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CFD Analysis of piston bowls geometry for CI direct injection engine using finite element analysis

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Abstract

Both NOx and soot emissions are major concerns in compression ignition (CI) engine with diesel fuel and the enhancement of variety of fuel and air can increase the performance of combustion engine. There are several methods to enhance the variety of air-fuel within the cylinder. Altering the geometry of piston bowl is one of the methods to improve the air-fuel mixture. This article proposes the effect of piston bowl geometry on the direct injection diesel engine performance and emissions, where various profiles of piston bowl referred as hemispherical combustion chamber (HCC), toroidal combustion chamber (TCC) and shallow depth combustion chamber (SCC) are designed using computer aided design and drafting (CADD) tool and ANSYS workbench is adopted for analysis. In addition, Karanja oil mixed with base fluid diesel at different volume fractions like 0.2%, 0.3% and 0.4% and are calculated for their combination properties. Further, theoretical calculations are considered to determine the properties of Nano fluids which are later used as inputs for the analysis. Finally, CFD analysis is employed on different geometries at different fluid volume fractions and thermal analysis is done for piston bowl geometries with different composite materials like carbon fiber and armide fiber.

Keywords: (Compression Ignition Engine, Direct Injection Engine, Piston Bowl Geometry, CFD analysis, Finite Element Analysis.)

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1. Introduction

Durability and higher thermal efficacy nature of CI engine makes them to be considered for the utilization of heavy-duty as compared to the engines with spark ignition [[26],[7]]. However, conventional engines of diesel combustion (CDC) are confronting substantial disputes in fulfilling growing regulations of rigorous emission because of NOx and emissions of particulate matter [[8]]. Advances in the flexibility and exactness of commo-rail injection systems [[35]] have permitted the detailed investigation of conceptions of low-temperature combustion (LTC) like partially premixed combustion [[33], [9]], intelligent charge compression ignition [[13], [34]], homogenous charge compression ignition [[17]-[18]], reactivity-controlled compression ignition [[27], [12]] and diesel methanol dual fuel [[14]-[31]] etc. In most cases, one fuel is injected directly into the cylinder of these LTC engines all the way through the stroke of intake and/or compression to form a lean in relative manner and ranked mixture of fuel and/or air before the ignition onset [[22]]. Therefore, it is always necessitated a high compression ratio for the LTC engines to ignite the mixture of lean. In addition, the staged combustion also noticed because of the in-cylinder stratification of mixture, which extends a chance to obtain higher thermal efficacy and lower emissions of NOx and particulate matter at the same time without employing the valuable after-treatment technologies. The low-reactive fuels such as gasoline had a sustained delay of ignition as compared to diesel fuel and therefore an enhanced mixing of fuel-air renders great advantages in the extensions of load and knock control in the engines with direct-injection compression ignition [[19]]. Arumugam et al. [[11]] studied the performance of diesel engine with the usage of ethanol-based rice bran oil methyl ester at variety ratios such as 1%, 2%, and 5%. This study disclosed that biodiesel concentration improvement in the fuel blend determines the emissions of NOx and CO2 and diminishes HC and CO emissions. It was also described that the blends of ethanol-B20ROME decreases the emission of NOx and CO2, which are the major global warming contributors. In [[29]], authors investigated the performance, characteristics of emission and combustion of a direct injection diesel engine with single cylinder using the Annona methyl ester as a fuel by the antioxidant's summation like a-tocopherol acetate, p-phenylenediamine, 1-ascorbic acid, and 1, 4-dioxane etc. The produced results shown that the additives of antioxidants are surprisingly efficacious in controlling the emission of the NOx. Ellis [[1]] reported that the effective mixing of fuel-air has substantially enhanced with the combustion chamber alteration by appropriate piston bowl and greatly improved the release rate of peak pressure heat. In [[3]], authors have attempted to obtain the advancement in the formation of mixture with the geometry alteration of combustion chamber and they have reported that the re-entrant cavity with a round lip rendered more prominent spray volumes and broader spray spreading. In addition, bottom corner radius innovation assists to disseminate the accumulated fuel at the bottom corner and there by increases the spray volume. A recent study [[20]] made on the performance efficiency of combustion chamber geometry with the blend emission of ethanol-diesel in a diesel engine disclosed that the TCC created more beneficial swirl, squish, and turbulence at higher ratios of compression (19.5:1) as equated to HCC. In addition, it was also described that the brake thermal efficacy for TCC is 33% and there was also an increment in the peak pressure and release rate of peak heat in the cylinder. Further, they have also concluded that emissions of Co, HC, NOx, and smoke were mitigated to 60%, 20%, 40%, and 90%, respectively for TCC as compared to the HCC. Authors in [[10]] studied the emission features and its performance in both TCC, and HCC with 20%, and 80% of orange oil methyl ester and diesel, respectively. This study revealed that the emissions of NOx and HC were mitigated in TCC as compared to HCC. However, the emission of smoke was bit lower in HCC when compared to TCC. Rajan and Kumar [[24]] tested the diesel engine performance with the biodiesel made of using internal jet and methyl ester of Jatropha oil, where the emissions of exhaust gas has been reduced greatly at full load because of air's turbulence motion betterment. The performance comparison of traditional and re-entrant combustion chambers w.r.t. combustion process, smoke, and NOx emission and the engine performance for diesel engine is studied by Saito et al. [[28]]. The results demonstrated that the re-entrant combustion chamber improved the combustion due to the more prominent velocity of in-cylinder followed by enhanced turbulence. A numerical investigation on the influence of the geometry of piston bowls on the combustion and emission features in a biodiesel and its blends fueled diesel engine is studied in [[15]], where the experimentation results reported, lower CO emissions and higher NO emissions for the operation of Omega combustion chamber with biodiesel. A numerical study on the effect of the high swirl inducing piston to mitigate the emissions of exhaust is presented in [[23]] and reported that obtained results led to a 27% and 85% reduction in the emissions of NOx, and level of soot, respectively as equated to the base engine. The performance of injection pressure and re-entrant combustion chamber with 20% of Pongamia biodiesel in diesel engine was studied [[5]] and found that the emissions of smoke, CO, and UBHC have been mitigated, and NO has enhanced with injection pressure of 220bar because of combustion improvement. An experimental analysis on the internal jet induced piston bowl effect with the emulsified diesel fuel is addressed by Wamankar and Murugan [[30]], in which a superior mitigation of emission has been obtained through an altered piston bowl because of variation in swirl and fuel-air interaction. In [[6]], authors investigated the performance study of TCC and shallow depth re-entrant combustion chamber with a Pongamia biodiesel to power a diesel engine. The results demonstrated that there was an improvement in the formation of mixture using the re-entrant bowls with the enhanced fuel-air interaction which led to the performance characteristic enhancement. Bapu et al. examined the effect of an altered profile of combustion bowl on a diesel engine with Calophyllum inophyllum methyl ester [[25]] and reported that the bowl with the smaller diameter to the ratio of depth had a larger flow of squish ensuring in the improvement of performance features. Li et al. examined the CFD analysis of piston bowl geometry in biodiesel supplied diesel engine by three distinct combustion bowls like hemispherical, omega and shallow depth with solitary cylinder [[16]]. The obtained results disclosed that omega combustion chamber attained engines with high-speed as a result of high-quality squish motion, and there has been a performance enhancement due to the complete admixture of fuel-air. Harshavardhan and Mallikarjuna [[4]] studied the CFD analysis of in-cylinder flow and the interaction of fuel-air on various geometries of combustion chamber in direct injection spark ignition engine, in which the speed of engine and the crank angle was fixed. Authors in [[21]] studied the performance characteristics of fuels in engines and reported that conflicts in the composition of fuels played a substantial role on engine performance since they led to the establishment of combustion chamber deposits. In addition, the component of the fuel substantially varies in their tendency of implant shaping, and hence the combustion chamber implants in gasoline engines can enhance the emission of NOx and hydrocarbon. But still, higher emissions of unburned hydrocarbon and CO are the serious concerns of gasoline direct injection spark ignition engines, and the issues of cold start at the lower loads resulting in low fuel reactivity. Further advances are necessitated for the gasoline direct injection compression ignition engines to obtain the optimal distribution of fuel in the cylinder, that powerfully influenced with the system of fuel injection, and its strategy, design arguments of injector-nozzle, chemical and physical attributes of fuel, shape of combustion chamber and their operation circumstances such as compression ratio, intake temperature and pressure. Therefore, the major contribution of this work is as follows:

- To perform the static analysis on different geometries namely HCC, SCC and TCC with different materials to study the deformation, stress, and strain.

- Perform thermal analysis on the different geometries using different materials to examine the

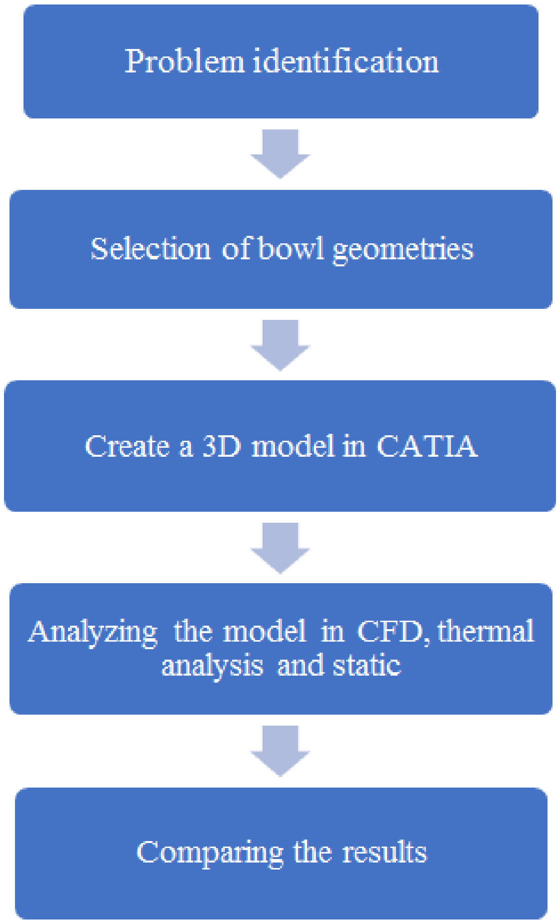

Figure 1: Proposed work flowchart

distribution of temperature and heat flux.

- Perform CFD analysis on the existing model of the piston bowl geometry for velocity inlet to find out the turbulence intensity, pressure drop, and emissions (NOx, CO, ..., etc.).

2. Materials and methods

Proposed flowchart of piston bowl geometry analysis using CFD is illustrated in Figure 1, where it comprises of 5 phases. Initially, it requires a problem identification and then bowl geometries should be selected. Now, a 3-D model will be created using CATIA and then it is analyzed in CFD, static and thermal. Finally, the obtained results are compared to find out the best suitable geometry. The biodiesel can be generated from the renewable resources such as animal fat and vegetable oils and this will be used as a fuel in diesel engine by just blending it with diesel or in its actual form. In general, a lesser harmful gassed will be emitted from these sorts of biodiesel blended diesel fuels as compared to regular diesel fuel. India is still developing country where the importing of petroleum products is $<70\%$ as of current statistics. As mentioned above, the biodiesels generated from local renewable resources renders energy security, reduced bill for importing, employment generation and mitigated harmful gases emission. However, the production of biodiesel using the comestible oil has not economical for India due to their higher cost. Thus, several non-comestible oil seeds such as

Table 1: Thermo physical properties of fluids

Specification	Diesel	Karanja
Density (kg/m3)	959	920
Thermal conductivity (w/m-k)	0.13	0.0168
Specific heat (j/kg-k)	2220	1572
Viscosity (kg/m-s)	0.006123	0.003831

Table 2: Obtained thermo-physical properties of diesel fuel mixed with Karanja oil at different volume fractions

Volume fraction	Density (kg/m3)	Specific heat (j/kg-k)	Thermal conductivity (w/m-k)	Viscosity (kg/m-s)
B10	951.21	2094.650	0.13944	0.00918
B15	947.3	2031.202	0.14433	0.01071
B20	943.4	1967.229	0.149349	0.01224

Karanja, Neem, Jatropha, Mahua and Sal etc. are widly utilized due to their low cost. In this article, Karanja oil is used to produce the biodiesel because they can grow on roadsides, canal, and portions of agricultural lands boundary with minimal care.

2.1. Calculations to determine properties of fluid by changing volume fractions

- **Density of fluid**

$$\varsigma_f = \phi \star \varsigma_k + [(1-\phi) \star \varsigma_d] \tag{2.1}$$

- **Specific heat of fluid**

$$C_{pnf} = \frac{\phi \star C_{pk} + [(1-\phi)(\varsigma_d \star C_{pd})]}{\phi \star \varsigma_k + [(1-\phi) \star \varsigma_d]} \tag{2.2}$$

- **Viscosity of fluid**

$$\mu_{nf} = \mu_w (1 + 2.5\varphi) \tag{2.3}$$

- **Thermal conductivity of fluid**

$$K_{nf} = \frac{K_k + 2K_d + 2(K_k - K_d)(1+\beta)^3 \star \phi}{K_k + 2K_d - (K_k - K_d)(1+\beta)^3 \star \phi} \star K_d \tag{2.4}$$

2.2. Materials used in piston

Usually, the thermal expansion coefficient of cast iron piston is quite less as equated to the piston of aluminum, however, the loss of power is bit of high due to the piston weight and the density of cast iron is 2.5 time greater than the piston of aluminum. In addition, the thermal expansion coefficient of aluminum is 2.5 times greater than the value of cast iron. Hence, an enhanced authorization needs to be provided between the cylinder wall and the piston to prevent striking of piston while operating the engine at every point under heavier loads.

Table 3: Thermal, physical, and mechanical properties of materials

Specification	Cast iron	Aluminum alloy	Silicon
Density(kg/m3)	7200	2700	2330
Thermal conductivity(w/m-k)	52	155	1.23
Youngs modulus (Mpa)	24400	68000	140000
Poisson ratio	0.26	0.3	0.275

2.2.1. Aluminum alloy

Aluminum is noteworthy for the low-density metal and the potential to elude erosion on account of the passivation development. The structural components formed by employing aluminum and their alloys are necessary to the industry of aerospace and are even crucial in many research fields like transportation and structural materials. Both the oxides and sulfates are greatly useful combinations of aluminum based on the foundation of weight. In addition, aluminum is lightweight, ductile, soft, tensile, and durable as compared to other materials and it has an effective electrical and thermal properties. It is having 59% of copper conductivity and 30

2.3. Comparison between aluminum alloy and cast iron

The alloys of aluminum employed for pistons have higher conductivity of heat which is approximately 4 times of cast iron. Thus, these pistons guarantee higher heat transfer rate and hence keeps down the difference of maximum temperature of the center and edge of piston crown or head. In addition, the thermal expansion coefficient of aluminum is 2.5 times greater than the value of cast iron. Hence, an enhanced authorization needs to be provided between the cylinder wall and the piston to prevent striking of piston while operating the engine at every point under heavier loads.

2.4. Silicon

It is the 8th most common element in the universe, but quite seldomly happens as the pure free element in nature. It is greatly propagated in sands, planets, dusts, and planetoids as different silica forms. In addition, silicate minerals are composed over 90% of the crust of earth which makes the silicon as the 2nd most abundant element after oxygen. It is a solid at the temperature of room, with 1414^0 C of high melting point and 3265^0 C of high boiling point, respectively. The alloys of aluminium-silicon are broadly utilized in the casting industry of aluminium alloy, whereas the silicon is the single most significant linear to aluminium to enhance the properties of casting.

3. Modeling and simulation

3.1. CATIA parametric software

CAD is a computer software tool employed for the design of product and CAM is a computer software/hardware that is utilized for controlling, planning, and managing of manufacturing product operations. CATIA stands for computer-aided 3-D interactive application, which is a leading 3-D software tool utilized in most of the industries from automobile, and aerospace fields.

3.2. ANSYS

The governing equations in ANSYS Forte adopts mainly the equation of momentum, continuity, and energy to resolve the issues of computational fluid dynamics. The conservation equation for species is given by:

$$\frac{\partial \rho}{\partial t} + \nabla.\rho k \mu = \nabla.\rho DT \nabla \rho k \rho + \rho Kc + \rho ksk = 1, ...K \tag{3.1}$$

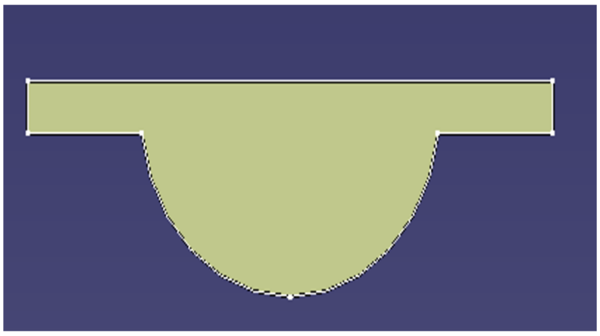

Figure 2: Design of hemispherical chamber

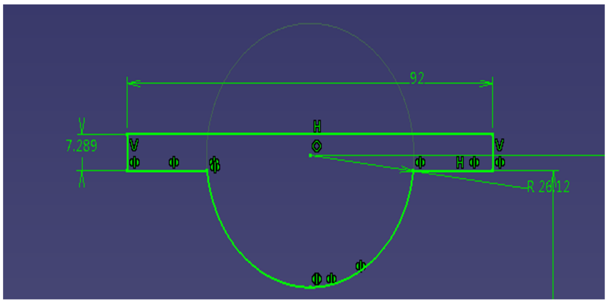

Figure 3: 2D drawing of hemispherical chamber

Where, density is denoted as ρ, number of spices and the index of species are denoted as K and k, respectively. The vector of flow velocity is represented as μ. DT denotes a mixture-averaged turbulent coefficient of diffusion. The source terms obtained due to the reactions of chemical and spray evaporation are denoted as pkc and pk. Below equation gives the continuity for the total fluid

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho . \mu) = \rho \tag{3.2}$$

4. Results and discussion

4.1. Grid models of HCC, TCC, and SCC

In general, grid independency is used to check the result for solution that is independent from different mesh types and size, which means that the result is only depends on the boundary circumstances of CFD domain.

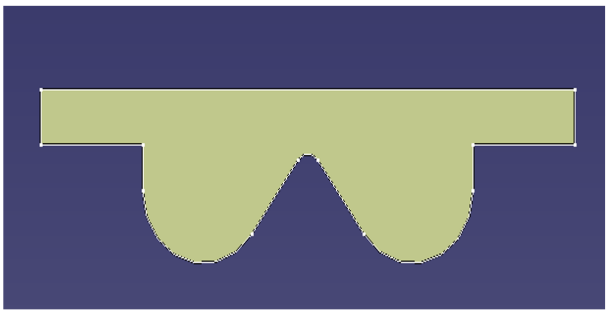

Figure 4: Toroidal chamber

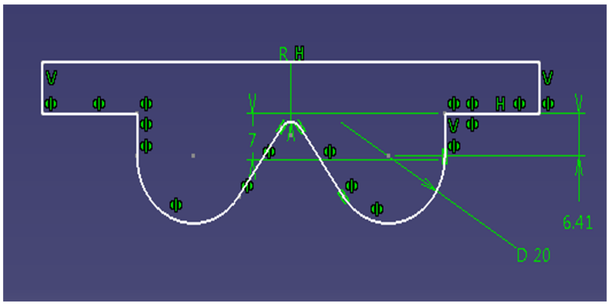

Figure 5: 2D drawing of toroidal chamber

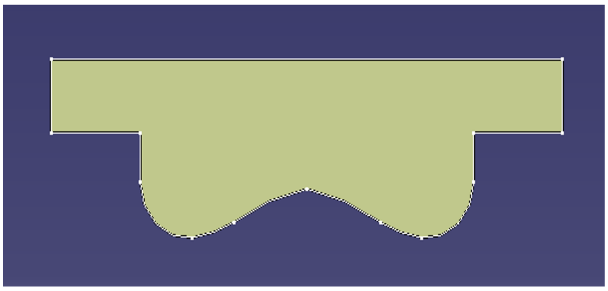

Figure 6: Shallow depth chamber

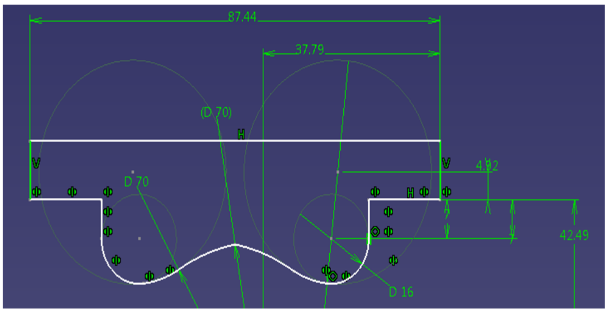

Figure 7: 2D drawing of shallow depth chamber

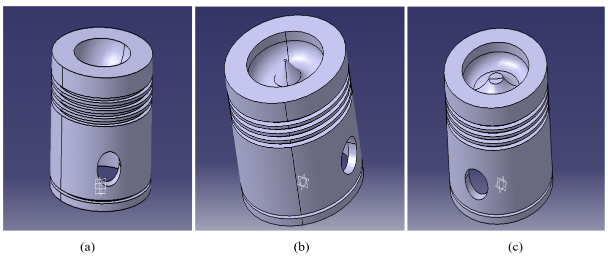

Figure 8: 3D model of piston bowl geometries. (a) Hemispherical chamber. (b) toroidal chamber. (c) shallow depth chamber.

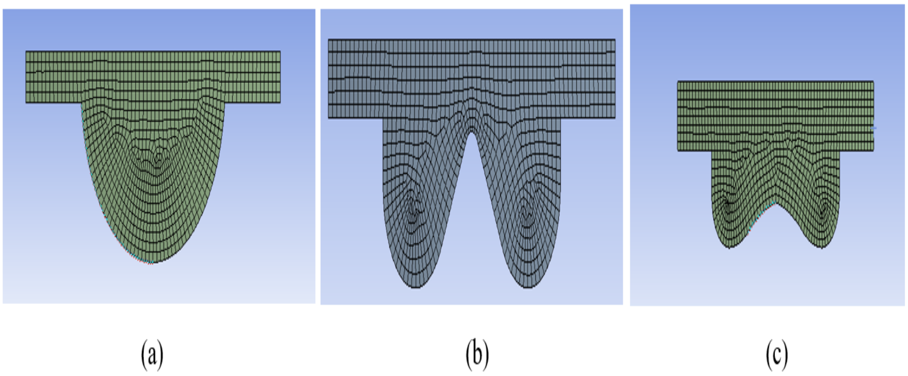

Figure 9: Meshing models piston bowl geometries. (a) HCC. (b) TCC. (c) SCC.

Table 4: Input parameter of CFD domain

Parameter	Magnitude
Crank shaft speed	1500
Crank radius	47
Bore	85
Stroke	85
Fuel	Diesel + B20 (Karanja oil)

The meshing models are designed with the help of CATIA as shown in Fig. 8(a), (b), and (c) which are then imported on ANSYS for meshing (shown in Fig. 9(a), (b), and (c)) and analysis. The analysis of CFD approach is used to compute the pressure, turbulence intensity, velocity, N2 plots and CO2. For meshing, the fluid ring is divided into two connected volumes. Then all thickness edges are meshed with 360 intervals. A tetrahedral structure mesh is used. So, the total number of nodes and elements are 21264 and 109297.

4.2. Observations

This section describes the observations made after the CFD analysis of HCC, TCC and SCC with various piston bowl geometries. Figure 10 illustrates the HCC at fuel diesel+B20, path lines and counter plots where Fig. 10(a) represents the pressure plot, Fig. 10(b)-(d) demonstrates velocity plot, turbulence intensity, and molar concentration of N2. Figure 10(e) discloses the molar concentration of CO2. Similarly, Fig. 11, and Fig. 12 demonstrates the TCC, and SCC profiles at fuel diesel+B20, path lines and counter plots, respectively. From Fig. 10, it is observed that there is improper propagation of air molecules, and uneven distribution of pressure and velocity as well, whereas the TCC profile of piston bowl geometry resulted in uniform distribution of air molecules and swirl. In addition, the distribution of pressure also more uniform as equated to HCC profile of piston bowl geometry. But still, the air molecules velocity is observed as low compared to HCC. In the case of SCC, there is enhanced distribution of air molecules and pressure, production of swirl as compared to both TCC, and HCC profiles of piston bowl. Further, the distribution of velocity and air molecules velocity within the cylinder also enhanced.

Fig. 13 is plotted between pressure and piston bowl geometries, where the pressure is a significant attribute of a diesel engine due to that it takes care of rate of fuel mass flow and the value of heating. The graph compares the pressure of various fuels (D100, B10, B15, and B20) used in the diesel engine. It shows that while increasing in the blend composition automatically it increases the pressure. The

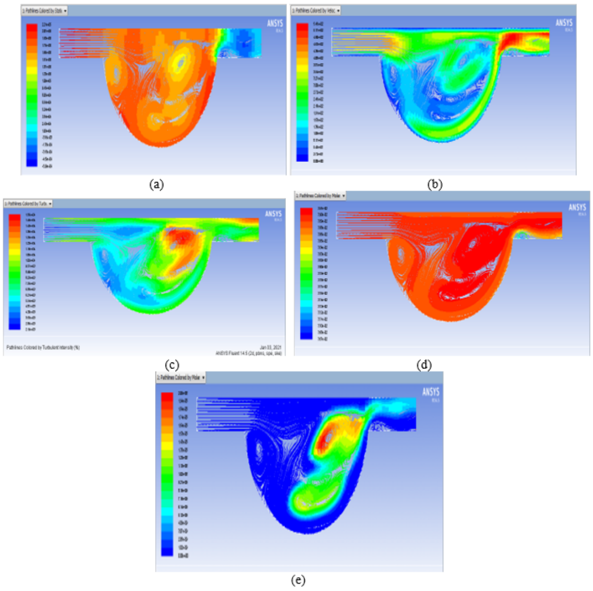

Figure 10: HCC at fluid diesel+B20, path lines counter plots. (a) pressure plot. (b) velocity plot. (c) Turbulence intensity. (d) molar concentration of N2. (e) molar concentration of CO2.

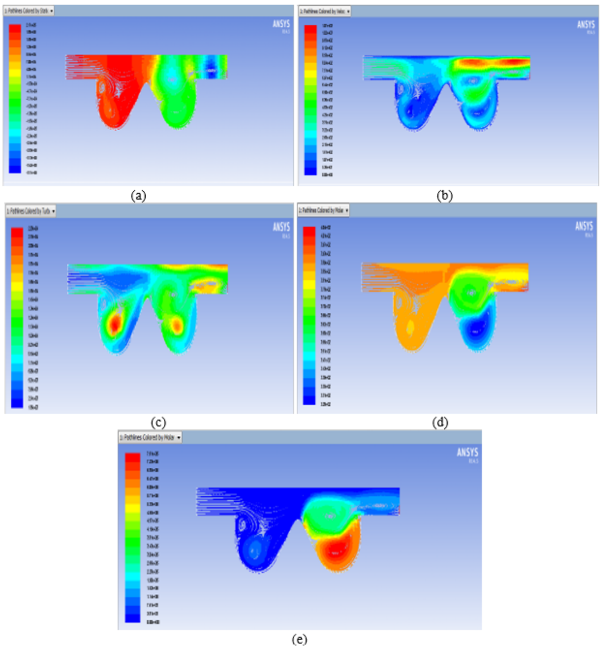

Figure 11: TCC at fluid diesel+B20, path lines counter plots. (a) pressure plot. (b) velocity plot. (c) Turbulence intensity. (d)molar concentration of N2. (e) molar concentration of CO2

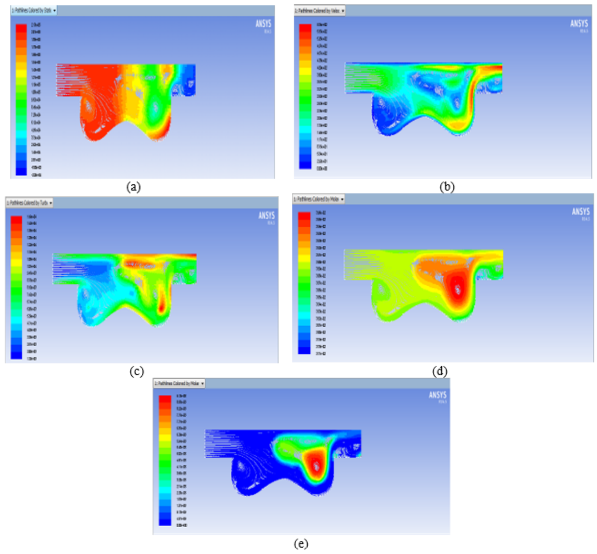

Figure 12: SCC at fluid diesel+B20, path lines counter plots. (a) pressure plot. (b) velocity plot. (c) turbulence intensity. (d)molar concentration of N2. (e) molar concentration of CO2

Table 5: Obtained results using CFD analysis

Shape of geometry	Fluid and volume fraction (%)	Pressure (Pa)	Velocity (m/s)	Turbulence Intensity (%)	Molar concentration of N2	Molar concentratio of CO2
Hemispherical	Diesel	1.95e+05	4.16	9.81e+03	0.0542	1.85e-07
	B10	2.01e+05	4.72	9.99e+03	0.0492	1.95e-07
	B15	2.12e+05	5.12	1.13e+04	0.0421	2.01e-08
	B20	2.25e+05	5.45	1.56e+04	0.0391	2.05e-08
Toroidal chamber	Diesel	2.45e+05	6.83	2.13e+04	0.0611	8.91e-05
	B10	2.76e+05	8.12	2.34e+04	0.0593	8.08e-05
	B15	3.27e+05	9.16	2.56e+04	0.0445	9.07e-05
	B20	3.76e+05	10.04	2.74e+04	0.0419	4.04e-06
Shallow depth chamber	Diesel	1.75e+05	4.23	1.12e+04	0.0552	2.95e-07
	B10	1.91e+05	4.84	1.34e+04	0.0498	5.95e-07
	B15	1.99e+05	5.25	1.67e+04	0.0412	8.45e-07
	B20	2.13e+05	5.84	1.94e+04	0.0396	9.13e-08

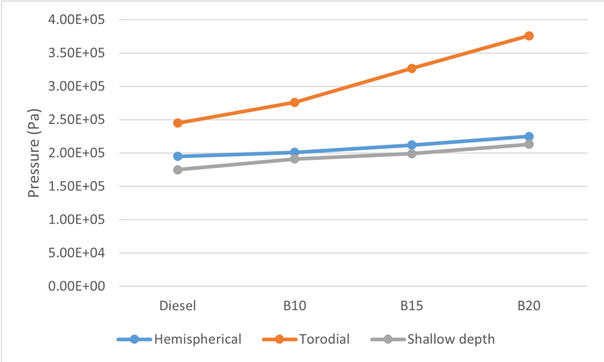

Figure 13: Performance of various piston bowl geometries with respect to pressure

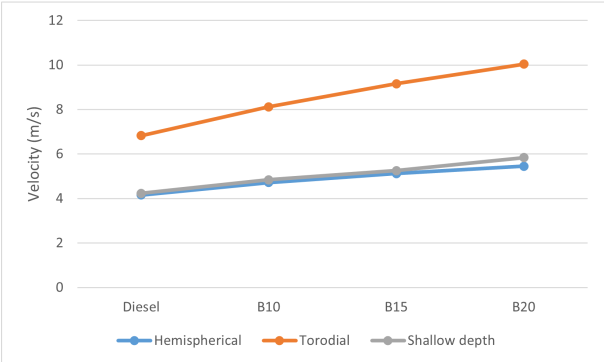

Figure 14: Performance of velocity with various piston bowl geometries

above graph shows that biodiesel blend B20 is higher than the diesel (D100) fuel under loading condition.

Fig. 14 is plotted between velocity and piston bowl geometries, where the velocity is a significant attribute of a diesel engine due to that it takes care of rate of fuel mass flow and the value of heating. The graph compares the velocity of various fuels (D100, B10, B15, and B20) used in the diesel engine. It shows that while increasing in the blend composition automatically it increases the velocity. The above graph shows that biodiesel blend B20 is higher at toroidal piston bowl than the diesel (D100) fuel under loading condition.

Fig. 15 demonstrates the turbulence intensity performance with different piston bowl geometries, where the turbulence intensity is a significant attribute of a diesel engine due to that it takes care of rate of fuel mass flow and the value of heating. The graph compares the turbulence intensity of various fuels (D100, B10, B15, and B20) used in the diesel engine. It shows that while increasing in the blend composition automatically it increases the turbulence intensity. The above graph shows that biodiesel blend B20 is higher at toroidal piston bowl than the diesel (D100) fuel under loading condition. The above graph is plotted between fluids and N2. The graph compares the N2 emissions of various fuels (D100, B10, B15, B20) used in the diesel engine. It shows that increasing in blend compositions automatically Decrease in NO emissions.

Fig. 17 discloses the plot between fluids and CO2.The graph compares the CO2 emissions of various fuels (D100, B10, B15, B20) used in the diesel engine. It shows that increasing in blend compositions automatically Decrease in CO2 emissions.

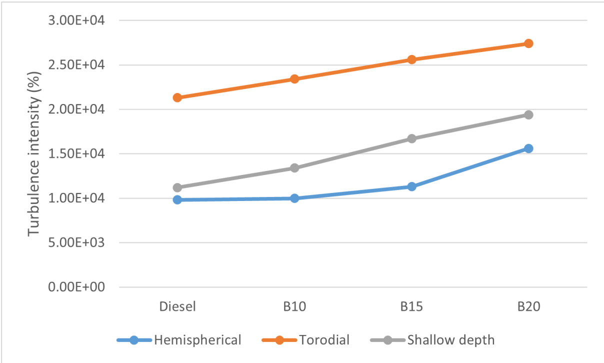

Figure 15: Turbulence intensity performance with different piston bowl geometries

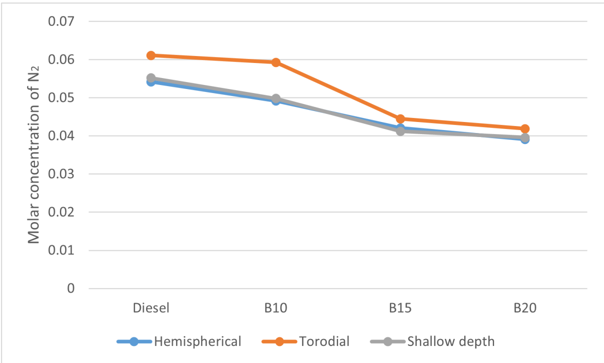

Figure 16: Performance of N2 vs fluids with different piston bowl geometries

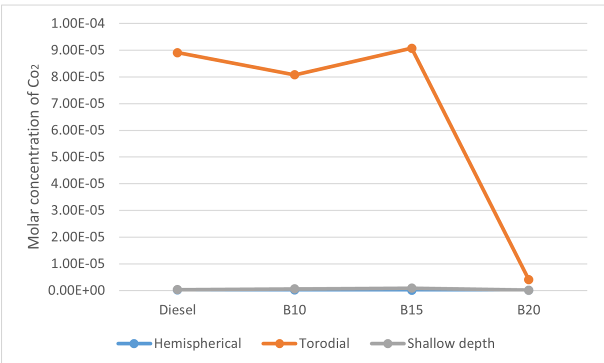

Figure 17: Performance of Co2 vs fluids with different piston bowl geometries

5. Conclusion

This article proposed the effect of piston bowl geometry on the direct injection diesel engine performance and emissions, where various profiles of piston bowl referred as HCC, TCC and SCC are designed using CADD tool and ANSYS workbench has been adopted for analysis. In addition, Karanja oil mixed with base fluid diesel at different volume fractions like 0.2%, 0.3% and 0.4% and are calculated for their combination properties. Further, theoretical calculations also considered to determine the properties of nano fluids which are later used as inputs for the analysis. Finally, CFD analysis has been employed on different geometries at different fluid volume fractions and thermal analysis also done for piston bowl geometries with different composite materials like carbon fiber and armide fiber. It was concluded from the results obtained using CFD analysis that a precise combustion can be achieved with the alteration of piston bowl geometry and there by enhanced the formation of swirl. Furthermore, it is also shown that the emissions of NOx are diminished as the increment in the compositions of blend.

Conflict of Interest

Authors declared that there is no conflict of Interest in Publication.

Data availability statement

The data used to support the findings of this study are included within the article.

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