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Modelling of Engine Performance Fuelled with Second Generation Biodiesel

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Abstract

Increasing interest in diesel engine technology and the continuous demand of finding alternative sustainable fuels as well as reducing emissions has motivated over the years for the development of numerical models, to provide qualitatively predictive tools for the designers. Among the alternative fuels, biodiesel especially second generation biodiesel is considered as a sustainable and the most promising option for diesel engine. In this study an engine combustion model has been developed using computational fluid dynamics (CFD) software, AVL Fire, which can predict the engine performance, and emission characteristics for second generation biodiesel produced from Australian native beauty leaf seed (BLS). This model involves simulation of fuel atomization, burning velocity, combustion duration, and temperature and pressure development in a combustion chamber. The model has been developed for petroleum diesel (normal diesel used in automobiles), 5% BLS biodiesel (B5) and 10% BLS biodiesel (B10) for different injection timings and compression ratios. The simulation results revealed that overall B10 biodiesel provides better performance and efficiency, and significantly reduced engine emissions. On the other hand, the B5 blend provides slightly improved performance and efficiency, and moderately reduced emissions compared to petroleum diesel.

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Keywords: Second generation biodiesel; CFD model development; internal combustion engine performance and emission.

1. Introduction

In recent times there is an extensive focus on developing sustainable energy supply options and reducing the global reliance on non-renewable fossil fuels with finite reserves, as well as reducing the effects energy production has on global warming, largely related to the burning of these fossil fuels. The transport industry relies very heavily

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on the use of oil, and in particular the oil derived fuel diesel, used in a large number of trucks, buses, trains and ships as well as an ever growing number of cars. It is essential that a sustainable alternative fuel source is to be developed to reduce the global dependence on oil, particularly as cheap and reliable oil supplies are reducing. Second generation biodiesel is a significant step forward in the quest to develop a sustainable alternative fuel source [1]. It can be used in unmodified diesel engines; it has been shown to substantially reduce exhaust emissions of carbon monoxide, carbon dioxide, hydrocarbons and particulate matter [2-5], so it is good for the environment. It could have a number of economic benefits through increasing the stability of Australia's fuel market, creating new industries and jobs in both refineries and agriculture, without impacting significantly on food supplies.

The second generation biodiesels are mainly produced from non-edible oils [6, 7], and sometimes produced from waste or recycled oil and animal fats [8-10]. The biodiesel produced from non-edible oil has gained the attention due to the problems associated with food versus fuel, environmental and economic issues related to edible oils [11]. Moreover, non-edible vegetable oils are considered over the edible vegetable oils due to its low feedstock cost [11-13]. Unlike first generation biodiesels, this means they have minimal or no impact on food supply or food prices [6, 7]. The Australian BLS (*Calophyllum inophyllum*) has a high potential for large scale second generation biodiesel production as it can tolerate harsh environmental conditions such as drought, salinity, acidity and a large range of temperature, requires little maintenance, is non-edible, has a large yield of fruit of around 3,000-10,000 seeds/tree/year and has high kernel oil of around 65%. The wild tree lives for up to 200 years, producing fruit twice a year. The BLS is estimated to be able to produce up to 4,000 litres of oil per hectare per year [14, 15].

Modern diesel engines can run on biodiesel and biodiesel blends with no modifications, however the performance, efficiency and emissions can all be optimized by making adjustments within the engine. There are a range of different parameters that can be adjusted to optimize the compression ignition (CI) engine running on biodiesel, including fuel injection timing, injection pressure, air-fuel ratio, crank angle and combustion chamber geometry such as piston, piston ring, cylinder head, inlet and outlet valve. Some recent studies [16-22] have investigated the performance and emission characteristics of biodiesel engines at different engine speeds, loads and biodiesel ratios. These results indicated that the engine performance is sensitively affected by the ratio of biodiesel in the fuel. Nevertheless, there is no shortcut way to determine the optimal biodiesel ratio because the factors (e.g., fuel cost and amount of exhaust emissions) are opposing each other [1]. It is the only way to determine the optimal biodiesel ratio by conducting numerous experiments on a dynamometer subject to the user's requirements. Therefore, creating a computational model for biodiesel engines may be the best solution to the above abridgement because the optimal biodiesel ratio can then be determined by applying computer-aided optimization method to the engine model. However, the main aim of this study is to develop a combustion model to maximize the combustion performance of an automobile engine fuelled with second generation biodiesel produced from BLS. The computational fluid dynamics (CFD) model for the turbulent combustion of biodiesel in an internal combustion engine will allow a range of benefits to be evaluated and be a guide for engine manufacturers, biodiesel producers, biodiesel users and policy makers. Some of these benefits include improving internal combustion engine technology, reducing harmful gas emissions, and increasing fuel efficiency, sustainability and optimum uses of second generation biodiesel as engine fuel.

2. Engine Specifications

The diesel engine is the most efficient of all current types of internal combustion engines, with a higher thermal efficiency and lower specific fuel consumption due to the high compression ratio used. The diesel engine that was used in this study for modelling is a Kubota V3300 that utilizes four cylinders, natural aspiration, indirect injection and compression ignition. The engine's technical specifications include a displacement volume of 3318 cc, a bore of 98 mm and stroke of 110 mm and a compression ratio of 22.6:1. The engine coupled to an eddy-current dynamometer, located at the thermodynamics laboratory of Central Queensland University (Australia) is shown in Fig. 1.

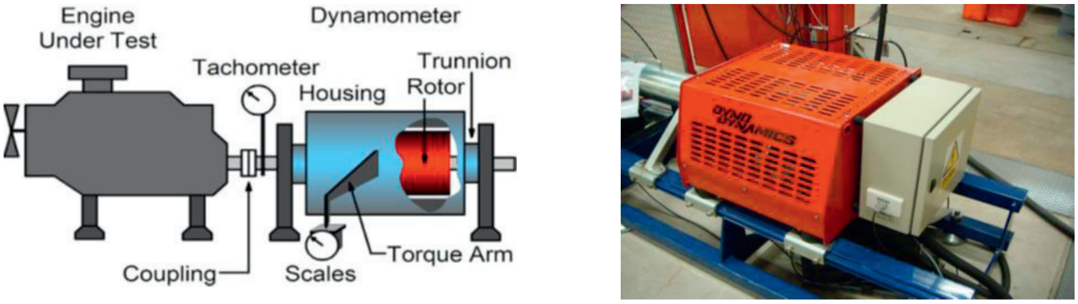

Fig. 1. Schematic diagram of engine used in this study (left side: engine bed and right side: dynamometer)

3. CFD Modelling and Simulation

An engine combustion model was developed using CFD software, AVL Fire that could predict the performance, emissions and component wear of the CI engine. . AVL Fire is a powerful multi-purpose thermo-fluid dynamics software with a particular focus on handling fluid flow applications related to internal combustion engines. The *Engine Simulation Environment* (ESE) Diesel is a CFD simulation tool that is used to setup, perform and analyze the injection and combustion process in diesel engines. The simulation parameters are shown in Table 1. The ESE has been developed in order to maximize the ease of use, reliability and accuracy. The AVL Fire ESE Diesel allows the analysis and the maximization of the flow in diesel engines during the compression and expansion stroke, including combustion, fuel injection and emission rate. The computational grid generation is based on parameterized, two-dimensional templates, describing the combustion chamber and optionally the injector geometry.

Based on the piston and injector geometry parameters and mesh parameters, the piston model mesh has been created. For the initial simulation to compare the three different fuel types, petroleum diesel, 10% biodiesel blend (B10), and 5% biodiesel blend (B5), the injection timing has been set at a crank angle (CA) of 11° before top dead centre (TDC). This is done based on the workshop manual specifications for the Kubota V3300 diesel engine. This model is capable of simulating a range of different parameters in the combustion chamber including combustion duration, burning velocity, fuel atomization and pressure development. The model could then be maximized in a number of different ways including making adjustments to the fuel injection timing, injection pressure, air-fuel ratio, crank angle and combustion chamber geometry such as piston, piston ring, cylinder head, inlet and outlet valve to increase the performance and efficiency, and reduce the emissions and operational limitations for the engine running on second generation biodiesel.

4. Results and discussion

The results of this simulation have been obtained from AVL Fire ESE Diesel. The performance as well as efficiency of the different fuels can be compared by looking at the engine specific outputs for different injection timings of 709^0 CA, 705^0 CA and 719^0 CA which are shown in Tables 2, 3 and 4, respectively. It can be seen from Table 2 (for injection timing of 709^0 CA), in terms of indicated power as well as brake mean effective pressure (BMEP), the B5 biodiesel blend produces the higher power and BMEP compared to the petroleum diesel and B10 biodiesel. On the other hand, in Table 3 (for injection timing of 705^0 CA), B10 biodiesel produces higher power and BMEP than the petroleum diesel and the B5 blend. However, it can be noted from Table 4 (injection timing of 719^0 CA), that the B10 biodiesel blend produces the less power and BMEP than the diesel and the B5 blend. It is evident from the Tables 2, 3 and 4 that the highest indicated power was obtained for B10 biodiesel for injection timing of 705^0 CA (Table 3). It can be also illustrated from the Tables 2, 3 and 4 that the indicated torque from the simulation results was the highest for the B10 biodiesel blend for injection timing of 705^0 CA compared to that of diesel and B5 blend, and the injection timings of 709^0 CA and 719^0 CA. It is indicated that under standard conditions for the engine, there is very little difference between the three fuel types in terms of indicated power, torque and BMEP.

However, the B10 blend shows the highest performance followed by the standard petroleum diesel and the 5% biodiesel, B5. The differences in performance between the three fuel types, according to the simulated model, are only between approximately 0.3-0.4%.

Table 1. Simulation parameters

Parameter	Value
Engine Layout	Inline
Number of Cylinders	4
Bore (m)	0.098
Compression Ratio	22.6
Crank Radius (m)	0.055
Connecting Rod Length (m)	0.094
Stroke (m)	0.11
Number of injection holes	4
Engine Speed (RPM)	2000
Friction Power (W)	1000

Table 2. Engine specific output (injection timing 709^0 CA)

Output parameters	Diesel	B10	B5
Brake mean effective pressure BMEP [bar]	2.82	2.82	2.83
Brake specific fuel consumption BSFC [kg/kWh]	0.2455	0.2460	0.2450
Indicated efficiency [-]	0.44	0.43	0.44
Indicated mean effective pressure IMEP [bar]	3.54	3.54	3.55
Indicated fuel consumption [kg/kWh]	0.1954	0.1957	0.1951
Indicated power [kW]	4.90	4.89	4.91
Indicated torque [Nm]	23.40	23.36	23.44

The indicated efficiency of the engine from the simulation results were obtained 44% for the petroleum diesel and 5% biodiesel blend, and 43% for 10% biodiesel blend for injection timing of 709^0 CA. On the contrary, the indicated efficiency for the B5 biodiesel blend is slightly higher than the B10 biodiesel but the same as diesel for injection timing of 719^0 CA, and the indicated efficiency for all the three cases are same for injection timing of 705^0 CA. This shows that, again just like the differences between the fuel types in performance, there is only a small difference in the engine efficiency. Moreover, the highest indicated efficiency was obtained for the injection timings of 709^0 CA as well as 705^0 CA. Fuel consumption is another indicator of the efficiency of the diesel engine while running the different fuels. It is evident from the simulation results (Table 3) that the brake specific fuel consumption as well as the indicated fuel consumption was the lowest for the B10 biodiesel blend compared to petroleum diesel and B5 biodiesel blend. These results show that upon comparison of the efficiency and fuel consumption of the different fuel types, the differences are quite small, in the range of 1% for efficiency and 0.3% for fuel consumption.

The engine emissions from the different fuels are compared by the mass fraction graphs which are illustrated in Figs. 2 and 3. A comparison of the NO emissions is shown in Fig. 2 in terms of mean NO mass fraction. Fig. 2 shows that the diesel fuel has the highest fraction of NO after the combustion is completed followed by B5 biodiesel blend approximately 3% lower and B10 biodiesel approximately 14% lower. A comparison of the soot emissions is shown in Fig. 3. It can be seen from the Fig. 3 that the diesel fuel has the highest fraction of soot after the combustion is completed followed by B5 biodiesel blend approximately 6% lower and then B10 biodiesel approximately 18% lower.

Table 3. Engine spe. output (injection timing 705^0 CA)

Output parameters	Diesel	B10	B5
Brake mean effective pressure BMEP [bar]	2.85	2.87	2.86
Brake specific fuel consumption BSFC [kg/kWh]	0.2426	0.2411	0.2419
Indicated efficiency [-]	0.44	0.44	0.44
Indicated mean effective pressure IMEP [bar]	3.58	3.59	3.59
Indicated fuel consumption [kg/kWh]	0.1935	0.1926	0.1931
Indicated power [kW]	4.95	4.97	4.96
Indicated torque [Nm]	23.62	23.73	23.67

Table 4. Engine spe. output (injection timing 719^0 CA)

Output parameters	Diesel	B10	B5
Brake mean effective pressure BMEP [bar]	2.44	2.39	2.44
Brake specific fuel consumption BSFC [kg/kWh]	0.2843	0.2898	0.2838
Indicated efficiency [-]	0.39	0.38	0.39
Indicated mean effective pressure IMEP [bar]	3.16	3.11	3.16
Indicated fuel consumption [kg/kWh]	0.2192	0.2225	0.2189
Indicated power [kW]	4.37	4.30	4.37
Indicated torque [Nm]	20.86	20.55	20.89

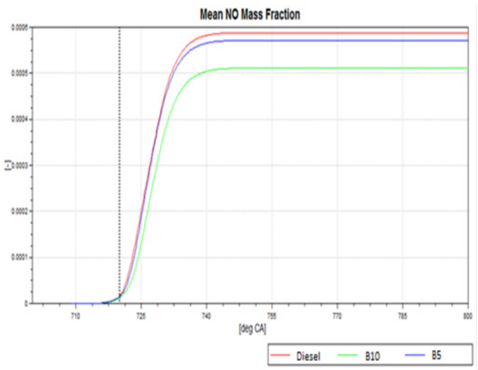

Fig. 2. Mean NO mass fraction (Inject. timing 709° CA)

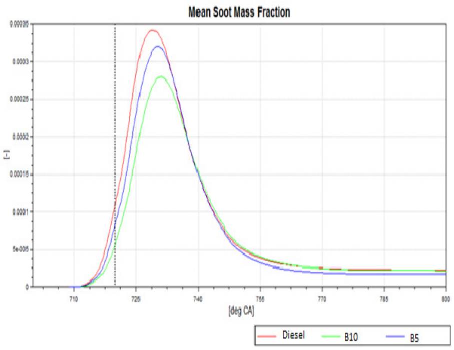

Fig. 3. Mean soot mass fraction (Inject. timing 709° CA)

The results indicate that there is a fairly significant difference in both NO and soot production between the fuel types. The difference between the petroleum diesel and B5 biodiesel blend is not overly large, but B5 does have lower emissions and slightly better performance and efficiency. When comparing diesel to B10 biodiesel, the difference is substantial, and the performance is higher so, it would be expected to produce significantly less emissions. The large 14-18% reduction in emissions indicates that the biodiesel is much better for emissions than petroleum diesel. The CFD simulation output images for emissions: NO mass fraction and soot mass fraction are presented in Figs. 4, 5 and 6 for diesel, 7, 8 and 9 for B10 biodiesel blend, and 10, 11 and 12 for B5 biodiesel blend fuel. These images show the fraction of NO and soot within the combustion chamber at each of the stages of the piston cycle. These can be used to see when the emissions are being produced and the amount that is present.

4.1. Parameters effects on performance and emissions

The parameters that were used to maximize the diesel engine performance while running biodiesel were the injection timing and the compression ratio which are shown in Tables 5 and 6, respectively. Advancing the injection timing (709^0 CA) increased the engine performance and efficiency for B10 biodiesel, and as expected, retarding the injection timing (719^0 CA) reduced the performances which are shown in Table 7. In addition, the injection timing affected on the engine emissions and the results was being reduced the soot as the timing was advanced but increase the NO mass fraction. However, a significant change was observed in the NO mass fraction with the change in timing because the earlier the injection, the higher the temperature, which caused the NO formation to begin earlier. Advancing the injection timing further to 705^0 CA actually resulted in an increase in performance because the combustion started to occur at early. Table 7 shows that advancing the injection timing caused the better improvements in performance for B10. While this was done the NO and soot mass fractions were remain the lowest of the fuel types, despite having the highest performance.

This displays that advancing the injection timing is very effective for the use of biodiesel. However, retarding the injection timing reduced the performance as shown in Table 7, and resulted in B5 biodiesel blend having the slightly higher performance and NO emissions, and slightly less soot emissions than diesel. From the simulation results in Table 8, it was found that increasing compression ratio increased the performance. In this table the engine with a reduced compression ratio of 20, the standard 22.6 and an increased 24 are compared.

Table 5. Injection timing optimisation parameters

Injection Timing	Value
Standard	709^0 CA
Advanced	705^0 CA
Retarded	719^0 CA

Table 6. Compression ratio optimisation parameters

Compression Ratio	Value
Standard	22.6
Increased	24
Decreased	20

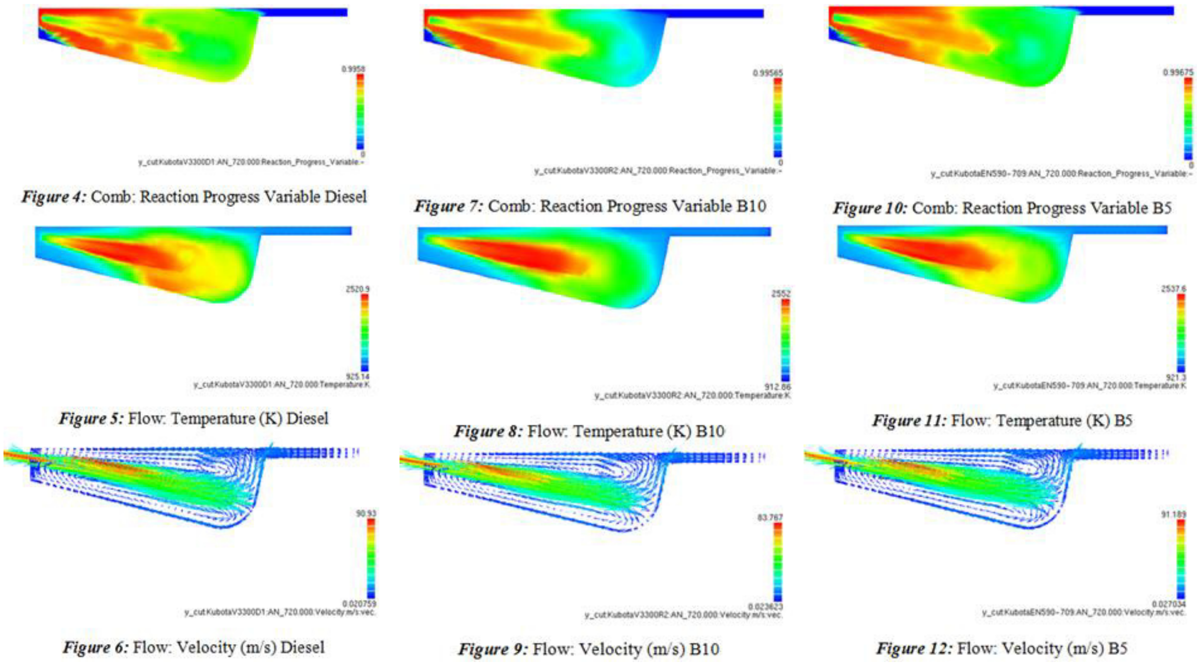

Fig. (4-12). CFD simulation outputs at 720^0 CA (TDC) (a) for petroleum diesel; (b) B10 biodiesel; and (c) B5 biodiesel blend

Table 7. Engine output injection timing comparison for B10

Injection Timing	705°	709°	719°
Brake mean effective pressure BMEP [bar]	2.87	2.82	2.39
Brake specific fuel consumption BSFC [kg/kWh]	0.2411	0.2460	0.2898
Indicated efficiency [-]	0.44	0.43	0.38
Indicated mean effective pressure IMEP [bar]	3.59	3.54	3.11
Indicated fuel consumption [kg/kWh]	0.1926	0.1957	0.2225
Indicated power [kW]	4.97	4.89	4.30
Indicated torque [Nm]	23.73	23.36	20.55

Table 8. Engine output compression ratio comparison for B10

Compression Ratio	22.6	24	20
Brake mean effective pressure BMEP [bar]	2.82	2.86	2.81
Brake specific fuel consumption BSFC [kg/kWh]	0.2460	0.2424	0.2464
Indicated efficiency [-]	0.43	0.44	0.43
Indicated mean effective pressure IMEP [bar]	3.54	3.58	3.53
Indicated fuel consumption [kg/kWh]	0.1957	0.1934	0.1959
Indicated power [kW]	4.89	4.95	4.89
Indicated torque [Nm]	23.36	23.64	23.33

Increasing the compression ratio has increased the power by approximately 1.2% but the NO mass fraction was remaining almost the same and there was a reduction in soot mass fraction. Reducing the compression ratio has resulted in a minimal reduction in performance but a significant reduction in NO as well as soot mass fractions.

5. Conclusion

An engine combustion model was developed using the CFD in AVL Fire. This simulation model was used to compare the results of engine performance using diesel, 10% biodiesel blend and 5% biodiesel blend as fuels and then modify the engine model for maximizing the performance and efficiency, and minimizing the emissions while running on BLS biodiesel. It could be concluded from the simulation results that under standard conditions, the engine fuelled with the B10 provides slightly better performance and efficiency, and significantly reduced the engine emissions. On the other hand, the B5 blend provides slightly improved performance and efficiency, and marginally reduced emissions compared to petroleum diesel. It could be predicted from the simulation results that the maximum BMEP, maximum indicated power and torque can be found with B10 biodiesel blend compared to the petroleum diesel and B5 blend for the injection timing of 705^0 CA. This investigation will assist in the development of BLS biodiesel as a viable sustainable fuel source through the use of a CFD model, optimised engine configuration and technical report.

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