Effect of Modifications of Piston Bowl Geometry in Stationary Diesel Engine Fuelled with Biodiesel–A Comprehensive Review

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Abstract: The fossil fuels are depleting at an alarming rate and as a result its cost is also increasing rapidly. Effect of fossil fuel emissions in the atmosphere is observed more. In this context, effective alternator with suitable changes in the existing CI engine are required. One such alternator is Biodiesel. As literature reveals that usage of Biodiesel in the existing engine will not give the original performance as diesel. Therefore, it is necessary to study the suitable changes that are to be done in the existing engine.
Piston Bowl Geometry (PBG) is the major factor in diesel engine, even slight modifications done in the PBG gives the large changes in the fuel consumption rate, Performance, Emissions and combustion parameters.
This present article, reviews the detailed study of various Piston Bowl Geometries such as Re-entrant type, Toroidal type, trapezoidal, shallow depth etc.., in relevance with its design, performance, emissions and combustion characteristics. And it also reviews the suitability of modified PBG with Biodiesel fuelled CI engine as compared to existing Hemispherical PBG diesel engine which can be used in future to overcome the problems encountered in petroleum based fuel engines.

1. Introduction

Oil reservoirs are depleting at a seriously alarming rate which has gained the attention of researchers to identify an alternate fuel. One such alternate fuel is biodiesel. It was observed that with petroleum based fuel, produces lesser emissions of hydrocarbons, CO but NO_x emissions are higher due to rich oxygen content during chemical combustion process [1-6]. Biodiesel is obtained from plant or biomass. The reaction of palatable and non-palatable with alcohol as a base catalyst yields in esters, which is used as biodiesel. Due to renewability, biodegradability, high flashpoint, less sulphur content of biodiesel makes it a suitable alternate fuel [7-12].

With the use of biodiesel researcher's aim at lesser fuel consumption, higher efficiency and lesser emissions when compared to existing fuel. Mainly in existing engines, chemical burning process taken place in clearance volume in the combustion cavity, by modifying chamber design/piston bowl geometry could achieve the better air fuel mixing and enhance the engine characteristics reasonably [13-16].

Air-Fuel mixture movement has a large impact in the amount of fuel consumption and engine device characteristics. The types of air movement are swirl, squish and turbulence. Among these air movements, efficient one is Swirl type. In this, air is circulated along the circumference of the PBG, as it circulated, increases the exterior air velocity which leads the efficient air fuel mixing to get combusted completely and reduction in emissions [17-25].

Manjunath Channappagoudra K et al [26] investigated the effect of DICI-Toroidal PBG engine functioned with B20 dairy scum methyl ester and the results revealed that 6.5% of brake thermal efficiency improved, 8.75% of fuel consumption per kg was decreases and 15% of reduction in HC and CO emissions was observed whereas NO_x emissions increased by 8.16%.

Kumar V et al [27] modified the standard piston bowl geometry into piston B (toroidal) and C (hemispherical). It was observed that BTE increased by 2.9% for B and 1.9% for C. The BSFC decreased by 8.7% for B and 5.9% for C. HC emissions reduced by 3.1% for B and 2.1% for C. CO emissions lowered by 12.5% for B, whereas NO_x emissions increased by 9.1% for B and 4.2% for C.

Sankar Ganesh R et al [28] instilled two different piston geometries, they are deep bowl geometry and toroidal bowl geometry operated with grape seed oil methyl ester. The studies substantiated that toroidal bowl geometry gave middling engine characteristics for all the mixture. In 25% mixed fuel seen in increases in brake thermal efficiency up to 4.7%. Retardation of Smoke, HC and CO emissions in order of 9.2%, 30.2% and 4.6% respectively. Deep bowl with 25% of biodiesel showed the best results.

A.Ravichandran et al [29] investigated performance and emission characteristics of CI engine with modified PBGs such as shallow depth PBG and re-entrant type PBG. The results exposed that, high in brake thermal efficiency and fuel consumption was observed less for re-entrant type PBG with 20% biodiesel. And also the results showcased that marginal retardation in HC, CO and particulate matter However, NO_X emissions increased.

P. Manikalithas et al [30] modified the standard piston into a piston of toroidal shape and spherical shaped centre and experimentation was conducted. The results revealed that, in higher compression ratio thereby increasing the temperature of combustion chamber. Efficient mixing of the charge was seen providing better fuel efficiency and decreased emissions.

The survey, concludes that PBG is of great importance for performance, combustion and emissions characteristics of an engine. The principle objective of present article is to reveals the suitability of alternate fuels (Liquid and gaseous) for conventional PBG with altered piston bowl geometries and theoretical assessment of effect of altered PBGs on DICI (Direct injection compression ignition) Engine.

2. Piston Bowl Geometry (PBGs)

To get complete combustion and effective performance in CI engine mixing of air and fuel place a very important role. Modifications in piston bowl geometry is the method by which effective design of piston bowl can be considered which gives good circulation of air and fuel during combustion. The various piston bowl geometries are conferred below [31-45]:

Figure 1. Photographic view of Piston with Flat Bowl, before fabricating.

2.1. Hemi-spherical type PBG (HPBG)

It is the conventional design technology of piston bowl for fossil fuels. If biodiesel used as a primary fuel in HPBG, the ratio of depth to diameter doesn't affect the motion and its combustion but in case of conventional fuel this ratio can varied. Biodiesel with conventional PBG does not give proper fuel atomization and incomplete combustion, this lead to the high fuel consumption, retardation in brake thermal efficiency and rise in NO_x emission. This is due to high viscous nature in methyl ester biodiesel. The schematic line diagram and photographic view of HPBG as depicted in Figure 2.

By this contrast, newly developed PBGs and its investigations, effect and applications needs to be explored.

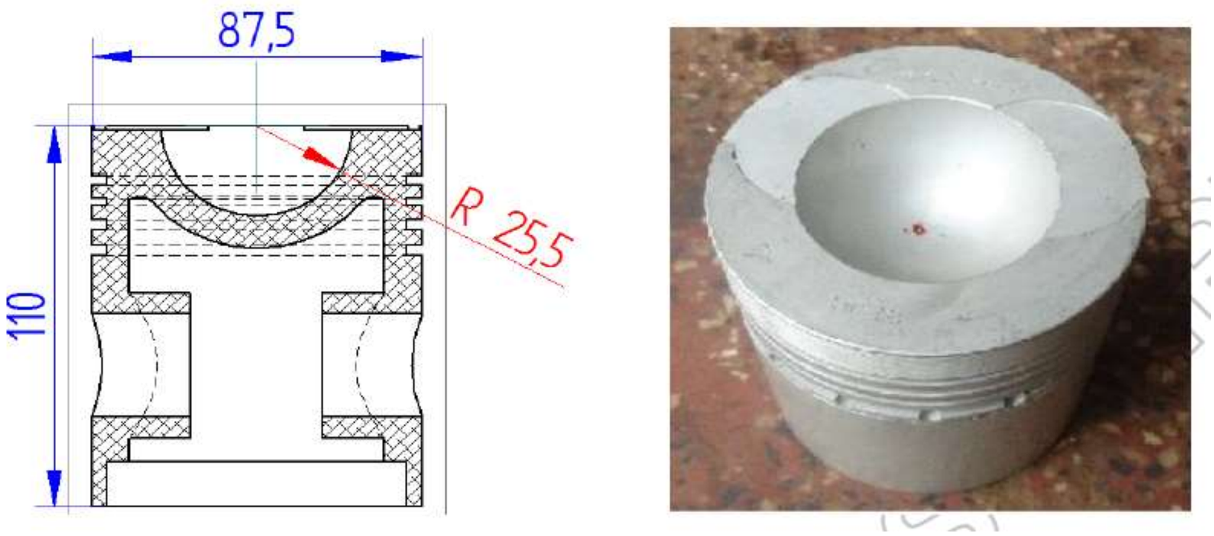


Figure 2. Cut sectional 2D view and Photographic view of Hemi-spherical type PBG

2.2. Square type PBG [SQPBG]

The line diagram and photographic view of SPBG shown in Figure 3. In this type, as piston reaches near to the top dead centre (TDC), the compressed air and fuel mixture leads to the turbulent flow particularly in corner areas of the SPBG.

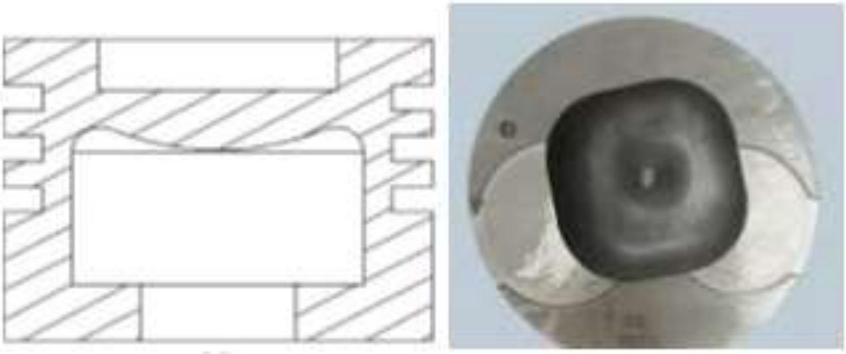


Figure 3. Cut sectional 2D view and Photographic view of Square type PBG

2.3. Shallow depth type PBG [SDPBG]

This type of PBGs generally employed in diesel engine with less speed. Biodiesel application in SDPBG give good combustion and efficiency with those of conventional designs. SDPBG normally fabricated with small depth to High diameter hole on the piston bowl and it is illustrated in Figure 4.

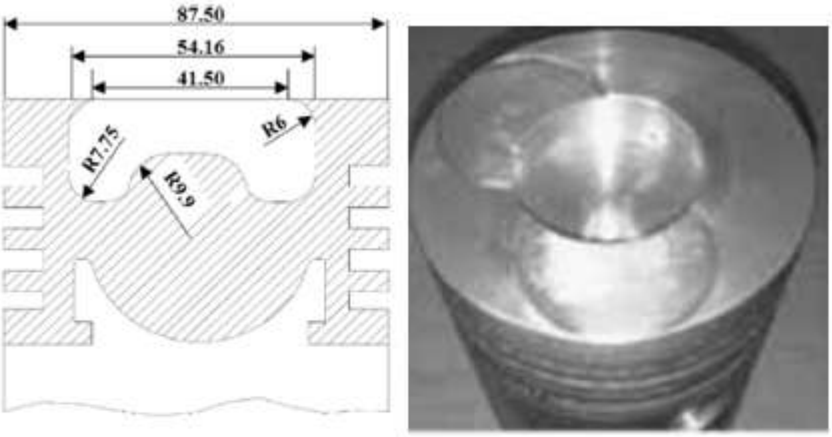


Figure 4. Cut sectional 2D view and Photographic view of Shallow depth type PBG

2.4. Toroidal type PBG [TPBG]

Air fuel circulation in TPBG is very much effective and good, than compared to HPBG and this imposes to the engine to perform well in terms efficiencies and emission parameters. It has two small compartments which are separated by a cone and it designed from 150^o to 160^o from the base of the bowl. This is shown in Figure 5.

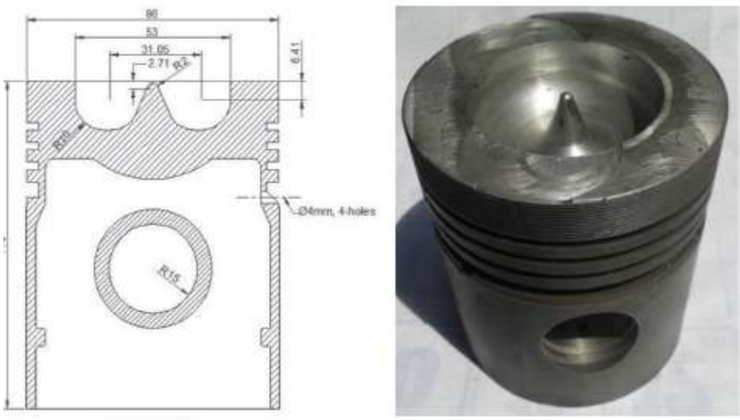


Figure 5. Cut sectional 2D view and Photographic view of Toroidal type PB

2.5. Cylindrical type PBG (CPBG)

In this type, the air fuel motion takes place due to centrifugal force, which is developed in the cylinder during fuel burning process and also the combusted flame layer takes in the form of cylinder. Here the hole designed in cylindrical shape just after the bowl and it can be modified with a cone base angle 90^o and it is inferred in Figure 6.

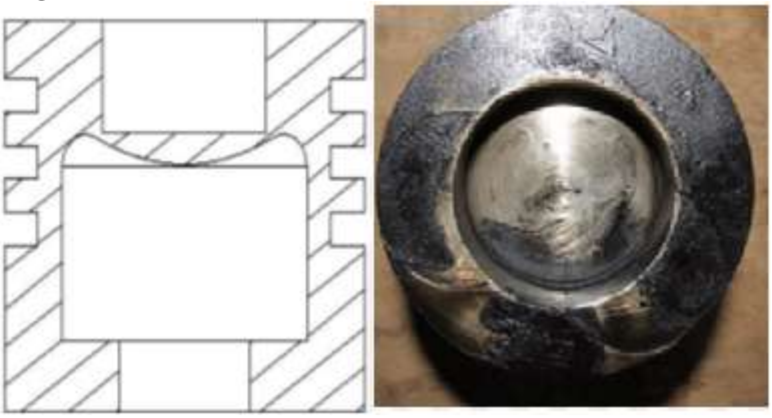


Figure 6. Cut sectional 2D view and Photographic view of Cylindrical type PBG

2.6. Indirect injection type PBG (IIPBG)

This type of PBG generally mounted in light duty diesel engines where high speed is necessary. This can be divided in two parts one in cylinder head and other one is in the main cylinder. Due its indirect injection gives the rapid mixing of air and fuel which gives better combustion and less particulates than equated with convention hemispherical PBG and it is depicted in Figure 7.

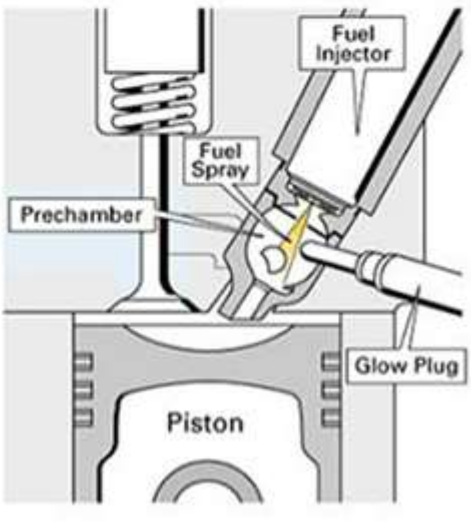


Figure 7. Schematic diagram of indirect injection type PBG

2.7. Swirl type PBG (SWPBG)

In this type the first half of the combustion starts from spherical swirl compartment then the next half of the burning process takes place in the piston head. The diameter of swirl cylinder is less than 100mm and designed in spherical shape. This kinds of PBG usually seen in small engines and it has high heat loss due to its combustion nature. Line and photographic view of SWPBG shown in Figure 8.

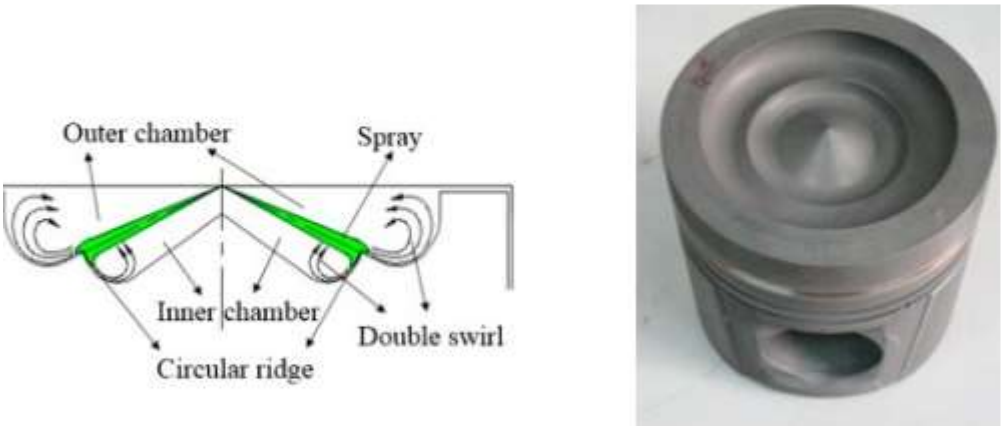


Figure 8. Line and Photographic View of Swirl type PBG

2.8. Pre combustion PBG (PCPBG)

Pictorial representation of Pre combustion PBG is depicted in Figure 9. In this type, pre combustion cavity contains 40% volume of total volume of combustion cavity and it contains number of holes through which fuel is injected at a pressure less than 450psi.

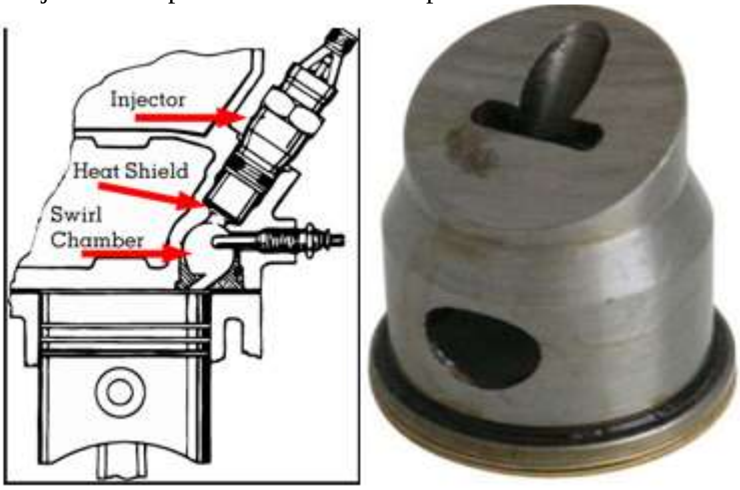


Figure 9. Pictorial and photographic view of Pre combustion PBG

2.9. Re-entrant type PBG (REPBG)

Figure 10 explore the geometrical dimensions and photographic view of REPBG. Re-entrant PBG has a smaller in diameter at the opening as well as in central in cavity. In this type the edge of the compartment gives considerable development in engine performance and retardation emissions factors. The bowl edge avoids the circulation of air suck by pushing fuel above the piston bowl. Therefore it creates better air fuel motion and gives good combustion.

Figure 10. Cut sectional 2D view and Photographic view of Re-entrant type PBG

2.10.Deep PBG (DPBG)

The design and construction of DPBG as shown in the Figure 11. DPBG are more effective than SDPBG due to its complete mixing of fuel air and combustion nature.

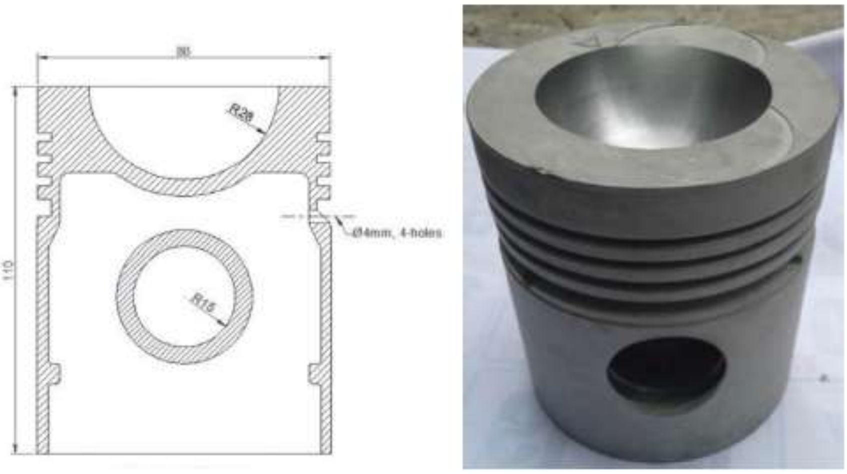


Figure 11. Cut sectional 2D view and Photographic view of Deep PBG

2.11.Trapezoidal PBG (TPBG)

The new design of PBG which has been tried to incorporate in existed diesel engine shown in Figure 12 and this has been discussed in detailed in the section 4.

Figure 12. Photographic view of Trapezoidal PBG

Table 1 Air fuel circulation in various PBGs [46-55]

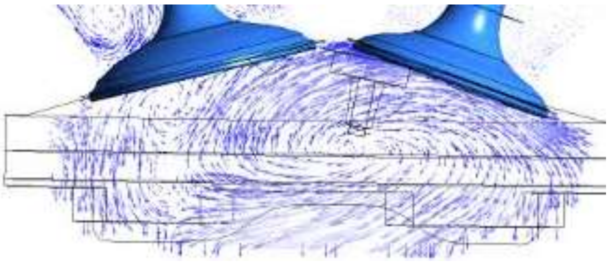
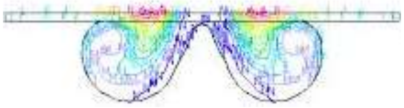
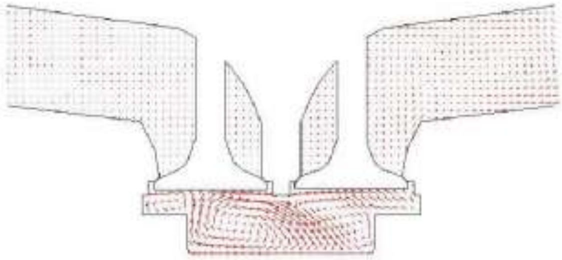
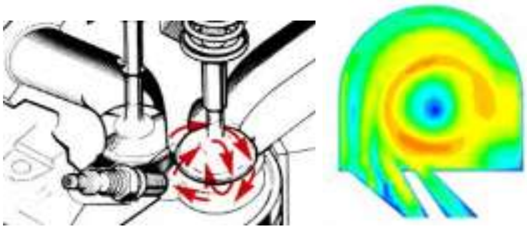
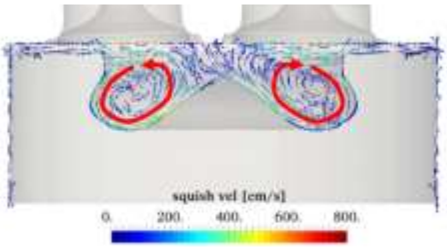
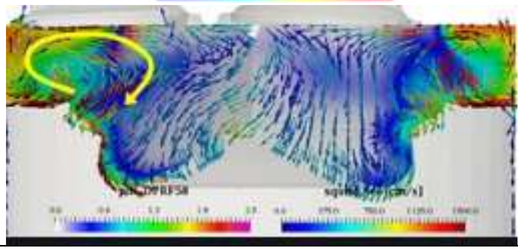
Type of Piston bowl geometry	Air Fuel circulation
Hemi-spherical type	
Shallow depth type	
Toroidal type	
Cylindrical type	
Swirl type	
Pre combustion type	
Re-entrant type	
Stepped lip bowl	

Table 2 Fabricated Piston geometry specifications [56,57]

Particulars	Type of Piston		
	Standard (HPBG)	**TPBG**	**REPBG**
Bowl Volume (mm^3)	34,727.95	34,727.44	34724.5
Throat diameter(mm)	51	51	41.93
Bowl depth (mm)	25.5	17.15	20.0
Piston diameter (mm)	87.5	87.5	87.5

Table 1 and 2 shows the flow pattern of air fuel and geometrical specifications of the various piston bowl geometries.

3.Factors considered while designing/fabricating piston bowl

The design of the piston bowl strongly determines the air fuel circulation which strongly effect the fuel burning process and its effect on engine characteristics. Therefore, it is necessary some factors has to be considered while designing piston bowl and they are conferred under the following sections [58, 59].

3.1. Molecular structure of fuel

Detonation greatly depends upon the fuel employed. Generally, if molecular structure is compact, there is lower tendency to detonate.

3.2. Detonation temperature

If fuels have less detonation temperature, they leads less detonating during working stroke and vice-versa.

3.3. Effect of High pressure and temperature developed at the end of fuel ignition

The flame velocity, retards the detonation and improves the pressure and temperature at closer to the compression stroke. This leads to the reduction in delay period of the beginning chemical burning process there by more detonation and this results the predomination.

3.4. Burning rate of fuel

If fuel burning rate is high, leads to the large detonation due to generation of high temperature, this results in faster rate of heat flow to the walls of the cavity.

3.5. Timing of spark during fuel burning

It is the one of important factor by which engine efficiency can evaluated. Therefore care has to be taken while adjust the ignition timing and it is depends on the manufacturer’s specifications. If spark is retarded during burning this leads to the engine crack and overheating and also some amount of heat entering in to the engine block, cylinder head surface and through exhaust gas without using to produce some power and hence spark timing has to keep in such a way that burns the fuel as fast as possible.

3.6. Ratio of Air-fuel

The air fuel ratio has to maintain according to the stoichiometric ratio. If this ratio not maintained according to the standards and working condition, leads the incomplete burning fuel and produce less power and increases the emissions.

3.7. Chamber volume ratios

It is necessary, care has to be taken while designing volume of combustion chamber such as clearance and stroke volume. If compression ratio is more, that leads the large engine power and vice-versa. Therefore the designed piston bowl should give the high compression ratio.

3.8. Engine speed

As a result of increase in the engine speed, the flame speed decreases which will not affect the effect of the delay period much. This will decrease the tendency of detonation of most of the fuels. But some fuels may detonate more quickly during higher speed. The reason for this has yet not been established.

4. Impact Analysis of various designed piston bowl geometries on DICI engine

In this section reviewed the impact of various designed piston bowl geometries on DICI engine efficiencies, combustion and emission parameters from various literature study [60-63].

4.1. Specific fuel consumption of Brake Power

Experimentation on Biodiesel with different PBGs and the results reveals that the fuel consumption rate is less at full load condition than compare to neat diesel fuel. This is due to high viscus, density and lower heating value of biodiesel. It was seen that from various PBGs results, TPBG gave better SFC other than those of CPBG, SQPBG, SPBG etc..,

In Biodiesel, the Heating value is less than the diesel and BSFC level is more compared to diesel, thus biodiesel has low brake thermal efficiency than compared to diesel fuel. Reduction of BTE in biodiesel is due to high viscus, low air-fuel mixture, higher volatility and low calorific value. When different bowl geometries were tested against biodiesel alone, it gave good result for TPBG due to complete combustion.

4.2. In cylinder pressure variation

Biodiesel has high viscus and denser in nature therefore it is necessary to maintain high injection pressure (IP) to get complete atomization of fuel droplets. The results of HPBG inferred that at high IPs say about 240 bar observed BTE was more than compare to standard IP, this is due to high pressure in cylinder. This leads better atomization of fuel, proper mixing and enhanced engine characteristics. Three different PBG such as HPBG, TPBG and SPBG considered with varying injection pressure say 200 to 260 bar respectively and conducted Experimentation, the results inferred that, at 20% blend rise in cylinder pressure was less than compare to standard fuel, this due to high viscus nature in biodiesel and 20^{o} after TDC, jump in cylinder pressure has been observed for all blends of biodiesel with SPBG. An assessment done for TPBG and HPBG, the results shown that, depressed in cylinder pressure at 20% mixture than compare to standard fuel due to high viscous and low calorific value. Based on the discussions it seen that, modified PBG gave reasonable pressure rise at different proportion of mixture than compare to standard PBG and fuel.

4.3. Heat release rate (HRR)

As discussed earlier, better air fuel blend gave economic rate heat release due to complete combustion. This can be achieved by modifications of PBG specifically for alternate fuels. The standard PBG and fuel Experimentation was conducted on three different PBGs such as steeped, bathtub and stock type PBG and the results depicted that the HRR was reasonably high for stepped type than compare to stock type and better combustion was seen in bathtub type PBG. Investigated the effect of TPBG, CPBG and HPBG on mahua biodiesel and the results reveals that HRR was high in TPBG than compare to rest of all the PBGs. This is due to proper fuel mixing and atomization. Finally the literature reveals that, to get high HRR in biodiesel modifications in PBG is must and very much essential.

4.4. Delay in detonation

Investigative studies on ignition delay/ delay in detonation (ID), on various biodiesels with unmodified chamber, out comes reveals the results that shown are reasonable reduction in burning time, this is due to high viscous and density of all blends and ID decreases along with the load for all shapes of cavity such as TPBG, HPBG, CPB and RPBG. This is due to complete combustion and proper mixing of fuel droplets, high pressure and temperature in the cylinder.

4.5. UBHC emission

Unburnt Hydrocarbons (UBHC) from exhaust observed was less in biodiesel at all percentage of combinations with standard combustion compartment this is due to high oxygen availability and cetane number. Same trend seen in various modified compartments and it also observed was improved reduction in UBHC than compared to standard PBG.

4.6. CO emission
Investigated the emission of CO for various biodiesel with and without modified cavity. The results discloses that % of CO in exhaust gas is depleting as load increases for all type of PBGs this is due to high oxygen content and cetane number but it observed that TPBG gave acceptable depletion of CO emission than compare to other PBGs.

4.7. NO_x emission
When biodiesel was operated instead of diesel, there was a minor increase in NO_x emission in all type of geometries and increase of NO_x emission depends on biodiesel blend, which is due to the high cetane number of biodiesel compared to diesel. But this also depends on the load applied. It was observed that there was an increase in NO_x emissions at high loads but a slight decrease at low loads because at low load, less fuel injected in the combustion chamber by which less oxygen content in the combustion chamber and produces low temperature.

4.8. Smoke
Particle solution reduces for biodiesel than compare to diesel fuel due to high oxygen content and cetane number. As oxygen content is more, complete oxidation reaction take place even in each zone leading to a less emission of smoke and particulate matter. Biodiesel has more cetane number where the ignition delay is cut off and also increases combustion time period hence reducing the smoke emission. Biodiesel has been used in three different bowl geometry and it is noticed that in toroidal geometry, the emission is least. Smoke denseness was observed for SPBG, RPBG and TPBG are 134 mg/m^3, 131 mg/m^3 and 127 mg/m^3 in decrement order. This is due to turbulent flow of fuel and air and this provides better atomization and mixing and also due to high oxygen content. It is seen that TPBG gave less denser smoke almost it reduces 20% of less smoke than compare to standard PBG specifically at 20% of blend.

4.9. SO_2 emission
SO_2 content in exhaust emission of biodiesel observed was decrement in order as % of blend increases when compare to diesel. This is due to less content of sulphur in biodiesel. Further reduction of SO_2 seen in modified PBGs this is due to complete combustion and less sulphur content.

5. Conclusion

Effect various PBGs have been discussed and the following conclusions were arrived at.

- The various piston bowl geometry such as TPBG, SPBG and CPBG etc.., have been studied and it is seen that, all the modified chambers gave better fuel and air flow propagation and complete combustion than compare to standard one.
- Fuel spray tendency in modified geometry plays an effective role, because spray should provide excellent turbulent flow. RPBG fuel injection gave good turbulent flow and it was seen in RPBG effective combustion than compare to HPBG.
- From the previous discussions, it was observed that, effective circulation of air and fuel in decreasing order were shown as TPBG>SPBG > CPBG> HPBG > SQPBG.
- TPBG gave better air fuel circulation and it gave improved engine characteristics than compare to HPBG.
- RPBG gave less ignition delay than compare to HPBG. ‘

- The results obtained from numerical studies also conclude that, TPBG is the best design than compare to rest of all the PBGs and it is an effective tool (CFD tools Fluent, CFX, STAR- CD etc..,) by which all the flow behaviour could be analysed before experimental investigations.

Only limited number of experimental works have been carried out under modified piston bowl geometries with duel fuel mode of operation, coating on a piston bowl and optimization of engine operating variables such as Injection pressure, injection duration and compression ratio to enhance the working ability of an engine. Therefore, researchers could concentrate on these areas and come out with better CIDI engine for the society.

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