ASAE, 1982, 49085, p. 82.

[5] Srivastava A, Prasad R. Triglycerides- based diesel fuels. Renewable & Sustainable Energy Reviews 2000;4: 111–33.

[6] Ozsezen AN, Canakci M, Turkcan A, Sayin C. Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. Fuel 2009; 88(4):629e36.

[7] Lin Y, Wu YG, Chang CT. Combustion characteristics of waste-oil produced biodiesel/diesel fuel blends. Fuel 2007;86 (12e13):1772e80.

[8] Usta N, Ozturk E, Can O, Conkur ES, Nas S, Con AH, et al. Combustion of biodiesel fuel produced from hazelnut soapstock/waste sunflower oil mixture in a diesel engine. Energy Conversion and Management 2005;46(5):741e55.

[9] Gui MM, Lee KT, Bhatia S. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy 2008;33:1646e53.

[10] Cho, S.M., 1994. "Properly Apply Selective Catalytic Reduction for NOx Removal", Chem. Eng. Prog., Jan. 1994, 39-45

[11] Qi D.H , Chen H, Geng L.M, Bian Y.ZH, "Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends", Energy Conversion and Management 2010, Vol. 51, pp. 2985-2992.

[12] Syed Ameer Basha, Raja Gopal K, Jebaraj S, "A review on biodiesel production, combustion, emissions and performance", Renewable And Sustainable Energy Reviews 2009, Vol. 13, pp. 1628-1634.

[13] Metin Gumus,Cenk Sayin, Mustafa Canakci, "The impact of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fueled with biodiesel–diesel fuel blends", Fuel 2011.

[14] Muralidharan. K,Vasudevan.D, Sheeba K.N, "Performance, emission and combustion characteristics of biodiesel fuelled variable compression ratio engine", Energy 2011, Vol. 36, pp. 5385-5393.

[15] L.Karikalan, M.Chandrasekaran, K.Sudhagar, Comparative Studies on Vegetable Oil Usage in C.I Engines as an Alternative to Diesel Fuel, International Review of Mechanical Engineering (I.RE.M.E.), Vol. 7, N. 4, May 2013

[16] Jose Maria Lopez, Felipe Jimenez, Francisco Aparicio, Nuria Flores, "On-road emissions from urban buses with SCR + Urea and EGR + DPF systems using diesel and biodiesel", Transportation Research Part D: Transport and Environment 2009,Vol.14,pp.1-5.

[17] Lyn Mc William, Anton Zimmermann, "Emissions and Performance Implications of Biodiesel Used in an SCR-equipped Caterpillar C6.6", SAE 2010-01-2157.

[18] Cooper, B.J., A.C. McDonnald, A.P. Walker, M. Sanchez, 2003. "The Development and On-Road Performance and Durability of the Four-Way Emission Control SCRT System", US DOE, 9th Diesel Engine Emissions Reduction Conference (DEER), Newport, RI, August2003

[19] Sathiyagnanam A.P, Saravanan C.G, "Experimental Studies on the Combustion Characteristics and Performance of A Direct Injection Engine Fueled with Biodiesel/Diesel Blends with SCR", Proceedings of the World Congress on Engineering (London) 2011, Vol III

[20] Mukundan Devadas, Selective Catalytic Reduction (SCR) of Nitrogen Oxides with Ammonia over Fe-ZSM5, Diss. ETH No. 16524, Swıss Federal Instıtute Of Technology Zurıch for the degree of Doctor of Technıcal Scıences, 2006

[21] Erlangung des Grades, Development and characterization of NOx – reductive catalytic coating systems for lean burn engines, Dissertation, BOCHUM University, 2008

[22] DIESEL EXHAUST FLUID, SCR: The Leading Technology to meet 2010 Emission Regulations, CUMMINS Filtration – Bulletın

[23] Koebel M, Elsener M, Kleemann M, "Urea-SCR: a promising technique to reduce NOx emissions from automotive diesel engines", Catalysis Today 2000, pp. 335–345.