The effect of Zinc Oxide on Operation of Compression Ignition Engine with EGR fueled with Waste Cooking Oil Biodiesel

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Abstract: - Nanoparticles are being used increasingly along with second and third generation biofuels. One major advantage of nanoparticles is its surface to volume ratio and also the number of active surfaces it possess which make it ideal for application as a catalyst in a chemical reaction or in biodiesel’s case an additive. Zinc Oxide (ZnO) has been employed in the current experimentation as an additive because it improves the properties such as the flash and fire point of the fuel in which it is blended in. Also, ZnO disperses well in fluid and provides advanced theoretical density along with not getting clogged in the fuel pump. In the present work Biodiesel derived from Waste cooking oil-Waste cooking oil methyl ester (WCOME) has been used along with ZnO nanoparticle and the amount of ZnO used is 80 ppm. The engine is also fitted with hot Exhaust Gas Recirculation system in order to decrease the Nitrogen Oxides (NOx) emission. Combustion properties such as Heat Release Rate and P-θ diagram have been thoroughly studied. The performance parameters like Brake Specific Fuel Consumption and Break Thermal Efficiency are also calculated and plotted on graphs for evaluation. Exhaust gases from the engine are measured and the results have been plotted on graphs for comparison. The properties of exhaust gases considered are % of Carbon Monoxide, Nitrogen oxides, Unburnt Hydrocarbons & Smoke Opacity. From the results it was revealed that all 3 parameters: Performance, Combustion & Emissions of the engine was improved by using ZnO as additive.

Keywords: Waste Cooking Oil Methyl Ester; Diesel Engine; Zinc Oxide; nanoparticle; performance; emissions; combustion.

1. Introduction

Biodiesel is becoming a preferred substitute for diesel because not only does it reduce Nitrogen Oxide [1, 2] emissions thanks to the higher oxygen amount existing in the fuel but also reduces particulate matter due to it being a short-chain paraffin hydrocarbon, and biodiesel does all this without requiring any external modification of the engine and without negatively affecting the characteristics of the engine [3]. Waste cooking oil (WCO) is a promising feedstock as it is 90% renewable and numerous biodiesel production facilities are presently utilizing it and WCO can be employed with no penalty on efficiency [4–6] and substantial diminution of Smoke opacity [1,7,8], CO [1,2,7,8], HC [1,2] and NOx [1,2] emissions with respect to diesel. Biodiesel has problems like greater density, inferior calorific value and higher BSFC compared to conventional fuels, and to overcome these shortcomings, additives play an important role. Metallic additives is an attractive option which was a popular in the early 2000s but its usage decreased until recently, but it has started increasing due to the accessibility and availability of nanoparticles. Interest in metallic additives is reinvigorated due to the attractive proposition nanoparticles provides, with mixing it with diesel and biodiesel and the nanoparticles acting as catalyst [9, 10]. Metal based additives are effective in reducing because of reaction with H2O vapor by metals in the emissions at the exhaust to yield extremely reactive Hydroxyl ions (OH-), and also the metals behave like oxidation catalyst lowering the temperature of oxidation for soot leading to improved particle burn out. Nanometal oxide particles plays the role of an oxidation catalyst leading to complete combustion and ignition due to higher carbon combustion activation [11]. Zinc Oxide (ZnO) is one such nanoparticle additive which is very promising and not much research has been carried out on it. Zinc oxide has high reactivity because of superior surface area, ZnO stores energy in its crevices, provides higher theoretical densities and stabilization for the mixtures. Zinc oxide is a nano additive which reduces knocking, enhances burning rate, rises the fuel viscosity and makes the fuels...
conductive. Since nanoparticles have small diameters their concentration in the fluid is minimal the distribution stability of nanoparticles is good. Nano scale particles settle down rapidly after distribution of nano scale particles and can be suspended for weeks under favorable conditions. Settling rates may be explained using the Stokes–Einstein theory [12]. Zinc Oxide improves the dispersion rate of the blend and has several active surfaces, at the same time circumventing clogging in the fuel injectors [13, 14]. The ZnO employed in the current experimentation is passivated with oxygen to achieve a stable oxide coating. Nanoparticles can overcome the density difference because of its better interaction between particles caused by its high surface to volume ratio [14-16]. ZnO boosts the heat/mass transfer and radiative properties of the WCO blends which results in the droplets being ignited at a much lesser temperature in contrast to diesel [10]. Viscosity is increased with ZnO concentration in the fuel and when highly viscous fuel is passed through the injectors, the injection process occurs with the formation of uneven fuel droplets which unfavorably impact the dispersion and fuel penetration in the cylinder [17].

2. Preparation of Fuel

2.1 Transesterification

The authors have run the engine with various concentrations of Zinc Oxide nanoparticle in the fuel blends to test out the most ideal concentration of the additive. From the results, 80 parts per million (ppm) proved to be the most favorable concentration for ideal results. There were totally 3 blends used: Diesel, 20% Biodiesel+80% Diesel (B20) and B20+80 ppm ZnO. The biodiesel was obtained from the Transesterification process. Transesterification has been used to convert WCO which is predominantly triglycerides to glycerol, using methanol as the alcohol and Potassium Hydroxide as a catalyst. The steps carried out in transesterification is similar to Lobo [18]. The fuel properties are given in Table 1.

![Figure 1. Transesterification of Oil](image)

2.2 Experimental Setup

For experimentation, 80 ppm ZnO Nanoparticle is blended with WCOME and this biofuel is used in a Kirloskar TV2 (shown in Fig. 2) engine the technical specification of the engine is mentioned in Table II. The TV2 engine has been loaded from 0-100% for investigation and all the values were plotted on a graph for easy comparison. In total, three blends are used for experimentation which are Diesel, B20 WCOME (20% WCOME + 80% Diesel) and B20 WCOME+80 ppm ZnO.
Table 1. Properties of Fuels

| Properties                        | Diesel | WCO (Waste Cooking Oil) | WCOME (WCO Methyl Ester) | B20WCOME (20%WCOME+80%Diesel) |
|-----------------------------------|--------|-------------------------|--------------------------|-------------------------------|
| Kinematic Viscosity (40°C)        | 3.05   | 43                      | 5.83                     | 4.01                          |
| Heat Value (MK/Kg)                | 44.5   | 29                      | 38                       | 42.2                          |
| Density (Kg/m³)                   | 830    | 914                     | 887                      | 842                           |
| Flash Point °C                    | 60     | 307                     | 150                      | 98                            |
| Cetane Number                     | 40     | 53                      | 51.48                    | 49.18                         |
| Iodine Number                     | 6      | 125                     | 59                       | 17.42                         |

Figure 2. Kirloskar TV-2 Engine used for this experimentation

Table 2. Technical Specifications of the Engine

| Manufacturer                      | Kirloskar oil Engines Ltd |
|-----------------------------------|---------------------------|
| Model                             | TV-2                      |
| No of Cylinder                    | Two                       |
| Type of Engine                    | Vertical, 4-Stroke cycle, Single acting |
| Cooling                           | Water                     |
| Fuel                              | Diesel                    |
| HP                                | 16 HP                     |
| Starting                          | Hand Cranking             |
| Bore                              | 87.5mm                    |
| Stroke                            | 110mm                     |
| Cubic Capacity                    | 1322cc                    |
| Compression Ratio                 | 17.5:1                    |
| Valve Clearance Inlet             | 0.18mm                    |
| Valve Clearance Exhaust           | 0.20mm                    |
2.3 Error analysis and uncertainty

Error Analysis and Uncertainty is done for this experimentation similar to Lobo [18] the experiment uncertainty was 1.765%

3. Results and Discussion

3.1 Brake Thermal Efficiency (BTE)

![Figure 3. Variation of Brake Thermal Efficiency with Load](image)

Fig. 3 illustrates that Brake Thermal Efficiency of the Waste cooking oil B20 blends decreases at all loads (except at full load) when compared to Diesel. A possible explanation for the reduction of BTE can be that the requirement of oxygen for combustion is reduced because of the oxygen buffer of ZnO [19]. Nanoparticles help to split the H2 atoms from H2O which could have participated in the combustion process along with improving the rate of heat conduction which lowers BTE [20, 21]. When EGR is applied to the nanoparticle blend the BTE decreases by 3% in comparison with diesel and 5% when paralleled to the nanoparticle blend without EGR. There is a fall in BTE, because for EGR to work there has to be a pressure difference between the inlet and exhaust manifolds to make sure the exhaust gases reach the inlet manifold and partially replace the air used for combustion. This is achieved by throttling the air of the inlet flow which adds extra load on the engine because it rises the pumping work. Thus for the same output more work has to be done thereby decreasing the thermal efficiency. This is offset by pumping more fuel but increases the BSFC when EGR is applied [22]. Similar results were obtained for Brake Thermal Efficiency by Prabakaran & B.Vijayabalan [34].

3.2 Brake Specific Fuel Consumption (BSFC)

Fig. 4 shows the Fluctuation of BSFC with Load. There is reduction of 10% for the BSFC of B20 and 12% for B20+ZnO (compared with the baseline Diesel reading). One of the causes for reduction of BSFC can be better combustion caused by shorter delay of ignition as a result of addition of a nanoparticle like ZnO [23]. The combustion is also improved by addition of an oxidizing agent, and
ZnO plays that role of an oxidizing agent when added to the blend, and because ZnO is an oxidizing agent it also improves the Air to Fuel ratio reducing the BSFC [23]. Employing an additive like Zinc Oxide increases the flash point properties and reduced the pour point of the blend, thereby reducing BSFC [24]. Also the lower oxidation temperature caused by the catalyst effect of the ZnO nanoparticle directly affects the decline of BSFC [25]. The same trend in BSFC is backed by studies 50-53.

![Figure 4. Variation of Brake Specific Fuel Consumption with Load](image)

### 3.3 Cylinder pressure v/s Crank Angle (P-θ)

Fig. 5 shows the Fluctuation of Cylinder pressure with crank angle. The peak in-cylinder is 11% lesser for B20 when matched with diesel at 100% load and 10% for B20+ZnO as a consequence of superior viscosity of the Zinc Oxide blend [26]. With increase in pressure the delay of ignition reduces and the fuel is better atomized [27]. There is lesser buildup of the fuel in the first phase which causes decrease of the peak pressure as amount of prepared fuel in the first phase is associated with peak pressure in the cylinder. Enhancement of the catalytic property takes place as a result of ZnO because the addition of ZnO enhances the ignition and as an outcome of that there is accelerated combustion [28-30]. For B20+ ZnO and B20+ZnO (EGR) there is a slight shift in peak pressure away from TDC which is caused by ignition delay as a result of the higher density and viscosity of the B20 & B20+ZnO blend. This higher density and viscosity causes a small delay of atomization of the fuel and thereby a minor delay in combustion of the fuel with oxygen thus causing Ignition Delay. This can be easily overcome by changing the injection parameters like injection timing or injection pressure. When we come to EGR there is decrease of nearly 4% when compared to diesel at 100% load and 1% in comparison to the blend without EGR, the decrease in peak pressure is due to the different composition which EGR introduces mainly Carbon Dioxide. And this subsequently increases as load increases [31]. Comparable results were obtained by Kegl & Hribernik [49].
In the Fig. 6 the maximum HRR is represented. The value of HRR is lower (compared to diesel) by 6% for B20 and 11% for B20+ZnO at 100% load. The cause for decline is the lower end temperature of combustion due to lesser calorific value of B20 [32]. The greater cetane number and improved evaporation rate and A-F (Air fuel) mixture of the blends there is shorter ignition delay [32] leading to lesser HRR. Also the better volume to surface area ratio and upgraded ignition properties (due to addition of ZnO) causes better combustion of the blends compared diesel [33] leading to lower HRR. When EGR is applied to the blend there marginal variation in HRR value. Similar results were obtained by Sadhik Basha and Anand [28, 48].

3.4 Heat Release Rate (HRR)

Figure 5. Variation of Cylinder Pressure with Crank Angle

![Figure 5. Variation of Cylinder Pressure with Crank Angle](image1)

![Figure 6. Variation of Heat Release Rate with Load](image2)
3.5 Nitrogen Oxides (NOx)

Fig. 7 shows the variation of Nitrogen Oxides. The NOx emissions is reduced by 14% for B20 blend and 16% for B20+ZnO. One of the consequences of the blends having higher Calorific value is that the average temperature in the combustion chamber is increased leading to greater amount of oxygen to react and lowering the NOx emissions [28]. With employing thermally stable ZnO there is a decrease of NOx, another reason why NOx is reduced by addition of ZnO is because, ZnO introduces a shorter delay of ignition which results in better A/F ratio and creating an oxygen deficit in the chamber. Due to the poorer iodine number of WCO which is around 59 which warranted the presence of the extra saturated fatty acids in B20 [35]. The cetane number of biodiesel is superior in comparison to diesel due to the lengthier chains of fatty acids and greater degrees of saturation (lower iodine number) which leads to lower NOx emission [36-38]. This trend was also observed in studies 54-59. EGR is applied to B20+ZnO blend and the NOx emissions reduces by 20% (when compared to diesel) and 5% when compared to the same blend without EGR. EGR includes replacing the air used for combustion by CO2 and H2O vapor which has higher specific heat capacity than the main components of air which is oxygen and nitrogen leading to lower gas temperatures. Decrease in oxygen content due to it being replaced in EGR also leads to inferior flame temperature and thereby reducing NOx emissions as formation of NOx is a highly temperature dependent phenomenon [39]. This decreasing trend of NOx was also observed by Prabakaran, Udhoji & Anurag [60].

3.6 Carbon Monoxide Emissions (CO)

From the Fig. 8 it is clear that for full load the CO (% volume) emissions decrease by nearly 30% for both the blends B20 and B20+ZnO. CO emissions are decreased because greater amount of fuel is being burnt in the chamber and this is elucidated by the presence of ignition delay as depicted in the P-θ diagram. Another plausible explanation can be that more CO is converted to CO2 as ZnO acts as an oxygen donating catalyst. Prabakaran et al. [34] mentioned that CO emissions can be shrunk by increasing the combustion average temperature. And because of the advanced calorific value of the blends, this could also be a possible explanation for reduction of CO emissions. The decrease in CO emissions is also because by increasing the concentration of additives it leads to enhancement of oxygen owing to ZnO and by addition of biodiesel which increases the air-fuel ratio and gives better and more complete combustion [40]. Enrichment of oxygen is another major factor, when the biodiesel
is added as it is rich in oxygen, this increase in oxygen content leads to carbon molecules being burned and combusted and thus releases CO2 rather than the poisonous CO. When EGR is applied to B20+ZnO blend there slight increase in CO emissions. Carbon Monoxide tends to increase because of the lower oxygen which is available for combustion which results in rich A/F mixtures at various regions in the combustion chamber. This CO trends are backed by studies 23 & 30.

![Variation of Carbon Monoxide Emissions with Load](image1)

**Figure 8.** Variation of Carbon Monoxide Emissions with Load

### 3.7 Hydrocarbon Emissions (HC)

![Variation of Unburnt Hydrocarbon Emissions with Load](image2)

**Figure 9.** Variation of Unburnt Hydrocarbon Emissions with Load
Fig. 9 shows the Fluctuation of Hydrocarbon emissions with Load. The drop in HC emission can be caused due to the avoidance of undesirable fuel build-up which is brought about by the ZnO nanoparticle and results are as seen in the Fig. 9 [41]. From Fig. 9 it is seen that ZnO is highly operative in tackling HC emissions at 80-100% loads possibly because of the supply of extra oxygen and also by ZnO acting as an oxygen buffer. HC emission drops because of higher O2 quantity of the blends which causes improved overall combustion and higher cetane number which is provided by ZnO which enhances the combustion leading to lower hydrocarbon emissions. Lower excess oxygen content results in improper combustion. But this deficit in oxygen is countermanded when B20 is added because B20 has molecular oxygen which decreases the oxygen necessary for combustion resulting in lower HC emissions [42]. Biodiesel has greater oxygen content, which can accomplish improved combustion and lessen the HC emissions [43]. The occurrence of oxygen in the blends increases oxidation process of UBHCs (Unburnt hydrocarbons) post flame in the combustion chamber. Similar results were obtained by 19 & 40.

3.8 Smoke Opacity

From the Fig. 10 it can be seen that Smoke opacity falls by 8% for B20 and 3% for B20+ZnO (when compared to diesel). There is decrease of Smoke Opacity because of the superior volume to surface area ratio of Zinc Oxide and also the superior cetane Number of the biodiesel blend, so both these factors result in better more complete combustion. [47] The reduction of Smoke Opacity can be caused by the higher Sulphur and oxygen content in the blend [44]. Smoke Opacity is reduced because of the bonded oxygen which is higher in biodiesel that tends to reduce the soot formation [44, 45]. It is seen that smoke opacity decreases for EGR because of drop in the available oxygen level in the combustion chamber which is unfavorable for development of Soot. Also this reduction in oxygen causes decline of the flame temperature which again is negative for soot formation [46]. Also the decline of aromatic compounds (which are considered soot precursors) because biodiesel does not provide the preliminary radicals which are required for development of aromatic rings [47]. This type
Smoke opacity trend was also noticed by Prabakaran and Vijayabalan [34] & Karthikeyan and Elango [43].

4. Conclusions

The superior properties of Zinc Oxide have already been demonstrated in this experimentation. Zinc oxide nanoparticle has superior Volume to Surface area ratio and also high thermal efficiency, thus when ZnO nanoparticle is added to a fuel, it considerably enhances the combustion reaction by increasing the volume available for combustion in the combustion chamber. Furthermore, metal nanoparticle additives in general have more reactive surfaces than conventional metal additives thus being more effective and efficient as an additive.

1) The Brake Thermal efficiency reduces because of oxygen buffer of ZnO which lowers requirement of oxygen complete combustion process.
2) BSFC reduces by 12% in comparison with diesel at 100% load because Zinc Oxide acts as an oxidizing agent which results in better combustion. EGR when applied to the mixture rises the BSFC by 9% because oxygen deficit and the dwindling burn rate, thus making it harder to attain stable state for combustion.
3) Heat Release Rate for the Zinc Oxide blend reduces by 11% caused by the poorer calorific value of the blend. P-θ diagram shows that there is a reduction of peak pressure value by 10%. EGR affects the P-θ by reducing the maximum peak pressure value because of the different composition which EGR introduces mainly Carbon Dioxide.
4) Smoke Opacity of the Zinc Oxide blend marginally decreases due because of the superior volume to surface area ratio of Zinc Oxide and also the superior cetane Number of the blend, so both these factors result in better more complete combustion. When EGR is applied to the blend smoke opacity reduces further because of drop in the available oxygen level for combustion which is unfavorable for development of soot.
5) Nitrogen oxides/NOx emissions of the Zinc Oxide blend reduces by about 15% as Zinc Oxide increases the combustion temperature which results in greater oxygen in the blend to react giving lower NOx emissions. EGR when applied to the ZnO blend reduces the NOx emissions by about 20% because of decrease in oxygen content due to it being replaced in EGR also leads to poorer flame temperature and thereby reducing NOx emissions, as formation of NOx is a highly temperature dependent phenomenon.
6) CO and HC emissions decrease by 20% because more fuel is being burnt in the chamber and this is explained by the presence of ignition delay as depicted in the P-θ diagram and this decreases the CO and HC emissions.

References

[1] Mittelbach M and Trithart P, “Diesel fuel derived from vegetable oils, III. Emission tests using methyl esters of used frying oil,” J American Oil Chemists’ Soc 1988;65(7):1185–7.
[2] Payri F, Macián V, Arregle J, Tormos B and Martínez JL, “Heavy-duty diesel engine performance and emission measurements for biodiesel (from cooking oil) blends used in the ECOBUS project,” SAE paper 2005-01-2205, 2005. Doi: 10.4271/2005-01-2205
[3] Kelvin S and Gerpan J, “The effect of biodiesel fuel composition on diesel combustion and emission,” SAE paper 961086. Doi: 10.4271/961086
[4] Çetinkaya M, Ulaşay Y, Tekin Y and Karaosmanoglu F, “Engine and winter road test performances of used cooking oil originated biodiesel,” Energy Convers Manage 2005; 46:1279–91. Doi: 10.1016/j.enconman.2004.06.022
[5] Murillo S, Míguez JL, Porteiro J, Granada E and Morán JC, “Performance and exhaust emissions in the use of biodiesel in outboard diesel engines,” Fuel 2007; 86:1765–71. Doi: 10.1016/j.fuel.2006.11.031
[6] Dorado MP, Ballesteros E, Arnal JM, Gómez J and López F, “Exhaust emissions form a Diesel engine fueled with transesterified waste olive oil,” Fuel 2003; 82:1311–5. Doi: 10.1016/S0016-2361(03)00034-6
[7] Tat ME, “Investigation of oxides of nitrogen emissions from biodiesel-fueled engines,” PhD thesis, Iowa State University, 2003.
[8] Canakci M and Van Gerpen JH, , “Comparison of engine performance and emissions for petroleum diesel fuel, yellow grease biodiesel, and soybean oil biodiesel,” Trans ASAE 2003;46(4):937–44. Doi: 10.13031/2013.13948
[9] Yetter RA, Risha GA and Son SF., “Metal particle combustion and nanotechnology,” Proc Combust Inst 2009;32(2):1819–38. Doi: 10.1016/j.proci.2008.08.013

[10] Iyer H, Patrick EP, Ravi P, Robert P, Tawo I, Jose RP and Paul A., “Increased hot plate ignition probability for nanoparticle laden diesel fuel,” NanoLetters 8:1410–1416. Doi: 10.1021/nl080277d

[11] Mu-Jung Kao, Chen-Ching Ting, Bai-Fu Lin and Tsing-TsiihTsung, “Aqueous aluminum nanofluid combustion in diesel fuel,” J.Testing and Evaluation 36 (2) (2008). Doi: 10.1520/JTE100579

[12] Lai S L, Guo J Y, Petrova V, Ramanath G and Allen L H, “Size - dependent melting properties of small tin particle – Nano calorimetric measurement,”Phys Rev Lett, 77 (1996) 99 –102. Doi: 10.1103/PhysRevLett.77.99

[13] Bajpai S, Sahoo PK and Das LM, “Feasibility of blending karanja vegetable oil in Petrol-diesel and utilization in a direct injection diesel engine,” Fuel 2009; 88:705–11. Doi: 10.1016/j.fuel.2008.09.011

[14] Yanan Gan and Li Qiao Combustion characteristics of fuel droplets with addition of nano and micron-sized aluminium particles Combustion and Flame 2011; 158:354-368. Doi: 10.1016/j.combustflame.2010.09.005

[15] Murugesan A, Umarani C, Subramanian R and Neduzechian N., “Bio-diesel as an alternative fuel for diesel engines – A review,” Renew Sustain Energy Rev 2009; 13:653-62. Doi: 10.1016/j.rser.2007.10.007

[16] Sahoo PK and Das LM, “Comparative evaluation of performance and emission characteristics of jatropha,karanja and polanga based biodiesel as fuel in a tractor engine,” Fuel 2009; 88:1698-707. Doi: 10.1016/j.fuel.2009.02.015

[17] Justin LS, Daniel MD, Richard AY, Frederick LD and Ilhan AA., “Functionalized graphene sheet colloids for enhanced fuel/propellant combustion,” ACS Nano 3:3945–3954. Doi: 10.1021/nn901006w

[18] Lobo, Ashley., “Influence of Zinc oxide on Direct Injection CI Engine Fueled with Waste Cooking Oil Biodiesel,” International Journal of Scientific and Engineering Research. 6. 32-40. Doi: 10.17148/IJARSET.2019.61106

[19] Ashok, B.Nanthagopal, K. Mohan, AravindJohny and AjithTamilarasu, “Comparative analysis on the effect of zinc oxide and ethanox as additives with biodiesel in CI engine,” Doi: 10.1016/j.energy.2017.09.021

[20] S. K. Das, S. U. S. Choi, W. Yu, and T. Pradeep, Nanofluids: Science and Technology; Wiley, Hoboken, NJ, 2007.

[21] Soudagar, MKalam, Abul Badruddin, Banupurmath, Akram and Naveed, “The effect of nano-additives in diesel-biodiesel fuel blends : A comprehensive review on stability, engine performance and emission,” Energy Conversion and Management, doi: 10.1016/j.enconman.2018.10.019

[22] Nicos Ladommatos, RazmikBalian, Roy Horrocks and Laurence Cooper, “The Effect of Exhaust Gas Recirculation on Soot Formation in a High-Speed Direct-injection Diesel Engine,” SAE Technical Paper No. 960841. Doi: 10.4271/960841

[23] Selvan VA, Anand RB and Udayakumar M, “Effects of cerium oxide nanoparticle addition in diesel and diesel– biodiesel–ethanol blends on the performance and emission characteristics of a CI engine. J.EngAppl Sci. 2009 (7):1819-6608.

[24] May WR and Hirs EA., “Catalyst for improving the combustion efficiency of petroleum fuels in diesel engines,” 11th diesel engine emissions reduction conference, August 21–25; 2005. Chicago II

[25] Jung H, Kittelson DB and Zachariah MR., “The influence of a cerium additive on ultrafine diesel particle emissions and kinetics of oxidation,” Combust Flame 2005;142:276–88. Doi: 10.1016/j.combustflame.2004.11.015

[26] Sayin C., Ilhan M, Canakci M and Gumus M., “Effect of injection timing on the exhaust emissions of a diesel engine using diesel methanol blends,” Renew Energy 2009; 34:1261-6. Doi: 10.1016/j.renene.2008.10.010

[27] Puhun S, Jegan R, Balasubramanian K and Nagarajan G., “Effect of injection pressure on performance, emission and combustion characteristics of high linolenic linseed oil methyl ester in a DI diesel engine,” Renew Energy 2009:34; 1227e33. Doi: 10.1016/j.renene.2008.10.001

[28] Sadhik Bashua, J. and Anand, R.B., “An experimental study in a CI engine using nanoadditive blended water-diesel emission fuel,” J. of Green Energy, Vol.8, 332-348, 2011. Doi: 10.1080/15435075.2011.557844

[29] Sabourin, J.L., Daniel, M.D., Yetter, R.A., Frederick, L.D. and Ilhan, A.A., “Functionalized graphene sheet colloids for enhanced fuel/propellant combustion,” ACS Nano, Vol.3, 3945-3954, 2009. Doi: 10.1021/nn901006w

[30] Rajitha, V., Sohan, C.B., and Peterson G.P., “Experimental investigations on the effects of cerium oxide nanoparticle fuel additives on biodiesel,” Advances in Mechanical Engineering, Vol. 10, ID 581407, 2010. Doi: 10.1155/2010/581407

[31] N. Ladommatos, S. Abdelhalim, H. Zhao and Z. Hu, “The effects of carbon dioxide in exhaust gas recirculation on diesel engine emissions,” Proc. Inst. Mech. Eng., Part D: Automobile Eng. 212 (1998) 25–42. Doi: 10.1243/0954409781525777

[32] Murlihdharan, K. and Vasudevan, and D., “Performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends.Doi:10.1016/j.apenergy.2011.04.014

[33] Alla GH., “Using exhaust gas recirculation in internal combustion engines: a review,” Energy Convers Manage 2002;43: 1027–42

[34] Prabakaran and B Vijayabalani., “Influence of zinc oxide nano particles on performance, combustion and emission characteristics of butanol-diesel-ethanol blends in di CI engine,” IOP Conference Series: Materials Science and Engineering. Doi: 10.1088/1757-899X/377/1/012069

[35] Dhaif S., Tairam, K. Gopinath, A. Kumaresan and G.Velraj, “Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel,” Renewable and Sustainable Energy Reviews, 0016-2361. Doi: 10.1016/j.rser.2015.04.086

[36] Murphy MJ, Taylor JD and McCormick RL. Compendium of experimental cetane number data, NREL Report 2004: NREL/SR-540-36805.

[37] Graboski MS, Alvarez JR, McCormick R. NOX solution for biodiesel, NREL/ SR-510-31465.

[38] Bank-Geiss WA, Chen Y, Buchohol BA Dibble RW, “A numerical investigation into the anomalous slight NOx increase when burning biodiesel: a new (old) theory,” Fuel Process Technol 2007; 88(7):659–7. Doi: 10.1016/j.fuproc.2007.01.007

[39] Ladommatos, N Balian, Razmik, and Roy Cooper, “The effect of exhaust gas recirculation on soot formation in a high-speed direct-injection diesel engine,” SAE Technical Paper No. 960841. Doi: 10.4271/960841
[40] Venu, Harish Madhavan, and Venkataramanan, “Effect of Al2O3 nanoparticles in biodiesel-diesel-ethanol blends at various injection strategies,” Doi: 10.1016/j.fuel.2016.08.046
[41] Deepak Agarwal, Shailendra Sinha, and Avinash Kumar, “Experimental investigation of control of NOx emissions in biodiesel-fueled compression ignition engine,” Doi: 10.1016/j.renene.2005.12.003
[42] Abedin MJ, Masjuki HH, Kalam MA, Sanjid A, Rahman SMA, and Fattah IMR, “Performance, emissions, and heat losses of palm and jatropha biodiesels in a diesel engine,” Proc Crops Prod 2014; 59:96–104. Doi: 10.1016/j.soilbul.2014.01.015
[43] Karthikeyan, and S Elang, “An environmental effect of GSO methyl ester with ZnO additive fuelled marine engine,” Indian Journal of Geo-Marine Sciences 356 Vol. 43(4), April 2014, pp. 564-570. Doi: 10.1016/j.soilbul.2014.01.015
[44] Ladommatos, N., Balian, R., Horrocks, R., and Cooper, L., “The Effect of Exhaust Gas Recirculation on Combustion and NOx Emissions in a High-Speed Direct-injection Diesel Engine,” SAE Technical Paper 960840, 1996, doi: 10.4271/960840
[45] Wang WG, Lyons DW, Clark NN, Gautam M, Norton PM., “Emissions from nine heavy trucks fuelled by diesel and biodiesel blend without engine modification,” Environ Sci Technol 2000;34(6):933–9. Doi: 10.1021/es981329b
[46] Boehman AL, Song J, and Alam M., “Impact of biodiesel blending on diesel soot and the regeneration of particulate filters,” Energy Fuels 2005; 19:1857–64. Doi: 10.1021/ef0500585
[47] Wilson, R.P., Muir, E.B., and Pellicciotti, F.A., “Emissions study of a single-cylinder diesel engine, SAE Papers 740123, 1974.
[48] Sadhik Basha J, and Anand RB., “An experimental investigation in a diesel engine using CNT blended water-diesel emulsion fuel,” Proceedings of I Mech E. Part A. J Power Energy 225:279–288. Doi: 10.1177/0957650903253378
[49] Kegl B, and Hribernik A., “Experimental analysis of injection characteristics using biodiesel fuel,” Energy Fuels 2006; 20:2239e48. Doi: 10.1021/ef050025m
[50] Basha JS, and Anand RB., “Performance, emission and combustion characteristics of a diesel engine using carbon nanotubes blended jatropha methyl ester emulsions,” Alexandria Engineering Journal, 2014; 53(2):259-73. Doi: 10.1016/j.aej.2014.04.001
[51] Vijay KumarA., Veeresh Babu, and P.Ravi Kumar, “The impacts on combustion, performance and emissions of biodiesel by using additives in direct injection diesel engine,” Alexandria Engineering Journal. Doi: 10.1016/j.aej.2016.12.016
[52] Kim SH, Fletcher RA, and Zachariah MR., “Understanding the difference in oxidative properties between flame and diesel soot nanoparticles: the role of metals,” Environ Sci Technol 2005; 39:4021. Doi: 10.1021/es048828a
[53] Jung H, Kittelsson DB, and Zachariah MR., “The influence of a cerium additive on ultrafine diesel particle emissions and kinetics of oxidation,” Combust Flame 2005; 142:276–88. Doi: 10.1016/j.combustflame.2004.11.015
[54] Metin Gürü, Atilla Koca, 0zer Can, Can Cinar, and Faith Sahin, “Biodiesel production from waste chicken fat based sources and evaluation with Mg based additive in a diesel engine,” Renewable Energy 2010; 35:637–43. Doi: 10.1016/j.enpol.2009.05.049
[55] Mittelbach M, Remschmidt, Biodiesel, The comprehensive handbook. Boersedruck Ges.m.b.H., Viena; 2004. Doi:
[56] Lapuerta Magín, Rodríguez-Fernández José, and Fontde Mora Emilio., “Correlation for the estimation of the cetane number of biodiesel fuels and implications on the iodine number,” Energy Policy 2009; 37:4337–44. Doi: 10.1016/j.enpol.2009.05.049
[57] Chang DY, and Van Gerpan JH. , “Fuel properties and engine performance for biodiesel prepared from modified feedstocks,” SAE Paper 2005:2005-01- 2200. Doi: 10.4271/971684.
[58] Prabakaran, B Udhoji, and Anurag., “Experimental investigation into effects of addition of zinc oxide on performance , combustion and emission characteristics of diesel-biodiesel-ethanol blends in CI engine,” Alexandria Engineering Journal, Volume 55, Issue 4, December 2016, Pages 3355-3362. Doi: 10.1016/j.aej.2016.08.022