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Review

A Review of Performance-Enhancing Innovative Modifications in Biodiesel Engines

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Received: 1 August 2020; Accepted: 24 August 2020; Published: 26 August 2020

Abstract: The ever-increasing demand for transport is sustained by internal combustion (IC) engines. The demand for transport energy is large and continuously increasing across the globe. Though there are few alternative options emerging that may eliminate the IC engine, they are in a developing stage, meaning the burden of transportation has to be borne by IC engines until at least the near future. Hence, IC engines continue to be the prime mechanism to sustain transportation in general. However, the scarcity of fossil fuels and its rising prices have forced nations to look for alternate fuels. Biodiesel has been emerged as the replacement of diesel as fuel for diesel engines. The use of biodiesel in the existing diesel engine is not that efficient when it is compared with diesel run engine. Therefore, the biodiesel engine must be suitably improved in its design and developments pertaining to the intake manifold, fuel injection system, combustion chamber and exhaust manifold to get the maximum power output, improved brake thermal efficiency with reduced fuel consumption and exhaust emissions that are compatible with international standards. This paper reviews the efforts put by different researchers in modifying the engine components and systems to develop a diesel engine run on biodiesel for better performance, progressive combustion and improved emissions.

Keywords: biodiesel; modifications; intake manifold; fuel injection; exhaust manifold; efficient engines

1. Introduction

The internal combustion (IC) engine is the prime mover as far as transportation is concerned in our society. The IC engine converts the chemical energy contained by the fuel into heat energy and subsequently heat into work. Engine modifications and developments have been taking place for better efficiency and lower fuel consumption. Fuels also have a major impact on engine design, modifications and developments.

The diesel engine, which is one of the prime movers for transportation, has undergone many modifications since its invention for better performance, low fuel consumption besides lower emissions due to stringent emissions norms of the legislature. Diesel has a higher energy density compared to gasoline. Therefore, diesel engines in automobiles provide higher mileage, making it an obvious choice for heavy-duty transportation and equipment. Diesel engines employ compression-ignition for igniting the fuel. Thus, the diesel engine design is simpler than the gasoline engine, which needs a spark plug in order to ignite the fuel and air mixture. However, fossil fuels are depleting rapidly, and it has even been projected that they may only last for few decades more [1–3]. Therefore, the search for new alternate fuels for diesel engine has gained momentum in recent decades [4–7].

Though biodiesel has emerged as an alternate to diesel for compression ignition engines, the formation of oxides of nitrogen (NOx), lesser brake thermal efficiency, and increased fuel consumption are still the major concerns in the unmodified diesel engine [8–10]. Hence, the focus is to make the diesel engine more efficient by modifying the engine components or systems for an engine operated on biodiesel–diesel blends. The fluid flow in intake manifold, fuel injection system, combustion, heat transfer, etc., are relevant to the internal combustion engine for better performance, efficiency, emissions and fuel requirements [11]. Hence, the focus is to make the diesel engine more efficient by modifying the engine components or systems for engine operated on biodiesel–diesel blends. The fluid flow in intake manifold, fuel injection system, combustion, heat transfer, etc., are relevant to the internal combustion engine for better performance, efficiency, emissions and fuel requirements [12–17]. The impact of variables of the IC engine and other parameters on biodiesel engine performance and emissions were reviewed. It was concluded that the optimized engine variables and parameters would give maximum possible efficiency with minimum emissions [18,19]. Combustion chamber (CC) geometry is an important engine design parameter. The progressive and efficient combustion in any internal combustion engine depends on the type of CC geometry. The effect of different combustion geometries on the performance and emissions has been reviewed [20]. However, to the best of authors' knowledge, there is no paper that reviews the modifications that have taken place in the biodiesel engines. This paper reviews the research carried out by modifying the different engine components, namely intake manifold, fuel injection and exhaust manifold using biodiesel–diesel blends as fuel.

2. Intake Manifold Modifications

The air or air–fuel mixture (charge) flow in the intake manifold is a complex phenomenon in diesel and petrol engines, respectively. The effectiveness of the air induction intern depends on intake system which is known with the help of volumetric efficiency. This section reviews the various methods of modifications done in the intake manifold of the biodiesel engine.

2.1. Hydrogen Addition

Rocha et al. [21] installed a small L-shaped tube in the center of the intake pipe. They anticipated that the fluctuations due to the rapid functioning of both valves improve the mixing of hydrogen and air. Furthermore, hydrogen addition increased the energy content of the fuel (biodiesel + hydrogen). The results showed a reduction in specific fuel consumption besides a decrease in emissions such as carbon dioxide (CO_2), carbon mono-oxide (CO) and hydrocarbons (HC). However, there was an increase in nitrogen oxide (NOx) due to a higher cylinder temperature [21]. An experimental and numerical study on combustion and performance was conducted with 20% rapeseed biodiesel and 80% diesel with different fractions of hydrogen contents. Both studies concluded with a decrease in CO, smoke and the total unburned hydrocarbon (TUHC) emissions and an increase in Nox by adding fractions of hydrogen contents with air in the intake manifold. There was no significant change in ignition delay by enriching hydrogen with the diesel and biodiesel blend [22]. Tests conducted on the diesel engine by using diesel, neat grapeseed oil and grapeseed biodiesel for different shares of hydrogen additions showed an increase in brake thermal efficiency (BTE) from 3% to 4% for a maximum share of hydrogen energy. There was a decrease in emissions such as HC, CO and CO_2 but the trend of Nox was found to be increased [23]. A comparison study of enriching pure hydrogen and hydroxyl (HHO) with sunflower biodiesel was carried out by Mustafa et al. [24]. They found the engine better in terms of performance when run on biodiesel by enriching HHO with the intake air. However, the engine run on biodiesel with enriching pure hydrogen was found to be better as far as emissions are concerned [24]. The thermal efficiency of biodiesel engine run on tamanu methyl ester is less besides high smoke compared to diesel engine. The trend obtained regarding the performance and emissions was same as discussed above. In addition to hydrogen induction in the intake manifold, the biodiesel was blended with ethanol, which resulted in an increase in BTE and a reduction in Nox, CO and smoke [25]. The experiments conducted with different volumetric flow rates of biodiesel and diesel mixtures in a test engine with hydroxyl gas addition showed an improved engine performance with lesser emissions except Nox. The brake power was improved by 8.3%, 7.1% of brake torque and 10% of brake specific fuel consumption [26]. According to Radu and Nicolae [27], there were some contradictory results on emissions when 20% biodiesel–diesel blend was used. They conducted combustion and emissions tests on conventional tractor by using B20 (rapeseed biodiesel) enriched with hydrogen. There was no significant change in engine combustion characteristics. The addition of hydrogen lowered emissions such as smoke and CO but with a significantly higher concentration of Nox [27]. Rapeseed biodiesel–butanol blend also produced a higher concentration of Nox with reduced concentrations of CO and particulate matters. However, it was reported that exhaust gas recycle (EGR) could be used to control the excessive formation of Nox [28]. Hydrogen was inducted at varying flow rates of 4–12 L/m with honge biodiesel. The results obtained showed the similar trends of improved thermal efficiency with reduced CO, HC, smoke and a higher concentration of Nox [29].

It could be summarized that the formation of Nox is a major issue when hydrogen is added in the intake manifold of the diesel engine when operated on blends of biodiesel and diesel. There are few researchers who have tried to reduce the formation of Nox. Higher in-cylinder temperature and availability of oxygen are responsible for the formation of Nox in compression ignition engines. Hence, water in biodiesel emulsions has been tested for increased thermal efficiency and a reduction in the formation of Nox [30–35]. There was a reduction of 32% in formation of Nox, a 7.4% reduction in smoke, and a 2.3% and 1% reduction in CO and hydrocarbon (HC) were reported when water emulsified pongamia biodiesel was used in a 4-S diesel engine [36]. There are many issues in using hydrogen as a singular fuel in diesel engines. To overcome these issues a mixture of hydrogen and carbon monoxide was injected in the intake manifold in biodiesel engine. This resulted in a decrease in biodiesel consumption with a minimal increase in the formation of Nox [37]. The formation of Nox along with other emissions can also be reduced by methods such as intake manifold water injection, combined effect of steam injection and ferric chloride, etc., in diesel engines [38–43]. Intake manifold water injection was employed for rapeseed biodiesel-based four stroke, compression ignition and turbo-charged engines. It was reported that injecting the water at 3 kg/h reduced the formation of Nox by 50%. However, there was no significant change in performance and combustion parameters of the engines [44]. A similar trend of performance and emissions was reported recently for the diesel–canola biodiesel blend with steam injection in the intake manifold [45].

2.2. Alcohol Fumigation Modes

Diesel engine particulate matter, CO, HC and Nox are serious threats to human health and the environment [46]. To control these emissions, more and more tough norms are being implemented around the globe through legislations. Hence, reducing these emissions from any engine is of prime importance and of course one of the most significant challenges for any researcher who is working on engine design and development. The after-treatment processes and in-cylinder combustion techniques are being developed and improved by modifying fuels to mitigate the tailpipe Nox emission and formation in the cylinder, respectively. Some literature is available on the review of the alcohol fumigation mainly methanol and ethanol [47,48]. In this section, the recent literature on alcohol, gaseous fumigation modes used in biodiesel engines has been reviewed. Fumigation of ethanol in the intake manifold of a CI engine run on B7 fuel gave an increase in both thermal and exergy efficiencies. A substantial reduction of 69% in smoke index and also a reduction in the formation of CO and CO_2 were reported. Nevertheless, an increase in HC and specific fuel consumption were noted. There was not any mention about Nox; however, there was a reduction in exhaust gas temperature [49]. Edvin Geo et al. [50] studied the effects of ethanol fumigation on the performance, combustion as well as emissions of diesel engines run on crude rubber seed oil and its methyl esters. The researchers found that an increase in the quantity of ethanol injection increased the BTE of the engine operated on rubber seed oil as well as its biodiesel besides reduced smoke emissions with higher concentrations of Nox, CO and HC. The combustion parameters such as in-cylinder pressure and rate of peak pressure rise also increased. However, the combustion duration was less, which led to an increase in heat release rate [50]. Higher viscosity and low volatility are the two main problems associated with crude oils when they are used in diesel engines directly instead of diesel though they have suitable energy contents. To overcome these issues, engine with low heat rejection (LHR) concept, carbureting the alcohols in the intake manifold were tested by using jatropha crude oil as the fuel. The performance of the engine jatropha crude oil was found to be better for engines with an LHR combustion chamber and a maximum induction of alcohol than the conventional engine with appropriate injection parameters. Furthermore, it was reported that ethanol injection was better for conventional engines and methanol injection was suitable for engines with an LHR combustion chamber. However, an increase in the levels of oxides of nitrogen Nox was reported [51].

It should be noted that the prime factor for Nox formation is a higher temperature inside the engine cylinder. Thus, it can be said that any effort that reduces the engine temperature should also be able to curb the Nox formation. Such possible efforts are noted in the work of engines run on pure diesel. In a 4-S diesel engine, bioethanol was fumigated in the intake manifold at different flow rates during suction stroke. It was found that, by fumigating the bioethanol at a rate of 0.48 kg/h, the brake specific nitric oxide (BSNO) and smoke were found to be lower by 24.2% and 25%, respectively, than that of pure diesel at full load operating conditions. The researchers concluded that the reduction in BSNO was due to high latent heat of vaporization of bioethanol, reduction of air induction and slow start of heat release rate [52]. A similar trend was obtained by using bioethanol E85 when used in three cylinder direct injection diesel engine [53].

Goldsworthy [54] fumigated ethanol-water mixture in heavy duty common rail marine diesel engine. The vaporized ethanol-water mixture was injected into intake manifold at different flow rates. The test set up for manifold injection is shown in Figure 1.

Figure 1. Installation of an ethanol injector in an intake manifold.

It was reported that Nox reduced with an increase in the flow rate of the ethanol–water mixture. The reduction of Nox may be attributed to the presence of water contents in the combustion chamber, which reduces the combustion temperature inside the cylinder [54]. Notwithstanding the complication of dual fuel supply systems and proper phasing of combustion, the operating conditions need to be fully understood. Furthermore, the material used for port ethanol injection systems is mainly carbon steel which is liable to stress corrosion cracking (SCC) [55]. SCC does not provide any form of prior warning to failure and it has far more adverse effects [56].

It was found from the vast literature available on diesel and biodiesel that the trend of performance and emissions of these two types of fuels go hand in hand. Thus, it can be predicted that any parameter that reduces the Nox in the diesel engine would also reduce the Nox in the biodiesel engine. On this basis, the Nox reduction in biodiesel engine should be tried as per the modifications adopted in diesel engines [52–54].

2.3. Gasoline Fumigation

In gasoline engines, air and gasoline are premixed outside the engine cylinder during intake stroke of the cycle. Combustion of the charge is followed by the spark initiated by spark plug. If this gasoline is fumigated in diesel engines, then it has been reported in the literature that the engine performance and emissions would be improved [22,57,58]. This concept of gasoline fumigation has been tested in diesel engine run on B20 biodiesel two different ratios. Using B20 biodiesel with gasoline fumigation increased the formation of Nox slightly, but a considerable reduction in unburned hydrocarbon (UHC), CO, and smoke capacity exhaust gas temperature were noted [59]. The energy and exergy analysis was carried B20 biodiesel and diesel. It was found that the efficiencies of both energy and exergy were almost equal at higher operating loads. However, destructed exergy with biodiesel and the fumigation of gasoline were greater in biodiesel and fumigation [60].

2.4. Incorporating Guide Vanes

The airflow behavior in both intake manifold and cylinder are essential factors in forming an ideal air–fuel mixture. As the engine speed increases, flow rate increases with a corresponding increase in swirl and turbulence. This increases the rate of fuel evaporation, mixing of fuel vapor and air and combustion that leads to improved combustion efficiency [19,61,62]. Swirl is used in many modern CC designs to enhance the burning process and achieve greater combustion stability [63]. The nature of air flow in the intake manifold of an engine is an extremely complex phenomenon that makes it extremely difficult to be determined experimentally. This factor has motivated many researchers to rely on simulation as against experimentation [64–70].

Swirl can be created by bringing the intake flow into the cylinder with an initial angular momentum. Swirl can be developed by engine designs with a bowl in piston combustion chambers, setting up the rotational motion of air by modifying the intake system, etc.

The effects of incorporating guide vanes at different angles in the intake manifold was studied for a diesel engine generator run on higher viscous biodiesel. The optimum vane angle was found to be 350 by computer simulation. The other vane parameters, such as vane height, vane number and vane length, were kept constant. Though the optimum vane angle was 350, the researchers fabricated and tested the generator for different vane angles ranging from 25° to 45° experimentally. Figure 2 shows the photographs of the different guide vanes.

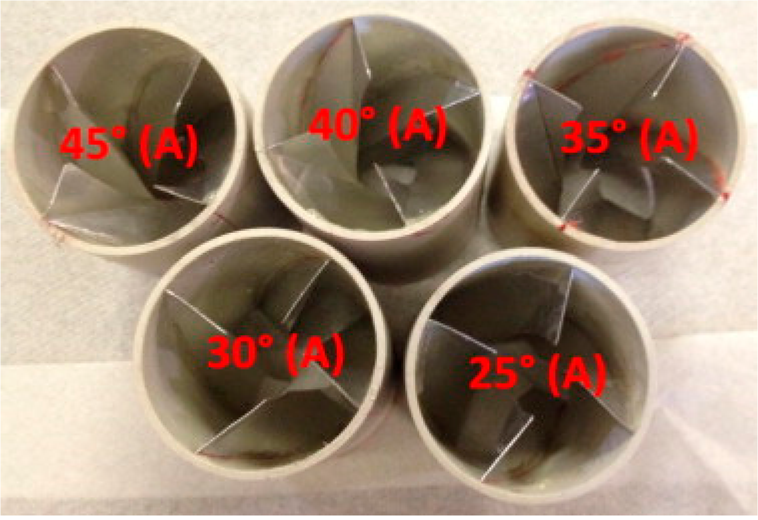

Figure 2. Images of the guide vanes.

They concluded that a vane angle of 35° gave the best possible efficiency, reduced brake specific fuel consumption (BSFC) and reduced emissions [64]. The same researchers further studied the performance by optimizing the vane height by simulation using SolidWorks and ANSYS-CFX. The vane height of 0.70 times the radius of intake runner obtained by simulation results was fabricated and tested on a compression ignition diesel engine generator run on biodiesel. They found that a reduction in BSFC, CO and HC improved thermal efficiency [65]. It is a known fact that biodiesel possesses higher viscosity than diesel, which is responsible for lower combustion efficiency. This issue was mitigated by installing guide vane swirl and tumble device (GVSTD) in the air intake system to aid the effective breaking of biodiesel particles and mixing it with the molecules of air. It is a promising way to have a better mixing of air and biodiesel mixture [66]. Similar type of trend with respect to performance was obtained for different optimizations and configuration [67–69]. Therefore, it can be stated that, by optimizing the guide vanes height, number and length, the combustion efficiency could be improved beside improved performance and lower emissions for biodiesel engines.

2.5. Intake Manifold Water Injection (IMWI)

The formation of Nox is the result of a high-temperature combustion process. It affects the respiratory system. The high latent heat and specific heat of water that is being injected in the intake manifold may reduce the in cylinder temperature and hence may reduce the quantity of Nox being formed in the diesel engine [71]. However, some researchers attributed to the dilution effect affected the engine performance and emissions [72]. Intake manifold water injection was claimed to be an effective way to contain the in cylinder combustion temperature and formation of Nox. The CFD simulation tests conducted on direct injection diesel engine and turbocharged engine produced remarkably less amounts of both Nox as well as soot [38]. The same trend of reduction in Nox was observed when diesel engine was run with 100% biodiesel prepared from rapeseed oil at two different engine loading conditions. Water was injected at different mass flow rate of 0 kg/h, 1.8 kg/h, 3 kg/h. The formation of Nox was found to decrease at various engine operating conditions with an increase in the speed of the engine. Higher engine speed increases the volumetric efficiency and gas flow motion, which leads to the rapid mixing of air with fuel, resulting in shorter ignition delay. Therefore, the time available for the reaction between the oxygen and free nitrogen is significantly reduced. Shorter ignition delay minimizes the formation of Nox. Furthermore, by Nox was reduced with an increase in water flow rate proportionately [44].

2.6. Thermal Barrier Coating

The engine cylinder, combustion chamber and many other components of internal combustion engine are made up of metals. Metals are low-temperature materials and good thermal conductors, which is why heat losses from the engine cylinder are greater. The heat losses from the engine reduces the power developed and hence the performance [73–76]. Thermal barrier coatings minimize the heat losses from the engine and they also increase durability of the engine components due to their excellent thermal insulation properties [77–80]. The recent study carried out by using Moringa oleifera biodiesel blended with an additive in direct injection water cooled diesel engine showed improved brake thermal efficiency and reduced brake specific fuel consumption in a coated engine. The emissions CO, HC and Nox were in fact less in the biodiesel–antioxidant blend than diesel fuel [81].

The piston and both valves of the single cylinder compression engine were modified by coating with the layers of different ceramic B2040TiO_2 materials. The performance and emissions tests were carried out by using biodiesel from waste cooking oil at same engine operating conditions for both coated engine and without coated engine. The results show that the performance was better, and parameters such as brake specific fuel consumption reduced considerably beside lower emissions except Nox. Increased Nox were the result of increased combustion temperature [82]. The top surface of the piston and valves were coated with two layers. A total of 100 μm of Nickel Chromium Aluminum (NiCrAl) was used as the first layer, known as a lining layer, by the plasma spray coating method. Furthermore, this layer was coated with a 400 μm layer consisting of a mixture of 88% zircon oxide (ZrO_2), 4% MgO (magnesium oxide) and 8% Aluminum oxide (Al_2O_3). Some improvements in the performance and combustion parameters of the engine when tested for different biodiesel fuel blends were found [83].

2.7. Pre-Heating CI Biodiesel Engines

The engine performance and emissions of any engine intern depends upon the quality of the fuel being used in the engine [84–86]. Biodiesel as a fuel for a diesel engine has major problems, such as higher viscosity, low heating value and low volatility [87–93]. The pre-heating of biodiesel or crude oils decreases their viscosity and makes them suitable for diesel engines [94,95]. The pre-heating and exhaust gas recycle (EGR) tests were conducted by using jatropha biodiesel–diesel blend. The optimum blend was B40. In the beginning, the fuel was heated to 102 °C in the intake manifold, which reduced the kinematic viscosity and density of the biodiesel by 49% and 4.3%, respectively. There was a significant decrease in BSFC and an increase in thermal efficiency. The formation of emissions such as unburned hydrocarbon and carbon monoxide were reduced, but oxides of nitrogen increased by 17.5%. This increased in Nox was reduced by 68.8% by inclusion of EGR [96]. The heat carried by the exhaust gases was utilized to pre-heat the biodiesel made by palm oil. The pre-heated palm oil/diesel blends tested in a diesel engine at a constant speed of 1500 rpm at different loading conditions are shown in Figure 3. The blend of 20% palm oil and diesel was found to the most suitable blend for different performance and emissions parameters. Furthermore, the pre-heated palm oil with the addition of an antioxidant gave better performance with reduced emission levels than diesel [97].

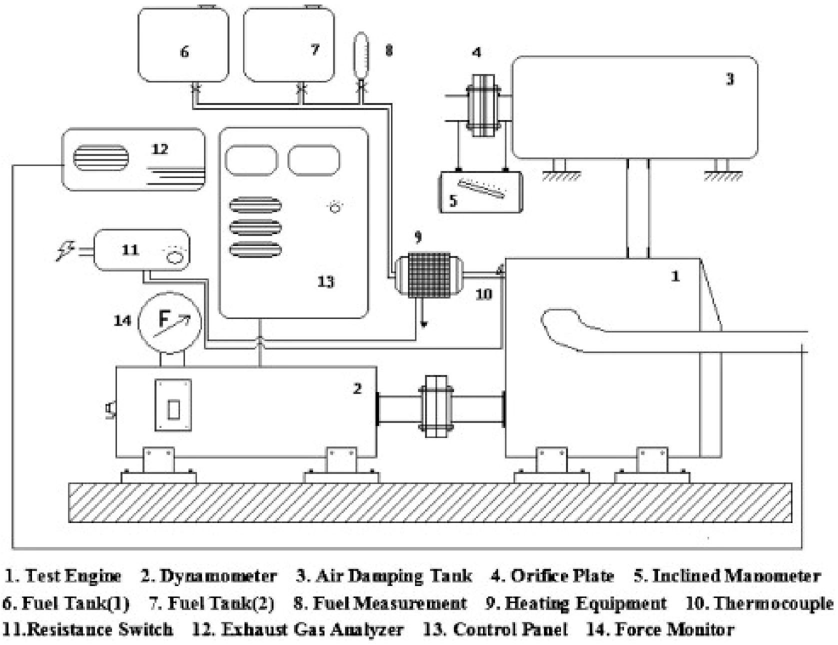

Figure 3. Schematic diagram of diesel engine set-up.

Nadir [98] studied the effect of air pre-heating on the operation of a diesel engine when operated on the blends of biodiesel and methanol with different concentrations. The pre-heating of the intake or lowering the methanol concentration in the blend of biodiesel and methanol reduced CO and HC but not Nox [98]. It can be observed that Nox emissions are more when either air or biodiesel fuel is pre-heated, but its formation may be controlled by installing EGR. Figure 4 indicates the summary of intake manifold modifications.

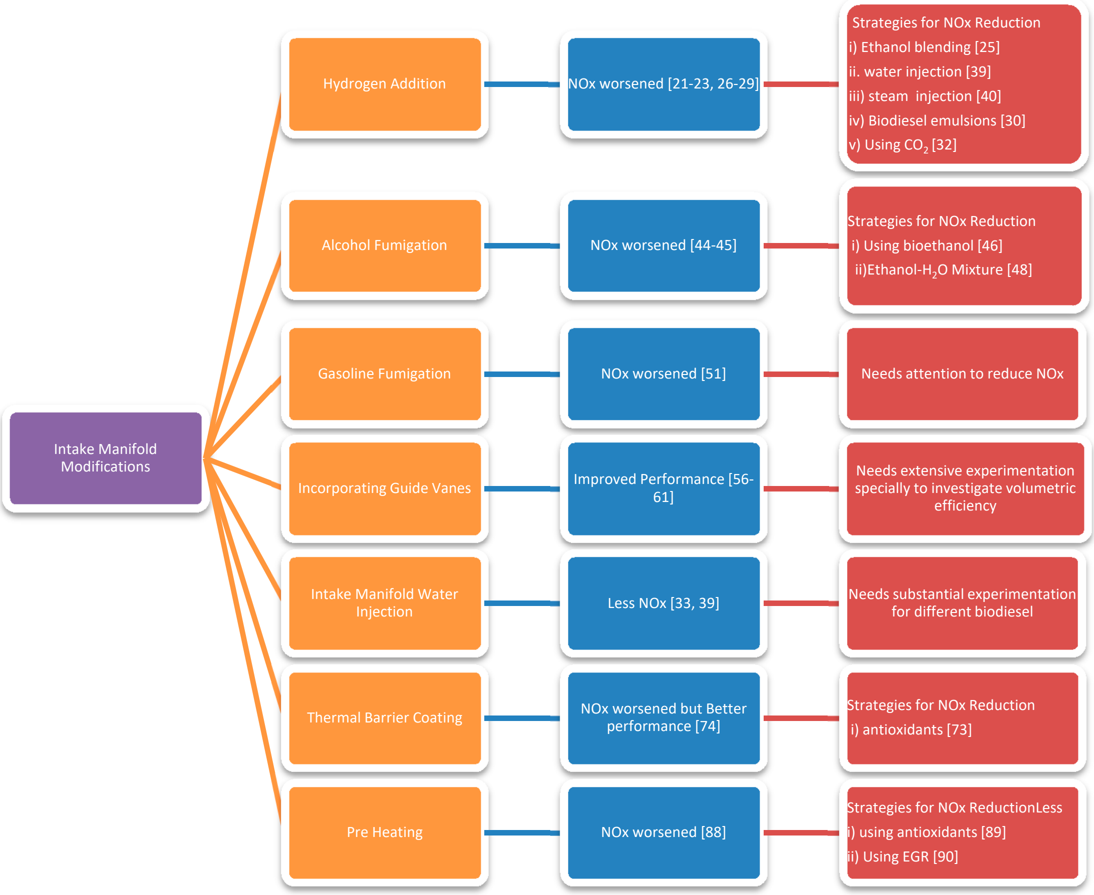

Figure 4. Schematic diagram of intake manifold modifications.

3. Fuel Injection

Fuel injection affects the combustion and emissions significantly [99]. The main components of a diesel fuel injection system are an injection pump, delivery pipe and fuel injector nozzles. The requirements of a fuel injection system are [100–105]:

- Fuel must be injected at desired timing of combustion;
- The injected fuel must have correct quantity as required;
- The spray pattern should ensure rapid mixing of air with the fuel;
- The beginning and end of the fuel injection should be sharp.

The fuel-injection rate, fuel nozzle design (including number of holes), and fuel-injection pressure all affect the characteristics of the diesel fuel spray and its mixing with air in the combustion chamber [100,106–108].

3.1. Nozzle Geometry

Nozzle geometry is one of the parameters on which the quality of atomization of the fuel in the diesel engine depends [109–112]. In fact, the effectiveness of the combustion and performance of a compression ignition diesel engine depends on the nozzle geometry [113,114]. Mahua biodiesel blended with diesel was run in CI diesel engine for performance, combustion and emissions. The fuel injector nozzle had three holes with different sizes of Ø = 0.20 mm (modified), Ø = 0.28 mm (base), and Ø = 0.31 mm (modified), as shown in Figure 5.

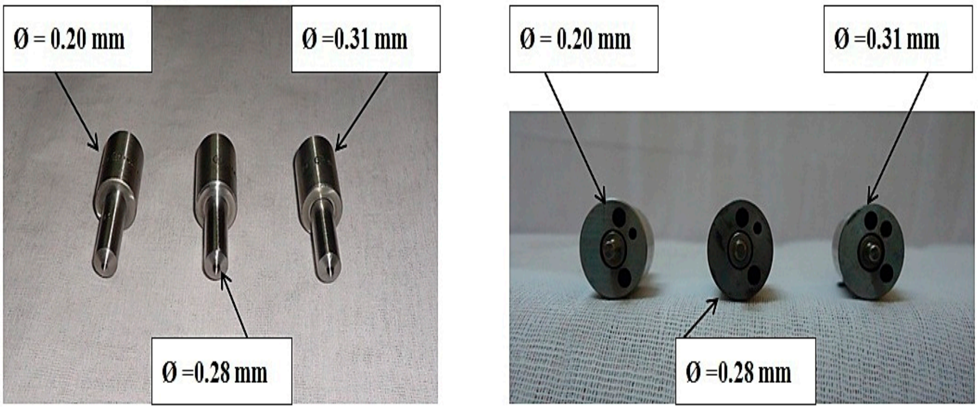

Figure 5. Nozzles of different sizes.

The results show that the performance, combustion and emissions parameters were better for a smaller nozzle diameter of 0.20 mm because the small nozzle diameter makes the mixing of biodiesel–diesel blend with air effective, which makes the combustion more efficient. In this research, the combination of B20 biodiesel and diesel blend with smaller nozzle diameter resulted in improved performance, combustion and emissions characteristics. However, an increase in the formation of Nox was a matter of concern [115]. Mahantesh et al. [116] recently studied the combined effects of nozzle geometry and combustion chamber shapes. They conducted the performance and emissions tests on a four-stroke diesel engine with different blends of pongamia pinnata biodiesel and diesel. They compared the results of unmodified engine with three-hole nozzle geometry and HCC (Hemispherical Combustion Chamber) with that of different modified combustion chamber shapes such as CCC (Cylindrical Combustion Chamber), SCC (Shallow-depth Combustion Chamber) and TCC (Torroidal Combustion Chamber) with five-hole nozzle geometry. The operating conditions of an engine, such as injection pressure, injection timing and compression ratio, were held constant. The different combinations gave different results with some advantages and some drawbacks. However, they concluded that emissions were less in all the modified engines with reduced brake thermal efficiency [116]. Effect of nozzle holes and combustion chamber geometry was studied by using honge methyl esters (HOME) and producer gas combination in a diesel engine. The study was carried out in two stages. In the first phase number of nozzle, hole diameter and injection pressure were optimized to 4, 0.25 mm and 230 bar, respectively. These optimized nozzle geometries were used to conduct the performance tests by using two different types of combustion chambers, such as hemispherical combustion chamber (HCC) and re-entrant combustion chamber (RCC). On an average with optimized nozzle geometry with a 230 bar injection pressure, the combination of honge and producer gas with RCC gave increased brake thermal efficiency, reduced emissions such as smoke, HC, and CO but increased Nox level [117]. Increased injector hole number decreased the BSFC, smoke opacity, CO, HC and increased Nox and CO_2 , especially for the higher concentrated biodiesel–diesel blends (B50 and B100) [118]. The increase in the formation of Nox was also noticed in multi-injection strategies in biodiesel engines though; there was a decrease in the formation of soot, HC and CO. However, there was an increase in indicated mean effective pressure [119]. A detailed study on effects of injection parameters, including the nozzle geometry and swirl was studied by Tumbal et al. [120] on honge oil methyl ester. They concluded that running the diesel engine with an increased number of holes with a smaller hole size in the fuel injector will improve the performance of the engine significantly [120].

The literature on nozzle geometry and combustion chamber reveals that either performance is better or Nox formation is less. To obtain both the improved performance and reduced emissions in general and Nox in particular, cerium oxide nanoparticle (CON), a nano fuel additive, was added to Calophyllum Inophyllum Methyl Ester (CIME). The tests were conducted with different nozzle geometries having holes of three (base, Ø = 0.280 mm), four (modified, Ø = 0.220 mm) and five (modified Ø = 0.240 mm) holes. It was found that emissions such as hydrocarbon and Nox reduced considerably with improved brake thermal efficiency (BTE) and reduced brake specific fuel consumption with NH5 (five holes and Ø = 0.240 mm). In these tests, CON acted both as an oxidation and reducing catalyst, which provided the oxygen for the oxidation of CO and absorbed oxygen to reduce the formation of Nox [121]. Modified nozzle configuration (six holes) reduced the Nox emissions for a B20 biodiesel–diesel blend in a diesel engine. It was observed that Nox formation was reduced from 7.4 g/kW-hr with the base nozzle configuration to 6.6 g/kW-hr with modified nozzle configuration due to the reduction in penetration distance and reduced cylinder temperature. There were tangible benefits of reduction in other emissions as well [122].

3.2. Split Injection

Nowadays, customers wish to have their engines more efficient and at the same time Governments are implementing strict emissions norms. These specific demands can be met by replacing the mechanical fuel supply system with electronic fuel supply. Today's engines are as much electronic as they are mechanical [123]. The literature review on the development of advanced injection strategies emphasizes the importance of an electronically operated fuel injection system. The authors described the electronically operated fuel injection system as the heart of an engine in these years for improved performance and low emissions [124].

Split injection term is also referred to as multiple injection, wherein the injection is divided into two smaller injections, i.e., pre-injection and main injection [108,125]. The split injection strategies also include change of injection pressure, injection timing and injection interval [125]. Split injection has been considered as an effective way to tackle the problems associated with exhaust emissions, especially the formation of Nox and particulate matter from diesel engines without adding more complexity to the existing engine [126–130]. The effects of split injection on flame temperature and soot distribution were studied on biodiesel and diesel as the fuels in an optical CI engine by both numerically and experimentally at different injection timings and quantities. It was concluded that the biodiesel-fueled engine developed a higher flame temperature and lower soot formation than its counterpart diesel-fueled engine. The higher flame temperature could be reduced by increasing the pilot fuel mass. It is known that biodiesel properties have a negative impact on the spray development, but split injection allows for biodiesel fuel injection to reduce the exhaust emissions and improve the atomization of biodiesel and hence better mixing with air [131]. The tests conducted by using different blends of Karanja biodiesel in the single common rail direct injection (CRDI) research engine showed higher BSFC and BTE for higher biodiesel concentrated blend. However, lower concentrated biodiesel–diesel blends produced lower emissions such as brake specific carbon monoxide (BSCO) and brake specific hydrocarbon (BSHC) emissions than diesel but with increased Nox [132]. The experiments conducted to study the impact of advanced injection strategies on CRDI engine by using biodiesel showed an improved engine performance with less emissions including Nox [107]. The formation of Nox was decreased considerably in a soybean biodiesel engine by recirculating the exhaust gas (EGR), but BSFC and soot formation increased slightly [133]. Optimum double-injection strategy was recently implemented after having a parametric study for B20 biodiesel made from waste cooking oil. This strategy also reduced the formation of Nox but with higher particulate matter compared to a diesel engine [134]. There are two studies carried out on the same diesel engine and using coconut oil methyl esters and diesel blends by implementing two-stage and triple-stage injection strategies. The strategies produced lesser Nox and smoke simultaneously [135,136]. The engine used for the tests has been shown in Figure 6.

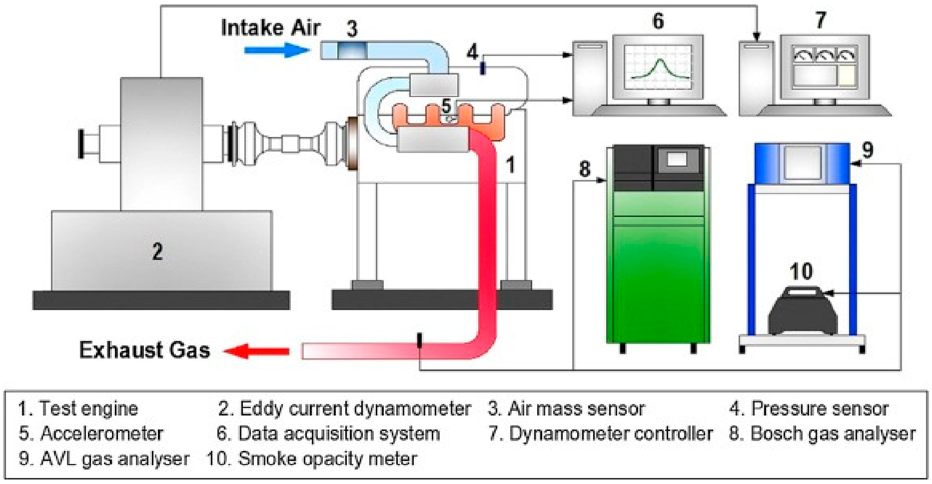

Figure 6. Engine multi-stage injection.

It is observed that split injection can prove to be the recommended method in diesel engines as far as Nox reduction is concerned. However, the use of split injection in biodiesel does not follow the trend of that of the diesel engine. In fact, the use of split injection for biodiesel has worsened Nox formation [132]. Thus, it can be inferred that there are some other strategies that need to be implemented, such as EGR and triple-stage injection [107,131,133–136]. Triple-stage injection in particular has proved to be more effective in controlling Nox as well as other emissions simultaneously [135]. This should prompt researchers to try even for four-or-more-stage injection. Similarly, other strategies, such as water injection, steam injection, etc., could be an interesting choice to be tested.

3.3. Solenoid Injector

Today, every modern engine is managed by an electronic control unit (ECU) module. Therefore, a lot of research is being spent on implementing the ECU-based fuel supply to increase the performance of an engine with reduced emissions. This has also increased the complexity of the engine design and its cost. In order to develop an efficient engine with lesser emissions, a very sophisticated fuel injection process is required [11,137–139]. The performance, combustion noise and emissions of an engine depend mainly on the accuracy at which the quantity of fuel is supplied at an elevated injection pressure [140–145]. Solenoid-driven injectors are widely used in the common rail direct injection (CRDI) engines for a desired fuel injection process. The solenoid technology is reliable and cost effective [146–148]. The effect of diesel and biodiesel on the hydraulic behavior of a solenoid-operated common rail injection system was studied by a one-dimensional model. The study was carried out by characterizing the different injector components. Both single and multiple injection strategies were analyzed for diesel and rapeseed biodiesel fuels. Finally, the authors proposed a modification in the geometry of the injector for the biodiesel-fueled engine to get the performance of the biodiesel engine on par with that of the standard diesel engine. The authors tested the engine with the modified configuration by using biodiesel as a fuel. It was concluded that the modified injector with high injection pressure showed similar results to the one obtained by the standard diesel-fueled engine. Furthermore, the main plus post-injection strategies also gave similar results when they were compared with diesel fuel [149]. A combination of experimental and computational methods has been carried out by Payri et al. [150] to evaluate the influence of rape methyl ester (RME) biodiesel physical properties on the injection process on the CRDI engine at different injection strategies, including main injection and main plus post injection. They found some important differences in the diesel and biodiesel, especially at low injection pressure. However, they proposed modifications in the hardware to rectify the differences [150].

3.4. Piston Bowl

The angular momentum of air developed inside the intake manifold decays during the suction and end of compression stroke due to friction at the walls and turbulent dissipation within the fluid. However, swirl in the cylinder can be maintained and improved further by designing the combustion chamber suitably, such as a compact bowl-in-piston combustion chamber [151,152]. This swirl increases the heat transfer, evaporation, mixing and combustion rates. The shape of combustion chamber plays an important role in generating the swirl and maximum turbulence leading to desired rapid combustion [152–155]. The combined effect of different engine variables and geometries of the piston bowl was studied recently. First of all, the engine variables, such as injection opening pressure, injection timing, nozzle holes and compression ratio, were optimized to 230 bar, 26 degree before top dead center (BTDC), 18 and five holes, respectively. The performance tests were conducted on diesel engine by using B20 dairy scum biodiesel–diesel blend for different types of combustion chamber geometries at optimum engine operating conditions. It was found that Re-entrant Toroidal Piston Bowl Geometry (RTPBG) resulted in improved performance, combustion and reduced emission characteristics compared to other types of piston bowl geometries [156]. Figure 7 shows the summery of modifications done in fuel injection system.

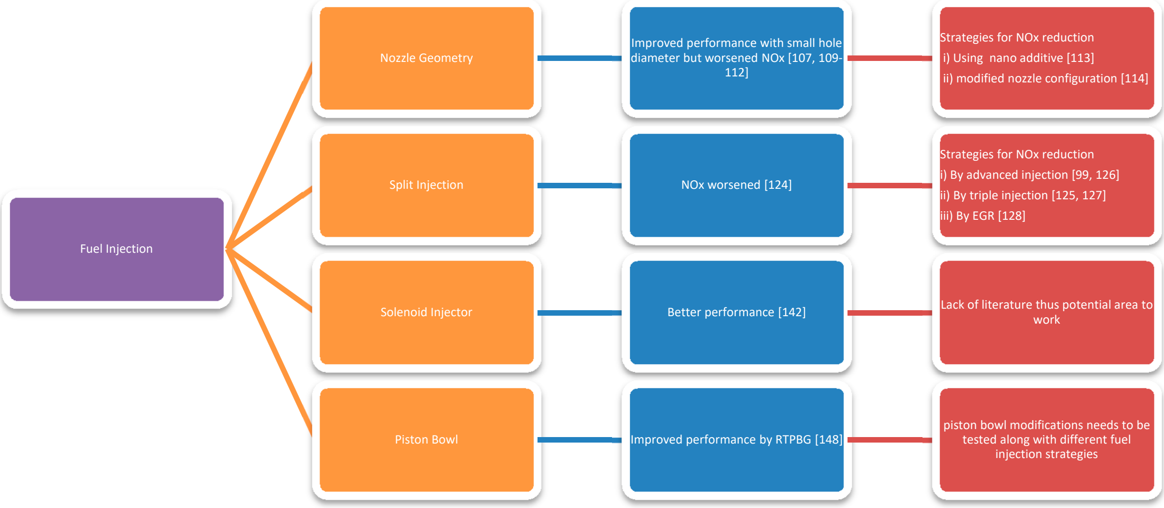

Figure 7. Schematic diagram of fuel injection modifications.

4. Exhaust Manifold

At the end of power stroke when the exhaust valve opens the cylinder pressure is much higher than that of exhaust manifold pressure. So, the burnt gases flow out of the cylinder through the exhaust valve into the exhaust manifold until the cylinder pressure and exhaust manifold pressure are same. The exhaust system typically consists of an exhaust manifold, exhaust pipe, often a catalytic converter for emission control [11].

Exhaust Gas Recycle (EGR)

The exhaust gas recycle (EGR) is a technique to minimize the formation of NOx in IC engines [157–160]. A fraction of the exhaust gases is recycled through a control valve from the exhaust to the engine intake manifold, which reduces the cylinder temperature and hence the quantity of Nox being formed is reduced [161–165]. It is an established fact that biodiesel engines produce more Nox, hence many researchers have studied the effect of EGR in reducing the Nox formation. The effect of EGR on the diesel engine was studied using palm biodiesel. It was found that the Nox formation reduced significantly due to lower cylinder temperature, but fuel consumption and other emissions increased [166]. The higher rate of EGR is necessary for low temperature combustion for biodiesel engines [167]. The tests in a single cylinder, direct injection, four-stroke diesel engine using soybean biodiesel–diesel blend B20 at different loading conditions and constant speed with various EGR rates showed a reduction of 55% and 15% in the formation of Nox and smoke, respectively, at a high engine load. However, the specific fuel consumption increased and thermal efficiency reduced [168]. The higher premixed combustion phase was attributed for an increase in the higher NOx concentrations when cottonseed B20 biodiesel was used as fuel in a single-cylinder diesel engine with a power rating of 3 kW and at a constant speed of 1500 rpm. However, utilizing a small quantity of EGR could reduce the NOx concentrations. A higher quantity of EGR could reduce the engine efficiency and increase the fuel consumption [169]. Similar type of results and trends were obtained with respect to NOx and performance when EGR was used for dual fuel engines as well [170,171]. Some researchers have obtained the desired low NOx emissions without compromising on the performance by implementing different techniques [172,173]. Experiments were conducted by using the blend of Calophyllum Inophyllum biodiesel, TiO2 nano additives and EGR. A dosage of 40 ppm nano particles were dispersed into B20 biodiesel–diesel blend (B2040TiO_2). Different tests on diesel engine were conducted by using different combinations of biodiesel, nano additives and EGR, such as B20, B2040TiO_2, B20 + 20%EGR, B2040TiO_2 + 20% EGR at different engine loading conditions. The brake thermal efficiency of the engine increased by 3.1% when biodiesel–diesel-nano additives blend was used as fuel. When the combination of biodiesel–diesel-nano additives blend and EGR was used, the thermal efficiency was found to increase by 2.5%. However, when only the biodiesel–diesel–EGR combination was used, the thermal efficiency decreased by 1.8%. The overall performance of the engine with reduced emissions was found when the EGR was coupled to the engine and the blend of Calophyllum Inophyllum biodiesel–diesel–nano additives was used as the fuel [172]. Selective Catalytic Reduction (SCR) technique is a lean NOX after-treatment technology [174]. It has been used to reduce the NOx formation in biodiesel engines. The engine was run at a constant speed of 1500 rpm, 20° BTDC of injection timing and an injection opening pressure of 250 bar by using Mahua biodiesel and its blend. Figure 8 shows the typical SCR used in a single-cylinder diesel engine.

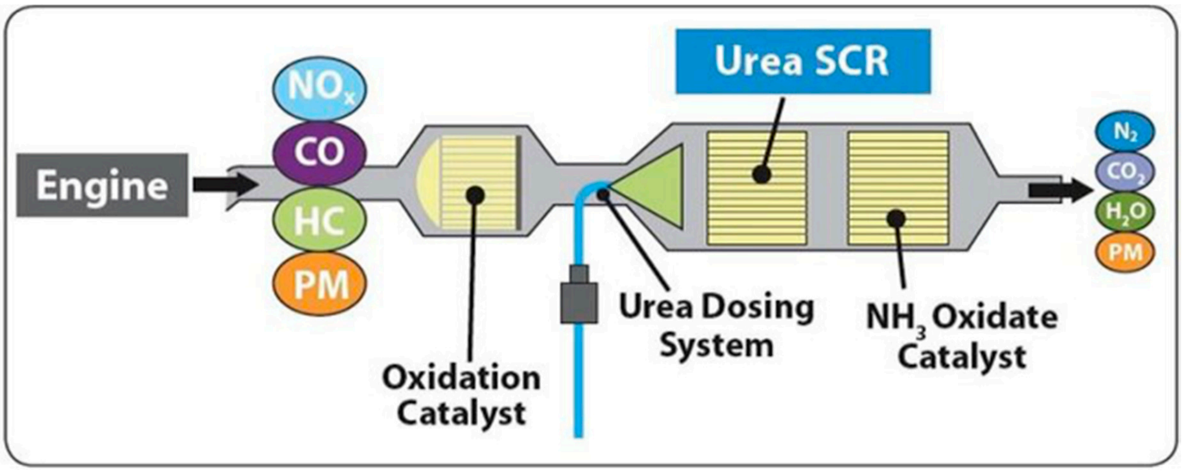

Figure 8. Schematic diagram of Selective Catalytic Reduction (SCR) geometry.

The results obtained show that SCR gives a substantial reduction in oxides of nitrogen in combination with cold and hot exhaust gas recirculation [173]. The EGR is one of the techniques to curtail the formation of NOx, which is successfully implemented. However, the adoption of EGR alone has a negative impact on the engine performance, leading to reduced thermal efficiency and higher specific fuel consumption. The negative impact of EGR in terms of reduced thermal efficiency and specific fuel consumption can be overcome by using nano additives in biodiesel–diesel blend or Selective Catalytic Reduction (SCR) in the exhaust manifold. Figure 9 represents the modifications carried out in exhaust manifold.

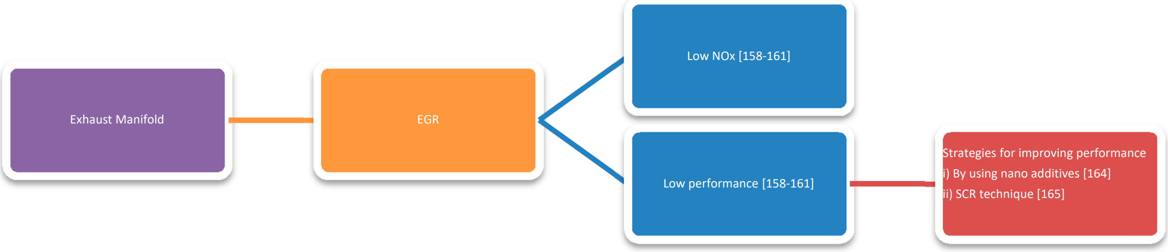

Figure 9. Schematic diagram of Exhaust manifold modifications.

5. Conclusions

The continuous demand of human comfort has put lot of pressure on the transportation sector. However, the decreasing and environmental issues have compelled scientists and researchers to look for new designs of IC engines to boost its performance by using not only fossil fuels but other alternate fuels, such as biodiesel. It should be comprehensively understood that the IC engine will remain the backbone of the transportation sector at least for a few decades to follow. Thus, any improvement in the IC engine design to enhance its efficiency and reduce the emissions would be very much desirable as well as appreciable. The current article gives an updated review of such attempts to improve the performance of the IC engine fueled by biodiesel. The following conclusions can be drawn from this article.

- Modifications in the intake manifold lead to a higher concentration of NOx but it can be minimized by using different techniques, such as water injection, steam injection, bioethanol addition, antioxidants in fuel and EGR.
- Split injection and small-hole diameter nozzle geometry give better performance with increased NOx but implementing triple injection, using an RTPBG combustion chamber, reduces NOx.
- A low rate of EGR minimizes the formation of NOx without affecting performance.

Funding: This work was funded by King Khalid University under the grant number R.G.P. 2/107/41.

Acknowledgments: The author extend his appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through research groups program under grant number (R.G.P 2/107/41).

Conflicts of Interest: The author declares no conflict of interest.

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