EFFECT OF STATIC INJECTION TIMING ON THE PERFORMANCE AND EMISSIONS OF DIESEL ENGINE WITH BLENDS OF MAHUA BIODIESEL

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ABSTRACT
The engine performance, combustion and emission characteristics of Mahua (\textit{Madhuca Indica}) biodiesel and its different blends with diesel is presented. The engine tests are conducted on a four stroke Tangentially Vertical (TV) single cylinder kirloskar 1500 rpm direct injection diesel engine with eddy current dynamometer at different static injection timings of 19°, 20°, 21°, 22° and 23° bTDC (standard) and with nozzle opening pressure of 250×10\textsuperscript{5} N/m\textsuperscript{2} at full load. From the test results, it is observed that a retarded static injection timing of 20° bTDC for B0 and B25 give better performance, combustion and lower emissions. Among all the blends, the B25 with static injection timing of 20° bTDC gives higher CO\textsubscript{2} of 28.31\% in terms of percentage increase. Lower specific fuel consumption of 4.10\%, HC of 10\%, Smoke density of 26.70\% and NO\textsubscript{x} of 24.89\% in terms of percentage reduction as compared to standard injection timing of 23° bTDC.

Keywords: Mahua biodiesel, Static Injection Timing, Nozzle Opening Pressure, Performance, Emissions.

1. INTRODUCTION
Every country in the world is improving their infrastructure rapidly. With the improvement of roads for transport facility world over, the automobile sector is witnessing a gigantic growth. Particularly diesel engines are used widely for in-sea and on-land transportation because of its specific advantages over other power sources like simple mechanism, fuel efficiency, low cost, easy maintenance etc. At the filip side, the diesel engine has become the major source of air pollution as its emissions contain harmful waste like black smoke, hydrocarbon and oxides of nitrogen (NO\textsubscript{x}) apart from causing noise pollution. The diesel engine emissions contribute heavily for the depletion of ozone layer, green house effect and acid rain productions which become causes for many human diseases and the degradation of the environment. As the fuel is the life-line of transportation sector, factors like fossil fuel depletion, environmental degradation have driven the automobile industries to invest heavily in research works to find alternative fuels and to invent newer technology to improve fuel efficiency, economy and reduce pollution from the existing fuels. This scenario has led to a renewed interest in the use of vegetable oils for making biodiesel because of their bio degradable, non-toxic, less polluting and renewable nature. Worldwide biodiesel is produced mainly from edible oils, but in India, non-edible oil seeds are available in abundance such as Pongamia (\textit{Pongamia Pinnata}), Jatropha (\textit{Jatropha Curcas}), Mahua (\textit{Madhuca Indica}), Neem (\textit{Azadirachta Indica}), and Rubber seed (\textit{Hevea Brasiliensis}) oil etc., which can be tapped for biodiesel production.

Raheman and Ghadge (2008) conducted experiments on a Ricardo E6 direct injection single cylinder diesel engine with different blends of Mahua biodiesel at various compression ratios for different load conditions with three different injection timings. It is reported that the B20 (20\% of Mahua biodiesel and 80\% of diesel) gave optimum performance with lower emissions as compared to neat diesel. They also found that Mahua biodiesel could be used at Compression Ratio of 20:1 with Injection Timing of 20° bTDC (CR20IT40) without affecting the performance of the engine. Based on the results reported by them and to get further insight in using Mahua biodiesel. This study has been carried out to study the performance of diesel engine with different injection timings (19° to 23° bTDC) at full load. A constant compression ratio of 17.5:1 with different blend ratio from B0 to B100 is used. From Table 3, it may be observed that Madhuca Indica has a lower calorific value but has higher density. This means that the calorific value of Madhuca Indica oil on a volumetric basis approaches the volumetric calorific value of diesel fuel. However, it is essential to compare the economy of the two fuel using brake thermal efficiency and not with respect to specific fuel consumption.

One of the ways by which the combustion characteristics of vegetable oils can be improved by means of transesterification process. Even though other methods like micro-emulsion and blending are available they are comparatively more costly and less stable. In the case of Madhuca Indica oil, the cetane number increases along with flash and fire point (refer Table 3) compared to petro-diesel. Compared to petro-diesel, biodiesel tends to have a much narrower range of temperatures between the cloud point and the pour point. Those who are used to dealing with petro-diesel may be surprised at this narrow range. While there may be a 20° difference between the cloud point and the pour point of petroleum diesel, biodiesel may have a difference of only a few degrees.
A brief literature review of research work related to Mahua biodiesel and its blends carried out by various researchers is presented below. No (2011) has reported the application of the seven different non-edible biodiesel including the Mahua biodiesel and its blends for CI engines. Raheman and Ghadge (2005; 2007; 2008); Godiganur et al. (2009) have worked on Mahua biodiesel. The biodiesel was prepared from raw Mahua oil (Madhuca Indica) having high free fatty acids. The engine performance was obtained by blend with different volumetric ratios of Mahua biodiesel. The 20% of Mahua biodiesel found to give optimum mixture. Kapilan and Reddy (2008); Puhan et al. (2005a; 2005b; 2005c; 2007); Saravanan et al. (2010) have carried out experiments on a single cylinder diesel engine with Mahua biodiesel. They found lesser emissions than that of diesel fuel. The performance of the diesel engine has been investigated by Bora et al. (2009) with Mahua oil methyl ester in terms of its fatty acid methyl ester. They have reported that the storage of Mahua oil methyl ester is possible with limited air contact and metal composition.

Padhi et al. (2005) have discussed the details regarding the production of the biodiesel and have discussed its percentage of acid catalyst as well as esterified and transesterified oils for constant methanol and oil ratios of the fuel. Ramadhas et al. (2005) have worked on rubber seed biodiesel and have stated calorific value to be lower than that of neat diesel. However, flash point and fire point values were higher than that of neat diesel. Storage of methyl ester of rubber seed oil was found to be is easy as that of neat diesel. The various blends of rubber seed oil was made and the same used for evaluating the performance, combustion and emission of diesel engine for all load conditions. Among all the blends, the B10 was found to give better performance like lower specific fuel consumption and higher brake thermal efficiency. It was found that the emissions of smoke and exhaust gas temperature found to decrease with increase in blend proportions. However, NOx was higher in the case of blends of fuel as compared to neat diesel. Subramanian et al. (2011) have conducted studies on a multi cylinder diesel engine with hybrid fuel. The hybrid fuel gave higher brake thermal efficiency and lower emissions with 10% of diesel, 80% of Pungamia oil methyl ester and 10% of ethanol. The performance evaluation of a direct injection diesel engine was carried out with methyl ester of thevetia peruviana oil by Balusamy and Marappan (2010) having an injection timing of 27° bTDC and injection pressure of 225x10^5 N/m². It was found to give lowest HC, CO, smoke density, and higher brake thermal efficiency.

A diesel engine has been tested using B20 and B100 jatropha biodiesel and neat diesel with various injection pressures and injection timings by Dhananjaya et al. (2009). The B20 was found to give higher performance and lower emissions with injection pressure of 220x10^5 N/m² and injection timing of 26° bTDC at full load condition. An investigation on a diesel engine was carried out with methyl and ethyl esters of soybean oil by Clark et al. (1984). It produced slightly less power and there was an increase in fuel consumption also. Emissions were found to be comparable with neat diesel. There were a larger carbon and varnish deposits on the piston with the methyl ester of soybean oil. Scholl and Sorenson (1993) have carried out studies on a direct injection diesel engine with methyl ester of soybean oil on a four cylinder naturally aspirated and have compared the results with the petrol-diesel fuel. The overall performance and combustion characteristics of soybean methyl ester were quite similar to diesel fuel with lower HC and smoke density emissions of optimized operating conditions. A diesel engine was operated with methyl soya blends in conjunction with a high-pressure injection scheme by Choi et al. (1997).

The test was conducted on a single cylinder caterpillar 3400 series heavy-duty diesel engine. Mixtures of 20% and 40% by volume of methyl soya with baseline fuel were used. It is reported that at high load conditions a large reduction in particulates with a slight increase in NOx with the biodiesel blends. In general, biodiesel exhibited similar combustion characteristics to that of diesel fuel. An investigation has been carried out on a four stroke diesel engine retrofitted into an alpha V-shaped stirling engine designed and tested with LPG by Idroas et al. (2011). It was found to give better performance, lower noise and emissions. Issues such as low engine power-to-weight ratio and high manufacturing costs remain major challenges that make the mass production of Stirling engines unfeasible at present. In Malaysia, the development of Stirling engines is still scarce and the most noticeable research is focused on the low temperature differential Stirling engine, such as solar Stirling engines. Due to its high thermal efficiency and load carrying capacity compared to other internal combustion engines, diesel engines are prominent until today (Sayem et al., 2011).

The literature review indicates that there is sustained effort all over the world to study the performance and emission characteristics of diesel engine using biodiesel. Since, it is perceived that biodiesel can be an alternative for petrol diesel lot of research work are being done. Hence, in this study it is proposed to evaluate the Mahua biodiesel towards its performance and emission characteristics.

2. EXPERIMENTAL SETUP AND PROCEDURE
Experiments have been conducted on a 4 stroke, kirlskar, Tangentially Vertical single cylinder (TV1) direct injection (DI) diesel engine developing power output of 5.2 kW at 1500 rpm connected with water cooled eddy current dynamometer. The schematic of the engine setup is shown in Figure 1. Specifications of the engine are presented in Table 1.

The static injection timings of 19°, 20°, 21°, 22° and 23° bTDC (standard) and the nozzle opening pressure of 250x10^5 N/m² are used for the entire experiments at full load condition of the diesel engine with eddy current dynamometer using B0, B25, B50, B75 and B100 as fuel
is presented. Table 2 reports the values for pure diesel (B0), a blend of 25% Mahua biodiesel and 75% diesel by volume (B25), a blend of 50% Mahua biodiesel and 50% diesel by volume (B50), a blend of 75% Mahua biodiesel and 25% diesel by volume (B75) and pure Mahua biodiesel (B100).

Table 1 Specification details of the engine

<table>
<thead>
<tr>
<th>Make</th>
<th>Vertical single cylinder, DI diesel engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore × Stroke</td>
<td>87.5 mm x 110 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>17.5:1</td>
</tr>
<tr>
<td>Brake power</td>
<td>5.2 kW (Rated)</td>
</tr>
<tr>
<td>Speed</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Water cooled</td>
</tr>
<tr>
<td>Nozzle Opening Pressure</td>
<td>250x10^5 N/m^2 (modified) at full load</td>
</tr>
<tr>
<td>Static Injection Timings</td>
<td>19°, 20°, 21°, 22° and 23° bTDC (standard)</td>
</tr>
</tbody>
</table>

Table 2 Properties of Mahua biodiesel and its diesel blends

<table>
<thead>
<tr>
<th>Name of the Properties</th>
<th>AST Code</th>
<th>B0</th>
<th>B25</th>
<th>B50</th>
<th>B75</th>
<th>B100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross calorific value in MJ/kg</td>
<td>D480 9</td>
<td>45.6</td>
<td>43.9</td>
<td>43.3</td>
<td>42.5</td>
<td>41.9</td>
</tr>
<tr>
<td>Kinematic viscosity at 40°C in cSt</td>
<td>D221 7</td>
<td>2.6</td>
<td>3.49</td>
<td>4.17</td>
<td>4.98</td>
<td>6.04</td>
</tr>
<tr>
<td>Flash Point in °C</td>
<td>-</td>
<td>65</td>
<td>71</td>
<td>78</td>
<td>112</td>
<td>170</td>
</tr>
<tr>
<td>Fire Point in °C</td>
<td>-</td>
<td>70</td>
<td>79</td>
<td>88</td>
<td>123</td>
<td>183</td>
</tr>
<tr>
<td>Cloud Point in °C</td>
<td>-</td>
<td>-15</td>
<td>4</td>
<td>8</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>D445</td>
<td>0.82</td>
<td>0.83</td>
<td>0.85</td>
<td>0.87</td>
<td>0.88</td>
</tr>
<tr>
<td>Cetane number</td>
<td>-</td>
<td>46</td>
<td>51.6</td>
<td>51.7</td>
<td>51.8</td>
<td>52.4</td>
</tr>
</tbody>
</table>

As far as properties are concerned, it is clear that specific gravity, acidity, kinematic viscosity, flash point, fire point and cloud point increases as the biodiesel content in the biodiesel-diesel blends increases. The significant increase in the fire point shows that the volatility of the mixture with increased biodiesel content will decrease. It is also observed that the flash point and fire point of biodiesel blend in various volumetric proportions increase. Therefore the blends of fuel are very easy to store and safe for transportation as compared with B0 (pure diesel).

Table 3 Accuracy details of the Gas analyzer and Smoke meter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Percentage Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO_x</td>
<td>± 0.1</td>
</tr>
<tr>
<td>CO_2</td>
<td>± 0.01</td>
</tr>
<tr>
<td>HC</td>
<td>± 0.1</td>
</tr>
<tr>
<td>Kinematic viscosity</td>
<td>± 1.3%</td>
</tr>
<tr>
<td>SFC</td>
<td>± 1.5%</td>
</tr>
</tbody>
</table>

The gross calorific value decreases as the biodiesel in the mixture increases. This is due to the oxygen concentration in the fuel. AVL 444 di-gas analyzer is used for the measurement of exhaust emissions of hydrocarbon (HC), CO, CO_2, O_2 concentration and NO_x. Smoke level is measured using standard AVL 437 smoke meter.

Table 3 and 4 show the accuracy and uncertainty analysis of combustion and emission parameters of diesel engine. Experiments have been carried out under steady state conditions of the engine.

Table 4 Uncertainties of some measured and calculated parameters

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameter</th>
<th>Percentage Uncertainties</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NO_x</td>
<td>± 0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>CO_2</td>
<td>± 0.01</td>
<td>± 10 ppm</td>
</tr>
<tr>
<td>3</td>
<td>HC</td>
<td>± 0.1</td>
<td>± 10 ppm</td>
</tr>
<tr>
<td>4</td>
<td>Kinematic viscosity</td>
<td>± 1.3%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>SFC</td>
<td>± 1.5%</td>
<td>± 1% full scale reading</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

In this section the typical performance, combustion and emission results obtained are presented and discussed.

3.1 Specific Fuel Consumption (SFC)

Figure 2 shows the variation of specific fuel consumption with respect to blend ratio for various static injection timings of 19°, 20°, 21°, 22°, and 23° bTDC (standard) at full load. For B0 and B25 fuel, static injection timing of 20° bTDC gives almost the same specific fuel consumption of 0.256 and 0.257 kg/kWh respectively as compared with all other static injection timings. As can be seen this is the lowest specific fuel consumption for the blends under consideration. Similar trend was found by Raheman and Ghadge (2008) in their studies using Mahua biodiesel at 40° bTDC. The percentage reduction of specific fuel consumption for static injection timing of 20° bTDC for B0, B25, B50, B75 and B100 is 4.12%, 4.10%, 3.79%, 3.41%, and 2.92% respectively as compared with standard static injection timing of 23° bTDC. From Table 3, it is seen that all the blends have lower calorific value compared to B0. Specific fuel consumption increase with increase in biodiesel content. This may be attributed to comparatively higher viscosity and lower calorific value. Similar results were reported by Clark et al. (1984); Puhan et al. (2005a); Raheman and Ghadge (2008) when tested with methyl ester of Soy bean and Mahua oil.

![Figure 2 Specific fuel consumption vs Blend ratio](image)

3.2 Heat Release Rate (HRR)

Figure 3 shows the variation of heat release rate for various blend ratio with different static injection timings of 19°, 20°, 21°, 22°, and 23° bTDC (standard) at full load. From the test results, it is observed that heat release rate decreases with respect to increase in blends of biodiesel with fossil diesel fuel. For B0 fuel, static injection timing of 20° bTDC gives highest heat release rate as compared with all other static injection timings for all blends of fuel. The percentage increase in heat release rate for static injection timing of 20° bTDC for B0, B25, B50, B75 and B100 is 0.079%, 0.076%, 0.005%, 0.007% and 0.023% respectively as compared with standard static injection timing of 23° bTDC. Among all the blends, B0 and B25 give almost the same heat release rate. For other blends the values are lower which may be due to lower calorific value of B50, B75 and B100 as compared with B0. Optimum static injection timing is a must for better combustion. Higher injection timing and higher nozzle opening pressure to be better performance with thevetia peruviana biodiesel (Balusamy and Marappan, 2010). However, present study shows lower static injection timing of 20° bTDC and optimum nozzle opening pressure gives better results.

![Figure 3 Heat release rate vs Blend ratio](image)

3.3 Exhaust Gas Temperature (EGT)

Figure 4 shows the variation of exhaust gas temperature with respect to blend ratio for the static injection timings of 19°, 20°, 21°, 22° and 23° bTDC (standard).

It is seen that static injection timing of 20° bTDC gives lowest exhaust gas temperature as compared to all other static injection timings. The percentage reduction in exhaust gas temperature for static injection timing of 20° bTDC for B0, B25, B50, B75 and B100 is 3.31%, 3.30%, 3.28%, 3.29% and 2.44% respectively as compared with standard static injection timing of 23° bTDC. Too much retarding like 19° bTDC gives relatively higher exhaust gas temperature (Raheman and Ghadge, 2008). Among all the blends, the B0 gives highest percentage of reduction in exhaust gas temperature. However, B25 also closer to that of B0. From the figure, it is also observed that there is an increasing trend of exhaust gas temperature as increase in blend ratio of biodiesel with diesel fuel. This could be due to the slow burning rate with higher percentage of biodiesel content. This is also reflected in their lower brake thermal efficiencies as

![Figure 4 Exhaust gas temperature vs Blend ratio](image)
compared with neat diesel. Similar results were found by Raheman and Ghadge (2007); Puhan et al. (2005a) when the engine was operated with Mahua oil methyl esters.

3.4 Carbon dioxide (CO₂)

Figure 5 shows the variation of carbon dioxide emission with respect to blend ratio for the static injection timings of 19°, 20°, 21°, 22° and 23° bTDC (standard). From Figure 5, it may be seen that static injection timing of 20° bTDC gives highest CO₂ compared to all other timings. The percentage increase in CO₂ for static injection timing of 20° bTDC for B0, B25, B50, B75 and B100 is 27.94%, 28.31%, 26.80%, 27.53% and 21.92% respectively compared with standard static injection timing of 23° bTDC. Among all the blends, the B25 gives highest CO₂ of 28.31% in terms of percentage increase in CO₂ at full load. It may be due to better combustion of B25 blend which can cause higher CO₂ emissions. Similar findings were reported by Ramadhas et al. (2005) when the engine was tested with methyl ester of rubber seed oil.

![Figure 5 Carbon dioxide vs Blend ratio](image)

3.5 Smoke Density (SD)

Figure 6 shows the variation of smoke density with respect to blend ratio for the static injection timings of 19°, 20°, 21°, 22° and 23° bTDC (standard).

![Figure 6 Smoke density vs Blend ratio](image)

From the results, it is observed that static injection timing of 20° bTDC gives lowest smoke density (HSU) as compared to all other timings.

The percentage reduction in smoke density for static injection timing of 20° bTDC for B0, B25, B50, B75 and B100 is 26.58%, 26.70%, 18.52%, 14.29% and 16.51% respectively as compared with standard static injection timing of 23° bTDC. Among all the blends, the B25 gives 26.70% in terms of percentage reduction in smoke density at full load. This may be due to the chemistry of fuel blend which may provide conducive atmosphere for almost same smoke density for B25 compared to B0. From Table 3, it is evident that specific gravity change for B25 compared to B0 is quite small (0.82 to 0.83) and fire point increase is less than 10°C. Further there is good increase (46 to 51.6) in cetane number between B0 and B25. Probably this is the reason for having almost same smoke density at full load. This is to be expected because, more fuel is injected into the engine to take care of the load. As the engine is running at constant speed of 1500 rpm there is less time for complete combustion to take place which can cause an increase in smoke density for other blends of fuel like B50, B75 and B100. At full load, smoke levels decreased as biodiesel concentration is increased. Similar findings have been reported by Choi et al. (1997); Ramadhas et al. (2005) while testing with pure methyl ester of Soybean and Rubber seed oil.

3.6 Hydrocarbon (HC)

The variation of hydrocarbon with respect to blend ratio of the static injection timings of 19°, 20°, 21°, 22° and 23° bTDC (standard) is shown in Figure 7. From the test results, it is observed that static injection timing of 20° bTDC gives lowest hydrocarbon emission compared to other static injection timings for various blends of fuel.

![Figure 7 Hydrocarbon vs Blend ratio](image)

The percentage reduction in hydrocarbon (kg/kg of fuel) for static injection timing of 20° bTDC for B0, B25, B50, B75 and B100 is 9.76%, 10%, 8.11%, 8.33% and 3.26% respectively as compared with standard static injection timing of 23° bTDC. Among all the blends, the B25 gives 10% of percentage reduction in hydrocarbon at full load. This may be due to the viscosity and surface tension affects the penetration rate, maximum penetration and droplet size of the fuel, which in turn affecting the mixing of fuel and air. Cetane number of the fuel also plays a vital role in ignition process. From Table 3, it could be seen that the cetane number of B25 is higher than that of B0 (46 to 51.6). Therefore the B0 emits more
hydrocarbon than that of B25. Similar results were reported by Puhan et al. (2007); Godiganur et al. (2009) when tested with methyl ester of Mahua oil.

3.7 Oxides of Nitrogen (NOx)
Figure 8 shows the variation of Oxides of nitrogen (NOx) with respect to blend ratio for the static injection timings of 19°, 20°, 21°, 22° and 23° bTDC (standard). From the test results, it is seen that static injection timing of 20° bTDC gives lowest NOx (kg/kg of fuel) as compared to all other static injection timings for all blends of fuel. The retarded injection timing of 20° bTDC gives lower NOx. Similar results found by Dhananjaya et al. (2009) when tested with Jatropha biodiesel at 20° bTDC. The percentage reduction in NOx for static injection timing of 20° bTDC for B0, B25, B50, B75 and B100 is 24.04%, 24.89%, 23.73%, 24.74% and 24.89% respectively as compared with standard injection timing of 23° bTDC. Among all the blends, the B25 and B100 give 24.89% in terms of percentage reduction in NOx at full load. It is well known that vegetable based fuel contains a small amount of nitrogen and the spray properties depends on droplet size, droplet momentum and degree of mixing with air and penetration rate, evaporation rate and radiant heat transfer rate. Any one of the above properties can change the NOx production (Puhan et al., 2005c).

Figure 8 Oxides of nitrogen vs Blend ratio

4. CONCLUSIONS
From the present study, it is concluded that the B25 can be recommended as an alternative fuel for operating four stroke tangentially vertical single cylinder kirloskar direct injection water cooled constant speed diesel engine with a retarded static injection timing of 20° bTDC and with nozzle opening pressure of 250×105 N/m² This, it is found to give higher performance, better combustion and lower emissions from engine without much modification. This can save 25% of petro-diesel.

REFERENCES


