Strategies for Reduction of Harmful Emissions from Diesel Engines

Vipin Sharma¹, Yogesh Dewang², Supriya Jain³, Sachin Jat⁴ and Mukesh Singh Baghel⁵

¹Department of Mechanical Engineering, Sagar Institute of Research & Technology, Bhopal
²Department of Mechanical Engineering, Lakshmi Narain College of Technology, Bhopal
³Department of Civil Engineering, Sagar Institute of Research & Technology, Bhopal
⁴Department of Civil Engineering, Sagar Institute of Research & Technology-Excellence, Bhopal
⁵Department of Mechanical Engineering, Sagar Institute of Research & Technology-Excellence, Bhopal
Email: vipinsati@gmail.com

Abstract. Reduction of harmful exhaust emissions from combustion of fossil fuels from automotive sectors is of prime importance and extensively researched by various strategies. Engine emissions control techniques can be bifurcated in categories of active control techniques and passive control techniques. In the active control techniques, the emissions are controlled in the combustion chamber itself while in the passive control techniques the emissions are controlled after completion of combustion. There are different strategies such as alternative fuels, fuel additives, nanofluids, water-in-diesel etc. commonly used to reduce harmful emissions and improve performance of fossil fuel-based energy systems. The alternative fuels such as alcohol and biodiesel are gaining importance. Biodiesel has certain limitations but blending with alcohol enables the maximum usage of biodiesel in the fuel blends. In this paper active control strategies are highlighted and discussed.

Keywords. Energy, Emissions, Environment, Fuel Additives, Nanoparticles

1. Introduction

Energy is the key to dealing with critical issues such as global warming, climate change, health, sustainable development, technological advancement and global energy [1-3]. Energy demand is increasing exponentially owing to increasing in population and technological advancements [3, 4]. Major source of energy is fossil-based fuels which are depleting fast and are also associated with harmful emissions. Exhaust emissions cause an environmental concern as it affects health, climate change and global warming issues [4, 5].

Diesel engines are extensively used owing to high power, durability and high fuel efficiency. Nonetheless, diesel engines are also a source of harmful emissions [6, 7]. Typical fossil fuel emission comprises carbon monoxide (CO), carbon dioxide (CO₂), nitrous oxide (NOx), particulate matter (PM), unburned hydrocarbons (HC) and sulphuric compounds. Research community is working to
increase the efficiency of fossil fuel-based energy sources and reduce the harmful emissions [7, 8]. There are a variety of approaches used to control the harmful emissions such as alternative fuels, particulate filter, catalytic reduction, fuel additives and engine design modifications. In the past decade, alternative fuels and fuel additives have extensively used approaches to enhance engine performance and decrease harmful emissions [8-10].

The alternative fuels like biodiesel and alcohol are the most promising alternative to fossil fuels due to its production from renewable resources [11]. Typically, biodiesel is produced from vegetable oils, waste cooking oil and animal fats [11, 12]. The biodiesel is also free from harmful compounds like polycyclic aromatics and sulphur and almost similar to diesel in combustion characteristics. Nonetheless, biodiesel cannot be blended in diesel owing to its higher viscosity and density. Alcohols are also added in biodiesel-diesel blended fuels (ternary blend) to optimize the properties of the fuel blend [13]. It is worth noting that the cetane number is higher for the biodiesel fuels whereas for alcohols it is lower as that of pure diesel [13, 14].

Fuel additives have also gained importance as their presence can improve performance characteristics of diesel and biodiesel blended fuels [15, 16]. Alternative fuels such as alcohols or biodiesel have certain limitations in maximum usage in biodiesel-diesel blends. The fuel additives can also be advantageous in enabling the maximum blending of alternatives fuels in diesel [16]. Nanotechnology significantly enhances the effectiveness of fuel additives and nanoparticles of metals, non-metals, metal oxides etc. are used as fuel additives. The fuel additives basically shorten the ignition delay and improve the physicochemical properties of fuel [16, 17]. Furthermore, nanoparticles of the fuel additive provide extra oxygen and act as a lubricant which enhances combustion characteristics and engine performance [16]. Nano-fluids is an important class of additives to harness the full potential of nanotechnology. The clustering of nanoparticles is avoided in stable dispersion of nano-fluids and thus efficacy of nanoparticles is significantly increased [18].

The present work aimed to briefly discuss the emission reduction strategies used in diesel engines. Alternative fuels, fuel additives, nano-fluids and water-in diesel approaches are discussed for performance enhancement and reduction in harmful exhaust emissions.

2. Alternative Fuels

Alternative fuels are attractive choices for partial replacement of fuel owing to ease in blending, enhanced performance and decrease in harmful emissions [19]. The alternative fuels produced from renewable biomass such as biodiesel and alcohols are promising solutions to fulfil increasing energy requirements and decrease emissions [19, 20]. Schematic representation of alcohol preparation process from biomass is presented in figure 1.

![Figure 1. Schematic representation of alcohol production from biomass.](image-url)

Biodiesel is commonly produced by the chemical process of transesterification from non-edible or edible vegetable oils [21]. Production steps of biodiesel preparation are schematically represented in figure 2. The biodiesel is a biodegradable, renewable and non-toxic fuel. It was reported that the combustion characteristics of biodiesel are also similar to diesel. Nonetheless, biodiesel has some limitations like high viscosity, high density and low volatility [21, 22]. Higher viscosity is one of the
major limitations of biodiesel as viscosity of fuel dictates the distribution of droplet size, degree of atomization and the uniformity of fuel mixture. These limitations of biodiesel restrict its usage as an alternative fuel. Alcohols can be added for reducing the biodiesel density and viscosity. Furthermore, alcohols are an appropriate additive for diesel, gasoline and biodiesel to decrease harmful emissions and enhance combustion characteristics due to higher oxygen content [23, 24]. The high oxygen content of alcohols resulted in improved combustion characteristics and thus reduction in the emissions. Most commonly used alcohols are methanol, ethanol and butanol as alternative fuels. However, butanol is a most suited alcohol owing to its similar fuel properties with diesel and high cetane number as compared to methanol or ethanol [24].

3. Fuel additives

Fuel additives are the class of chemicals mixed with the fuels in smaller quantities to enhance their characteristics and performance [25, 26]. Major functions of the fuel additive are (i) to enhance combustion characteristics, (ii) to decrease harmful exhaust emissions, (iii) to increase fuel stability (iv) ease in the handling of fuel, (v) to maintain engine cleanliness, (vi) to protect engine parts from corrosion and (vii) to decrease fuel consumption. The fuel additive can be classified into various categories according to their functions [26-28]. The fuel additives of nano size are attracting significant research interest due to exceptional properties. Size factor of nanoparticles enables them to exhibit extraordinary physico-chemical characteristics. It is well known that nanoparticles have a significantly higher specific surface area and the larger proportion of atoms is on the surface of the nanoparticle [28].

Janakiraman et al. [29] studied the effect of nano size fuel additives of CeO$_2$, ZrO$_2$ and TiO$_2$ in 20% biodiesel blended diesel fuel. It was reported that fuel additives demonstrated a reduction in CO and NOx emissions. The fuel additive of TiO$_2$ showed an enhanced brake thermal efficiency and decrease in NOx emissions as that of base fuel. Patel and Kumar [30] investigated the effect of nano size Al$_2$O$_3$ fuel additive in biodiesel-diesel blend. They reported that knocking caused by blending of biodiesel was eliminated due to the presence of nano-Al$_2$O$_3$ fuel additive. The fuel additive in the fuel blend promotes better oxidation which improves combustion characteristics. Wei et al. [31] added nano Al$_2$O$_3$ fuel additive in concentration of 100 ppm into methanol-diesel blend. They found that fuel additive decreases the ignition delay and duration of combustion. Emissions of CO$_2$ smoke and HC were significantly decreased. On the other hand the fuel additive enhanced the peak cylinder pressure, brake thermal efficiency and heat release rate.
3.1. Nano-fluids

Nano-fluids are simply stable distribution of nanoparticles in a liquid medium such as water, ethylene glycol, oil etc. [32]. Schematic presentation of nanofluid preparation is shown in figure 3. The nanoparticles because of high surface area have a propensity to form clusters to decrease their overall energy. Clustering of nanoparticles decreases their reactivity and efficacy [32, 33]. It is essential that nanoparticles remain as an individual particle unit to harness the full potential of nanoparticles. In the nano-fluids, particles are suspended uniformly due to which properties are enhanced as that of solid nanoparticles. The nano-fluids are prepared by a variety of nanoparticles like metals or metal oxides and diamond [32-34]. The nano-fluid is prepared simply by adding nanoparticles in a liquid such as water, alcohol, oil etc. with the help of surfactant and followed by ultrasonic agitation as shown in figure 2.

![Figure 3. Schematic presentation of nanofluid preparation](image)

Addition of water-based nano-fluids in the fuels is a widely used strategy to reduce the NOx emissions. It is reported that NOx emissions is increased owing to biodiesel blending in diesel fuel [35, 36]. Chaichan et al. [35] mixed nano-fluid (Al₂O₃ + water) in diesel fuel and studied its effect on combustion characteristics. They found that addition of nano-fluid increases brake thermal efficiency and decreases the consumption of fuel. Except emission of CO₂, all other emissions were decreased due to usage of nano-fluid. In a study magnetite nano-fluid is added to biodiesel and results indicated a significant reduction in harmful emissions [36].

4. Water-in-diesel

Water-in-diesel emulsion fuel is a prominent fuel modification strategy which resulted in enhanced combustion characteristics and decrease in exhaust emissions [37]. Typically an emulsion is a combination of different fluids that are suspended in one another. The emulsion is prepared with the aid of mechanical mixing and surfactant. For stable suspension, the surfactants are added [38]. It was found that the ultrasonic method provides better characteristics of emulsified fuel as compared to mechanical homogenizer for preparation of emulsified diesel fuels [39, 40]. Attia and Kulchitskiy [41] reported an increase in engine efficiency by 1.2 times by employing water-in-diesel emulsified fuel as that of unmixed diesel. Similarly, Ithnin et al. [37] found experimentally that specific fuel consumption has reduced considerably in all variations of water-in-diesel emulsions.

Studies reported on water-in-diesel fuel explained that the micro-explosion process takes place in the combustion chamber because of water. This micro-explosion resulted in secondary atomization of fuel which means further disintegration of fuel droplet. The secondary atomization increases the surface area of fuel and facilitates improved ignition characteristics [38]. Schematic representation of the micro-explosion process in water-in-diesel fuel is shown in figure 4. It was reported that ignition delay found to be increased due to water-in-diesel fuel. It is suggested that an increase in ignition delay provides enough time for physical preparation (evaporation and mixing) of fuel [39, 40]. The increase in ignition delay is because of water and it is responsible for delay in both the physical and
chemical process. Latent heat absorption by the water decreases temperature which results in physical delay. On the other hand, reduction in fuel concentration leads to chemical delay [37-40]. Larbi and Bessrour [42] reported that the addition of water content in diesel resulted in the decrease of emission levels of nitrogen oxides considerably which is actually polluting air.

![Figure 4. Secondary atomization of fuel droplet due to presence of water](image)

The water-in-diesel emulsion is very effective for reduction of hydro-carbons, particulate matter, soot and NOx emissions [43]. Kannan and Udaykmar [44] conducted experiments on diesel engine and found improvement in brake thermal efficiency and specific fuel consumption due to the effect of water-in-diesel and also found reduction in emission level of hydrocarbon and nitrogen oxides with increment in water content in water-in-diesel emulsion. Nonetheless, Ghannam and Selim [45] found that for stability of higher content of water in emulsified diesel fuel concentration of surfactant and number of revolutions need to be increased. Alahmer et al. [46] realized that increment of water content in water emulsified diesel results in reduction in emission level of nitrogen oxide while at the same time carbon dioxide emission level increased as compared to diesel fuel.

Vellaiyan and Partheeban [47] employed SB20W emulsified fuel which includes the inclusion of ZnO nanoparticles found to increase the emission of carbon dioxide particles. It was also gathered that CO₂ emissions level increased at high loads and a decrement trend is gathered at low loads in CO₂ levels. Ashikhmin et al. [48] drew a fish-cut diagram for various ratios of diesel fuel/water and found an increment in the relative fraction of water in micro-emulsified fuel. They also observed reduction in the stability as well as in PIT. Sartomo et al. [49] thoroughly reviewed the technologies that are being applied since past decade used for water emulsified fuel mixing and identified that for future generation mixing technology for water emulsified fuel, such a machine will be developed which would be simple and cost effective to prepare water emulsified fuel mixture effectively and efficiently, without the usage of surfactants. Elumalai et al. [50] compared the nitrogen oxides content for blended PPNP 150 ppm with that of diesel fuel within a coated engine and gathered a decrement of 12.53 % owing to the water content present in the fuel as well as due to reduction in temperatures of combustion process. Vigneswaran et al. [51] concluded that water and diesel based emulsified fuels are found to be very superior in controlling the performance characteristics of engines. They found increment in cumulative heat release rate, in-cylinder pressure and in heat release rate both for emulsified water-diesel as well as for nano-emulsified fuels as compared to diesel fuel owing to delay in ignition process.
5. Conclusions

Alternative fuels are promising solutions for fast depleting fossil fuels and associated harmful emissions. Technological advances in the near future can fully replace fossil fuels. Alcohols and biodiesel are important alternative fuels. Both are used extensively due to high oxygen content but research reported suggested that alcohol-biodiesel-diesel blended fuels provide superior results compared to dual blended fuels. Nanoparticle fuel additives are also important in enhancing the performance and reducing emissions in diesel engines. The fuel additives also improve the physicochemical properties of the fuel. Water-in-diesel emulsion is also triggering new research frontiers for performance improvement and decrease in harmful exhaust emissions.

References
[1] Mikulčić H, Baleta J, Klemeš J J, Wang X 2021 Energy transition and the role of system integration of the energy, water and environmental systems Journal of Cleaner Production 292 126027
[2] Mishra S, Dubey M, Raghuwanshi J, Sharma V 2018 Advancements in solar stills for enhanced flow rate Proc. , Int., Conf., on condensed matter and applied physics, 2nd, (AIP Conference Proceedings vol 1953) 24-25 November, Bikaner India, ed M S Shekawat et al. p 030268
[3] Sorrell S 2015 Reducing energy demand: a review of issues, challenges and approaches Renewable and Sustainable Energy Reviews 47 74-82
[4] Johnsson F, Kjärstad J, Rootzén J 2019 The threat to climate change mitigation posed by the abundance of fossil fuels Climate Policy 19(2) 258-74
[5] Jones G A, Warner K J 2016 The 21st century population-energy-climate nexus Energy Policy 93 206-12
[6] Pronk A, Coble J, Stewart P A 2009 Occupational exposure to diesel engine exhaust: a literature review Journal of Exposure Science & Environmental Epidemiology 19(5) 443-57
[7] Arcaklioğlu E, Çeliktentel 2005 A diesel engine’s performance and exhaust emissions Applied Energy 80(1) 11-22
[8] Leung D Y, Luo Y, Chan TL 2006 Optimization of exhaust emissions of a diesel engine fuelled with biodiesel Energy & Fuels 20(3) 1015-23
[9] Ramalingam S, Rajendran S, Ganesan P 2018 Performance improvement and exhaust emissions reduction in biodiesel operated diesel engine through the use of operating parameters and catalytic converter: a review Renewable and Sustainable Energy Reviews 81 3215-22
[10] Ma Y, Zhu M, Zhang D 2013 The effect of a homogeneous combustion catalyst on exhaust emissions from a single cylinder diesel engine Applied Energy 102 556-62
[11] Joy N, Devarajan Y, Nagappan B, Anderson A 2018 Exhaust emission study on neat biodiesel and alcohol blends fueled diesel engine Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 40(1) 115-19
[12] Gülüm M, Bilgin A 2018 A comprehensive study on measurement and prediction of viscosity of biodiesel-diesel-alcohol ternary blends Energy 148 341-61
[13] Emiroğlu A O, Şen M 2018 Combustion, performance and exhaust emission characterization of a diesel engine operating with a ternary blend (alcohol-biodiesel-diesel fuel) Applied Thermal Engineering 133 371-80
[14] Jaichandar S, Annamalai K 2011 The status of biodiesel as an alternative fuel for diesel engine-an overview Journal of Sustainable Energy & Environment 2(2) 71-75
[15] Ağbulut Ü, Sardemir S 2019 A general view to converting fossil fuels to cleaner energy source by adding nanoparticles International Journal of Ambient Energy 1-6
[16] Khan S, Dewang Y, Raghuwanshi J, Shrivastava A, Sharma V 2020 Nanoparticles as fuel additive for improving performance and reducing exhaust emissions of internal combustion engines International Journal of Environmental Analytical Chemistry 1-23
[17] Khan S, Dewang Y, Raghuwanshi J, Sharma V 2019 Nanoparticles exceptional properties:
Applications in internal combustion engines. Proc., Prof. Dinesh Varshney memorial Nat. Conf. on physics and chemistry of materials (AIP Conference Proceedings vol 2100) 27-28 December, Indore India, ed N Kaurav et al. p 020146

[18] Kegl T, Kralj A K, Kegl B, Kegl M 2021 Nanomaterials as fuel additives in diesel engines: A review of current state, opportunities, and challenges Progress in Energy and Combustion Science 83 100897

[19] Kalghatgi G T 2014 The outlook for fuels for internal combustion engines International Journal of Engine Research 15 (4) 383-98

[20] Bae C, Kim J 2017 Alternative fuels for internal combustion engines Proceedings of the Combustion Institute 36(3) 3389-13

[21] Coronado C R, de Carvalho Jr J A, Yoshioka JT, Silveira J L 2009 Determination of ecological efficiency in internal combustion engines: The use of biodiesel Applied Thermal Engineering 29(10) 1887-9

[22] Badruddin IA, Badarudin A, Banapurmath NR, Ahmed NS, Quadir GA, Al-Rashed AA, Khaleed HMT and KamangarS 2015 Effects of engine variables and heat transfer on the performance of biodiesel fueled IC engines Renewable and Sustainable Energy Reviews 44 682-91

[23] Mofijur M G R M, Rasul AM, Hyde J, Azad A K, Mamat R, Bhuiya M M K 2016 Role of biofuel and their binary (diesel-biodiesel) and ternary (ethanol-biodiesel-diesel) blends on internal combustion engines emission reduction Renewable and Sustainable Energy Reviews 53 265-78

[24] Ağbulut Ü, Sardemir S, Albayrak S 2019 Experimental investigation of combustion, performance and emission characteristics of a diesel engine fuelled with diesel–biodiesel–alcohol blends Journal of the Brazilian Society of Mechanical Sciences and Engineering 41(9) 1-12

[25] Lenin M A, Swaminathan M R, Kumaresan G 2013 Performance and emission characteristics of a DI diesel engine with a nanofuel additive Fuel 109 362-65

[26] Shah P R, Ganesh A 2016 A comparative study on influence of fuel additives with edible and non-edible vegetable oil based on fuel characterization and engine characteristics of diesel engine Applied Thermal Engineering 102 800-12

[27] Ribeiro N M, Pinto A C, Quintella C M, da Rocha G O, Teixeira L S, Guarieiro L L, do Carmo Rangel M, Veloso M C, Rezende M J, Serpa da Cruz R, de Oliveira A M 2007 The role of additives for diesel and diesel blended (ethanol or biodiesel) fuels: a review Energy & Fuels 21(4) 2433-45

[28] Kumar S, Dinesha P, Ajay C M, Kabbur P 2020 Combined effect of oxygenated liquid and metal oxide nanoparticle fuel additives on the combustion characteristics of a biodiesel engine operated with higher blend percentages Energy 1971171

[29] Janakiraman S, Lakshmanan T, Chandran V, Subramani L 2020 Comparative behavior of various nano additives in a diesel engine powered by novel Garcinia gummi-gutta biodiesel Journal of Cleaner Production 245 118940

[30] Patel H K, Kumar S 2017 Experimental analysis on performance of diesel engine using mixture of diesel and bio-diesel as a working fuel with aluminum oxide nanoparticle additive Thermal Science and Engineering Progress 4 252-8

[31] Wei J, Yin Z, Wang C, Lv G, Zhuang Y, Li X, Wu H 2021 Impact of aluminium oxide nanoparticles as an additive in diesel-methanol blends on a modern DI diesel engine Applied Thermal Engineering 185 116372

[32] Khond V W, Kriplani V M 2016 Effect of nanofluid additives on performances and emissions of emulsified diesel and biodiesel fueled stationary CI engine: A comprehensive review Renewable and Sustainable Energy Reviews 59 1338-48

[33] Karthikeyan N R, Philip J, Raj B 2008 Effect of clustering on the thermal conductivity of
Wang X, Zhang J, Yin M A, Wang G, Han J, Dai M, Sun Z Y 2020 A comprehensive review on the properties of nanofluid fuel and its additive effects to compression ignition engines Applied Surface Science 504 144581

Chaichan M T., Kadhum, A. A. H., & Al-Amiery, A. A. (2017) Novel technique for enhancement of diesel fuel: Impact of aqueous alumina nano-fluid on engine's performance and emissions Case Studies in Thermal Engineering 10 611-20

Ramanan M V, Yuvarajan D 2016 Emission analysis on the influence of magnetite nanofluid on methyl ester in diesel engine Atmospheric Pollution Research 7(3) 477-81

Ithnin A M, Ahmad M A, Bakar M A A, Rajoo S, Yahya W J 2015 Combustion performance and emission analysis of diesel engine fuelled with water-in-diesel emulsion fuel made from low-grade dieselfuel Energy Conversion and Management 90 375-82

Ithnin A M, Noge H, Kadir H A, Jazair W 2014 An overview of utilizing water-in-diesel emulsion fuel in diesel engine and its potential research study Journal of the Energy Institute 87(4) 273-88

Lin C Y, Chen L W 2008 Comparison of fuel properties and emission characteristics of two and three phase emulsions prepared by ultrasonically vibrating and mechanically homogenizing emulsification methods Fuel 87(10-11) 2154-61

Mondal P K, Mandal B K 2019 A comparative study on the performance and emissions from a CI engine fuelled with water emulsified diesel prepared by mechanical homogenization and ultrasonic dispersion method Energy Reports 5 639-48

Attia A M Kulchitskiy A R 2014 Influence of the structure of water-in-fuel emulsion on diesel engine performance Fuel 116 703-08

Larbi N, Bessrour J 2010 Measurement and simulation of pollutant emissions from marine diesel combustion engine and their reduction by water injection Advances in Engineering Software 41(6) 898-06

Armas O, Ballesteros R, Martos F J Agudelo J R 2005 Characterization of light duty diesel engine pollutant emissions using water-emulsified fuel Fuel 84(7-8) 1011-18

Kannan K, Udayakumar M 2009 NOx and HC emission control using water emulsified diesel in single cylinder diesel engine ARPN Journal of Engineering and Applied Sciences 4(8) 59-62

Ghannam M T, Selim M Y E 2009 Stability behavior of water-in-diesel fuel emulsion Petroleum Science and Technology 27(4) 396-11

Alahmer A, Yamin J, Sakhiriah A, Hamdan M A 2010 Engine performance using emulsified diesel fuel Energy Conversion and Management 51(8) 1708-13

Vellaiyan S, Partheeban C A 2020 Combined effect of water emulsion and ZnO nanoparticle on emissions pattern of soybean biodiesel fuelled diesel engine Renewable Energy 149 1157-66

Ashikhmin A, Piskunov M, Yanovsky V, Yan W M 2020 Properties and phase behavior of water-in-diesel microemulsion fuels stabilized by nonionic surfactants in combination with aliphatic alcohol Energy & Fuels 34(2) 2135-42

Sartomo A, Santoso B, Muraza O 2020 Recent progress on mixing technology for water-emulsion fuel: A review Energy Conversion and Management 213 112817

Elumalai P V, Nambiraj M, Parthasarathy M, Balasubramanian D., Harirhan V, Jayakar J 2021 Experimental investigation to reduce environmental pollutants using biofuel nano water emulsion in thermal barrier coated engine Fuel 285 119200

Vigneswaran R, Balasubramanian D, Sastha B S 2021 Performance, emission and combustion characteristics of unmodified diesel engine with titanium dioxide (TiO₂) nano particle along with water-in-diesel emulsion fuel Fuel 285 119115.