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The Combined Effect of the Piston Bowl Geometry and Injection Fuel Pressure on the Compression Ignition Engine Characteristics

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ABSTRACT

In this study, the combined effect of the piston bowl geometry and fuel injection pressures on combustion, performance and emission characteristics of compression ignition (CI) engine fueled with baseline Diesel (D100) and microalgae-biodiesel (MA100) was studied. In this paper, the comparison study for the two different piston bowl geometry, namely: hemispherical combustion chamber (HCC) and toroidal re-entrant combustion chamber (TRCC), was carried out with the various fuel injection pressures (200-240 bar) performed. A single-cylinder, direct injection, and four strokes were chosen to simulate the compression ignition (CI) engine by developing a zero-dimensional simulation model using Diesel-RK commercial software. The data was validated by comparing the results against experimental data, which showed that the results obtained from the numerical simulation were in good agreement with the experimental results. MPRR, EGT, HRR, BTE, and NO_x exhibited an increase with increased fuel injection pressure, while an inverse trend was observed with ID, CO, and HC. When using MA100 biodiesel with HCC piston bowl geometry at fuel injection pressure (200 bar), the maximum predicted brake specific fuel consumption (BSFC) was 0.545 kg/kWh. A significant reduction of nitrogen (NOx) oxides emissions was also observed with low fuel injection pressures. In contrast, the emission characteristics such as hydrocarbons and CO were enhanced by increasing fuel injection pressure and modifying the piston bowl geometry.

1. Introduction

The internal combustion (IC) engine is the heat engine, which is most common for driving the motor of the vehicle including various kinds of working machines [1]. Newly, internal combustion (IC) engines are used in stationary applications, while there is a wide range of internal combustion engines. The stationary application is typically constructed as a compression ignition (CI) engine, offering several advantages over spark-ignition engines. The essential characteristics of such engines are: fuel economy, higher power range, higher reliability, and higher torque. The growing demand for energy in the form of fuels and the ever-increasing concern about environmental degradation produced by the unregulated use of traditional fossil fuels are driving the energy demand. This leads

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to the focus of investigations on alternative fuels, which is attributed to essential types of environmentally friendly and renewable fuels. Biodiesel has been highlighted as among the most active alternatives to diesel fuel to reduce environmental pollution [2] . Essentially, biodiesel fuel in liquid form is made from esterified vegetable oil, which has the advantage of being mixed with, or an alternative to, diesel fuel in internal combustion engines. Though, it is interesting to study using biodiesel in diesel engines as a supplement, aiming to reduce the emission of pollutants and increase operational efficiency. To overcome the crisis obtained from utilizing biodiesel as a replacement fuel to the diesel within the compression ignition(CI) engines. Azizul *et al.,* [3] conducted an experimental study to investigate the effect of the storage and ambient characteristics on the water-containing and flash points for three different biodiesel (jatropha, waste cooking oil, and palm crude) and make a comparison with the baseline diesel fuel. They reported that a higher proportion of the biodiesel and for a long time of storage period found has a significant effect on the biodiesel properties such as acid value, density, kinematic viscosity and flash point found. Veza *et al.,*[4] conducted an investigation study to convert the oil from algae into biodiesel, exchanging the alkoxy group with the other alcohol. Algae oil performs a reaction with alcohol producing glycerol and esters. Yusof *et al.,*[5] Conducted an identification study to evaluate the biodiesel transesterification process's waste. The glycerin and soap identify as take a significant quantity of this waste. The authors reported that glycerin impacts the environmental thread and must be stored in anaerobic digestion. Also, soap is not allowed to be discharged free into the drain channel without any treatment due to the grease value & oil, which are considered an environmental hazard. According to the author’s recommendations, soap and glycerin as transesterification product must be treat before releasing.

Many experimental studies have been conducted on the emission, performance and combustion characteristics of biodiesel fuel, namely rapeseed oil, roybean oil, ralm oil, canola oil, mustard oil, jatropha oil, sunflower oil,ricebran oil, pongamia oil, etc., without any mechanical modifications to the structure of the diesel engine. These studies have stated that using biodiesel and diesel blends in CI engines increases brake thermal efficiency and mean effective pressure. Further, there was a decrease in exhaust emissions, namely CO, UBHC, and hydrocarbon, compared to baseline diesel fuel. However, the disadvantage was that NO_x emissions were higher [6, 7]. Biodiesel has a longer hydrocarbon structure chain which gives potential to the combustion emission and performance characteristics. Still, on the other hand, biodiesel has a higher density and viscosity, contributing to severe problems like low atomization, injector clogging, and a higher level of carbon deposition. linn *et al.,*[8] suggested that producing biodiesel with additives improves combustion emissions and performance emissions, a numerical investigation study carried out by CONVERGE CFD software. The results ensure that n-butanol additive reduces combustion emissions, while the spray characteristics can be enhanced when biodiesel is blended with diethyl ether.

A detailed examination and further study are required to determine whether an acceptable engine change is needed without compromising the engine's combustion, performance, or emission characteristics. A better understanding of the high turbulence intensity of the flow field inside the combustion chamber plays a crucial role in the internal combustion (IC) engine characteristics. The shape of the combustion chamber may be used to steer the turbulence in a given direction [9]. As a result, it is necessary to thoroughly investigate the combustion chamber geometry. The principal objective in the combustion chamber design is to guarantee that the air-fuel mixture is sufficient to eliminate the effects of the fuel-rich areas phenomena [10]. Most of the researchers have focused on the piston bowl geometry, which significantly impacts the turbulence of air motion. Researchers Cankci *et al .,* [11] stated that piston bowl geometry, toroidal re-entrant combustion chamber (TRCC), enhanced the air circulation in the combustion chamber, which improves air-fuel mixing, resulting in decreased brake specific fuel consumption (BSFC) and increased brake thermal efficiency (BTE). TRCC piston bowl geometry reduces the ignition delay (ID) duration. It introduces a proper condition for a better air-fuel mixture than the conventional combustion chamber [12]. The researchers Jaichandar and Annamalai [13] conducted an experimental study to evaluate the influence of the combustion chamber geometry effect on the emissions and performance of compression ignition(CI) engines. The results show that the air circulation intensity inside the combustion chamber significantly relates to the piston bowl profile. Which in turn improves air: fuel mixture decreases specific fuel consumption (SFC) and increases brake thermal efficiency (BTE). In addition, the author observed that TRCC piston bowl drop CO and UBHC emissions while NO_x was higher than the other. Karthickeyan [14] conducted an experimental study to investigate the effect of two different types of piston bowl profiles (TRCC and HCC) on the characteristics of compression ignition (CI) engines and make a comparison with the conventional piston bowl. The results show that TRCC improves the squish and swirl movements within the combustion chamber compared with the HCC, which helps in good air: fuel mixing results in a complete combustion process and drops emissions. At the different start of injection (SOI) (20^o,21^o,22^o, and 24^o before TDC) and with 20% of methyl ester Jaichandar and Annamalai [15] investigated the effect of the piston bowel profile on the CI engines characteristics , the results shows that TRCC enhancing the combustion emission characteristics (HC ,CO, smoke) ,while NO_x emissions increased in compared conventional piston bowl geometry . Identify trend were observed for the results as Jaichandar and Annamalai [16] extend their investigation domine in various facts relevant to the piston bowl geometry characteristics such as re-entrance and combustion chamber shallow depth .

One of the essential strategies developed to enhance the diesel engine's performance while using biodiesel as test fuel is increasing the fuel injection pressures [17]. When fuel is injected into the combustion chamber with high pressures, the diameter of injected fuel droplets becomes smaller [18] . Moreover, when fuel injection pressures are increased, it reduces the particle diameter of the air-fuel mixture, reaching a better mixing rate. Therefore, the CO and soot are reduced. However, the ignition delay is significantly reduced when the fuel injection pressure is too high, reducing the mixture homogeneity and engine efficiency [19]. Celicten [19] investigated the effects of various fuel injection pressures (100-200 bar) on the diesel engine's characteristics. Based on the results obtained through an experimental study, it was found that decreasing fuel injection pressure leads to higher CO content, smoke, and hydrocarbon amounts; simultaneously, the levels of nitrogen oxides (NO_x) fall. Purushothaman and Nagarajan[20] conducted an investigation study focusing on fuel injection pressure effect on pollutions emitted from diesel engines. The current study used orange powder solution as test fuel in an experimental diesel engine. The extracted results are shown that NO_x emissions level slightly increase along with an increase in fuel injection pressure. Gumus *et al.,* [17] investigated the fuel injection pressure influence on diesel engines emissions levels when the different ratio of diesel-biodiesel blends is used. The results demonstrate that increased fuel injection pressure results in elevated NO_x amounts.

Computational fluid dynamics (CFD) is crucial in providing extensive detail on air-fuel mixing flow while also reducing the number of experiments required to model compression ignition (CI) engines. Recently, Diesel-RK is a new generation of engine simulation software developed to simulate the entire thermodynamic cycle of compression ignition (CI) engines. Tool Diesel-RK has advanced to employ a zero-dimensional and a multi-zone diesel spray mixture formation for the combustion process model. Also, it can account for piston bowl geometry, fuel properties, physicochemical fluid interaction and detailed chemistry. The data of the results obtained from the simulation process could be visualized using some technical means that would give a significant comprehensive understanding of the modification strategy in the diesel engine. On the other hand, the numerical model has the advantage of providing a thorough understanding of the parameter influence in diesel engines performance and output emissions when running on various test fuels.

In accordance with the best of the author's understanding based on the literature reviews. It can be concluded that is minimal experimental study investigated the combined influence of various fuel injection pressure (200-240 bar) along with diverse piston bowl geometry (HCC, TRCC) on the diesel engine characteristics fueled with diesel and microalgae-biodiesel (MA100). Hence, the objective of this study is to perform an investigation that provides significant results to cover the lack of literature.

2. Methodology

In this study, the aim is to conduct an investigation involves the companied effects of piston bowl geometry (HCC, TRCC) along with various fuel injection pressure (200 -240 bar) on the combustion, performance, and emission characteristics of the compression igniting (CI) engines fueled with diesel(D100) and microalgae-biodiesel (MA100). Besides, there has been interested in conducting a deep investigation to study the complete behavioral characteristics of MA100 biodiesel which is intended to be used as an alternative to conventional diesel fuel. Based on the importance and feasibility of these parameters in influencing the outline compression igniting (CI) engines behavior. Table 1 shows the specifications of the diesel engine used in this work, and the study was limited to the initial boundary conditions as indicated in the contents of Table 2.

Table 1
Standard engine specification

Parameter	Value
Type	Vertical diesel engine, four stroke, water cooled, single-cylinder
Displacement	661 cc
Bore & stroke	87 mm&110mm
Compression ratio	17.5 mm
Length of connection rod	234 mm
Fuel	Diesel(D100), microalgae-biodiesel (MA100)
Rated brake power	5.2 kW @ 1500 rpm
Fuel injection timing	23° CA before TDC
Inlet valve closing (Ivc)	35.5° CA after BDC
Exhaust valve opining (Evo)	35.5° CA before BDC
Injection fuel pressure	200-240 bar
Piston bowl geometry	HCC, TRCC
Fuel spray angle	110° degree
Nozzle hole diameter and number	0.3 mm & 3 holes {P-4]

Table 2
Initial boundary condition for Diesel-RK Model

Parameter	Value
Initial pressure	1.0 bar
Initial temperature	300 K
Piston temperature	530 K
Liner temperature	470 K
Head temperature	500 k

The parameters that are calculated to evaluate the performance of compression igniting (CI) engines are: ignition delays (ID) and brake thermal efficiency (BTE). While the parameters calculated to find the combustion characteristics are: maximum pressure rise rate (MPRR), exhaust gas temperature (EGT), and heat release rate (HRR). In contrast, the computed parameters representing exhausted emissions are NO_x, CO, and HC for each piston bowl geometry along with various fuel injection pressure (200-240 bar).

2.1 Numerical Simulation Approach
2.1.1 Diesel-RK model

Diesel–RK simulation software is designed to model the combustion process of compression igniting (CI) engines, including necessary operating parameters. The Diesel-RK model is propose based on the first law of thermodynamics and is used to calculate combustion, performance, emission characteristics, and ecological analysis parameters of pure Diesel (D100) and microalgae-biodiesel(MA100) [21] . With the inclusion of swirl profile, can be modelled sprayer location, multiple injection strategies, and the number of nozzles, the diameter of the nozzle, and direction of the nozzle holes, as well as the interaction of the sprays with the walls, and combustion chamber geometry for any application. Accurate results, less time-consuming, and dependable output parameters were the main reasons researchers moved forward with the numerical simulation approach to studying the characteristics of compression ignition (CI) engines [22]. The Diesel-RK model was proposed to reduce the extensive cost and time-consuming process required for data collection.

2.1.2 Combustion chamber geometry selection

The main purpose of paying attention to the combustion chamber design is to improve the mixing rate of air-fuel mixtures. Combustion chambers in diesel engines enhance the swirling rate of air-fuel in a short time during the premixed phase of combustion. Moreover, the combustion chamber geometry generates a powerful squish along with the air-fuel movement, like the smoke ring. During compression stroke near the top dead center (TDC), Swirl flow and squish play a significant role in the turbulence generation process [23]. In the combustion chamber, the relation among squish, swirl, piston bowl ship, and turbulence are more pronounced. A prime objective of the piston bowl geometry is to prove turbulence in the air-fuel motion [24], which is found more beneficial for the mixing process to meet its performance and emissions targets. During compression stroke, as the piston approaches the top dead center (TDC), the induced swirl by intake port and squish is generated, creating a high intensity of turbulences through proper design of the bowl in the piston crown. Hence, the combustion process is linked to the design of the combustion chamber, which has a significant impact on the level of exhaust emissions [25]. Besides, it can also have a real effect on the engine's performance, which is one of the main goals of the researchers. Different piston bowl geometries such as hemispherical combustion chamber (HCC) and toroidal re-entrant combustion chamber (TRCC) were considered for this study. The piston bowl geometry has been done by changing the original HCC geometry with modified TRCC and keeping the bowl geometry volume constant, as shown in Figure 1.

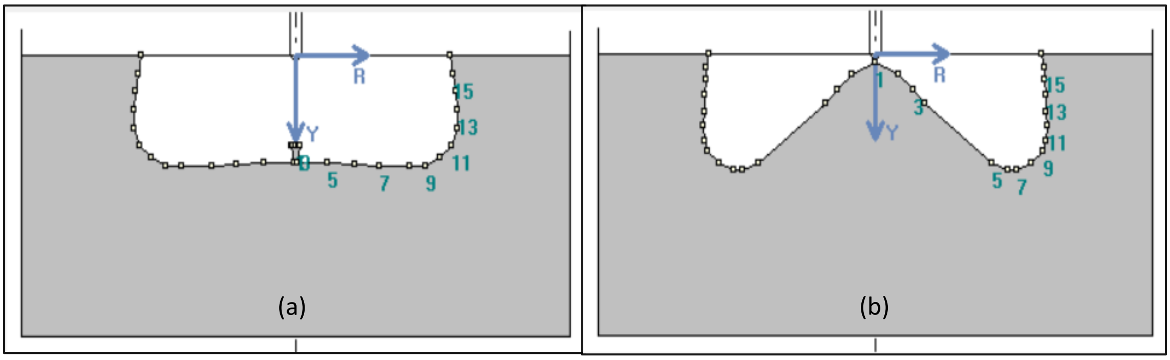

Fig. 1. Design the piston bowl geometries (a) HCC and (b) TRCC by the Diesel-RK

2.1.3 *Characteristic of the diesel spray zones*

In this software, the air-fuel mixture is analyzed by the multi-zone approach, in which the spray is divided into seven different zones, as shown in Figure 2. The specific evaporation and combustion conditions are specified individually in each model zone. The spray passes are divided into three different steps: (1) the initial configuration of solid axial flow, (2) a cumulative spray valuation, and (3) the duration of the diffuse fuel interaction on the walls of the combustion chamber.

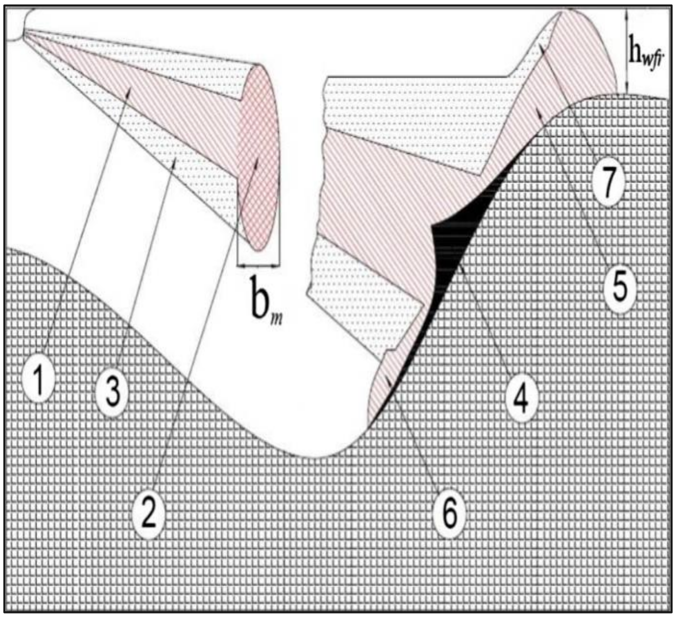

Fig. 2. Characteristic of the diesel spray in zones

For the spray evolution, the border between the main and initial stage corresponds to the moment. If the spray tip is close to the axil flow, it is deformed and break up and forming the condensing mushroom–shape in front of spray flow [26]. The spray is a breakup during the moving forward; injection pilot fuel compensates for the portion's losses of breakup spray; droplets congregate to the environment from the spry breaking front. The gas velocity is low in the combustion chamber environment, while gas velocity is rapidly accelerated to the same velocity droplets in the axial core [27]. The core diameter equals 0.3 of the spray outside diameter in the cross-section. The instants position and speed of the elementary fuel mass (EFM) that injected through small time step are related as:

$$\left(\frac{U}{U_o}\right)^{3/2} = 1 - \frac{l}{l_m} \quad (1)$$

Where U: control portion velocity of the fuel (m/s), U_o: spray initial velocity at the nozzle (m/s), U_o: spray front velocity (m/s), l: spray current length (m), and l_m: control portion penetration distance of the fuel (m). The variation of the spray evaluation parameters, which is a function of time, is shown in Figure 3.

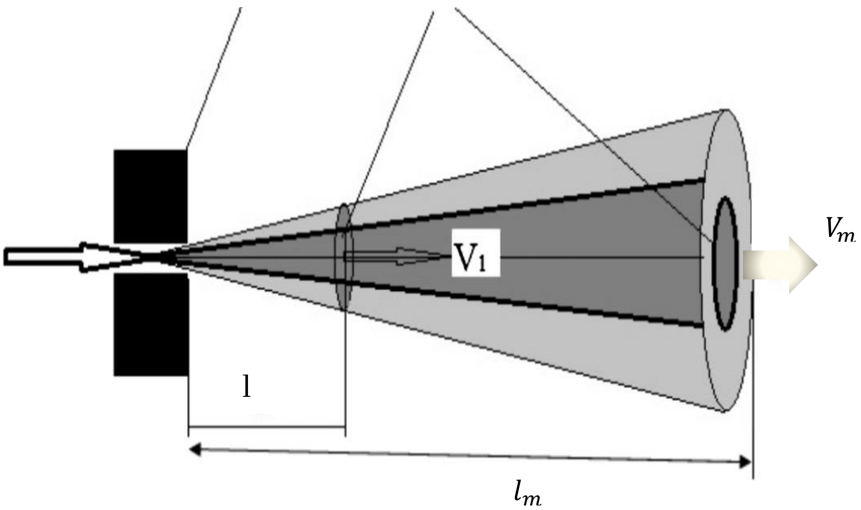

Fig. 3. Spray injection schematic physical quantities associated with an elementary fuel mass (EFM)

2.2 *Fuels Used for Simulation*

From the perspective of economic and environmental aspects, biodiesel has been considered as one of the more suitable alternatives to diesel fuel. Because of biodegradability and non-toxicity, biodiesel obtained a wide range of attention in the last few years. The commercial software Diesel-RK model was used to simulate the effects of different piston bowl geometry (HCC, TRCC) and various fuel injection pressures (200-240 bar) on the diesel engine characteristics fueled with microalgae-biodiesel (MA100) and pure diesel (D100). The properties of the two test fuels were taken from Venu *et al.,* [25] as illustrated in Table.3.

Table 3
Properties of microalgae-biodiesel and diesel

Properties	Diesel (D100)	Microalgae-Biodiesel (MA100)
Density at 20 °C (kg/m3)	830	860
Viscosity at 20 °C (N-s/m2)	2.6	5.66
C (%)	87	78.44
H (%)	12.6	12.04
O (%)	0.4	9.23
CN	48–52	52.0
CV (MJ/kg)	42.5	41.36
Flash Point (°C)	50	>128

2.3 *Model Validation*

The proposed tool Diesel-RK model has the advantage to provide a significant high quality of results for various operation conditions and different test fuels. The simulated results obtained from the Diesel-RK model has been proven to give very close results against experimental data. A simulation result has been validated with the experimental results of Lalvani *et al.,* [9] as benchmark. The author has used the same boundary conditions to validate the tool Diesel-RK with experimental data. The injection timing (23° CA bTDC), the fuel injection pressure (200 Bar), compression ratio (17.5), piston bowl geometry (HCC) and the brake rate power (5.2 kW @ 1500 rpm) were constant. The in-cylinder pressure versa crank angle degree, heat release rate (HRR), and NO_x were obtained from Diesel-RK and compared with the experimental results to validate the Diesel-RK software tool. The author was found a good agreement between the experimental and simulation results as shown in Figure 4 (a-c), the prediction results of the numerical solvers were deemed fit.

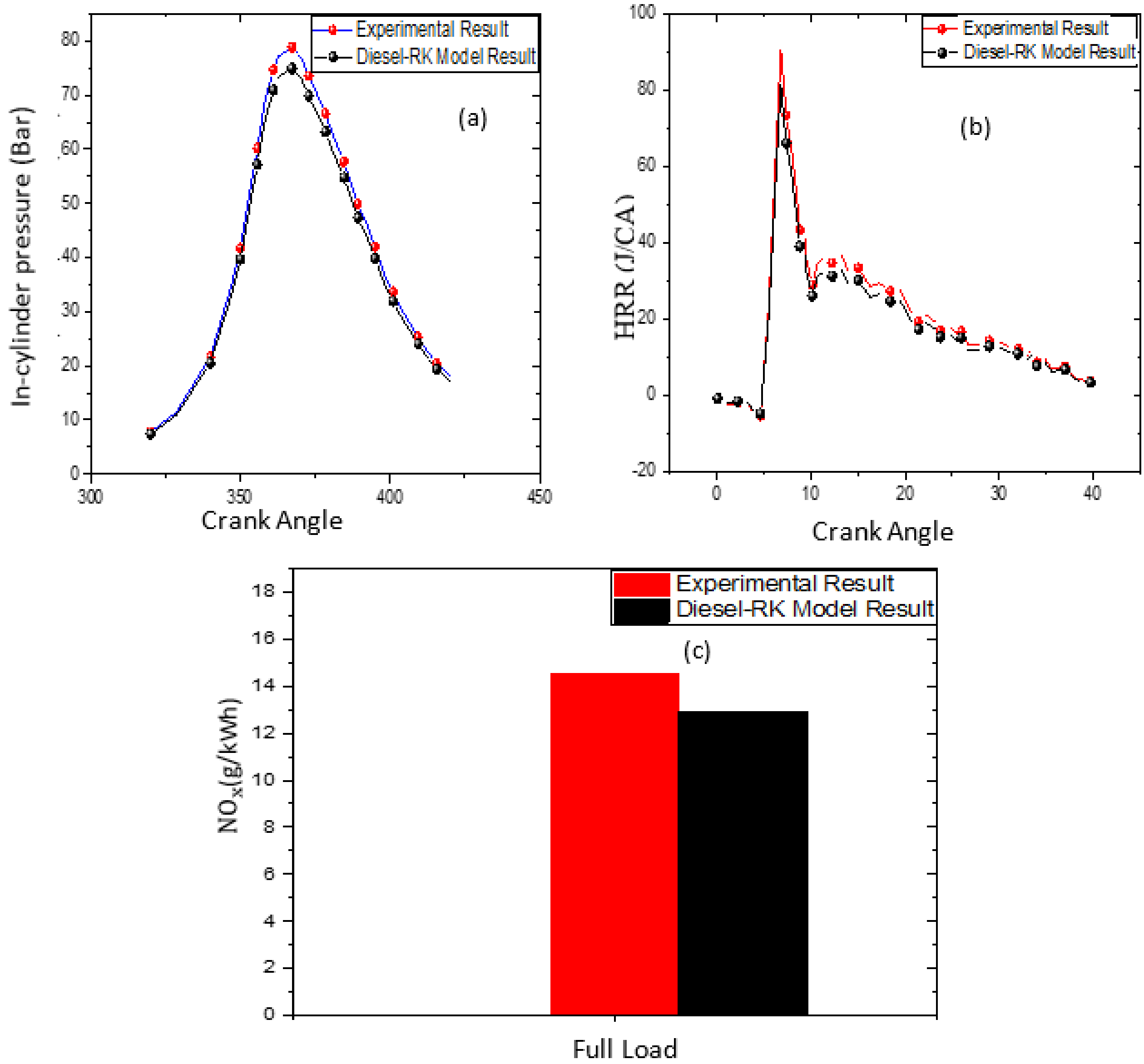

Fig. 4. (a) Variation of cylinder pressure with crank angle, (b) Variation of heat release rate versa crank angle, (c) Variation of brake thermal efficiency versa load

The error ratio between experimental and simulation results was within an acceptable range, which was obtained to be 2.23%, 4.7%, and 7.3% for in-cylinder pressure, HRR, and NO_x, respectively, as shown in Table 4. The error deviation (ED) analysis is calculated based on Eq. (2) for experimental and numerical results.

$$\mathrm{ED} = \left(\frac{\mathrm{X} - \mathrm{Y}}{\mathrm{X}}\right) \times 100 \tag{2}$$

Where X represents the higher value, and Y is the lower value.

Table 4
Comparison of the experimental and numerical results

Parameter	Experiential	Numerical	ED/ (%)
In-cylinder pressure (bar)	78.7.3	85.4	2.23
Cylinder heat release (J/CA)	75.2	81.5	4.7
NO_x (g/kWh)	14.1	13.4	7.3

3. Results

3.1 Ignition Delay

Ignition delays consider a qualitative measure of the combustion process. The combined effect of the injection pressure and piston bowl geometry with diesel and biodiesel test fuel on the ignition delay (ID) is shown in Figure 5. It was seen, the ignition delay for biodiesel test fuel was slightly lower than for the diesel when used as test fuel in both cases TRCC and HCC piston bowl geometry. The higher cetane number, lower calorific value, lower compressibility and high viscosity of biodiesel compared to the diesel [28] reduce ignition delay period. It may mention that the lower ignition delay of biodiesel leading to shortening the combustion duration results in concentrating the accumulated energy in the premixed combustion phase, which is the main reason for improving thermal efficiency. It was also visualized that TRC piston bowl has ignition delay higher than HCC, two reasons contributing to this phenomenon. The first reason is that TRCC piston bowl generates a higher swirl motion, which increases the influence of piston bowl geometry on the air-fuel motion and subsequent combustion process. Another reason relates to the higher combustion chamber wall temperature of the TRCC piston bowl.

The effect of fuel injection pressure on the ignition delay for D100 and MA100 biodiesel fuel is discussed deeply to give a clear vision. The combustion process in diesel engines depends on the air-fuel mixing rate, evaporation rats. As shown in Figure 5, increasing injection pressure leads to ignition delay reduction for TRCC and HCC piston bowl. This is due to the higher injection pressure decreasing the fuel droplet size, which leads to a high evaporation rate, improved air-fuel mixing process, and fine atomization, which results in improved quality and completed combustion.

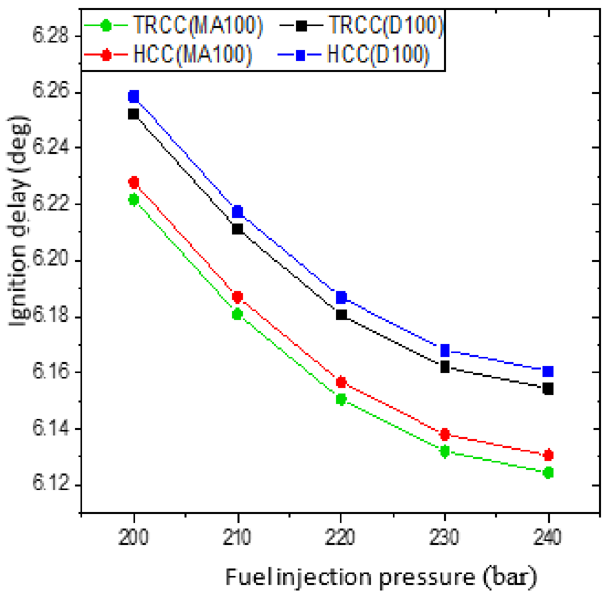

Fig. 5. Ignition delay variation

3.2 Brake Thermal Efficiency

Brake thermal efficiency (BTE) define as the ratio of power output to the energy released from the fuel, in other words, it represents the inverse of BSFC. The combined effects of the fuel injection pressure and piston bowl geometry of the diesel engine fueled with D100 and MA100 biodiesel on the BTE are shown in Figure 6. It can be observed, the BTE in the case of MA100 biodiesel is lower than D100 for any shape of piston bowl geometry (HCC, TRCC). This is due to two reasons, BSFC for the MA100 biodiesel test fuel is higher than D100. Secondly, MA100 biodiesel test fuel has a heating value lower than D100, which contributes to higher BTE [29]. The reduction in BTE with MA100 biodiesel test fuel is due to poor spray in the combustion chamber, higher viscosity, insufficient air-fuel mixing, higher volatility and lower calorific value [30]. Another reason associated with the ignition delay (ID) for the MD100 biodiesel is the shortest, leading to initiating the combustion process early before TDC.

As a result, increasing the heat loss and compression work leads to BTE reduction. For more explanation of combustion chamber geometry effect on the brake thermal efficiency (BTE), Figure 9 shows the effect on BTE of various fuel injection pressures along with different piston bowl geometries of diesel engine fueled with D100 and MA100 biodiesel test fuel. It can be observed that BTE for the TRCC piston bowl was higher than HCC, the flame did not reach the squish region, which increased the air-fuel turbulence motion for the TRCC piston bowl. The improvement in BTE is attributed to the turbulent and swirl motion, which is higher than HCC, and better mixing of the air-fuel combination. Figure 6 shows the effect of fuel injection pressure on the BTE for diesel engines. The fuel injection pressure significantly impacts the fuel spray droplet size and the penetration within the combustion chamber.

The result in Figure 6 shows that increasing injection pressure leads to increased BTE due to improved air-fuel breakup and promoting the evaporation process. Reduction of the droplet size results in improved atomization and mixing, which contributes to lower combustion duration and faster heat release rate (HRR) at higher fuel injection pressure. Moreover, increased fuel injection pressure produces a fully developed fuel spray pattern within a short time; this helps enhance the vaporization process as the surface area of the air-fuel core increases. This trend is identical to any piston bowl geometry also for diesel and biodiesel test fuel.

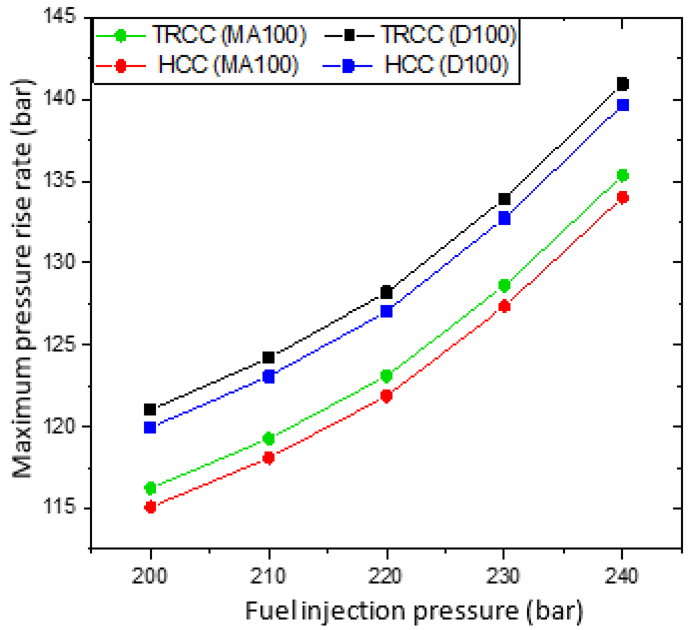

Fig. 6. Brake thermal efficiency variation

3.3 Maximum Pressure Rise Rate

The combustion process for the direct injection diesel engines is described as a complex process influenced by a number of factors, including the design of the combustion chamber, fuel properties, engine operating parameters, and fuel injection strategy. The combined effects of the fuel injection pressure and piston bowl geometry with D100 and MA100 on the maximum pressure rise rate (MPRR) are shown in Figure 7. It can be observed MPRR for D100 was higher than MA100 biodiesel when compared to both TRCC and HCC piston bowls geometry. This is attributed to the improper mixing quality of MA100 biodiesel with air due to its lower calorific value and higher viscosity than D100. Also, the decrease is related to the higher latent heat of evaporation.

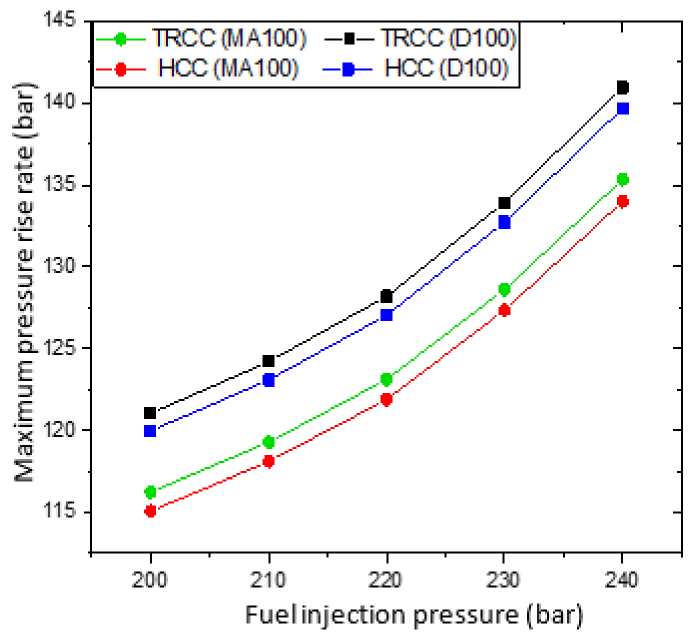

Fig. 7. Maximum pressure rise rate variation

To get a deeper investigation into the combustion process, the MPRR versa injection pressure for different piston bowl geometry are compared for D100 and MA100 biodiesel as shown in Figure 7. As can be seen, the MPRR of TRCC shows a higher than the HCC piston bowl for both fuels. An increased turbulence and swirl ratio of the TRCC engine helps attain complete combustion, which is endorsed to a better combustion process due to improved air entrainment and air-fuel mixing rates. Noticed a similar trend of MPRR in TRCC piston bowl with D100 and MA100 biodiesel in diesel engines, and a similar finding was also reported by Erodogan *et al.,* [31]. As seen in Figure 7, increasing the fuel injection pressure leads to an increase in MPRR, which can be explained as follows. The higher fuel injection pressure raises the velocity of fuel droplets injected and improves the air-fuel mixture formation within the ignition delay period. This provides a significant combustible charge quantity to the burning process within the premixed phase, resulting in higher maximum pressure.

3.4 Exhaust Gas Temperature

Exhaust gas temperature (EGT) gave qualitative information over the combustion process. Figure 6 shows the effect of injection pressure on the exhaust gas temperature (EGT) for different piston bowl geometry (HCC, TRCC) with D100 and MA100 biodiesel as a test fuel. It was observed that the EGT of MA100 biodiesel for both piston bowl geometries were higher than that of D100. This is because the MB100 biodiesel has a higher oxygen content, which improves the combustion efficiency, resulting in a higher EGT this finding is supporting by the outcome from previous experimental study by Tan *et al .,* [32] .

As observed in Figure 8, TRCC showed higher EGT than the HCC piston bowl. This phenomenon is attributed to the higher maximum pressure rate of the TRCC piston bowl. On the other hand, the TRCC piston bowl affords higher turbulence intensity, shortening the ignition delay period across the combustion chamber, causing the flame temperature to rise faster, resulting in higher combustion temperature. Besides, the higher turbulence in the TRCC piston bowl creates a very homogenous air-fuel mixture, resulting in sufficient intense combustion and higher EGT.

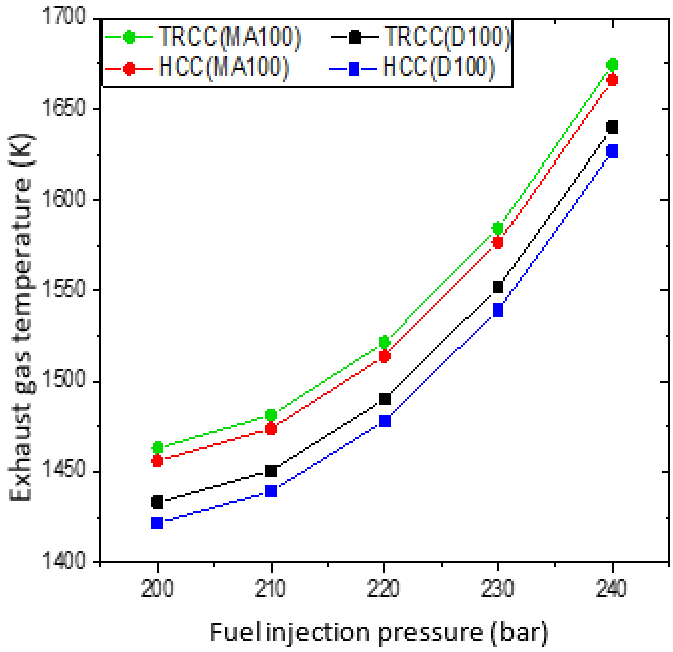

Fig. 8. Exhaust gas temperature variation

The fuel injection pressure effect on the EGT has been conducted, as shown in Figure 8. Increasing the fuel injection pressure causes the mixing process of air-fuel to rapidly, leading to enhanced heat transfer between the mixture molecules, enabling faster fuel dispersion and evaporation [33]. This leads to shorting the chemical and physical ignition delay period. Hence, the combustion initiation takes place early, and a major amount of energy is accumulated through the premixed combustion phase, increasing the heat released and raising the EGT.

3.5 Heat Release Rate

The variation of heat release rate with respect to the crank angle degree for different piston bowl geometry (HCC, TRCC) with D100 and MA100 biodiesel fuel are shown in Figure 9. The increased heat release rate (HRR) is attributed to the ignition delay duration(ID) and retardation of the start of combustion [34]. The ignition delay (ID) is longer for D100 compared to MA100 biodiesel fuel in the standard compression ignition (CI) engines. Further, biodiesel fuel has a higher viscosity and surface tension responsible for the poor spray atomization, leading to a reduced heat release rate within the diffusion combustion phase [35]. With the longer ignition delay for diesel, a massive accumulated fuel will be ready for burning during the premixed phase of combustion, resulting in a much higher heat release rate [36]. Also, Figure 9 shows the effect of the piston bowl geometry (HCC, TRCC) on the HRR for D100 and MA100 biodiesel fuel. It can be observed that HRR was improved with TRCC piston bowl due to enhancing the swirling movement owning to piston bowl geometry which in turn prepares better evaporation conations of fuel. The higher air retention during the fuel injection period due to the increased turbulence movements in the modified piston bowl (TRCC) is most importantly responsible for better air-fuel [14]. Process of air-fuel mixing affected by airflow and spray characteristics inside the combustion chamber. Significantly affects the magnitude of heat release rate and profile shape by affecting the turbulence of bulk airflow. A good combustion chamber provides the best squish force that compels the air to the center of the combustion, which causes a high level of turbulences along with fuel injection.

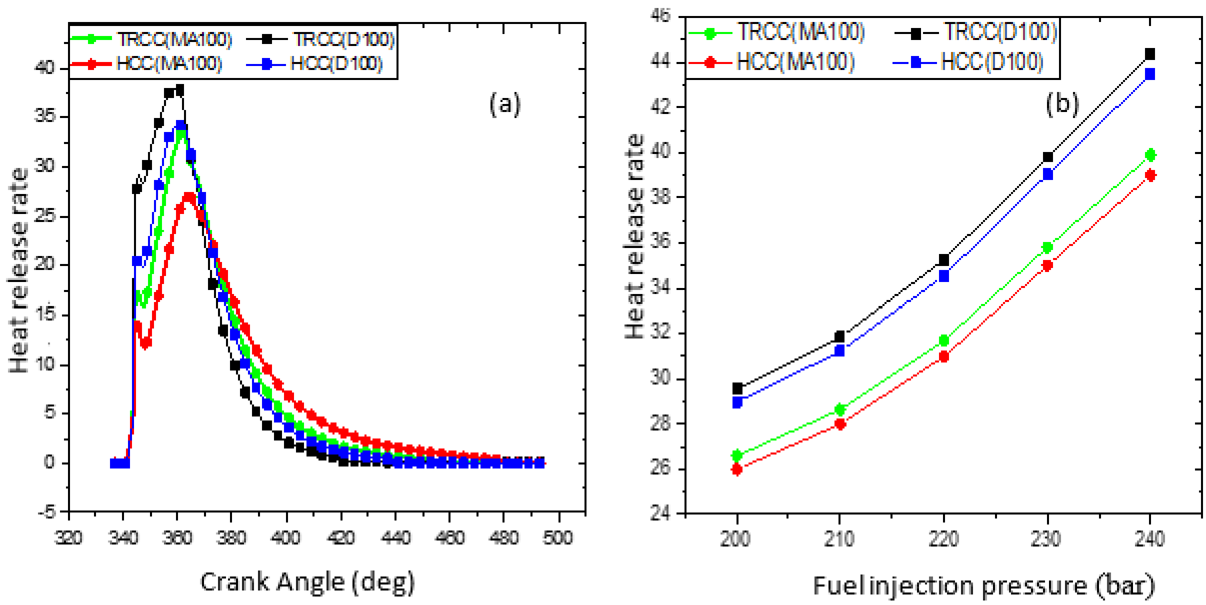

Fig. 9. Heat release rate (a) Versa crank angle variation (b) Versa fuel injection pressure

The piston bowl geometry controls the air-fuel movement during the compression stroke as piston moves up. Suitable modifications in the shape of piston bowl geometry result in generating the vortexes inside the piston bowl zone before the combustion process occurs, which create a better mixture formation. In this section of the paper, the discussion has been carried out on the changes of HRR of the diesel engine by varying fuel injection pressure, as shown in Figure 9(b). It can be seen that with the increased fuel injection pressure, the HRR further increased. This is because the fuel particle will be finer after the atomization process. So, better air-fuel mixing improves the fuel combustion process during the premixed combustion phase [37].

3.6 Oxides of Nitrogen

Figure 10 shows the variation of the Oxides of nitrogen (NO_x) for different piston bowl geometries (HCC, TRCC) with D100 and MA100 biodiesel test fuel at different fuel injection pressure. It is observed that, when operating with MA100 biodiesel test fuel, there is an observed increase in NO_x emissions compared to D100. This is related to various reasons; firstly, it is attributed to the higher cetane number of the MA100 biodiesel test fuel than D100. A higher cetane number results in a shorter ignition delay, allowing the majority of the combustion process to be completed before TDC, resulting in a higher heat release rate (HRR) and higher combustion temperature [38]. Secondly, the higher oxygen content within the molecular fuel structure boosts the combustion process. Two previous reasons leading to a higher cylinder temperature reached for MA100 biodiesel test fuel compared to D100, which plays a vital role in rising NO_x emissions. Figure 10 shows the effect of piston bowl geometry (HCC, TRCC) on NO_x emissions; as seen, the engine has TRCC piston bowl geometry that emitted NO_x more than HCC for D100 and MA100 biodiesel test fuel. This is because the TRCC piston bowl produces higher circulation and turbulence motion than the HCC, which improves the quality of the air-fuel mixture precisely during the premixed combustion phase. NO_x emissions highly temperature-dependent phenomenon, better air-fuel mixing is considered optimum environmental to facilitate the accomplished combustion entirely result in rising temperature, which is ideal for NO_x formation. So, it is seen, the NO_x emissions from the TRCC piston bowl is higher than HCC for D100 and MA100 biodiesel test fuel.

High fuel injection pressure is beneficial, especially in biodiesel engines, because it solves the problem of high viscosity [39]. Denser fuel droplets exist, which lead to poor dispersion and atomization. Figure 10 shows fuel injection pressure's effect on the NO_x formation for different piston bowl geometry. The results reveal that NO_x emitted increased with fuel injection pressure increased for both piston bowl geometry and D100 and MA100 biodiesel test fuel. This phenomenon can be explained as the high fuel injection pressure responsible for the atomization of the fuel. This factor plays a vital role in combustion efficiency and higher heat release rates (HRR). This is results in the rising cylinder temperature, the formation of the NO_x depends mainly on the temperature, So, increased injection pressure leads to an increase NO_x emitted from the diesel engine for both of the HCC and TRCC.

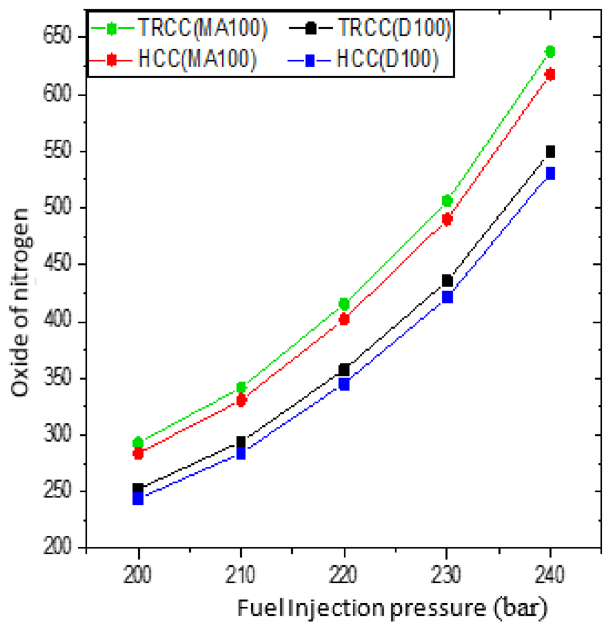

Fig. 10. Oxides of nitrogen variation

3.7 Carbon Monoxide

Figure 11 shows the effect of the piston bowl geometry and fuel injection pressure of diesel engines fueled with D100 and MA100 biodiesel test fuel. It is seen that, when the diesel engine operates with MA100 biodiesel it emits carbon monoxide (CO) less compared to D100 for identical operation conditions for both types of piston bowl geometry. The result shows a significant decrease in CO emissions when using MA100 as test fuel compared to D100. This is because MA100 biodiesel is an oxygen-enriched chemical element; the oxygen content of MA100 biodiesel is higher than those of D100. So it's considered a partial oxidizer fuel. Using biodiesel with a diesel engine as test fuel can provide a higher amount of oxygen for the combustion process, enhancing the quality of air-fuel mixing and improving emissions reduction. Erdoğan *et al.,* [31] also reported a similar trend through their experimentally study. Also, Figure 11 shows the effect of the piston bowl geometry of diesel engines with D100 and MA100 biodiesel test fuel on the CO. It's seen that CO emissions for the diesel engines have TRCC piston bowl geometry lower compared to HCC. TRCC piston bowl geometry has a significant impact on the CO formation due to the velocity of the air-fuel mixture is relayed to the shape of the piston bowl geometry. TRCC has a pretty narrow entrance into the combustion chamber than HCC, generating a higher intensity of the airflow entering the piston bowl, forming a higher squish motion. In addition, the reflected and generated airflow vortices within the squish zone of the piston bowl can improve the air-fuel mixing process and thus further improve combustion emissions. Another reason, TRCC performed the CO Chemical oxidization process to CO_2 faster than HCC [40] . This is one sign of the shorter ignition delay period. However, the combustion process takes place in the squish zone. It undergoes higher turbulence and swirl motion than the HCC, which leads to increased flame velocity and promotes combustion characteristics. According to the reasons mentioned above, the CO emissions reduction is justified compared with the HCC piston bowl geometry. So, the TRCC piston bowl promotes the combustion process and decreases CO emissions.

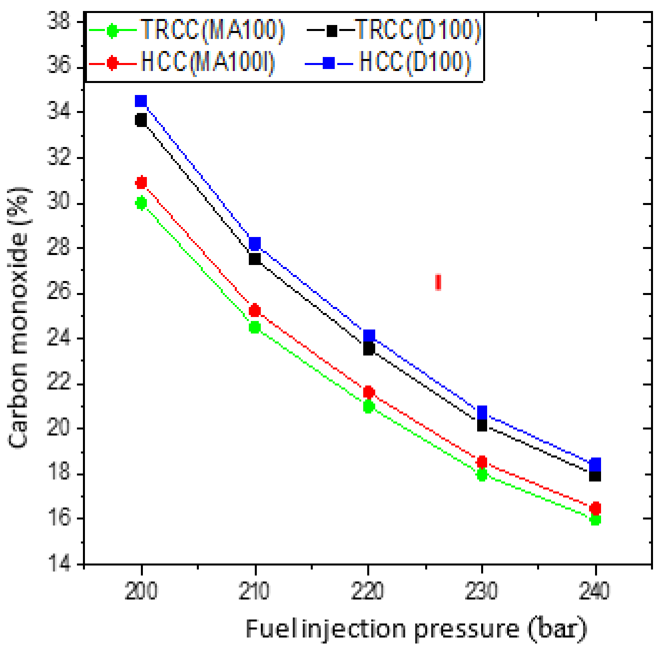

Fig. 11. Oxides of nitrogen variation

Moreover, Figure 11 shows the effect of the fuel injection pressure on CO emissions. It was observed that increased fuel injection pressure contributes to the decrease of CO emissions for both piston bowl geometry types and when tests were carried out with D100 and MA100 biodiesel test fuel. This is due to improving the atomization and evaporation process, which promote chemical reaction and facilitate the complete combustion process [40]. This causes to rise an associated temperature generated inside the combustion chamber; in turn, this helps to complete the CO to CO_2 oxidation process. Also, with increasing fuel injection pressure, the fuel droplets are reduced in diameter [40] and coated by a more air quantity; hence, the local fuel-rich zone has sufficient oxygen required for the oxidation process.

3.8 Hydrocarbon

Hydrocarbon (HC) considers an important parameter for reflecting the combustion process quality and completion. Figure 12 shows the combined effect of fuel injection pressure and piston bowl geometry of diesel engines carried out with D100 and MA100 test fuel. It is observed that when a diesel engine is carried out with MA100 biodiesel as the test fuel, it presents lower HC emissions compared to the D100. This is due to biodiesel having a higher amount of oxygen within its molecular fuel structure, which exhibits a promoter combustion quality within the combustion chamber [41]. Furthermore, this can be explained by the cetane number of MA100, which is higher than D100, resulting in a shorter ignition delay, which significantly reduces hydrocarbon emissions. Also, the results enunciated that the same pattern of HC variation was followed by both types of piston bowl geometry (HCC, TRCC). Figure 12 shows the influence of the piston bowl geometry (HCC, TRCC) on the HC emissions, it was observed that the diesel engine has TRCC piston bowl emitted HC lower than HCC. This is owing to the fact that the TRCC piston bowl generates greater circulation and turbulence motion than the HCC piston bowl. The reflected and vortices airflow within the piston bowl squish zone causes increased flame velocity and promotes combustion characteristics. Moreover, the combustion temperature of the TRCC piston bowl is higher than HCC, resulting in a higher oxidation rate due to reduced heat loss [42].

Figure 12 shows the effect of fuel injection pressure on the HC emissions for diesel engines fueled with D100 and MA100 biodiesel test fuel. It is observed that increased fuel injection pressure slightly reduces HC emissions levels. This is due to increased fuel injection pressure leading to increased combustion temperature, and pressure increases as a result of improving utilization of the available air and mixing of the fuel combination leading to an optimal combustion process. Also, higher fuel injection pressure cause to decrease in fuel droplet diameter, leading to more competing combustion, resulting in higher flam velocity, which helps consume the entire fuel mixture. However, lower HC emissions was obtained as evidence of combustion process improvement. Moreover, when the operation is performed with low fuel injection pressure, improper mixing of air-fuel lowers the combustion temperature and freezes the oxidation process rate.

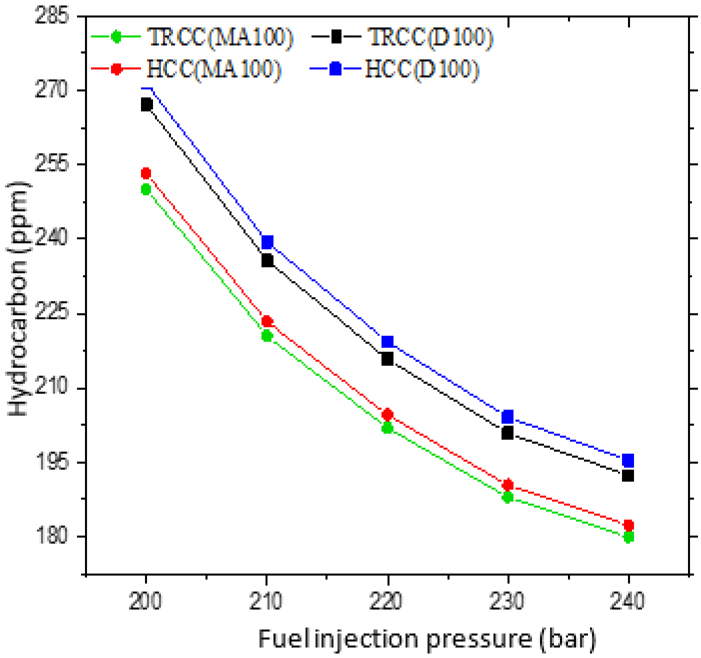

Fig. 12. Hydrocarbon variation

4. Conclusion

The combined effect of the piston bowl geometry and fuel injection pressure on the combustion, performance, and emission characteristics of diesel engine fueled with D100 and MA100 was studied. The conclusions obtained from the results are given below:

I. For modified engine having TRCC piston bowel geometry, brake specific fuel consumption (BSFC) decreased while the brake thermal efficiency (BTE) increased as a consequence of the fuel injection pressure increased.
II. Carbone monoxide (CO) and HC for the TRCC diesel engine were lower compared to the baseline engine having HCC piston bowl geometry. Besides, increase fuel injection pressure led to reducing CO and HC emitted due to improved combustion process.
III. For the modified engine TRCC piston bowel, NO_x emissions increased with higher fuel injection pressure due to improving the air-fuel mixing process. As well as, a higher content of oxygen within MA100 biodiesel molecule’s structure compared to D100 play a vital role in increasing the combustion chamber temperature.

IV. TRCC with D100 at 240 (Bar) fuel injection pressure had shown a maximum peak pressure rate (PRR) and maximum heat release rate (HRR) compared to the engine operated with MA100.
V. The engine test results compared with the standard diesel(D100) fuel indicated that the MA100 biodiesel showed that the reductions in the HRR, CO, and HC; however, BSFC and NO_x emissions increased.
VI. The ID of MA100 was found lower and EGT was higher for engines has TRCC piston bowel with higher fuel inaction compared to the baseline engines operated with D100 fuel and HCC piston bowel geometry.

The author has been concluding that MA100 biodiesel is quite suitable as an alternative to the conventional D100 fuel. Besides, modified diesel engine with the TRCC piston bowel type operated with increased fuel inaction pressure (200-240 Bar) improve the combustion, performance and emissions characteristics cause of enhance air-fuel mixing rate and improve the combustion process.

References

[1] Kalghatgi, Gautam. "Development of fuel/engine systems—the way forward to sustainable transport." *Engineering* 5, no. 3 (2019): 510-518. https://doi.org/10.1016/j.eng.2019.01.009
[2] Park, Hyunwook, Euijoon Shim, and Choongsik Bae. "Improvement of combustion and emissions with exhaust gas recirculation in a natural gas-diesel dual-fuel premixed charge compression ignition engine at low load operations." *Fuel* 235 (2019): 763-774. https://doi.org/10.1016/j.fuel.2018.08.045
[3] Azizul, Muhamad Asri, Amir Khalid, Nadiarulah Nanihar, Bukhari Manshoor, and Zuraidah Ngadiron. "Effects of Storage Characteristics on Flash Point and Water Content of Biodiesel derived from Crude Palm Oil, Jatropha, and Waste Cooking Oil." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 76, no. 2 (2020): 154-162. https://doi.org/10.37934/arfmts.76.2.154162
[4] Veza, Ibham, Mohd Farid Muhamad Said, Mohd Azman Abas, Zulkarnain Abdul Latiff, Mohd Rozi Mohd Perang, and Djati Wibowo Djamari. "Future Direction of Microalgae Biodiesel in Indonesia." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 25, no. 1 (2021): 1-6. https://doi.org/10.37934/araset.25.1.16
[5] Yusof, Siti Nurul Akmal, Siti Mariam Basharie, Nor Azwadi Che Sidik, Yutaka Asako, and Saiful Bahri Mohamed. "Characterization of Crude Palm Oil (CPO), Corn Oil and Waste Cooking Oil for Biodiesel Production." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 86, no. 2 (2021): 136-146. https://doi.org/10.37934/arfmts.86.2.136146
[6] Kapilan, N., and M. Vasudeva. "Influence of diethyl ether on the performance and emissions of a compression ignition engine fuelled with biodiesel." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 74, no. 1 (2020): 45-56. https://doi.org/10.37934/arfmts.74.1.4556
[7] Aydın, M., Uslu, S. and Çelik, M.B., 2020. Performance and emission prediction of a compression ignition engine fueled with biodiesel-diesel blends: A combined application of ANN and RSM based optimization. *Fuel*, *269*, p.117472. https://doi.org/10.1016/j.fuel.2020.117472
[8] Linn, Cheah Yi, Mohd Radzi Abu Mansor, and Zul Ilham. "Performance and Emission of B100 Biodiesel with Various Additives in Direct Injection Diesel Engine." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 80, no. 1 (2021): 24-36. https://doi.org/10.37934/arfmts.80.1.2436
[9] Lalvani, J. Isaac JoshuaRamesh, M. Parthasarathy, B. Dhinesh, and K. Annamalai. "Pooled effect of injection pressure and turbulence inducer piston on performance, combustion, and emission characteristics of a DI diesel engine powered with biodiesel blend." *Ecotoxicology and Environmental Safety* 134 (2016): 336-343. https://doi.org/10.1016/j.ecoenv.2015.08.020
[10] Rajak, Upendra, Prerana Nashine, Tikendra Nath Verma, and Arivalagan Pugazhendhi. "Performance, combustion and emission analysis of microalgae Spirulina in a common rail direct injection diesel engine." *Fuel* 255 (2019): 115855. https://doi.org/10.1016/j.fuel.2019.115855
[11] Canakci, Mustafa, Ahmet Erdil, and Erol Arcaklioğlu. "Performance and exhaust emissions of a biodiesel engine." *Applied energy* 83, no. 6 (2006): 594-605. https://doi.org/10.1016/j.apenergy.2005.05.003
[12] Saito, Takeshi, Yasuhiro Daisho, Noboru Uchida, and Nobuyuki Ikeya. "Effects of combustion chamber geometry on diesel combustion." *SAE transactions* (1986): 793-803. https://doi.org/10.4271/861186

[13] Jaichandar, S., and K. Annamalai. "Influences of re-entrant combustion chamber geometry on the performance of Pongamia biodiesel in a DI diesel engine." *Energy* 44, no. 1 (2012): 633-640. https://doi.org/10.1016/j.energy.2012.05.029
[14] Karthickeyan, V. "Effect of combustion chamber bowl geometry modification on engine performance, combustion and emission characteristics of biodiesel fuelled diesel engine with its energy and exergy analysis." *Energy* 176 (2019): 830-852. https://doi.org/10.1016/j.energy.2019.04.012
[15] Jaichandar, S., and K. Annamalai. "Effects of open combustion chamber geometries on the performance of pongamia biodiesel in a DI diesel engine." *Fuel* 98 (2012): 272-279. https://doi.org/10.1016/j.fuel.2012.04.004
[16] Jaichandar, S., and K. Annamalai. "Combined impact of injection pressure and combustion chamber geometry on the performance of a biodiesel fueled diesel engine." *Energy* 55 (2013): 330-339. https://doi.org/10.1016/j.energy.2013.04.019
[17] Gumus, Metin, Cenk Sayin, and Mustafa Canakci. "The impact of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fueled with biodiesel–diesel fuel blends." *Fuel* 95 (2012): 486-494. https://doi.org/10.1016/j.fuel.2011.11.020
[18] Horrocks, R. W. "Light-duty diesels—an update on the emissions challenge." *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 208, no. 4 (1994): 289-298. https://doi.org/10.1243/PIME_PROC_1994_208_196_02
[19] Celıkten, Ismet. "An experimental investigation of the effect of the injection pressure on engine performance and exhaust emission in indirect injection diesel engines." *Applied Thermal Engineering* 23, no. 16 (2003): 2051-2060. https://doi.org/10.1016/S1359-4311(03)00171-6
[20] Purushothaman, K., and G. Nagarajan. "Effect of injection pressure on heat release rate and emissions in CI engine using orange skin powder diesel solution." *Energy Conversion and Management* 50, no. 4 (2009): 962-969. https://doi.org/10.1016/j.enconman.2008.12.030
[21] Salam, Satishchandra, and Tikendra Nath Verma. "Appending empirical modelling to numerical solution for behaviour characterisation of microalgae biodiesel." *Energy conversion and management* 180 (2019): 496-510. https://doi.org/10.1016/j.enconman.2018.11.014
[22] Rajak, Upendra, and Tikendra Nath Verma. "Effect of emission from ethylic biodiesel of edible and non-edible vegetable oil, animal fats, waste oil and alcohol in CI engine." *Energy Conversion and Management* 166 (2018): 704-718. https://doi.org/10.1016/j.enconman.2018.04.070
[23] Dhinesh, B., M. Annamalai, Isaac JoshuaRamesh Lalvani, and K. Annamalai. "Studies on the influence of combustion bowl modification for the operation of Cymbopogon flexuosus biofuel based diesel blends in a DI diesel engine." *Applied Thermal Engineering* 112 (2017): 627-637. https://doi.org/10.1016/j.applthermaleng.2016.10.117
[24] Sathishkumar, Shriram, Bommisetty Sambasiva Rao, Sidharth Pradeep, Solai Sairam RM, Balaji Kalaiarasu, and Prabhu Selvaraj. "Modelling and Validating the Spray Characteristics of a Co-axial Twin-Fluid Atomizer Using OpenFOAM." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 91, no. 1 (2022): 35-45. https://doi.org/10.37934/arfmts.91.1.3545
[25] Venu, Harish, V. Dhana Raju, and Lingesan Subramani. "Combined effect of influence of nano additives, combustion chamber geometry and injection timing in a DI diesel engine fuelled with ternary (diesel-biodiesel-ethanol) blends." *Energy* 174 (2019): 386-406. https://doi.org/10.1016/j.energy.2019.02.163
[26] Rajak, Upendra, Prerana Nashine, Thokchom Subhaschandra Singh, and Tikendra Nath Verma. "Numerical investigation of performance, combustion and emission characteristics of various biofuels." *Energy Conversion and Management* 156 (2018): 235-252. https://doi.org/10.1016/j.enconman.2017.11.017
[27] Rajak, Upendra, and Tikendra Nath Verma. "Influence of combustion and emission characteristics on a compression ignition engine from a different generation of biodiesel." *Engineering Science and Technology, an International Journal* 23, no. 1 (2020): 10-20. https://doi.org/10.1016/j.jestch.2019.04.003
[28] Bennett, Maren, John Volckens, Rudy Stanglmaier, Ann P. McNichol, William D. Ellenson, and Charles W. Lewis. "Biodiesel effects on particulate radiocarbon (14C) emissions from a diesel engine." *Journal of Aerosol Science* 39, no. 8 (2008): 667-678. https://doi.org/10.1016/j.jaerosci.2008.04.001
[29] Zulkurnai, Fatin Farhanah, Norhidayah Mat Taib, Wan Mohd Faizal Wan Mahmood, and Mohd Radzi Abu Mansor. "Combustion Characteristics of Diesel and Ethanol Fuel in Reactivity Controlled Compression Ignition Engine." *Journal of Advanced Research in Numerical Heat Transfer* 2, no. 1 (2020): 1-13.
[30] Aydin, Hüseyin, and Hasan Bayindir. "Performance and emission analysis of cottonseed oil methyl ester in a diesel engine." *Renewable energy* 35, no. 3 (2010): 588-592. https://doi.org/10.1016/j.renene.2009.08.009
[31] Erdoğan, Sinan, Mustafa Kemal Balki, and Cenk Sayin. "The effect on the knock intensity of high viscosity biodiesel use in a DI diesel engine." *Fuel* 253 (2019): 1162-1167. https://doi.org/10.1016/j.fuel.2019.05.114
[32] Tan, Shin Mei, Hoon Kiat Ng, and Suyin Gan. "Numerical Studies of In-Cylinder Combustion and Soot Emission Characteristics of Biodiesel Fuels from Different Feedstock." *Journal of Advanced Research in Fluid Mechanics and*

Thermal Sciences 70, no. 1 (2020): 46-61. https://doi.org/10.37934/arfmts.70.1.4661
[33] Alloune, R., M. Balistrou, Sary Awad, Khaled Loubar, and Mohand Tazerout. "Performance, combustion and exhaust emissions characteristics investigation using Citrullus colocynthis L. biodiesel in DI diesel engine." *Journal of the Energy Institute* 91, no. 3 (2018): 434-444. https://doi.org/10.1016/j.joei.2017.01.009.
[34] Aydin, Hüseyin, and Cumali Ilkılıc. "Effect of ethanol blending with biodiesel on engine performance and exhaust emissions in a CI engine." *Applied Thermal Engineering* 30, no. 10 (2010): 1199-1204. https://doi.org/10.1016/j.applthermaleng.2010.01.037
[35] Jaichandar, S., and K. Annamalai. "Combined impact of injection pressure and combustion chamber geometry on the performance of a biodiesel fueled diesel engine." *Energy* 55 (2013): 330-339. https://doi.org/10.1016/j.energy.2013.04.019
[36] Zhu, Lei, Chun Shun Cheung, W. G. Zhang, and Zhen Huang. "Emissions characteristics of a diesel engine operating on biodiesel and biodiesel blended with ethanol and methanol." *Science of the Total Environment* 408, no. 4 (2010): 914-921. https://doi.org/10.1016/j.scitotenv.2009.10.078
[37] Krishania, Narendra, Upendra Rajak, Prem Kumar Chaurasiya, Thokchom Subhaschandra Singh, Anil Kumar Birru, and Tikendra Nath Verma. "Investigations of spirulina, waste cooking and animal fats blended biodiesel fuel on auto-ignition diesel engine performance, emission characteristics." *Fuel* 276 (2020): 118123. https://doi.org/10.1016/j.fuel.2020.118123
[38] How, Heoy Geok, Haji Hassan Masjuki, M. A. Kalam, and Yew Heng Teoh. "Influence of injection timing and split injection strategies on performance, emissions, and combustion characteristics of diesel engine fueled with biodiesel blended fuels." *Fuel* 213 (2018): 106-114. https://doi.org/10.1016/j.fuel.2017.10.102
[39] Guedes, Andrew David Mendes, Sergio Leal Braga, and Florian Pradelle. "Performance and combustion characteristics of a compression ignition engine running on diesel-biodiesel-ethanol (DBE) blends–Part 2: Optimization of injection timing." *Fuel* 225 (2018): 174-183. https://doi.org/10.1016/j.fuel.2018.02.120
[40] Li, J., W. M. Yang, H. An, A. Maghbouli, and S. K. Chou. "Effects of piston bowl geometry on combustion and emission characteristics of biodiesel fueled diesel engines." *Fuel* 120 (2014): 66-73. https://doi.org/10.1016/j.fuel.2013.12.005
[41] Hamdan, M. A., and Runa Haj Khalil. "Simulation of compression engine powered by Biofuels." *Energy Conversion and Management* 51, no. 8 (2010): 1714-1718. https://doi.org/10.1016/j.enconman.2009.10.037
[42] Rajashekhar, Chandrashekharapua Ramachandraiah, Tumkur Krishnamurthy Chandrashekar, Chebbiyyan Umashankar, and Rajagopal Harish Kumar. "Studies on effects of combustion chamber geometry and injection pressure on biodiesel combustion." *Transactions of the Canadian Society for Mechanical Engineering* 36, no. 4 (2012): 429-438. https://doi.org/10.1139/tcsme-2012-0030