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# Effects of piston bowl geometry on combustion and emission characteristics of biodiesel fueled diesel engines

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## HIGHLIGHTS

- Numerical study is done to investigate the effect of bowl geometry.
- Chemical kinetics is coupled with KIVA4 to model the combustion.
- The bowl geometry with less surface area is preferred at low engine speed.
- The bowl geometry generating strong squish is favorable at high engine speed.

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## ABSTRACT

This paper presents the numerical study of the effects of piston bowl geometry on combustion and emission characteristics of a diesel engine fueled with biodiesel under medium load condition. Three different bowl geometries namely: Hemispherical Combustion Chamber (HCC), Shallow depth Combustion Chamber (SCC), and the baseline Omega Combustion Chamber (OCC) were created with the same compression ratio of 18.5. To simulate the combustion process, computational fluid dynamics (CFD) modeling based on KIVA-4 code was performed. Moreover, CHEMKIN II code was integrated into the KIVA-4 code as the chemistry solver to incorporate detailed chemical kinetics mechanisms consisting of 69 species and 204 reactions for the biodiesel combustion, thereby improving the accuracy of the simulation. It is found that the narrow entrance of combustion chamber could generate a strong squish, especially at high engine speed, hence enhancing the mixing of air and fuel. Also, the simulation results indicate that in terms of performance SCC is favorable at low engine speed; whereas at high engine speed, OCC is preferred. As a consequence, SCC will generate relatively higher NO compared to other two piston bowl designs at low engine speed condition. Similarly, the high performance of OCC bowl geometry could result in a high NO emission at high engine speed condition.



## 1. Introduction

Diesel engines are facing a growing application due to their higher efficiency compared to gasoline engines. However, they also bring out significant environmental pollutions by emitting particulate matter (PM) and nitrogen oxides ($NO_x$) etc. To meet the increasingly stringent emission regulations, it is very crucial for researchers to find technical solutions or alternative fuels to reduce the engine emissions. Moreover, the increasing demand for petroleum fuels and the high oil prices exacerbate the urgency to find a renewable fuel as a substitute for diesel engines [1,2]. Recently, biodiesel has been considered as a promising fuel to substitute diesel fuel. The advantages of biodiesel include biodegradability, renewability, lower sulfur and aromatics, higher flash point and higher cetane number [3–6]. As biodiesel can be produced domestically, the dependence on imported oil can be reduced [3]. Furthermore, most of the investigations indicated that carbon monoxide (CO), unburned hydrocarbon (UHC) and PM emissions were reduced [7–12], whereas $NO_x$ and fuel consumption slightly increased in biodiesel fueled diesel engines [11–14].

The combustion and emission formation processes in diesel engines have a close relationship with the piston bowl geometry which can strongly affect the air fuel mixing before the combustion starts [15–20]. A few experimental studies on the effects of different bowl geometries of diesel engines fueled with biodiesel have been carried out recently. Jaichandar and Annamalai [21] studied the influence of bowl geometry on the engine performance in a diesel engine fueled with biodiesel. In their study, three bowl geometries, namely HCC (Hemispherical Combustion Chamber), TCC (Toroidal Combustion Chamber) and SCC (Shallow depth Combustion Chamber), were investigated. The biodiesel used in the experiment was a blend of 20% pongamia oil methyl ester by volume with 80% ultra-low sulfur diesel. It was found that,

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**Nomenclature**

| | |
|---|---|
| ATDC | after top dead center |
| BTDC | before top dead center |
| CFD | computational fluid dynamics |
| CO | carbon monoxide |
| DME | dimethyl ether |
| EOI | end of injection |
| HCC | Hemispherical Combustion Chamber |
| HRR | heat release rate |
| IVC | intake valve close |
| MD | methyl-decenoate |
| MD9D | methyl-9-decenoate |
| NO | nitrogen monoxide |
| $NO_x$ | nitrogen oxides |
| OCC | Omega Combustion Chamber |
| PM | particulate matter |
| SCC | Shallow Depth Combustion Chamber |
| SOI | start of injection |
| TCC | toroidal combustion chamber |
| UHC | unburned hydrocarbon |

compared to the HCC and SCC bowl geometries, decreased CO, UHC and PM emissions were observed with TCC, although a slightly higher $NO_x$ was detected. In addition, the brake thermal efficiency (ratio of mechanical work to energy input of fuel) of TCC was higher than those of HCC and SCC bowl geometries. Lately, Jaichandar et al. [17] studied the effect of injection timing and bowl geometry on the combustion and performance characteristics of a biodiesel fueled diesel engine. In this work, two configurations (HCC and TCC) of bowl geometry were considered and the fuel used was the same as that in the previous study. The tests were carried out at different loads (0%, 25%, 50%, 75%, and 100%) and different injection timings (20°, 21°, 22°, 23° and 24 °CA BTDC). The results showed that the brake thermal efficiency was improved by 5.64% and the brake specific fuel consumption was reduced by 4.6% for TCC compared to the HCC. In addition, the performance increased at first and then dropped with the retarded injection timing, whereas CO, UHC and smoke increased. Moreover, the $NO_x$ was increased by 11% which was believed to be resulted from the biodiesel fuel.

On simulation studies, an optimization method which combines genetic algorithms and KIVA–CHEMKIN has been applied for a series of studies on bowl geometry to minimize the pollutant emissions and gross indicated specific fuel consumption. Shi and Reitz [20] made a compromise among bowl geometry, spray targeting and swirl ratio using the optimization method to achieve low emissions and improve fuel economy for a heavy duty diesel engine at both low and high load conditions. Dolak and Reitz [15] optimized the bowl geometry of a light duty diesel engine using a two spray angle nozzle by considering variables such as start of injection, the fractional amount of fuel per injection and the swirl ratio. Finally, the stepped bowl geometry was selected for the two spray angle nozzle study. However, those optimization studies all focused on conventional diesel fuel. Most recently, Park [18] carried out an optimization study on a diesel engine fueled with dimethyl ether (DME). Since the properties of DME are different from those of diesel, the combustion and emission formation in DME engines are dramatically different from those in diesel engines. Finally, comparing the DME engine optimization results with original diesel engine, significant improvements were obtained.

As can be seen from above, rare studies have been carried out to disclose the combustion characteristics of biodiesel in diesel engine. No numerical studies have been carried out on the effects of bowl geometry on the combustion process and emission formation of a diesel engine fueled with biodiesel. To bridge the gap, it is very necessary to numerically study the combustion process of a diesel engine with different bowl geometries fueled with biodiesel.

In this paper, the KIVA-4 code coupled with CHEMKIN was used to simulate the engine combustion process. At first, the validation of the baseline engine with OCC (Omega Combustion Chamber) was performed under 50% load at the engine speeds of 1200, 2400 and 3600 rpm, respectively. Subsequently, the engine performance and emission characteristics of a biodiesel fueled diesel engine with three different bowl geometries, namely HCC, SCC and the baseline OCC, were numerically investigated and compared under the same conditions.

## 2. Experiment setup

The experimental studies were conducted on a four-cylinder, four-stroke, common rail fuel injection diesel engine fueled with biodiesel. The biodiesel is made from waste cooking oil whose main composition is palm oil. The engine specifications are listed in Table 1. The detailed descriptions on the engine test bed and experimental procedures can be found in our previous experimental studies [8,22,23]. Table 2 displays experimental conditions. The fuel composition is listed in Table 3.

## 3. Computational tools

### 3.1. Detailed chemical reaction mechanism of biodiesel

The numerical simulation was performed using the KIVA-4 code coupled with CHEMKIN II solver for detailed chemistry calculation. By coupling KIVA-4 and CHEMKIN II, the initial species concentrations, pressure and temperature were given from KIVA-4 to CHEMKIN II. Subsequently, CHEMKIN II returned the calculated changes in species concentrations, and the amount of heat released to KIVA-4. In this study, the biodiesel fuel chemistry is presented by a multi- component chemical reaction mechanism which consists of 69 species and 204 reactions [24]. For pure biodiesel simulation, it is assumed that the biodiesel is a fuel mixture made of 50% n-heptane, 25% methyl-decenoate (MD) and 25% methyl-9-decenoate (MD9D) in mole. In addition, the physical properties for methyl palmitate and methyl oleate were calculated by using the prediction methods developed by authors' group [25], and assigned to MD and MD9D respectively in the KIVA-4 fuel library.

### 3.2. Sub-models

The KIVA-4 code is based on finite volume scheme which solves the conservation equations of mass, momentum and energy. The

**Table 1**
Engine specifications.

| Type | Toyota 4-cylinder inline DI diesel engine |
|---|---|
| Bore × stroke (mm) | 92 × 93.8 |
| Swept volume (L) | 2.494 |
| Rated engine speed (rpm) | 3600 |
| Rated power (kW) | 75 |
| Compression ratio | 18.5 |
| Fuel injection system | Common rail injection |
| Number of injector holes | 6 |