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Review Article

Effect of modifying bowl geometry for IC engine fueled with diesel and Biofuels - Review

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ABSTRACT

Bio-fuels are one of the most prominent, emerging, and promising fuels, which are aimed to replace diesel in the next decade. Though bio-fuels may not give the same performance as conventional diesel due to certain issues related to both technical and economic aspects, this fact leads to the need for alterations that are supposed to incorporate either changes in the shape of the combustion chamber or other critical factors that affect the performance of the engine. The shape of the top surface, which is known as the "bowl," in the piston plays a major role, and any slight modification in that shape leads to amplified effects on various combustion, emission, and performance parameters. This article shows the valid reason for accepting bio-fuels as fuel for CI engines by considering outcomes derived from experiments and numerical analysis with changes in the shape of the piston bowl. The results obtained are based on the attainment of various parameters, which leads to higher turbulence velocity distribution, better mixture fraction values, and lower soot formation distribution that can be obtained by modifying the shape of bowl. The pressure, temperature and heat release in the combustion chamber found to be changed due to the modification in bowl geometry.

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INTRODUCTION

The demand for energy and fuel due to rapid growth in the human population worldwide leads to a hike in the prices of petroleum. This increase in need also leads to a reduction in the stock of fossil fuels as reserves of fossil fuel are limited and maybe it lasts for a few decades [1]. In the majority of the commercial sector, transportation is a key factor. The transportation sector consumes the second largest amount of energy which is considered a key factor for projections of energy demand [2]. A diesel engine (CI) finds wide usage because of its higher effectiveness and reliability than gasoline engines in the transportation sector. High demand and dependability on diesel as a fuel have put challenges in front of researchers worldwide for finding out alternative fuels with or without making a change in available CI engines. It is desired that novel fuels fulfill the performance parameters and match emission standards. Biofuel is one of that due to local availability, renewability, biodegradability, high flashpoint, high cetane number, low cost and low sulfur value of extracted oil makes it a

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suitable option as a fuel[3–7]. Biofuel is widely accepted as an alternative to crude due to its salient features like ease in availability, higher index for lubricity, and lower values for emissions [8].

Siva Lakshmi *et al.* [9] observed a reduction in the value of carbon monoxide (CO), hydrocarbon (HC), and smoke emissions. Oxidation of excess HC creates high local temperature which generates thermal NOx [10–12]. They further worked on blended mahua oil for performance and emission analysis and derived that the rise in mixing ratio results in lower HC and CO emissions measurements, brake specific fuel consumption (BSFC), and NOx emission found higher side. They also tested jatropha oil methyl ester and reported improvement in fuel consumption and emissions besides that soot emission was found reduced.

Aiming for improvement in fuel consumption and to achieve emission standards there have been some techniques applied like improvisation in fuel quality by little modifications in properties, a small alteration in engine design, and treatments on the exhaust.

The objective of modifying fuel properties is aimed at quality mixing formation and enhancing combustion phenomena without any alteration in engine design. Improvement by the usage of different additives like antioxidants (L-Ascorbic) and oxygenated additives was used with biodiesel and resulted in decreased value for emissions. G Balaji *et al.* [13] used metal-based additives like magnesium-based fuel additives on CI engine outcomes. Monoxide emission and smoke were found to decrease by around 57% and by 35%, respectively.

The objective of modifying or redesigning work on the engine is meant to enhance turbulence kinetic energy and which in turn leads to the engine performance along with matching emission standards. Modification in the engine includes various parameters like bowl shape, injection pressure, injection timing, and ignition delay [14–16].

Biofuel Production, its Properties, and Comparison of Biofuel with Conventional Fossil Fuel Based on the Economy

Biodiesel production

Through chemical reactions and processes, oil is extracted from animal fat and vegetable oils to serve as biodiesel. The feedstocks for extracting oil can be classified in four ways[17]. Transesterification, pyrolysis, direct usage and blending of oils, and micro emulsification are some of the widely adopted techniques for producing yield for biodiesel from various feedstocks [18].

Transesterification

This process happens in presence of alcohol, also known as fatty acid alkyl esters (FAAE), which is an accurate method for the extraction of biodiesel. A reaction occurs in the presence of a catalyst like sodium or potassium hydroxide, between the oil containing triglyceride and methanol or ethanol. Glycerol is the end product of this process [19]. Catalysts were added to speed up the reaction. Other factors that influence the transesterification process include catalyst concentration, the intensity of the mixing process, reaction temperature, reaction time, and feedstock type [20].

Pyrolysis

Pyrolysis [21] is the process of heating in the absence of oxygen with or without a catalyst to convert one material into another. Comparatively the process is simple, pollution-free, and effective. Biodegradable yield can all be pyrolyzed [22,23].

A blending of oils

Biodiesel is not recommended for direct usage because it will result in coked injectors, high deposition of carbon, stuck oil ring, and lubricant thickening after a lengthy period of operation. In a compression ignition (CI) engine, however, blending extracted oils with diesel fuel can overcome the problem of thickening. Furthermore, preheating vegetable oils improves atomization and mixing whereas reduces viscosity, and results in better combustion [24].

Micro-emulsion

A microemulsion is a fluid microstructure having molecular dimensions ranging from 1 to 150 nm. It is made of two normally immiscible liquids and one or more than one ionic or non-ionic substances. It is structured as any of an oil phase, an aqueous phase, and a surfactant or mixture of these three phases [25].

Characteristics of Biofuel

Viscosity index, cetane number, heating value, flash point, and pour point are usually those properties that are taken into consideration while testing performance. Some researchers have indicated in the literature that the scale of fatty acids and chemical compounds of biodiesel have a measurable impact on the qualities of biofuel [26]. As a result, biodiesel must meet international standards like ASTM D6751 or EN 14214, which are the most often used specifications for biodiesel used as a CI engine fuel [27].

When the fuel has come across the proximity of flame or a spark as biodiesel's flash point is greater than that of fossil fuel, it is safe to transport, handle, and store. Several factors influence the flash point of a substance, like OH concentration, type of bond, and quantity of carbon atoms [28].

Another key metric that affects combustion quality is the cetane index. The greater the cetane value, the shorter the ignition delays, and hence the longer the duration of combustion. Biodiesel has a greater cetane number than petrol-diesel [29].

The viscosity index of extracted oil is the most critical metric to assess because it has a direct impact on the engine's injection system. Higher viscosity index forms big droplet sizes, improper vaporization, oil dilution, and narrow-angle of spray pattern in fuel atomization [30,31] thus resulting in poor fuel atomization, imperfect combustion, and increased pollutants [32].

The calorific value of a fuel reveals how much energy it contains. Because of higher oxygen concentration, biofuel has a low mass energy value. According to Jain *et al.* [25], the net shaft power and torque of a biodiesel-fuelled engine are low compared to those of a petroleum-fuelled engine due to increased density and lower heating value. Bio-oil yielded possesses good lubricity along with negligible sulfur compound. Hence, the wear of components is reduced [33]. Furthermore, the average fatty acid profile has a considerable impact on biodiesel's physical/chemical properties [34–36].

Economic Analysis of Biofuel in Comparison with Petroleum

Having a less negative effect on the environment and having better economic value studied by many researchers› biofuel is recommended as an alternative fuel in some countries. Still, one must check economic feasibility as it is one of the important concerns in long run. Economic analysis should be carried out while using biofuel as it is derived by different manufacturing techniques and from different feedstocks.

Rapid advances in biofuel production will have a direct impact on hikes in food-crops prices globally, posing a threat to food storage and security, particularly in countries comes either in poverty or are developing [37]. Feedstock costs climbed considerably after the year 2000, particularly for rapeseed and soybean oil, and peaked in 2008. Due to the drop in the price of crude oil, all feedstock prices have dropped since 2009. Increases in oil prices have an impact on feedstock prices due to transportation, farming, and food distribution expenses; in addition, fertilizer prices have a direct impact on prices. The price of feedstock is seen as having a significant impact on biofuel output and cost. Many countries have established subsidies to cut biofuel prices to prove it is competitive with crude oil [38,39]. Some studies looked from an economic standpoint and evaluate biofuel for promotion in light of the policy's numerous goals, life-cycle implications, and unexpected effects [39,40].

Many economic issues are related to biofuel production, as indicated in [41]. The cost, which accounts for 80% of the overall cost, is considered the most important economic aspect. Le LT *et al.* [42] conducted a detailed case study of Vietnam to assess economic and social issues related to biofuel.

Comparisons on cost-effectiveness between biomass-based fuel and crude-based fuels still require more research to reach a definite conclusion, as certain studies reveal that biodiesel stability is influenced by a variety of circumstances. Biodiesel is light and temperature sensitive [43], prone to oxidation processes [32,44], naturally hygroscopic [45], and more caustic than diesel [46]. It is supposed to degrade owing to compositional changes. The storage stability of biodiesel is affected when comes to air [47,48].

Non-edible feedstocks are viable resources for producing biodiesel since they do not harm food sources and are diverse. These sources resulted in a 60–90% reduction in spending. It is having several advantages, including low pricing, daily quantities of up to millions of tonnes, and little environmental impact. Algae is a possible biodiesel resource since the oil concentration appears to be excellent and promising. Algae claimed to produce 5 Kilo gallons per acre, compared to 1 Kilo gallons per acre for other vegetable oils [49]. Thus, biodiesel is a possible fuel that can meet both energy and environmental demands.

Techniques for Using Biofuels to Improve Combustion and Emission Parameters

Although biofuel has emerged as an alternative fuel for diesel, the generation of NOx, low efficiency at the shaft, and high consumption of fuel remain key concerns in unmodified diesel engines. As a result, the focus is on improving the efficiency of diesel engines by changing engine parts for running engines with biodiesel–diesel mixtures. The fluid flow field at the intake manifold entry and end, fuel fluid dynamics at the fuel injection system, combustion process and behavior, heat transfer properties, and process, etc., are the main key factors which are needed to be looked after.

As combustion is a complex phenomenon and its control are even very complex and complicated with many variables. So, an effort is made to concentrate on a few key factors for improvement some of which are listed below.

Pre-combustion Techniques

Mixing additives

Chemicals that are blended with fuels for betterment in efficiency value and fuel economy are known as fuel additives. The selection of additives compound is tested based on blending property, feasibility based on an economic scale, solubility based on ease, toxicity value, viscosity index, flash-point, and solubility index of water in the blend. All of these factors play an effective role in the additive selection process. Varieties of additives for a biofuel-run engine are used by the researcher in their research work such as metal-based additives, oxygenated additives [50], antioxidants [51], and cetane number improvers [52].

Recirculating exhaust gas for improvement in emission (EGR)

This is a NOx emission reduction method that is now employed with both diesel and biodiesel [53–56]. EGR is one of the promising NOx control methods, according to many researchers [55,57,58]. EGR works by redirecting a portion of the engine's exhaust smoke back to combustion. The in-cylinder peak temperature is thus minimized by dilution of the oxygen in the intake air stream by providing gases that are inert to combustion to act as heat absorbents. As a result, NOx generation can be dramatically decreased [58]. EGR works on mechanisms of dilution and chemical action which led to raised dissociation during the reaction [57]. As exhaust tailpipe back pressure is often having a high value compared with the intake pressure in normal suction engines, exhaust smoke enters the cylinder. The flow path which is usually in between the exhaust and intake manifolds is controlled by a throttling valve. The action is known as hot EGR when exhaust smoke is redirected to the intake manifold. The gas leaving from EGR is cooled by a heat exchanger in modern diesel engines to permit the admission of a larger recirculated gas mass; this action is known as cooled EGR. By increasing the EGR rate, NOx emissions are reduced [59,60]. Although employing EGR in a CI engine to reduce NOx emissions is an effective technology, there are certain drawbacks, such as a rise in smoke density, HC proportion, CO proportion, fuel consumption, and reduced efficiency at the shaft unless properly tuned [61].

Injecting Water for emission control (NOx)

The presence of water through injecting it in the combustion chamber leads to absorbing the heat of evaporation and thus reduces the local adiabatic flame temperature [62] because of which NOx emission considerably reduces. Injecting water at the entrance upstream of the inlet is known as fumigation. Although this technique has reduced NOx, it has a few demerits, such as considerably increasing other emissions and BSFC. Tauzia *et al.* [62] tested water injection on an automotive direct injection diesel engine to see how it affected ignition delay, heat release rate, and pollutants. The authors discovered that a larger water flow rate results in a longer ignition delay. It is advisable to combine water injection technology with other technologies.

Emulsification (oil, water)

The primary goal of the emulsification technique either through oil or through water is meant to improvise combustion efficiency while lowering NOx and other pollutants emissions. A blend of two immiscible fluids is known as an emulsion. Oil-phased emulsion, for example, aids in the uniform distribution of water droplets in the dispersed phase throughout the continuous phase of the fuel oil. The features of an emulsion are similar to those of the continuous phase. As a result, oil-phased emulsions have characteristics that are similar to those of fuel oil rather than water. Surface active agents, often known as «surfactants,» are used in the manufacturing of oil-phased emulsions to keep the emulsion›s composition. These surfactant compounds enclose the water droplets scattered throughout the continuous oil phase in an oil-phased emulsion, preventing them from coming together and coalescing. Water in the biodiesel emulsion affects the heating value of the fuel by increasing its kinematic viscosity. In comparison to B100 and diesel fuels, biodiesel emulsions also reduce PM soot fractions. Additionally, the dissociation of water can produce OH radicals, which can reduce NOx and PM emissions even more [63].

Modification in injection timing and injection pressure

Injection at exact timing has a major impact on engine performance and pollutants [64]. Because of the delayed injection time, the combustion process is slowed. The concentration level of thermal NOx is mostly determined by the combustion peak temperature; when the peak temperature remains low, the NOx level will be reduced [65]. However, employing ITR has some drawbacks, including higher HC emissions, higher smoke emissions, higher fuel consumption, lower BTE, and lower power[62]. Many studies [55,64] have found that delaying injection timing has an impact on both exhaust emissions and engine performance. Because of the lesser calorific value, this strategy hindered engine performance. The shorter ignition delays lowered NOx emissions because of the low burning rate and gradually boosted combustion temperature.

In diesel engines, the injection pressure has a measurable impact on pollution control and performance. Because of the enhanced atomization, raising the value of injection pressure produces an early beginning of combustion, resulting in desirable air-fuel mixing.

Modification in compression ratio on engine characteristics

Change or modification in compression ratio is a critical parameter that needs to be studied. Compression ratio plays a vital role in designing any internal combustion engine. Nowadays there is variable compression ratio design available in the field given the importance of this factor only on the performance of an engine. Several researchers have conducted their studies to determine the impact of compression ratio ranges from 16-20 on the performance and emissions of CI engines. Muralidharan and Vasudevan [66] worked to know the effect of CR on VCR engines fuelled by waste cooking oil and its blends with diesel. At CR 21, the experiment showed that the B40 blend performed better than regular diesel. EL Kassaby and Nemit Allah [67] observed an increase in BTE as CR increased for waste cooking oil blended with diesel. The change in CR between 14-18 resulted in an Approximately 30% increase in BTE for the B20 blend. Sayin and Gumus [68] investigated with CRs 17-19 on diesel engines and concluded the better performance with biofuel and its blend with diesel. According to the study, brake-specific energy consumption improved with an increase in CR. Comparing it to the original CR of 18, CO and HC emissions were shown to decrease as CR increased. For diesel engines driven with a used fried oil blended with methyl ester, Hirkude and Padalkar [69] discovered that as the CR increases, the specific fuel consumption decreases, and the rise in exhaust gas temperature (EGT) is noted. Sharma and Murugan [70] used a mixture of 4/5 proportion of biodiesel and 1/5 proportion of oil extracted from waste tires to investigate the impact of altering the CR. The highest BTE resulted be roughly 7-8% greater at CR of 18.5, compared to the initial CR of 17.5 for palm oil-based biodiesel and emulsified palm oil-based biodiesel in a study carried out by Debnath *et al.* [71]. The BTE for palm oil-based biodiesel-driven diesel engines improved by 7-8 % for CR between 16-18. Bora *et al.* [72] found an effect of CR on the output of a raw biogas-fuelled hybrid diesel engine. They found that increasing CR from 16 to 18 at 100 percent load reduced BSEC by 19.38 percent.

Modification by Combining two or More Techniques at a Time

Applying a combination of two or more technologies may give better combustion efficiency with improved outcomes and noticeably reduced output in terms of emission for biodiesel-fuelled CI diesel engines. These kinds of experiments for combining two techniques have been applied like emulsion process & EGR, additives & EGR [73–75], and EGR & ITR [55,76]. Saravanan *et al.* [77] experimented to see how a combination of 10-12 % EGR and 210–240 bar injection pressure influences diesel engines fuelled by rice bran-based biofuel and found improved outcomes.

Modification in Piston-bowl Geometry or Combustion Chamber Geometry

Not only injection parameters and/or other variables but piston bowl shape could also have an impact on engine outcomes. When compared to an open-piston bowl form, computational fluid dynamics (CFD) simulations show improved flow field characteristics during a compression stroke [78]. As a result, the piston bowl shape has a significant impact on swirl, squish, and turbulence in diesel engines [79]. When compared to lip-shaped combustion chambers, bottom-cornered combustion chambers have been shown to have an improvement in thermal efficiency and acceptable outcomes for NOx, CO, and soot emissions [80].

OBJECTIVES

Many works of literature show that the geometry and shape of clearance volume has a significant correlation with CI engine outcomes. Due to local flow field changes, the CC geometry ensures adequate air-fuel mixing [81]. The aim of the present study is meant to examine the different geometries utilized for biofuel compatibility and their impact on CI engine performance characteristics.

Parameters Influencing Combustion Chamber Design

The combustion chamber design, more than any other component of the engine, influences emissions, performance, and knocking features. The type of material used for the cylinder wall, the placement of valves, and the volume of air in various components of the chamber such as the bowl, clearance, valve seat gap, and so on, all play a role in the design of the chamber.

Piston head shape

The primary function of the piston head is to generate momentum for turbulence, which leads to perfect combustion. Its shape varies depending on the engine; for example, a flat head is used in low-cost engines, while a raised dome, such as a wedge, domed, or recessed head, is used to boost the combustion chamber›s compression ratio [82].

Nozzle dimensions

To optimize CI engine emissions and performance, the fuel injector nozzle is critical. It has essential design parameters such as hole arrangement, quantity, and size. Higher moments and better mixing conditions were induced by the nozzle [83].

Air turbulence

Like CC geometry, which improves whirling and squish action within the CC, air turbulence also improves the mixing of air-fuel and plays a critical role in the combustion phenomenon in internal combustion [81]. The movement of air allows for greater atomization, dispersion, and mixing of fuel, resulting in less afterburning and a shorter delay period, as well as better air utilization in the cylinder [84].

Heat transfer loss through a wall

Losses in the form of heat imply a reduction in the engine›s available energy, which has a direct impact on volumetric efficiency and starting issues, particularly in cold conditions in diesel engines. The pressure and temperature in the chamber reduce as an outcome of the higher rate of heat transfer from the combustion chamber wall [82,83].

Geometry/ Shape of Chamber

Bowl geometry has a measurable effect on performance and emission metrics. Many academics have been working on combustion chamber geometry designs using diverse fuels as an intake for a long duration [85]. As a result, the combustion chamber shape is classified as a single curve or double curve [86]. It is also determined that a geometry that performs well may be proven to be ineffective for another geometry [84].

DIFFERENT SHAPES/TYPES OF COMBUSTION CHAMBER/PISTON BOWL GEOMETRY

Direct Injection Combustion Chamber

The high swirl design and the low swirl design are two different design ideas for direct injection combustion chambers. In the first scenario, the injector has fewer holes and a deep bowl, but in the second situation, the injector has more holes and a skin-deep bowl. The following are a few of the most frequent geometries [84]:

Omega shape chamber

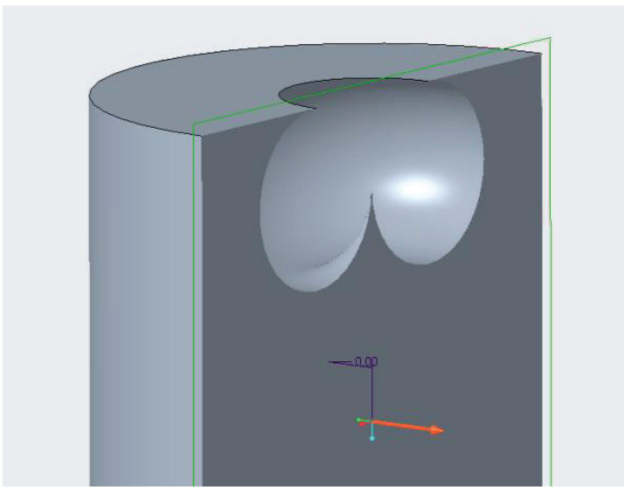

Figure 1. Omega shape chamber.

Figure 1 shows the geometry of the omega shape cylinder (OCC) that is found to be more practical for attaining solid squeeze in a short amount of time [87]. At medium to high engine speeds, the OCC's results were shown to be superior to those of a hemispherical combustion cylinder (HCC) or a shallow-profundity combustion cylinder (SCC). The effect of swirl power and turbulent force on engine behavior has revealed that using a bowl with very violent dynamics increases the capacity for effective fuel contact while reducing whirl movement [84].

Square combustion chamber (SqCC)

Figure 2 shows a square cavity chamber. With this geometry, powerful squish motion can be achieved especially at the corner region of the square chamber which creates forces for swirling during the compression into the bowl which creates a turbulent environment [82].

Hemi-spherical combustion chamber [HCC]

Figure 3 shows a conventional or basic design for diesel operated engine. The depth-to-diameter ratio in this combustion chamber allows adjustment to produce effective squish for improved outcomes. When operating with biodiesel as a fuel, however, it is ineffective. Because biodiesel has a more viscosity index than diesel, it cannot be atomized or burned properly in such geometry [82,84].

Shallow depth re-entrant combustion chamber [SCC]

The cavity depth in SCC is kept modest. Furthermore, because the cavity diameter is big, the squish and swirl actions are minimal. However, it atomizes biodiesel more

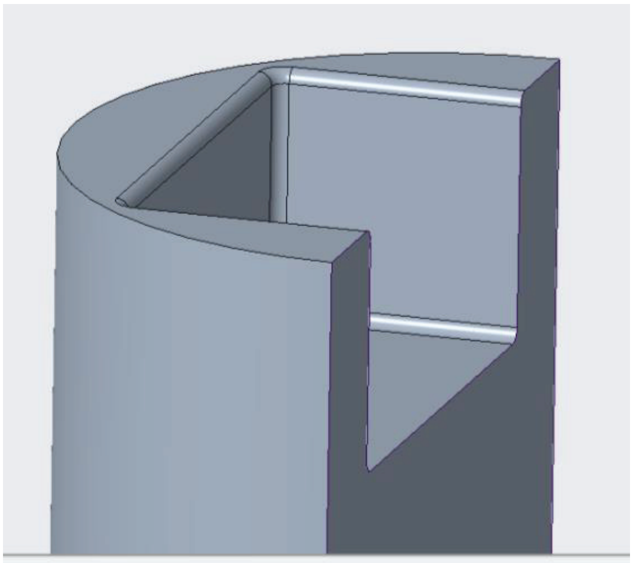

Figure 2. Square cavity chamber.

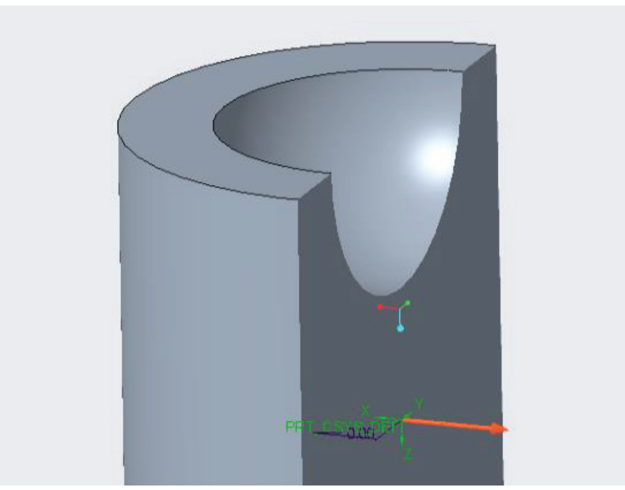

Figure 3. Hemispherical chamber.

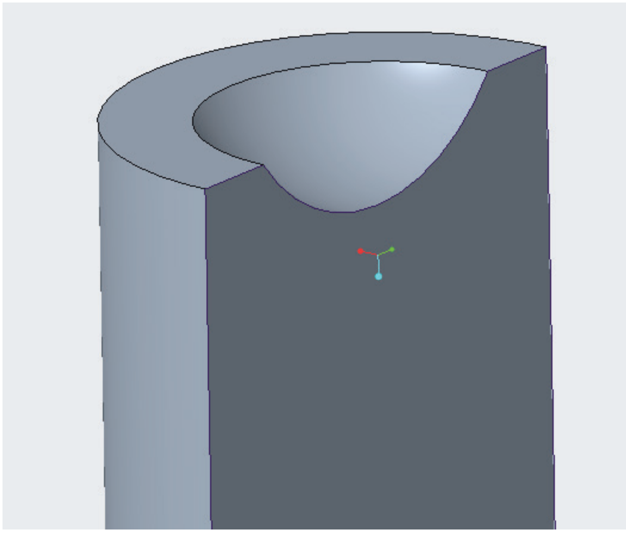

Figure 4. Shallow depth chamber.

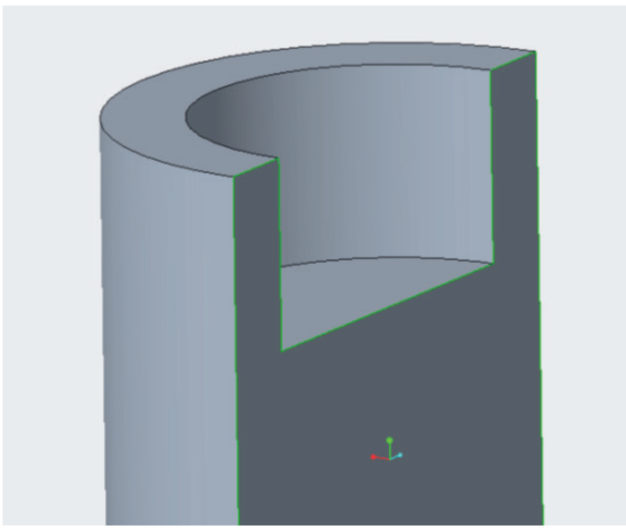

Figure 5. Cylindrical chamber.

effectively than HCC. At low speeds, this is mostly used in huge engines [82].

Cylindrical combustion chamber (CCC)

Figure 5 shows a cylindrical shape which is derived and hence a variant of a conical chamber. Here 180° turn of the complete circumference is used to create the swirl. The depth of squish can be altered [82].

Toroidal (re-entrant) combustion chamber [TCC]

Figure 6 shows a toroidal shape cavity whereas figure 7 shows a toroidal re-entrant shape cavity. The re-entrant cavity is nothing but a small modification in the basic toroidal shape [88]. Because TCC has a better squish motion than other geometries, the proper current of air in the CC results in proper combustion. The cone angle of TCC varies between 145 and 165 degrees [83,84].

Wave-shaped combustion chamber

A wave-shaped piston as shown in figure 8 has recently been demonstrated to increase late-cycle air mixing during diffusion combustion by efficiently diverting the near-wall jet flow back toward the chamber center. Increased turbulence in the reaction layer increases charge mixing and promotes faster and more complete combustion giving higher thermal efficiency and lower soot emissions [83].

Trapezoidal combustion chamber

Figure 9 shows a trapezoidal shape cavity that gives good air-fuel mixing comparatively and is thus used in some of the research for comparison with other geometries [84].

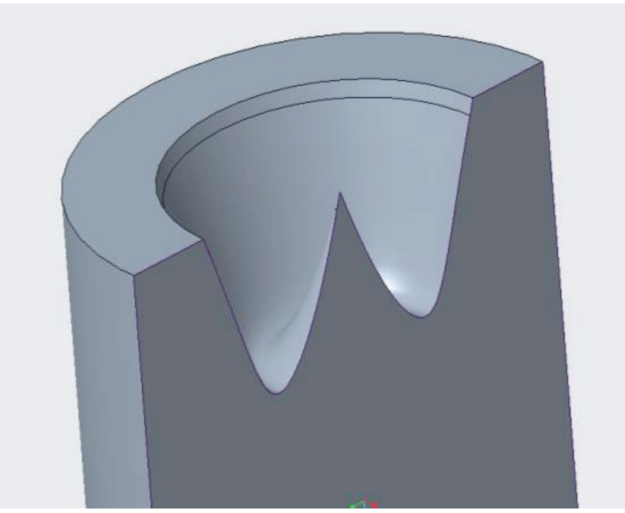

Figure 6. Toroidal chamber.

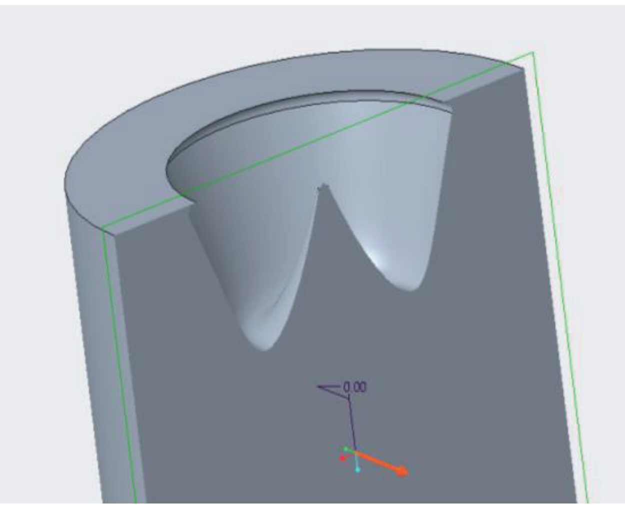

Figure 7. Toroidal re-entrant chamber.

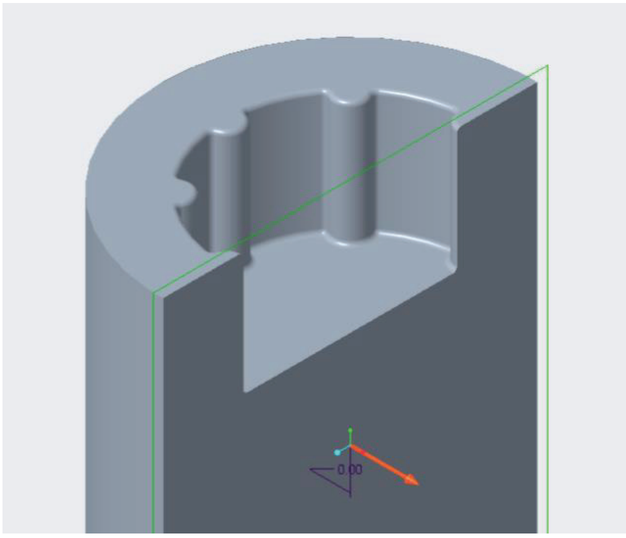

Figure 8. Wave-shaped chamber.

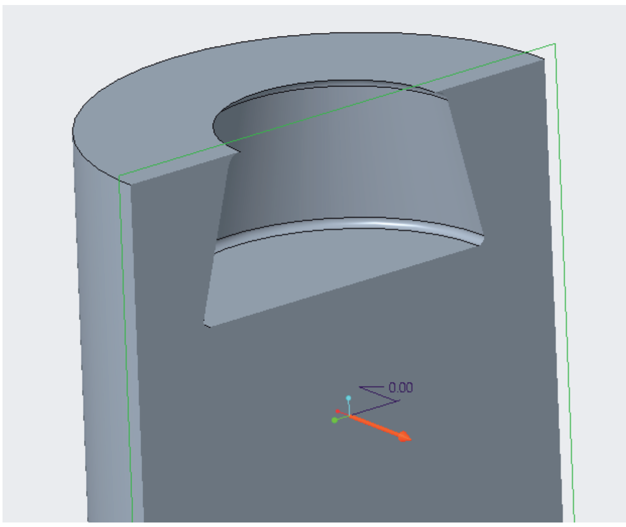

Figure 9. Trapezoidal chamber.

Other Modified piston bowl geometries

Novel swirling grooves have been provided and experimented with in the piston top face to inhibit the swirling motion. Dished piston, Dome piston, Mexican Hat design, and Trunk piston design are many other designs that have been tried for getting good results in some of the cases.

Indirect Injection Combustion Chamber

There are two parts to the indirect injection type of combustion chamber. The cylinder head contains one part, while the main cylinder contains the other. The cylinder head is injected with fuel. It produces the pressure difference during the combustion process [89].

Swirl combustion chamber

Swirl combustion chambers are typically seen in tiny CI engines with cylinder diameters around 80-100 mm or less. More heat losses are found in this type of geometry [90].

Pre-combustion chamber

The main chamber is connected by several holes to other parts in this combustion chamber. Fuel is injected at a pressure below 450 bar through the pintle nozzle. The main chamber holds 35-45 % of the overall capacity, and it is here that combustion takes place. Air enters the main chamber first and then flows to the secondary chamber through a hole. This results in increased turbulence in the flow field and improves fuel combustion [91].

OUTCOMES OF MODIFIED CHAMBER GEOMETRY ON COMBUSTION CHARACTERISTICS

The effect of change in the geometries of a bowl on several CI engines (performance, and emission characteristics) is discussed in this section.

Combustion Parameters

Variations occurred in-cylinder pressure

A highly pressurized injection is a prerequisite for fine-tuned atomization of biodiesel because of its high capillarity value and viscousness of veg oil [92]. The DI diesel engine's combustion, performance, and exhaust parameters are influenced by injection pressure [83]. According to Jaichandar and Annamalai [93], an increase in BSFC for injection pressures beyond 220 bar reported due to inefficient combustion happened because of low penetration and lacking oxygen. Further, they evaluated both the Toroidal Re-entrant combustion chamber (TRCC) and hemispherical open combustion chamber (HCC) and compared results for both by varying injection pressures in the range of 185 to 230 bar using a 20% blend of Pongamia oil methyl ester (POME20). They have noted that TRCC gives improved performances when compared to HCC due to the quality of air mixing and high atomization. Puhan *et al.* [94] tested the effects of IPs 200-240 bar on CI engine parameters utilizing a conventional hemispherical chamber design for linseed oil methyl ester (LOME) as fuel. The BSFC was found dropped and BTE was found marginally improved at 240 bars. Evaporative heat coefficient, quality of air-fuel mixing, and effective atomization are all factors that affect fuel combustion in diesel engines [95]. Better results were obtained by raising the rate of evaporation, improvising the quality of the A-F mixture, and atomization. A high value of injection pressure improves atomization, combustion, and smoke emissions [96]. Mamilla et al. [84] investigated three different chamber geometries of CI engines fuelled with a Jatropha methyl ester blend. At all loads, all these chambers followed the same pattern for pressure variation as diesel. Cylinder pressure for B20 JTME measured lower than diesel for all geometry. With SCC geometry, the increase in peak at 20° aTDC for B20-B100 was reported at 2.0%-7.7%. Venkateswaran and Nagarajan [97] employed a CFD code (STAR-CD) to know in-cylinder pressure at different conditions. The experimental and computational in-cylinder pressures and crank angles were plotted and found to be identical. Park [98] optimized chamber geometry and operating conditions of a CI engine fuelled by dimethyl ether using a micro-genetic algorithm. Because of the increased pressure, the optimized engine has a higher cylinder pressure. Banapurmath *et al.* [99] noted the impact of three different chamber geometry on the performance engine fuelled by mahua and neem blends. They found that mahua biodiesel has a greater peak pressure in TCC than neem biodiesel. It also demonstrates that when cylinder pressure rises, combustion acceleration rises dramatically as the piston approaches the BDC and converts fuel energy to work. The influence of changed geometry on engine performance, combustion, and emission characteristics was investigated by Manikalithas *et al.* [100]. The pressure variation at various crank angles and 100% load was tested and observed that the modified bowl piston reported high in-cylinder pressure of around 57 bar compared to 50 bar for the existing bowl geometry. Prasad *et al.* [79] studied the effects on engine parameters for modification in the shape of the bowls from hemispherical. They observed high values for peak pressure with modification in a bowl shape.

Heat release rate

The heat release rate was found better in the modified chamber geometry compared to the traditional combustion chamber fuelled with biodiesel. Biodiesel has a lower heating value, higher viscousness, and capillary due to which the heat release rate of biodiesel is low [101–105]. Mamilla *et al.* [84] used a customized combustion chamber to evaluate JTME blends and found that the HRR of diesel for B10-B100 were 65.5-71.5 J/°CA with 60°-80° CA bTDC, they also found that HRR for B20 with TCC was 40.21 J/°CA, while SCC and RCC were 38 J/°CA and 36 J/°CA, respectively, with changed geometry. According to Lalvani *et al.* [106], at crank angles between 6°-10° bTDC and injection pressures between 180-230 bar the maximum values for HRR are observed between 68-85 J/°CA. With half load, Li *et al.* [107] examined the heat escape rate for engine speeds between 1200-3600 rpm and found peak HRR at (54 J/°CA) 12°CA aTDC for square geometry at 1200 rpm. With average load, HRR drops to 25 J/°CA from 54 J/°CA at 2400 rpm and 3600 rpm. According to Park *et al.* [98], the heat release factor in the pre-mixed event of combustion was found high for diesel engines than for dimethyl ether engines because the diesel engine started combustion earlier, resulting in proper mixing of air-fuel in the chamber. Banapurmath *et al.* [99] found that TCC has a greater HRR than CCC and TrCC geometry. Heat loss and depth of the piston bowl directly vary with each other, according to Rakopoulos *et al.* [108], with values of 0.7 J/°CA and 0.6 J/°CA for d/D around 64 percent, 0.80 J/°CA and 0.67 J/°CA for d/D around 54 percent, 0.8 J/°CA and 0.68 J/°CA for d/D around 44 percent found in CFD models. Manikalithas *et al.* [100] studied that due to the good quality of atomization and vaporization of diesel, as well as improved swirl and turbulence conditions. Better mixing gives complete combustion with modified geometry which in turn gives a higher HRR than the existing bowl piston.

Ignition delay

Ignition delay is a very crucial factor that influences the knocking tendency in diesel engines. The ignition latency is reduced when the cetane number increases. Experiments have demonstrated that as blending increases, atomization quality degrades, and the mean droplet width & break up time of sprayed fuel increases. Moreover, several types of research conducted on the delay period and behavior of the combustion process for biodiesel-fuelled engines, as well as other variable parameters like engine load, compression ratio, pressure& timing of the injection process, and so on. High cetane rating and low calorific value of biofuel produce shorter delays and lower HRR [109]. Mamilla *et al.* [84] experimented and noted a reduced delay period at full load for a different blend. They found a 1.9 %-9.2% reduction for B20-B100 fuel. Due to the greater cetane number, Lalvani *et al.* [106] found that the delay period of the conventional piston found more while comparing to the turbulence inducer piston. Furthermore, Banapurmath *et al.* [99] found shorter delay while increasing brake power for all geometries (TCC, HCC, CCC, and TrCC) because more quantity of fuel is burned, resulting in a rise in the wall temperature of the cylinder. Because of the higher combustion temperature and fuel-air mixing, TCC had a lower ID than other combustion chamber shapes. Because of the greater cetane number of biodiesel blends, Jaichandar and Annamalai [110] evaluated 20 percent POME in engines with different chamber geometries and found delay duration of 20 percent POME was much lower than in an engine fuelled with diesel. They also found that at all loads, the ID times for re-entrant CC were shorter than those for open-type combustion chambers.

Peak pressure

The peak pressure is rated from the rate of heat released and the heating capacity of the fuel in general. As biofuel possesses a low heating value to diesel, the peak pressure recorded with any chamber is lower than diesel for biofuel [111,112]. An increase in peak pressure value with increasing brake load was reported for different fuels, during a test conducted by Mamilla *et al.* [84], since more fuel is burned at a high load. They also noticed a reduction in peak pressure and temperature as the exhaust gas absorbs more heat due to its greater specific heat. Jaichandar and Annamalai [16] reported that the peak pressure of B20 in a conventional engine is lower than that of diesel because of incorrect mixing of B20, high viscosity index, and a low calorific value of B20 POME.

Performance Parameters

Brake-specific fuel consumption

The BSFC is the mass of gasoline utilized per brake power output also it noted that fuel viscosity, rise in density of fuel, and low heating value of biofuel have resulted in a rise in BSFC. Because biofuel owns a low heating value, more quantity of the charge should be pumped for combustion to get the specified power output [113]. Also, it is observed that when 20 percent mixes of palm oil biodiesel and pure biodiesel (B100) were used instead of diesel, BSFC increased by 3.3 percent and 16.7 percent, respectively. Many researchers have changed the combustion chamber design and found that while using biodiesel, the BSFC decreases. When comparing TCC to traditional HCC with 20% POME, Jaichandar and Annamalai [16] found that TCC has an almost 6% lower BSFC. Chandrashekhar *et al.* [114] worked on a mono-cylinder engine using a hemispherical and a modified multi-chambered geometry at various injection pressures. Due to improved turbulence because of squish in a modified combustion chamber, they observed optimal injection pressure (IP) of around 200 bar. Ravichandran *et al.* [115] studied the performance of an engine fuelled with Corn biodiesel and its blends for hemispherical cavity pistons and toroidal cavity pistons. They concluded that the toroidal cavity piston had a lower BSFC than the hemispherical cavity piston. They investigated the impact of a smaller nozzle tip hole on diesel engine fuel consumption and emissions. They used conventional, group, and multi-hole nozzles. They showed that the group hole nozzle outperforms the standard hole nozzle in terms of BSFC because the injected fuel split optimally resulted in good air usage. They discovered that when the orifice is narrower, the brake-specific fuel consumption is lower with a short delay and improved turbulence, which reduces the combustion duration, lowering heat consumption and increasing BTE.

Brake thermal efficiency

Power output per fuel injection energy is known as thermal efficiency. The thermal efficiency of biofuel is low for any shape of a combustion chamber to diesel [114]. Fuel spray characteristics, viscosity index, a quantity of air-fuel mixture, calorific value, and volatile behavior all contribute to a lower brake thermal efficiency (BTE) with biofuel blends [115]. A shorter ignition delay while using biofuel allows combustion to begin far before TDC. As a result, the energy utilized for running compression increases resulting in a fall in efficiency. However, it is also observed that there is no substantial difference in thermal efficiency between biodiesel and diesel by some researchers [113]. Further, when the brake thermal efficiency of biodiesel was examined in different chamber geometries, the toroidal combustion chamber outperformed the others due to complete combustion. Mamilla *et al*. [84] also claimed that TCC has a superior BTE than SCC and RCC at all loads because TCC has more turbulence flow behavior. The effect of braking power and various combustion chamber designs on BTE was demonstrated by Banapurmath *et al*. [99]. They found TCC shape outperforms other geometries because of less exhaust soot and improved biodiesel–air mixing. Because the modified combustion chamber has better turbulent and swirl motion, Manikalithas *et al*. [100] observed that the BTE for the modified bowl is 31 percent at 80 percent load and 32 percent at full load, which is high compared to existing geometry values of 29.56 percent at 80 percent load and 31.62 percent at 100 percent load. Ravichandran *et al*. [115] discovered that the BTE of B25 and B100 corn biodiesel engines with toroidal combustion pistons were greater at all loads than engines with hemispherical combustion pistons. Because of improved combustion in the redesigned piston, Chandrashekhar *et al*. [114] discovered a 2–3% increase in BTE. At 80 percent load, BTE was 22.15 percent, 24.52 percent, and 22 percent at IP = 175, 200, and 225 bar, respectively, while CR was 17.5. The BTE for 200 bar IP was also higher, owing to the lower physical delay period. The redesigned combustion chamber has been tested and found pressurized injection, higher engine speed, and lowering the load, improve brake thermal efficiency.

Emission Parameters

UBHC emission

UBHC emissions fall as the mixing of bio-oil in the fuel is raised, irrespective of the change in chamber geometry [116]. UBHC emission is proportional to the oxygen proportion present; if it is present in excess, UBHC emission falls, and vice versa. The strong air swirl in a redesigned combustion chamber geometry leads to lower UBHC emissions [104]. Ryu *et al*. [51] evaluated soybean biodiesel and discovered that it has a 75 percent lower UBHC content than diesel fuel. They discovered a 28 percent, 32 percent, and 75 percent reduction in UBHC at different blends made from mixing soybean oil with diesel. The compression ratio affects UBHC emissions as reported by Bora *et al*. [72]. They found changing CR from 16 to 18 at 100% load reduced hydrocarbon emissions by 42 percent. This is because of better combustion. In comparison to diesel using methyl ester as a fuel gives complete combustion which in turn reduces UBHC. Jaichandar and Annamalai [16] examined B20 of Pongamia oil methyl ester in a varied chamber at various loads and found UBHC emissions of nearly 65, 60, and 55 ppm for HCC, SCC, and TCC respectively. As a consequence of the improved swirl motion and air mixing, modified TCC emits almost 8 ppm less UBHC than traditional HCC. UBHC emissions also increase with increasing load, according to Mamilla *et al.* [84]. They also concluded that methyl ester contains more oxygen than diesel, allowing for steadier burning. Lalvani *et al.* [106] tested an upright diesel engine at 25 rps with a 20% adelfa biodiesel blend in two distinct piston shapes, standard, and turbulence inducer pistons, as well as varied injection pressures and found dropped values for HC with an increase in the IP. Banapurmath *et al*. [114] demonstrated an experiment on neem, mahua, and diesel as fuel and discovered that TCC emits less HC than other geometries. Chandrashekhar *et al*. [114] observed fine atomization of fuel during different injection pressure and also noted reduced HC emissions at 200 bars compared to 175 bars and 225 bars. They also reviewed the effect of a smaller nozzle hole and a different configuration on CI engine emissions. At all equivalence ratios, they found that the group hole emits less HC than the conventional nozzle.

CO emission

Lack of oxygen in the combustion process causes CO formation. CO is generated due to a low gas temperature. Biodiesel has more oxygen than diesel, therefore CO emissions are reduced [117]. Mamilla *et al*. [84] found more CO emission for TCC geometry fuelled with a B-20 blend of JTME. They observed 0.245% v/V CO for TCC, 0.242% v/V for the re-entrant type chamber, and 0.240% v/V for the spherical chamber. Li *et al*. [107] employed the KIVA-4 code to test for different bowl geometries. SCC shape resulted in the lowest CO mass percentage for crank angle 25° aTDC. When compared to the other geometries, the OCC bowl geometry oxidized CO emissions faster at 3600 rpm. TCC, according to Banapurmath *et al*. [99], reduces CO emissions compared to other shapes due to high-temperature values. TCC with 20 percent POME had the lowest CO output, according to Jaichandar and Annamalai [16]. At 5.024 kW load, they measured 0.140% for TCC, 0.165% for HCC, and 0.185% for SCC by volume. Ryu *et al.* [51] worked on a heavy-duty engine with B10- B100 blend of soybean oil and measured a slight decrease of 6% -18% in CO emission. CO emission was reported to be 0.28-0.33 percent for 175-225 bar IP for multi-chamber pistons.

NOx emission

Almost all of the research discovered that using biodiesel instead of diesel results in a minor increase in the value of NOx emissions for all discussed combustion chamber geometry [118]. The reason for this is that biodiesel has a high cetane rating. However, the load condition is also a factor which is needed to be considered. At full load, Jaichandar and Annamalai [16] worked on different geometry with B20 POME and discovered that TCC emits 738 ppm of NOx, while HCC emits only 712 ppm (5.024 kW). As a result, the improved TCC geometry results in a nearly 3-4 percent higher value of NOx emission because of better air turbulence and more oxygen availability which raises the temperature of the chamber. Mamilla *et al.* [84] found that when using 20 percent Jatropha methyl ester, NOx emissions were reported to be 200 ppm at 1100 W, 300 ppm at 2200 W, 430 ppm at 3300 W, and 520 ppm at 4400 W. In comparison to diesel, methyl ester has more oxygen available for the generation of NOx. At all engine loads, NOx for modified bowl piston (MBP) was found better concerning existing bowl piston (EBP), according to Manikalithas *et al.* [100]. Because improved combustion raises the temperature of the chamber in MBP, it produces 660 ppm NOx at full load, while EBP produces 649 ppm NOx at full load.

Smoke

Because biodiesel molecules have more oxygen, lower sulfur levels, and a higher cetane number, particulate matter (PM) emissions are low compared to diesel. High temperature and plentiful oxygen availability cause a mixing of air and fuel which in turn helps particulate debris to burn near the diffusive flame›s boundary. Even in locally rich zones, the increased availability of oxygen in fuel causes complete fuel oxidation, resulting in a measurable reduction of smoke and PM. Jaichandar and Annamalai [16] investigated B20 Pongamia methyl ester in various combustion chambers and discovered that smoke emissions for biodiesel blends are greatly reduced at all loads. Due to complete combustion, TCC's smoke emissions were reduced further. At a load of 5.024 kW, smoke opacity for SCC, HCC, and TCC was found to be about 67 percent, 62 percent, and 58 percent, respectively. So, when compared to diesel, TCC produces 20% less smoke opacity due to effective mixing. Mamilla *et al.* [84] evaluated the performance of Jatropha methyl ester by applying spherical, re-entrant, and toroidal geometries and discovered that the toroidal type combustion chamber reduced smoke density more than the other two types of geometries. The smoke opacity was measured to be 135, 130, and 125 mg/m3 for the spherical, re-entrant, and toroidal combustion chambers, respectively. TCC produces less smoke density than TrCC, CCC, and HCC, according to Banapurmath *et al.* [99], because TCC generates significant turbulence in the chamber. Manikalithas *et al.* [100] discovered that modified geometry has less smoke opacity due to better squish and turbulent motion of the A-F mixture. Furthermore, Lalvani *et al.* [106] evaluated a vertical diesel engine at 25 rps with turbulence inducer piston geometries using a 20% blend of adelfa. They found smoke opacity for B20 was 63 percent for 180 bar, 54 percent for 200 bar, 53 percent for 210 bar, 52 percent for 220 bar, and 57 percent for 230 bar fuel injection pressure.

SO2 emission

Biodiesel has a lower sulfur content than diesel so it reduces SO2 emissions. Sulfur emissions are also affected by the load. Aydin et al. [119] discovered that SO2 emissions reported 300-700 ppm (Maximum) at 50-100 percent throttle positions, respectively. They studied the impact of ethanol blend on diesel engine SO2 emissions. The average SO2 decrease was 44-52 percent for80-20 and 20-80 blending, respectively. Tan et al. [50] tested light-duty engines for unregulated and regulated emissions by using fuel with varied sulfur concentrations. They tested S50-S1500 fuels, which contain 47-1473 ppm sulfur, and discovered that, except for S1500, all other fuels reduce SO2 emissions. Sulfur emissions dropped up to 57.7% when olive oil methyl ester was used also while studying the exhaust emission of tobacco oil and its blend as a fuel in a diesel engine with different values of load without modifying the combustion chamber. They discovered that at 50 percent, 75 percent, and 100 percent load, the SO2 levels reported approximately 59 ppm, 121 ppm, and 179 ppm, respectively, using tobacco oil, which contains less sulfur.

CO2 emission

The effectiveness of the fuel combustion as well as the total amount of fuel burned inside the combustion chamber are both reflected in the CO2 emission. Compared to biodiesel, diesel fuel generates more CO2 emissions. The CO2 release shows that the fuel has burned completely inside the combustion chamber. The fuel›s carbon-to-hydrogen ratio also has an impact. When a fuel is completely burned, the carbon in the fuel interacts with the extra oxygen to create carbon dioxide, which is released into the atmosphere. While using diesel fuel and a modified piston with shallow depth geometry instead of a regular piston with hemispherical geometry, carbon dioxide emissions are reduced by an additional 1.26%. This is so that fuel can burn more effectively with a long enough ignition delay and short quenching distance due to better fuel and air mixing.

RESULTS AND DISCUSSION

The future of fossil fuel is very short because of almost the end of reserves, uncontrolled increase in demand leads to economic aspects and some serious environmental aspects. Biofuel extracted from nonedible seeds with and without further blending captured the attention of many researchers as an alternative to crude. Further, it has shown some promising results in terms of emission content like UBHC and CO, also found better for performance parameters like thermal efficiency and fuel consumption. The performance of biofuel as a fuel still needs to be improved in many aspects by many other techniques and this challenge has been taken by many researchers in the current scenario. Many works of literature show that the geometry and shape of clearance volume has a significant correlation with engine outcomes. Due to local flow field changes, the geometry ensures adequate air-fuel mixing. The combustion chamber design, more than any other component of the engine, influences emissions, performance, and knocking features. Bowl geometry has a measurable effect on performance and emission metrics. Many academics have been working on combustion chamber geometry designs using diverse fuels as an intake for a long duration. Table 1 and Table 2 shows a summary of the experimental and numerical work of some researchers in which the influence of change in geometry considered along with engine control parameter and outcomes are listed accordingly.

Experimental Work

Numerical Work

Table 1. Summary of experimental work

Literature Studied	Fuel used	Engine Parameters & Control Parameter	Chamber geometry	Result
Mamilla *et al.* [84]	20% Jatropha methyl esters	DI engine- 4S, Single cylinder, Bore-87.5, Stroke-110 mm, CR-17.5:1, Rated Power-4.4 kW, Tested with different blends (20%-80%)	Spherical, Re-entrant, and Toroidal	Toroidal geometry was found better with minimum smoke density, HC, and CO2 emissions and a better value of efficiency (33.92%) compared to the other two. NOX emission is more which was a demerit of using toroidal geometry
Lalvani *et al.* [106]	20% blend of adelfa biodiesel	DI engine- 4S, Single cylinder, Bore-87.5, Stroke-110 mm, CR-17.5:1, Rated Power-5.2 kW, Injection pressure varied between 185 to 230 bar.	Hemispherical and Turbulence inducer piston	At 220 bar IP, the turbulent inducer piston produces the best results. 34.3 percent thermal efficiency was reported. Emission products were found lower, except for NOX value.
Banapurmath *et al.* [92]	Mahua and Neem biodiesel	DI engine- 4S, Single cylinder, Bore-87.5, Stroke-110 mm, Injection pressure set to 205 bar for all fuels used in testing	Hemispherical and Cylindrical	Toroidal geometry results in increases in BTE while decreasing the emission level
Ravichandran *et al.* [115]	25% blend of Corn biodiesel	DI engine- 4S, Single cylinder, Bore-87.5, Stroke-110 mm, Rated Power-4.4 kW, Tested engine for low, medium, and high loads	Hemispherical and Toroidal	At full load, both geometries reported the best results showing an increase in BTE while reducing emissions.

Table 2. Summary of numerical work

Literature Studied	Code /Fuel used	Engine Parameters	Chamber geometry	Control Parameter	Result
Venkateswaran *et al.* [75]	CFD -Simulation	DI engine- 4S, Six cylinder, Bore-108mm, Stroke-118 mm, CR-17.5:1, Rated Power-118 kW, N-2400 rpm	Re-entrant	By keeping the Compression ratio, Maximum diameter of the bowl, Squish clearance, and Injection rate fixed	Re-entrant type geometry creates more swirls compared to baseline geometry. As a result, it reports high thermal efficiency and lower emission levels of CO, UBHC, and NOX.
Gafoor *et al.* [101]	Numerical work	DI engine- 4S, Single cylinder, Bore-85, Stroke-82 mm, CR-17.5:1, Rated Power-5.2 kW, Single injection	Trapezoidal and Toroidal	The initial swirl ratio is kept at 0.5–4.5	The diameter-to-depth ratio of 55% and an initial swirl ratio of 2.5 gives optimal results in terms of performance and emissions.
Wei *et al.* [105]	Numerical work by using AVL-FIRE code for diesel	DI engine- 4S, Single cylinder, Bore-135, Stroke-150 mm, CR-17.5:1, Rated Power-14.7 kW	Swirl with re-entrant	Varying swirl ratio	The swirl ratio varies from 0.2 to 3.2. The flow of air is found best with a swirl ratio of 0.8. At 0.8, the mass fraction of NO and Soot decreases.
Rakopoulos *et al.* [108]	CFD-Simulation on diesel	DI engine- 4S, Single cylinder, Bore-85, Stroke-82 mm, CR-17.5:1, Rated Power-5.2 kW, Single injection	Piston with a cylindrical cavity	d/D varied from 44% to 64% and engine speed varied from 1500 to 2500 rpm	Maximum heat release value increases with decreases with a ratio of d/D %.
Prasad *et al.* [56]	CFD-Simulation	DI engine- 4S, Single cylinder, Bore-102, Stroke-116 mm, CR-16.3:1, Rated Power-7.5 kW	Re-entrant and Toroidal	Swirl number varied between 1 to 3.5	For better swirl and lower emissions, Re-entrant geometry without central projection was found best.

CONCLUSION

The present study reviews valid reasons for accepting bio-fuels as fuel for CI engines by considering outcomes derived from experiments and numerical analysis with changes in the shape of the piston bowl. Some important outcomes are listed below. Modifying or redesigning work on the engine is meant to enhance turbulence kinetic energy and which in turn leads to the engine performance along with matching emission standards.

Better performance from an engine could be obtained by working on variations in injection, combustion chamber geometry, and spray characteristics.

The presence of effective flow fields in the combustion phenomenon widely depends on flow parameters like swirl, squish, and tumble.

Change in bowl shape shown improvement in many aspects some of which are listed:

A re-entrant piston bowl is the best for swirling during the compression stroke.

TRCC found the best geometry for air-fuel mixing due to improved airflow.

NOMENCLATURE

4-S	4-Stroke
ASTM	American Society for Testing and Materials
aTDC	After Top Dead Center
B 100	Blend 100
B 20	Blend 20 (80% Diesel)
BSFC	Brake-Specific Fuel Consumption
bTDC	Before Top Dead Center
BTE	Brake Thermal Efficiency
CA	Crank Angle
CC	Combustion Chamber
CCC	Cylindrical Combustion Chamber
CFD	Computational Fluid Dynamics
CI	Compressed Ignition
CO	Carbon Monoxide
CR	Compression Ratio
DI	Direct Injection
EBP	Existing Bowl Piston
EGR	Exhaust Gas Recovery
EGT	Exhaust Gas Temperature
EN	European Standard
FAAE	Fatty Acid Alkyl Esters
HC	Hydro Carbon
HCC	Hemispherical Depth Combustion Chamber
HRR	Heat Release Rate
IC	Internal Combustion
ID	Ignition Delay
IP	Injection Pressure
ITR	Ignition Time Retardation
JTME	Jatropha Methyl Ester
kW	Kilowatt
LOME	Linseed Oil Methyl Ester
MBP	Modified Bowl Piston
nm	Nanometer
NOx	Oxides of Nitrogen
OCC	Omega Shape Combustion Chamber
OH	Hydroxide
PM	Particulate Matter
POME	Pongamia Oil Methyl Ester
PPM	Parts Per Million
rpm	Revolution per Minute
rps	Revolution per Second
SCC	Shallow Depth Combustion Chamber
SO2	Sulfur Dioxide
SqCC	Square (Cavity) Combustion Chamber
TCC	Toroidal Combustion Chamber
TDC	Top Dead Center
TRCC	Toroidal Re-entrant Combustion Chamber
UBHC	Unburnt Hydrocarbon
VCR	Variable Compression Ratio
W	Watt

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Kumar N, Varun, Chauhan SR. Performance and emission characteristics of biodiesel from different origins: A review. Renew Sustain Energy Rev 2013;21. [CrossRef]

[2] Ong HC, Mahlia TMI, Mahlia HHM. A review on energy pattern and policy for transportation sector in Malaysia. Renew Sustain Energy Rev 2012;16:532–542. [CrossRef]

[3] Yatish KV, Lalithamba HS, Suresh R, Arun SB, PVK. Optimization of scum oil biodiesel production by using response surface methodology. Process Saf Environ Prot 2016;102:667–6672. [CrossRef]

[4] Atabani A, da Silva CA. Calophyllum inophyllum L. - A prospective non-edible biodiesel feedstock. Study of biodiesel production, properties, fatty acid composition, blending and engine performance. Renew Sustain Energy Rev 2014;37:644−655. [CrossRef]

[5] Panneerselvam N, Murugesan A, Vijayakumar C, Arumugam K, Subramaniam D, Alagumalai A. Effects of injection timing on bio-diesel fuelled engine characteristics-An overview. Renew Sustain Energy Rev 2015;50. [CrossRef]

[6] Sanjid A, Masjuki HH, Kalam, Rahman SMA, Abedin MJ, Palash SM. Impact of palm, mustard, waste cooking oil and Calophyllum inophyllum biofuels on performance and emission of CI engine. Renew Sustain Energy Rev 2013;27:664−682. [CrossRef]

[7] Singh P, Goel V, Chauhan S. Carbonyl and aromatic hydrocarbon emissions from diesel engine exhaust using different feedstock: A review. Renew Sustain Energy Rev 2016;63:269−291. [CrossRef]

[8] Rashedul HK, Masjuki HH, Kalam MA, Ashraful AM, Ashrafur Rahman SM, Shahir SA. The effect of additives on properties, performance and emission of biodiesel fuelled compression ignition engine. Energy Convers Manag 2014:348−364. [CrossRef]

[9] Sivalakshmi S, Balusamy T. Effect of biodiesel and its blends with diethyl ether on the combustion, performance and emissions from a diesel engine. Fuel 2013;106:106−110. [CrossRef]

[10] Palash SM, Kalam MA, Masjuki HH, Masum BM, Rizwanul Fattah IM, Rahman MM. Impacts of biodiesel combustion on NOx emissions and their reduction approaches. Renew Sustain Energy Rev 2013;23:473−490. [CrossRef]

[11] JinKe EJ, Liu E, Teng L, Yang W, Deng Y, Gong J. A skeletal mechanism modeling on soot emission characteristics for biodiesel surrogates with varying fatty acid methyl esters proportion. Appl Energy. 2016;181:322−331. [CrossRef]

[12] Sanjid A, Masjuki HH, Kalam MA, Rahman SMA, Abedin MJ, Palash SM. Production of palm and jatropha based biodiesel and investigation of palm-jatropha combined blend properties, performance, exhaust emission and noise in an unmodified diesel engine. J Clean Prod 2013;65. [CrossRef]

[13] Balaji G, Cheralathan M. Experimental investigation to reduce emissions of CI (compression ignition) engine fuelled with methyl ester of cottonseed oil using antioxidant. Int J Ambient Energy 2014;35:13−19. [CrossRef]

[14] Kannan GR. Effect of Injection Pressures and Timings on the Performance Emission and Combustion Characteristics of a Direct Injection Diesel Engine Using Biodiesel-Diesel-Ethanol Blend. SAE Tech Pap 2013;2. [CrossRef]

[15] Kannan G, Ramanathan A. Experimental evaluation of DI diesel engine operating with diestrol at varying injection pressure and injection timing. Fuel Energy Abstr 2011;92:2252−2263. [CrossRef]

[16] Jaichandar S, Annamalai K. Effects of open combustion chamber geometries on the performance of pongamia biodiesel in a DI diesel engine. Fuel 2012;98:272-279. [CrossRef]

[17] Wan GWNM, Mamat R, Masjuki HH, Najafi G. Effects of biodiesel from different feedstocks on engine performance and emissions: A review. Renew Sustain Energy Rev 2015;51:585−602. [CrossRef]

[18] Wadhah HAD, Obed MA, Ahmed H. Ahmed HK. Comparative study of biodiesel production from different waste oil sources for optimum operation conditions and better engine performance. J Therm Eng 2022;8:457−465. [CrossRef]

[19] Abbaszadeh MA, Ghobadian B, Omidkhah M, Najafi G. Current biodiesel production technologies: A comparative review. Energy Convers Manag 2012;63:138−148. [CrossRef]

[20] Upendra R, Prerana N, Tikandra NV. Comparative assessment of the emission characteristics of first, second and third generation biodiesels as fuel in a diesel engine. J Therm Eng 2020;6:211−225. [CrossRef]

[21] Haili L, Jiaqiang E, Yuanwang D, Changqing XHZ. Experimental study on pyrolysis characteristics of the tobacco stem based on microwave heating method. Appl Therm Eng 2016;106:473−479. [CrossRef]

[22] Mihaela P, Rathbauer J, Monica N, Zeller R. Perspectives of safflower oil as biodiesel source for South Eastern Europe (comparative study: Safflower, soybean and rapeseed). Fuel 2013. [CrossRef]

[23] Brännström H, Alén R. Pyrolysis of vegetable oil soaps - Palm, olive, rapeseed and castor oils. J Anal Appl Pyrolysis 2011;91:154−158. [CrossRef]

[24] Martin MLJ, Prithviraj D. Performance of Preheated Cottonseed Oil and Diesel Fuel Blends in a Compression Ignition Engine, 2011.

[25] Jain S, Sharma MP. Prospects of biodiesel from Jatropha in India: A review. Renew Sustain Energy Rev 2010;14:763−771. [CrossRef]

[26] Ashraful AM, Masjuki HH, Kalam MA, Rizwanul Fattah IM, Imtenan S, Shahir SA, et al. Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: A review. Energy Convers Manag. 2014;80:202−228. [CrossRef]

[27] Datta A, Mandal BK. A comprehensive review of biodiesel as an alternative fuel for compression ignition engine. Renew Sustain Energy Rev. 2016;57:799−821. [CrossRef]

[28] Carareto NDD, CYCS K, Oliveira EC, Costa MC, Meirelles AJA. Flash points of mixtures containing ethyl esters or ethylic biodiesel and ethanol. Fuel. 2012;96:319−326. [CrossRef]

[29] Gopinath A, Puhan S, Govindan N. Effect of biodiesel structural configuration on its ignition quality. Int J Energy Environ. 2010;1.

[30] Rahmat N, Abdullah AZ, Mohamed A. Recent progress on innovative and potential technologies for glycerol transformation into fuel additives: A critical review. Renew Sustain Energy Rev. 2010;14:987−1000. [CrossRef]

[31] Lapuerta M, García-Contreras R, Campos-Fernández J, Dorado MP. Stability, Lubricity, Viscosity, and Cold-Flow Properties of Alcohol Diesel Blends. Energy Fuels. 2010;24:4497−4502. [CrossRef]

[32] Kannan D, Senthilkumar Pachamuthu, Nabi MN, Hustad JE, Løvås T. Theoretical and experimental investigation of diesel engine performance, combustion, and emissions analysis fueled with the blends of ethanol, diesel, and jatropha methyl ester. Energy Convers Manag. 2012;53:322−331. [CrossRef]

[33] Chang F, Hanna MA, Zhang D-J, Li H, Zhou Q, Song B-A, et al. Production of biodiesel from non-edible herbaceous vegetable oil: Xanthium sibiricum Patr. Bioresour Technol. 2013;140:435−438. [CrossRef]

[34] Martínez G, Sánchez N, Encinar JM, González JF. Fuel properties of biodiesel from vegetable oils and oil mixtures. Influence of methyl esters distribution. Biomass Bioenergy. 2014;63:22−32. [CrossRef]

[35] Zhiqing Z, Deng Y, Pham M, Wei Z, Peng Q, Yin Z, et al. Effects of fatty acid methyl esters proportion on combustion and emission characteristics of a biodiesel fueled marine diesel engine. Energy Convers Manag. 2021;159:244−253. [CrossRef]

[36] Liu T, Hui A, Cai H, Jiaqiang E, Yang W. Development of a skeletal mechanism for biodiesel blend surrogates with varying fatty acid methyl esters proportion. Appl Energy. 2016;162. [CrossRef]

[37] Sorda GA, Banse M, Kemfert C. An overview of biofuel policies across the world. Energy Policy. 2010;38:6977−6988. [CrossRef]

[38] Ajanovic A, Haas R. Economic challenges for the future relevance of biofuels in transport in EU countries. Energy. 2010;35:3340−3348. [CrossRef]

[39] Jaeger WK, Egelkraut TM. Biofuel economics in a setting of multiple objectives and unintended consequences. Renew Sustain Energy Rev. 2011;15:4320−4333. [CrossRef]

[40] Duer H, Christensen PH. Socio-economic aspects of different biofuel development pathways. Biomass Bioenergy. 2010;34:237−243. [CrossRef]

[41] Hasan M, Rahman PDMM. Performance and emission characteristics of biodiesel-diesel blend and environmental and economic impacts of biodiesel production: A review. Renew Sustain Energy Rev. 2017;74:938−948. [CrossRef]

[42] le Thanh L, van Ierland EC, Zhu X, Wesseler JHH. Comparing the social costs of biofuels and fossil fuels: A case study of Vietnam. Environ Econ Nat Resour. 2013;54:227−238. [CrossRef]

[43] Aquino IP, Hernandez RPB, Chicoma DL, Pinto HPF, Aoki IV. Influence of light, temperature, and metallic ions on biodiesel degradation and corrosiveness to copper and brass. Fuel. 2012;102:795−807. [CrossRef]

[44] Fazal MA, Haseeb ASMA, Masjuki HH. Effect of temperature on the corrosion behavior of mild steel upon exposure to palm biodiesel. Energy. 2011;36:3328−3334. [CrossRef]

[45] Fazal MA, Haseeb ASMA, Masjuki HH. Corrosion mechanism of copper in palm biodiesel. Corros Sci. 2013:50−59. [CrossRef]

[46] Fazal MA, Haseeb ASMA, Masjuki H. Degradation of automotive materials in palm biodiesel. Energy. 2012;40:76−83. [CrossRef]

[47] Yang ZY, Hollebone BP, Wang ZD, Yang C, Landriault M. Effect of Storage Period on the Dominant Weathering Processes of Biodiesel and Its Blends with Diesel in Ambient Conditions. Fuel. 2013;104:342−350. [CrossRef]

[48] Peng D-X. Effects of concentration and temperature on tribological properties of biodiesel. Adv Mech Eng. 2015;7:1687814015611025. [CrossRef]

[49] Galadima A, Muraza O. Biodiesel production from algae by using heterogeneous catalysts: A critical review. Energy. 2014;78:72−83. [CrossRef]

[50] Pi-Qiang Tan, Zhi-Yuan Hu, D-M Lou. Regulated and unregulated emissions from a light-duty diesel engine with different sulfur content fuels. Fuel. 2009;88:1086−1091. [CrossRef]

[51] Ryu K. The characteristics of performance and exhaust emissions of a diesel engine using a biodiesel with antioxidants. Bioresour Technol. 2010;101:78−82. [CrossRef]

[52] Kim H, Choi B. The effect of biodiesel and bioethanol blended diesel fuel on nanoparticles and exhaust emissions from CRDI diesel engine. Renew Energy. 2010;35:157−163. [CrossRef]

[53] Gomaa M, Alimin AJ, Kamarudin KA. The effect of EGR rates on NOX and smoke emissions of an IDI diesel engine fueled with Jatropha biodiesel blends. Int J Energy Environ. 2012;2:477−490.

[54] Choi S, Park W, Lee S, Min K, Choi H. Methods for in-cylinder EGR stratification and its effects on combustion and emission characteristics in a diesel engine. Energy. 2011;36:6948−6959. [CrossRef]

[55] Labecki L, Ganippa LC. Effects of injection parameters and EGR on combustion and emission characteristics of rapeseed oil and its blends in diesel engines. Fuel. 2012;98:15−28. [CrossRef]

[56] Kumarasway A, Prasad BD. Performance analysis of a dual fuel engine using lpg and diesel with egr system. Fuel Process Technol. 2012. [CrossRef]

[57] Song H, Tompkins BT, Bittle JA, Jacobs TJ. Comparisons of NO emissions and soot concentrations from biodiesel-fuelled diesel engine. Fuel. 2012;96:446−453. [CrossRef]

[58] Gill S, Turner D, Tsolakis A, York A. Controlling Soot Formation with Filtered EGR for Diesel and Biodiesel Fuelled Engines. Environ Sci Technol. 2012;46:4215–4222. [CrossRef]
[59] Aguilar FJ, Torres García M, Vélez Godiño J, Trujillo E, Villanueva J. Experimental analysis of low temperature combustion mode with diesel and biodiesel fuels: A method for reducing NOx and soot emissions. Fuel Process Technol. 2012;103:57–63. [CrossRef]
[60] Qi DH, Bae C, Feng YM, Jia CC, Bian YZ. Combustion and emission characteristics of a direct injection compression ignition engine using rapeseed oil based micro-emulsions. Fuel. 2013;107:570–577. [CrossRef]
[61] Shivakumar ShankarHarishchandra V Astagi, S R Hotti OH. Effect of exhaust gas recirculation (egr) on performance, emissions and combustion characteristics of a low heat rejection (lhr) diesel engine using pongamia biodiesel. J Therm Eng. 2016;2:1007–1016. [CrossRef]
[62] Xavier Tauzia, Alain Maiboom. Experimental study of inlet manifold water injection on combustion and emissions of an automotive direct injection Diesel engine. Energy. 2010;35:3628–3639. [CrossRef]
[63] Sahin Z, Tuti M, Orhan D. Experimental investigation of the effects of water adding to the intake air on the engine performance and exhaust emissions in a DI automotive diesel engine. Fuel. 2014;115:884–895. [CrossRef]
[64] Sayin C, Gumus M, Canakci M. Effect of Fuel Injection Timing on the Emissions of a Direct-Injection (DI) Diesel Engine Fueled with Canola Oil Methyl Ester−Diesel Fuel Blends. Energy & Fuels. 2010;24:2675–2682. [CrossRef]
[65] Şener R, Yangaz MU, Gul MZ. Effects of injection strategy and combustion chamber modification on a single-cylinder diesel engine. Fuel. 2020;266:117122. [CrossRef]
[66] Muralidharan K, Vasudevan D. Performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends. Appl Energy. 2011;88:3959–3968. [CrossRef]
[67] EL Kassaby M, Medhat A. Nemitallah. Studying the effect of compression ratio on an engine fueled with waste oil produced biodiesel/diesel fuel. Alexandria Eng J. 2013;52:1–11. [CrossRef]
[68] Sayin C, Gumus M. Impact of compression ratio and injection parameters on the performance and emissions of a DI diesel engine fueled with biodiesel-blended diesel fuel. Appl Therm Eng 2011;31:3182–3188. [CrossRef]
[69] Hirkude JB, Padalkar AS. Experimental investigation of the effect of compression ratio on performance and emissions of CI engine operated with waste fried oil methyl ester blend. Fuel Process Technol 2014;128:367-375. [CrossRef]
[70] Sharma A, Murugan S. Potential for using a tyre pyrolysis oil-biodiesel blend in a diesel engine at different compression ratios. Energy Convers Manag 2015;93:289–297. [CrossRef]
[71] Saha UK, Sahoo N, Debnath BK. Adjusting the operating characteristics to improve the performance of an emulsified palm oil methyl ester run diesel engine. Energy Convers Manag 2013;69:191–198. [CrossRef]
[72] Bora, B. J , Saha UK, Chatterjee S, Veer V. Effect of compression ratio on performance, combustion and emission characteristics of a dual fuel diesel engine run on raw biogas. Energy Convers Manag 2014;87:1000–1009. [CrossRef]
[73] Pandian, M. , Sivapirakasam, SP , Udayakumar M. Investigations on emission characteristics of the pongamia biodiesel-diesel blend fuelled twin cylinder compression ignition direct injection engine using exhaust gas recirculation methodology and dimethyl carbonate as additive. J Renew Sustain Energy 2010;2. [CrossRef]
[74] Swaminathan, C. ; Sarangan J. Performance and exhaust emission characteristics of a CI engine fueled with biodiesel (fish oil) with DEE as additive. Biomass and Bioenergy 2012;39:168–174. [CrossRef]
[75] Venkateswarlu K, Kumar K V, Murthy BS, R, Subbarao V V. Effect of exhaust gas recirculation and ethyl hexyl nitrate additive on biodiesel fuelled diesel engine for the reduction of NO^sub x^ emissions. Fuels Chem from Biomass 2012;6:304. [CrossRef]
[76] Liu J, Yao A, Yao C. Effects of injection timing on performance and emissions of a HD diesel engine with DMCC. Fuel 2014;134:107–113. [CrossRef]
[77] Saravanan S, Nagarajan G, Sampath S. Combined effect of injection timing, EGR and injection pressure in reducing the NOx emission of a biodiesel blend. Int J Sustain Energy 2014;33:386–399. [CrossRef]
[78] Varma PSP, Subbaiah KV. A review on thermal and CFD analysis of 3 different piston bowl geometry's. Mater Today Proc 2021;37:2341–2345. [CrossRef]
[79] Prasad BVVSU, Sharma CS, Anand TNC, Ravikrishna R V. High swirl-inducing piston bowls in small diesel engines for emission reduction. Appl Energy 2011;88:2355–2367. [CrossRef]
[80] Ghodke PR, Suryawanshi JG. Investigation of diesel engine for low exhaust emissions with different combustion chambers. Therm Sci 2015;19:2013–2024. [CrossRef]
[81] Chen Y, Li X, Li X, Zhao W, Liu F. The wall-flow-guided and interferential interactions of the lateral swirl combustion system for improving the fuel/air mixing and combustion performance in DI diesel engines. Energy 2019;166:690–700. [CrossRef]
[82] Vedharaj S, Vallinayagam R, Yang WM, Saravanan CG, Lee PS. Optimization of combustion bowl geometry for the operation of kapok biodiesel - Diesel blends in a stationary diesel engine. Fuel 2015;139:561–567. [CrossRef]

[83] Zhang T, Eismark J, Munch K, Denbratt I. Effects of a wave-shaped piston bowl geometry on the performance of heavy duty Diesel engines fueled with alcohols and biodiesel blends. Renew Energy 2020;148:512−522. [CrossRef]
[84] Mamilla VR, Mallikarjun M V., Rao GLN. Effect of combustion chamber design on a di diesel engine fuelled with jatropha methyl esters blends with diesel. Procedia Eng 2013;64:479−490. [CrossRef]
[85] Bhavesh Pathak, Nikul Patel. Thermodynamic Performance of an Engine by Modifying Piston Bowl Geometries Fuelled by SME-100, LA-100, KB-100 Biodiesel Blends, and Diesel. J Adv Res Fluid Mech Therm Sci 2023;102:1v13. [CrossRef]
[86] Doppalapudi AT, Azad AK, Khan MMK. Combustion chamber modifications to improve diesel engine performance and reduce emissions: A review. Renew Sustain Energy Rev 2021. [CrossRef]
[87] Mohan Das AN, Harish G, Palan SR, Shetty S, Hubli SS, Binani V. Effect of Modifications of Piston Bowl Geometry in Stationary Diesel Engine Fuelled with Biodiesel-A Comprehensive Review. J Phys Conf Ser 2020;1473:12037. [CrossRef]
[88] Temizer İ, Cihan Ö. Analysis of different combustion chamber geometries using hydrogen / diesel fuel in a diesel engine. Energy Sources, Part A Recover Util Environ Eff 2021;43:17−34. [CrossRef]
[89] Rajak U, Nashine P, Verma TN. Assessment of diesel engine performance using spirulina microalgae biodiesel. Energy 2019;166:1025−1036. [CrossRef]
[90] Azad AK, Halder P, Nanthagopal K, Ashok B. Investigation of diesel engine in cylinder flow phenomena using CFD cold flow simulation. Adv Biofuels Appl Technol Environ Sustain 2019:329−336. [CrossRef]
[91] Gadekar S, Agarwal AK. In-Cylinder Air-Flow Characteristics Using Tomographic PIV at Different Engine Speeds, Intake Air Temperatures and Intake Valve Deactivation in a Single Cylinder Optical Research Engine. J Energy Resour Technol Asme 2016;139.
[92] Khandal SV, Banapurmath NR, Gaitonde VN, Hiremath SS. Review of advanced injection strategies for diesel HCCI engines. Renew Sustain Energy Rev. 2017;70:369−384. [CrossRef]
[93] Jaichandar S, Annamalai K. Combined impact of injection pressure and combustion chamber geometry on the performance of a biodiesel fueled diesel engine. Energy 2013;55:330v339. [CrossRef]
[94] Puhan S, Jegan R, Balasubbramanian K, 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;34:1227−1233. [CrossRef]
[95] Sayin C, Gumus M, Canakci M. Effect of fuel injection pressure on the injection, combustion and performance characteristics of a DI diesel engine fueled with canola oil methyl esters-diesel fuel blends. Biomass and Bioenergy 2012;46. [CrossRef]
[96] Hwang J, Qi D, Jung Y, Bae C. Effect of injection parameters on the combustion and emission characteristics in a common-rail direct injection diesel engine fueled with waste cooking oil biodiesel. Renew Energy 2014;63:9−17. [CrossRef]
[97] Venkateswaran SP, Nagarajan G. Effects of the Re-Entrant Bowl Geometry on a DI Turbocharged Diesel Engine Performance and Emissions-A CFD Approach. J Eng Gas Turbines Power 2010;132. [CrossRef]
[98] Park S. Optimization of combustion chamber geometry and engine operating conditions for compression ignition engines fueled with dimethyl ether. Fuel 2012;97:61−71. [CrossRef]
[99] Banapurmath N, Yalival VS. Effect of Combustion Chamber Shapes on the Performance of Mahua and Neem Biodiesel Operated Diesel Engines. J Pet Environ Biotechnol 2015;6. [CrossRef]
[100] Manikalithas P, Venkatachalam R, Kalilrahiman M, Boopathi P. Comparison study of existing bowl piston and modified bowl piston diesel engine performance emission and combustion characteristics by using diesel Indexing terms / Keywords 2016;12:5243−5251.
[101] Abdul Gafoor CP, Gupta R. Numerical investigation of piston bowl geometry and swirl ratio on emission from diesel engines. Energy Convers Manag 2015;101:541−551. [CrossRef]
[102] Maji L, Liangshan X, Xiong L. Numerical simulation of the effects of combustion chamber geometry on nonroad diesel engine performance. 2011 Int. Conf. Electr. Inf. Control Eng., 2011;2407−2411.
[103] Galle J; DS; MC van de ; RRP; DQ; VA; VS. Experimental investigation concerning the influence of fuel type and properties on the injection and atomization of liquid biofuels in an optical combustion chamber. Biomass and Bioenergy 2013;57. [CrossRef]
[104] Sagaya Raj G, Mallikarjuna JM, Ganesan V. Energy efficient piston configuration for effective air motion - A CFD study. Appl Energy 2013;102:347−354. [CrossRef]
[105] Wei S, Wang F, Leng X, Liu X, Ji K. Numerical analysis on the effect of swirl ratios on swirl chamber combustion system of DI diesel engines. Energy Convers Manag 2013;75:184−190. [CrossRef]
[106] Isaac JoshuaRamesh Lalvani J. PM. DB. AK. Pooled effect of injection pressure and turbulence inducer piston on performance, combustion, and emission characteristics of a DI diesel engine powered with biodiesel blend. Ecotoxicol Environ Saf 2015. [CrossRef]

[107] Li J, Yang WM, An H, Maghbouli A, Chou SK. Effects of piston bowl geometry on combustion and emission characteristics of biodiesel fueled diesel engines. Fuel 2014;120:66–73. [CrossRef]
[108] Rakopoulos CD, Kosmadakis G, Pariotis EG. Investigation of piston bowl geometry and speed effects in a motored HSDI diesel engine using a CFD against a quasi-dimensional model. Energy Convers Manag 2010;51:470–484. [CrossRef]
[109] Ndayishimiye P, Tazerout M. Use of palm oil-based biofuel in the internal combustion engines: Performance and emissions characteristics. Fuel Energy Abstr 2011;36:1790–1796. [CrossRef]
[110] Jaichandar S, Annamalai K. Influences of re-entrant combustion chamber geometry on the performance of Pongamia biodiesel in a DI diesel engine. Energy 2012;44:633–640. [CrossRef]
[111] Rahman MM, Shahabuddin M, Liaquat A, Masjuki HH, Kalam MA. Ignition delay, combustion and emission characteristics of diesel engine fueled with biodiesel. Renew Sustain Energy Rev 2013;21:623–632. [CrossRef]
[112] Tesfa B, Mishra R, Zhang C, Gu F, Ball A. Combustion and performance characteristics of CI (compression ignition) engine running with biodiesel. Energy 2013;51:101–115. [CrossRef]
[113] Chauhan BS, Kumar N, Cho HM. A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends. Energy 2012;37:616–622. [CrossRef]
[114] Keerthi KN, Chandrashekar TK, Banapurmath NR, Yaliwal VS. Effect of combustion geometry on combustion, performance and emission characteristics of CI engine using simarouba oil methyl ester. IOP Conf Ser Mater Sci Eng 2018;376. [CrossRef]
[115] Annamalai R, Kuppusamy R, Krishnan Ramachandran S. Effect of piston bowl geometry and different injection pressure on the performance, emission, and combustion characteristics of diesel engine using biodiesel blend. Therm Sci 2018;22:1445–1456. [CrossRef]
[116] Upendra RAJAK, Prerana PKC, VermaTN. A numerical investigation of the species transport approach for modeling of gaseous combustion. J Therm Eng 2021;7:2054–2067. [CrossRef]
[117] Koten H. Performance analysis of a diesel engine with in a multi dimensional framework. J Therm Eng. 2018;4:2075–2082. [CrossRef]
[118] M. Z. Gül, H. Köten, M. Yılmaz İHS. Advanced numerical and experimental studies on CI engine emissions. J Therm Eng 2018;4:2234–2247. [CrossRef]
[119] Aydin H, Bayindir H. Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. Renew Energy 2010;35:588–592. [CrossRef]