Journal of Mechanical Engineering *Vol 14(1), 57-74, 2017*

Experimental Investigation on the Influences of Varying Injection Timing on the Performance of a B20 JOME Biodiesel Fueled Diesel Engine

S. Jaichandar
Department of Automobile Engineering,
VelTech Dr RR & Dr SR Technical University, Chennai, India
Email: jaisriram18@yahoo.com

K. Annamalai
Department of Automobile Engineering, Madras Institute of Technology,
Anna University, Chennai, Tamilnadu, India

ABSTRACT

This experimental study aims to optimize the injection timing to achieve higher performance from biodiesel fueled Direct Injection (DI) diesel engine. Experiments were performed using a naturally-aspirated single cylinder DI diesel engine equipped with a conventional jerk type injection system to study the effects of varying injection timing on the combustion, performance and exhaust emissions using a blend of 20% Jatropha Oil Methyl Ester (JOME) by volume with diesel. The test results showed that improvement in terms of brake thermal efficiency and specific fuel consumption for the engine operated at retarded injection timing, particularly at 21° bTDC. Substantial improvements in reduction of emission levels particularly oxides of nitrogen (NO_x) were observed for retarded injection timing of 21° bTDC. Compared to the engine operated at standard injection timing of 23° bTDC, the retarded injection timing of 21° bTDC provided a better performance of 2.27% and 3.4% in terms of BTE and BSFC respectively and NO_x emission level improvement of 4.5%. However, CO, UBHC and smoke emission levels were slightly deteriorated compared to standard injection timing operation. It has also been found that retarding the injection timing lowers marginally ignition delay, peak in-cylinder pressure and maximum heat release rate.

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2016-08-02
Accepted for publication: 2016-11-10
Published: 2017-06-15

Keywords: *Biodiesel; Diesel Engine; Injection Timing; Performance; Combustion; Emissions.*

Nomenclature

JOME	Jatropha Oil Methyl Ester	CI	Compression Ignition
B20	blend of 20% JOME with diesel fuel by volume	BSFC	Brake Specific Fuel Consumption
B100	100% JOME	DI	Direct Injection
BTE	Brake Thermal Efficiency	HRR	Heat Release Rate
CO	Carbon Monoxide	UBHC	Unburned Hydrocarbons
NOx	Oxides Of Nitrogen	bTDC	Before Top Dead Center
CA	Crank Angle	deg	Degree

Introduction

Vegetable oils have interested researchers, who seek alternatives to petroleum fuels for Internal Combustion (IC) engines [1-4]. In fact, when Rudolf Diesel invented the CI Engine, the fuel he used was peanut oil [5, 6]. Vegetable oils faded into the background due to copious availability of petroleum fuels consequent to the successful oil explorations in the nineteenth and twentieth centuries. Vegetable oils could not compete with petroleum fuels commercially. The scenario changed from the 1980s. The depletion and uncertain petroleum prices make the Governments in almost all countries seek alternatives in fuels for energy [7-9]. The vegetable oils do promise at least a partial replacement of petroleum fuels by vegetable oils and their derivatives. The vegetable oils compete well with their petroleum counterparts in the performance of the CI engines [10, 11]. The power produced and the thermal efficiency with the vegetable oils are as good as other alternative oil or fuel. The disadvantages in using the straight vegetable oil in the engine are [12-15]

(i) The soot in the exhaust and its pollution to the atmosphere.
(ii) The gum forming tendency of the oil resulting in stuck valves and piston rings and
(iii) Problems in fuel supply system due to the high viscosity of the natural oil which is more than ten times that of the standard diesel oil and it could clog the system.

For any success for vegetable oils as alternative fuel, the oil has to be reformed so that the properties required become favourable and comparable with the standard diesel oil. The vegetable oils may be edible or non-edible. The non-edible oils would certainly be more welcomed [16]. The use of edible vegetable oils would increase the pressure on prices of cooking oils.

Researchers have suggested different techniques for reducing the viscosity of the vegetable oils, which are blending, pyrolysis, micro-emulsification and transesterification [17- 20]. The transesterification process has been proved as the most effective method and widely utilized. Use of biodiesel as an alternative fuel can contribute significantly towards the twin problem of fuel crises and environmental pollution. Researchers [21, 22] have shown that biodiesel fuel exhibits physico-chemical properties which are similar or some even better than to those of diesel and hence can be used in diesel engines. However, certain properties of biodiesel such as viscosity, calorific value, density and volatility differ from diesel.

The combustion in a diesel engine is a complex process. It depends on many factors such as engine design particularly combustion chamber design, fuel properties, injection pressure and injection timing of fuel [23]. There are extensive research results showing that fuel injection and air motion have great effects on mixture preparation, combustion and combined improvement of smoke and NO_x emission. Fuel injection characteristics have significant effects on diesel engine performance and emissions [24, 25]. For example, a further injection delay with a higher injection rate, decrease NO_x and soot emission simultaneously [26-28]. Based on the analysis of diesel combustion heat release rate, if the premixed combustion is controlled within a reasonable limit, the combustion temperature will be lowered to some extent and the combustion generated NO_x emission will thus be lowered; if the diffusion combustion process keeps fast and ends sharply, the soot emission will be reduced.

It was reported and noticed from the previous studies that blending biodiesel leads to particulate emission reductions by interfering with the soot formation process [29, 30]. However, in the case of biodiesel fueling, there was a well-documented increase of 5-20% in NO_x emissions [31, 32]. As shown by the researchers [33-35], the NO_x increases with biodiesel fueling was attributed to an advance of fuel injection timing. The advance in injection timing was due to the higher bulk modulus of compressibility, or speed of sound, in the fuel blend, which leads to a more rapid transfer of the pressure wave from the fuel pump to the injector needle and an earlier needle lift. It was established that the injection timing influences all engine characteristics notably. The reason was that the injection timing influences the mixing quality of the air fuel mixture and hence the whole combustion process. The fuel property changes between biodiesel and diesel may ask for a change in the engine operating parameters such as injection timing, injection pressure etc. These operating parameters can cause different performance and exhaust emissions than the optimized settings chosen by the engine manufacturer for diesel operation. Hence it is necessary to determine the improved optimum values of these parameters. In this experimental investigation, the attention was focused on finding the optimal injection timing for the blend of B20 in DI diesel engine in terms of the performance, emission and combustion parameters.

Materials and Methods

Biodiesel Production and Properties

Usage of non-edible oils for the production of biodiesel is found to be best suited given the deficit supply of edible oils and their cost of production. Among the non-edible oils, Tree Borne Oil seeds (TBOs) like jatropha and pongamia gain importance [16]. Jatropha curcas is a drought-resistant perennial, growing well in poor soil. It is still uncertained where the centre of origin is, but it is believed to be Mexico and Central America. It has been introduced to Africa and Asia and is now cultivated world-wide. Greater potential exists in India for bringing millions of hectares of wasteland under extensive plantation of jatropha, virtually converting unproductive lands into green oil fields. Jatropha seeds contain 37% oil [36, 37]. To prepare JOME, the transesterification reaction was performed on raw Jatropha oil. The transesterification process is the reaction of a triglyceride (vegetable oil) with an alcohol to form esters and glycerol. This transforms large, branched, triglyceride molecules of vegetable oils into smaller, straight chain molecules, almost similar to diesel fuel. The process takes place by the reaction of raw jatropha oil with methyl alcohol in the presence of alkaline catalyst [38, 39]. The properties of the raw jatropha oil and JOME were experimentally evaluated. The properties of raw jatropha oil, JOME and its 20% blend with diesel are compared with the standard diesel in Table 1. Most of the properties of bio-fuels like calorific value, viscosity, density, flash point, cloud point and pour point are comparable with those of diesel. Even though properties of JOME are comparable with diesel the viscosity of JOME was found to be about 44.1% higher and calorific value was 2.9% lower, when compared to standard diesel.

Experimental Setup

The test engine used was the Kirloskar, single cylinder four-stroke water cooled DI diesel engine developing 5.2 kW at 1500 rpm. Figure 1 shows the schematic diagram of the experimental setup. The detailed technical specifications of the standard engine are given in Table 2. This engine was coupled to an eddy current dynamometer with a control system. The cylinder pressure was measured by a piezoelectric pressure transducer fitted on the engine cylinder head and a crank angle encoder fitted on the flywheel. Both the pressure transducer and encoder signal were connected to the charge amplifier to condition the signals for combustion analysis using SeS combustion analyzer. UBHC, CO and NO_X emissions were measured using a CRYPTON 5 gas analyzer. The smoke intensity was measured with the help of the AVL 437C Smoke meter.

Table 1: Properties of diesel, biodiesel from jatropha and their blends.

Properties	**B100**	**B20**	**Diesel**	**IS: 15607 specification**	**Test methods IS1448 / ASTM**
Density (Kg/m^3)	873	852	850	860-890	P16
Kinematic Viscosity (cSt)	4.18	3.02	2.9	2.5-6.0	P 25/ D 445
Calorific Value (MJ/kg)	42.73	43.75	44.12		D5865
Flash Pt (°C)	148	88	76	120	P 21 / D93
Cloud Pt (°C)	10.2	6.9	6.5	-	D2500
Pour Pt (°C)	4.2	3.3	3.1	-	D2500

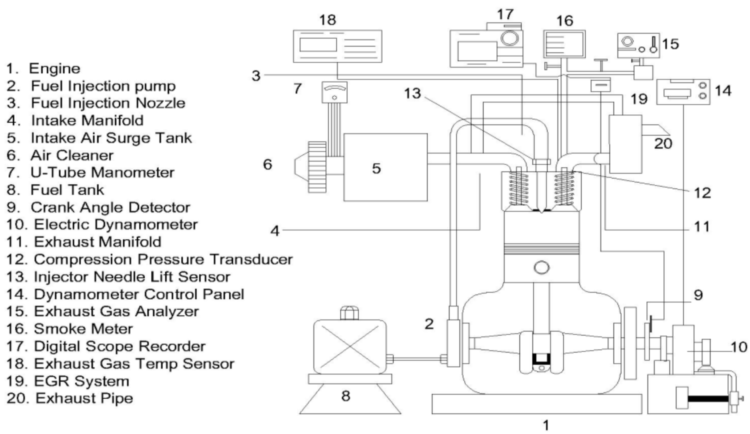

Figure 1: Schematic diagram of the experimental setup

Table 2: Standard engine specifications

Make	**Kirloskar TV1**
Type	Vertical diesel engine, 4stroke, water cooled, single cylinder
Displacement	661 cc
Bore & Stroke	87.5 mm & 110 mm
Compression ratio	17.5:1
Fuel	Diesel
Rated brake power	5.2 kW @ 1500 rpm
Ignition system	Compression ignition
Combustion chamber	Hemispherical combustion chamber

Engine Modifications

In the present investigation, to investigate the effects of varying the injection timing on performance, combustion and emission characteristics of biodiesel fueled direct injection diesel engines the injection timing of the Mico jerk type pump was varied by changing the number of shims under the pump body. The standard engine was fitted with three shims to give standard injection timing of 23^o before Top Dead Center (bTDC). By changing the no of shims, the injection timings were varied to 20^o, 21^o, 22^o and 24^o bTDC.

Test Method

For the experimentation, standard diesel and B20 were used as fuel. To start with the performance, emission and combustion tests were carried out using diesel and B20 at various loads for standard engine operating with fuel injection pressure of 200 bar and standard fuel injection timing of 23^o bTDC. The test was conducted by starting the standard engine with diesel fuel only. After the engine was warmed up, it was then switched to B20. Then the engine tests were carried out using B20 at different injection timings viz. 20^o bTDC, 21^o bTDC, 22^o bTDC, 24^o bTDC and at standard injection pressure of 200 bars and their results were compared and analysed with standard injection timing of 23^o bTDC. The engine tests were carried out at 0%, 25%, 50%, 75% and 100% load.

Results and Discussion

The performance, emission and combustion characteristics of the engine at different injection timings were determined, compared and analysed for brake specific fuel consumption, brake thermal efficiency, unburnt hydrocarbon, carbon monoxide, oxides of nitrogen, smoke emissions and combustion parameters such as ignition delay, cylinder peak pressure and heat release rate.

Performance Analysis

Brake Specific Fuel Consumption (BSFC) is a parameter that shows how efficiently an engine is converting fuel into work. The BSFC variations for engine with diesel and B20 for different injection timings starting from 20^o to 24^o bTDC are shown in Figure 2. At full load, the BSFC for diesel (0.28 kg/ kW-hr) was lower than B20 (0.295 kg/ kW-hr) at the standard injection timing. This was due to the lower calorific value of JOME than that of diesel. Furthermore, when the injection timing was retarded, at first the BSFC decreased and then it increased. Lowest BSFC was observed at an injection timing of 21^o bTDC. The BSFC of the engine was operated with the retarded injection timing of 21^o bTDC was slightly lower than standard injection timing of 23^o bTDC for B20. At full load, compared to the standard injection timing of 23^o bTDC, the retarded injection timing of 21^o bTDC provided a lower

BSFC of about 3.4%. This was due to better combustion of B20 due to better air fuel mixing. However, an increase in the BSFC was observed at retarded injection timing from 21° to 20° bTDC. The BSFC decreased with increase in load for the retarded injection timings too.

Figure 3 shows the comparison of Brake Thermal Efficiency (BTE) of diesel and B20 at different injection timings. It shows that the BTE increases with the increase in brake power for all fuel and with different injection timings. BTE of B20 is lower (28.65%) compared to that of diesel (29.5%) when operated at the standard injection timing. Since the engine is operated with the same injection timing and JOME has a smaller ignition delay, combustion is initiated much before TDC is reached. This can also be explained by the fact that maximum efficiency is obtained when most of the heat is released close to TDC [40]. This increases compression work and more heat loss and thus reduces the BTE of the engine. Further, it was observed that the BTE increased marginally with retarding the injection timing from 23° to 21° bTDC. This was mainly due to improved combustion as a result of better mixture formation. However further retardation in injection timing was found not so beneficial, in addition, it was also found advancement of injection timing too not so desirable as it led to drop in BTE of the engine. With B20 as fuel, the BTE at full load increased from 28.65% to 28.95% on retarding the injection timing by 1° and to 29.25% on retarding by 2° from standard injection timing of 23° bTDC. On advancing the injection by 1°, the thermal efficiency declined to 27%.

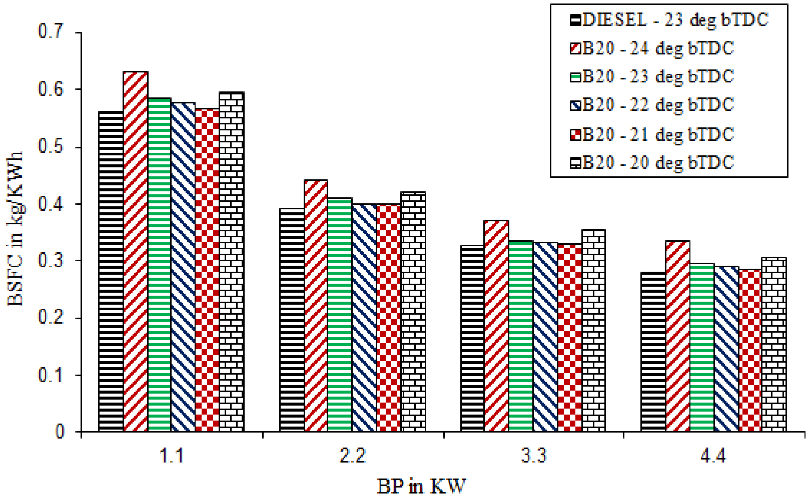

Figure 2: Variations of BSFC at different injection timings

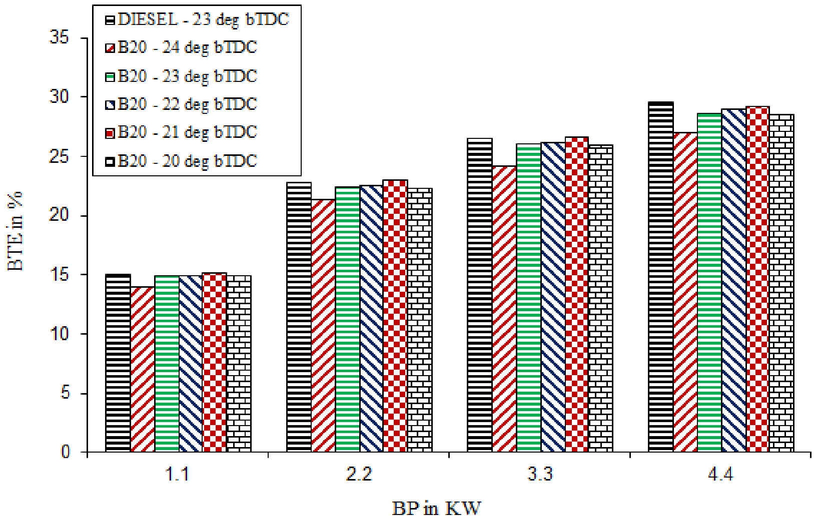

Figure 3: Comparisons of BTE at different injection timings

Emission Analysis

The comparisons of Unburnt Hydrocarbon (UBHC) emissions for diesel and B20 blend at different injection timings are shown in Figure 4. UBHC emissions were reduced over the entire range of loads for B20 when compared to diesel operation at standard injection timing. This was due to better combustion of B20 as a result of the presence of oxygen in JOME. However, marginal increase in UBHC emissions was observed for retarded injection timings. Compared to standard injection timing, the percentage increase of UBHC emissions for retarded injection timing of 20^o, 21^o and 22^o bTDC were 10%, 4.36% and 2.5% respectively. This was due to a slight decrease in premixed combustion phase and decrease in cylinder wall temperature. However for advanced injection timing of 24^o bTDC UBHC emissions were decreased by 10.9% compared to standard injection timing.

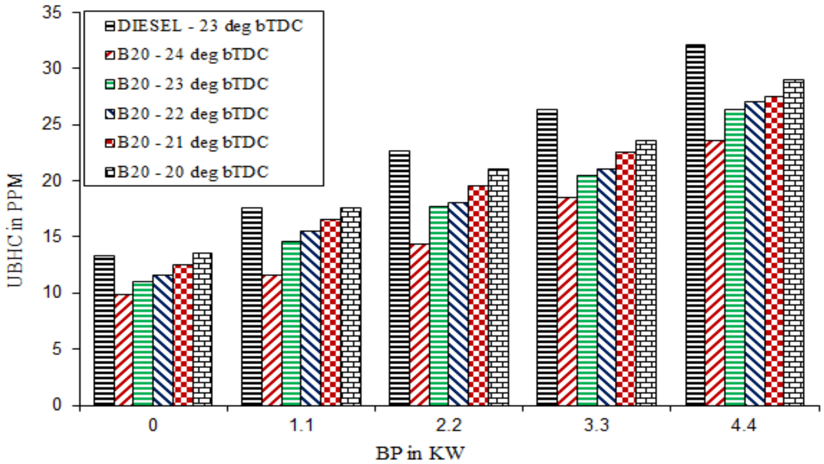

Figure 4: Variations of UBHC emissions at different injection timings

Figure 5 shows the comparison of CO emissions for diesel and B20 blend at different injection timings. At standard injection timing CO emissions with biodiesel blend decreased significantly when compared with those of standard diesel at all loads. This shows that CO emissions are greatly reduced with the addition of JOME to diesel. Increase in the proportion of oxygen in JOME promotes oxidation of CO during the engine exhaust process. Reduction in CO emissions was a strong advantage in favour of JOME. There was a reduction of 16% CO emissions for the B20 compared to standard diesel at full load operation. It has been noted that, marginal increase in CO emissions were noticed with retarded injection timings due to poor premixed combustion phase.

Figure 6 shows the variations of oxides of nitrogen emissions for standard engine with diesel and B20 with different injection timings. The NO_x emissions were higher for B20 than diesel at standard injection timing. The reason for the increase in NO_x may be attributed to higher combustion temperatures arising from improved combustion due to the presence of oxygen in JOME. At full load with B20 the NO_x emission was 670 ppm compared to 645 ppm for standard diesel at standard injection timing. There was an increase of about 3.9% NO_x emissions for B20 compared to standard diesel. However retarding the injection timing decreases NO_x emissions. Compared to standard injection timing, the percentage decrease of NO_x for retarded injection timings of 20^o, 21^o and 22^o bTDC were 6%, 4.49% and 2.2% respectively. This was due to shorter ignition delay owing to high cylinder pressure and temperature at retarded injection timing. The shorter ignition delay shortens the mixing time which leads to slow burning rate and slow rise in pressure and temperature. However for advanced injection timing of 24° bTDC, NO_x emissions were increased by 2.4% compared to standard injection timing.

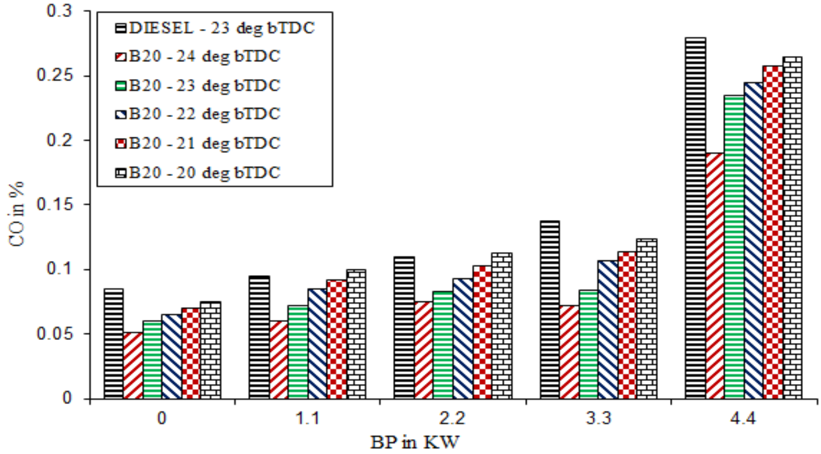

Figure 5: Comparisons of CO emissions at different injection timings

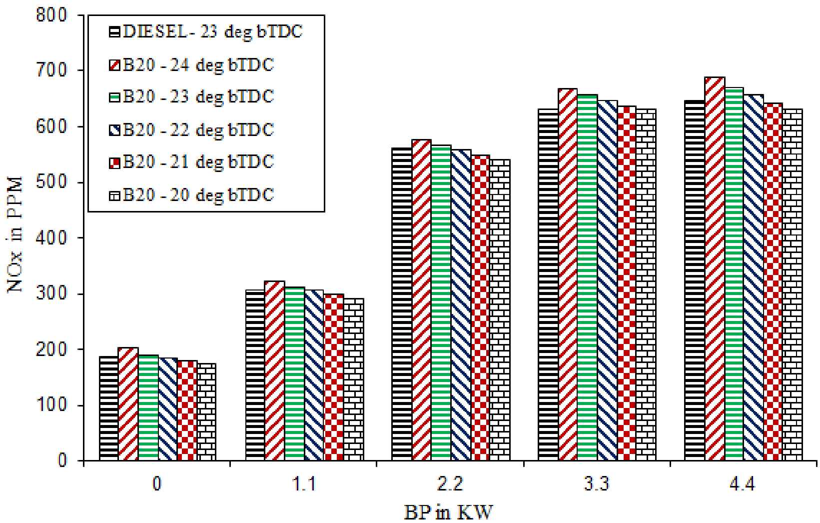

Figure 6: Comparisons of NO_x emissions at different injection timings

The smoke intensity comparison for diesel and B20 at different injection timings is shown in Figure 7. At all loads, smoke emissions for the blend decreases significantly when compared with those of standard diesel at standard injection timing. The reduction in smoke emission may be due to the presence of oxygen in biodiesel blend. B20 had shown a 15.4% reduction of smoke opacity when compared with standard engine fueled with diesel operation. It was also noticed that, retarding the injection timing increases smoke emission when compared with standard injection timing. The smoke opacity for retarded injection timing of 20°, 21° and 22° bTDC were measured as 56.5%, 54.6% and 53.1% respectively at full load compared to 51.6% at standard injection timing of 23° bTDC when fueled with B20. This was caused by lower in cylinder temperature due to reduction in premixed combustion phase as a result of the shorter ignition delay. The lower in-cylinder temperature inhibits the oxidation of soot particles that results in higher smoke emissions. However for advanced injection timing of 24° bTDC smoke opacity was decreased by 3.5% compared to standard injection timing.

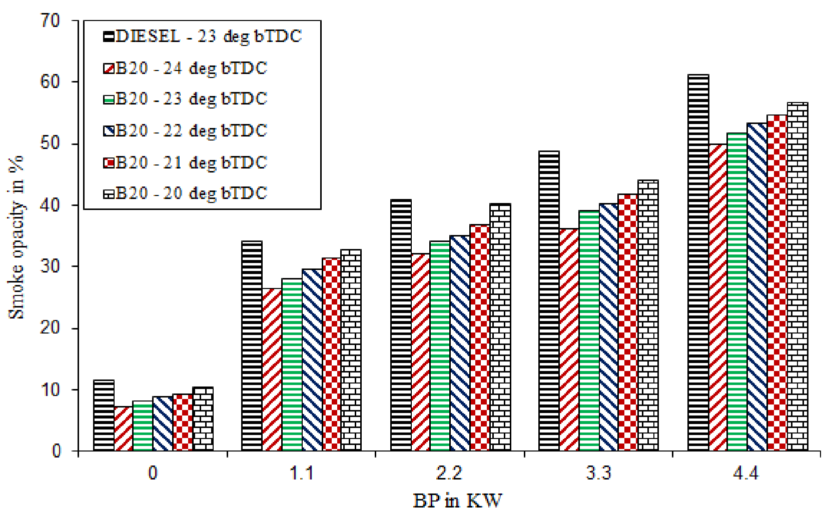

Figure 7: Variations of smoke emissions at different injection timings

Combustion Analysis

One of the most important parameters in the combustion phenomenon is the ignition delay. Figure 8 shows the variations of ignition delay for the engine with diesel and B20 at different injection timings. It was observed that the ignition delay period of B20 was significantly lower than that of diesel when tested in the standard engine at standard injection timing. This was due to higher cetane number of B20 compared to diesel. Further, it was found that at retarded injection timings, the ignition delay decreased due to high in-cylinder temperature and availability of oxygen in JOME. The ignition delays for the retarded injection timings of 20°, 21° and 22° bTDC were measured as 5.8° CA, 6.3° CA and 6.9° CA respectively at full load compared to 7.6° CA at standard injection timing of 23° bTDC. However for advanced injection timing of 24° bTDC the ignition delay was increased to 8.3° CA.

The comparison of the net heat release rate curves for engine with diesel and B20 at different injection timing is shown in Figure 9. The maximum heat release rate of B20 blend is lower than that of diesel in the standard engine. This may be attributed to shorter ignition delay for B20 compared with that of standard diesel. In addition the poor spray atomization characteristics of biodiesel due to higher viscosity and surface tension may be responsible for the lower heat release rate. Furthermore, it has been noticed that heat release rate during diffusion combustion phase of B20 is slightly higher than that of diesel. However the maximum heat release rate for retarded injection timings slightly lower compared to standard and advanced injection timings due to shorter ignition delay. As a result, the heat release rate during diffusion combustion phase was increased. The maximum heat release rate for retarded injection timing of 20°, 21° and 22° bTDC were recorded as 85.6 J/°CA, 84.8 J/°CA and 82.6 J/°CA respectively at full load compared to 86.2 J/°CA at standard injection timing of 23° bTDC for optimized engine fueled with B20. However for advanced injection timing of 24° bTDC the maximum heat release rate was increased to 88.2 J/°CA.

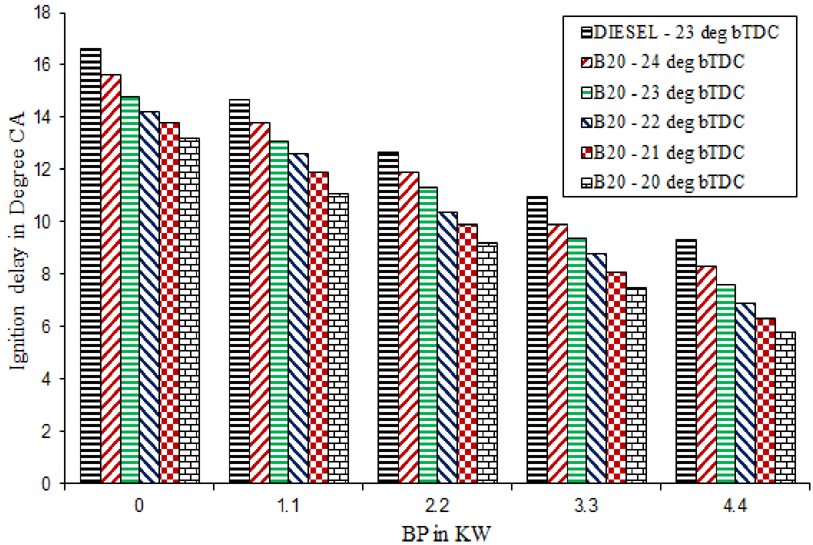

Figure 8: Variations of ignition delay at different injection timings

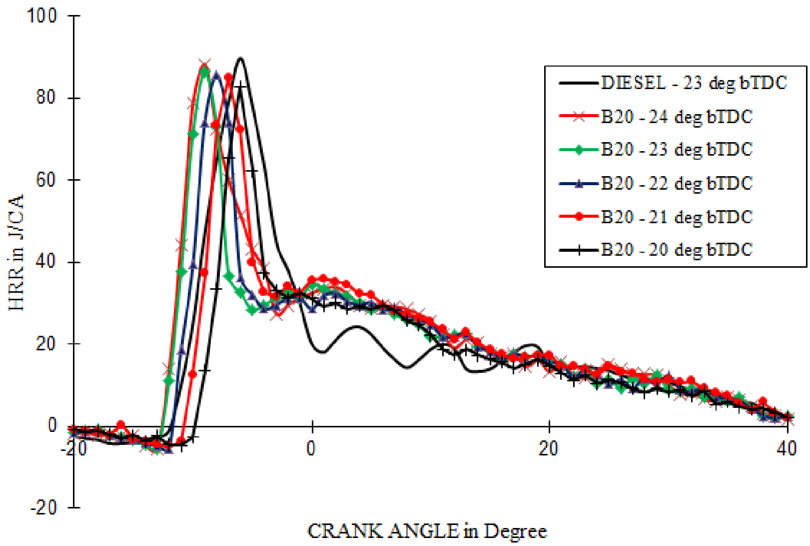

Figure 9: Comparisons of HRR at full load at different injection timings

The variation of peak pressures with respect to brake power for the engine at different injection timings with diesel and B20 is shown Figure 10. The pressure variations of the engine operated with B20 engine at different injection timings followed the similar pattern of pressure rise as that of the standard engine operated with diesel at all load conditions at standard injection timing. The peak pressure for B20 (75.8 bar) was slightly lower than that of diesel (78 bar) with the standard engine operated with the standard injection timing of 23° bTDC at full load. This was due to the lower calorific value of JOME than that of conventional diesel. Moreover, the peak pressure for the engine (74 bar) operated with the retarded injection timing of 21° bTDC was slightly lower than the standard injection timing of 23° bTDC (75.8 bar) caused by the lesser amount of heat release in the premixed combustion phase due to shorter ignition delay. A slight decrease in the peak pressure was observed for retarding the injection timing from 21° to 20° bTDC.

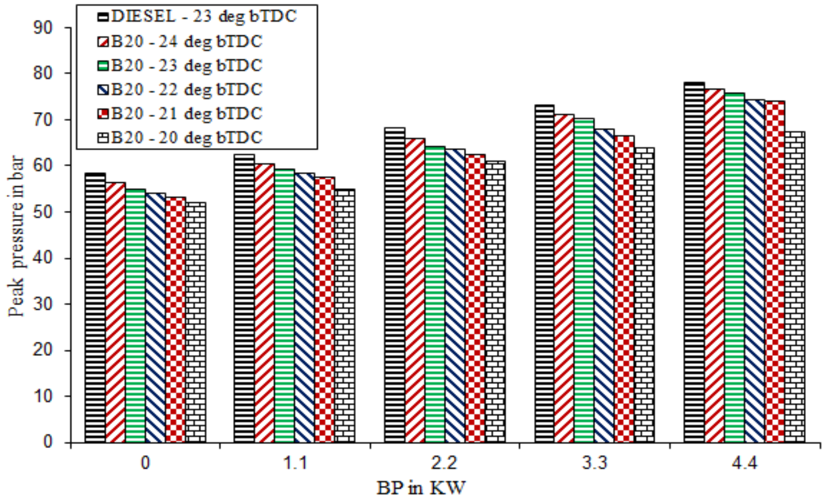

Figure 10: Variations of peak pressures at different injection timings

Conclusion

In this experimental phase, experiments were carried out to study the effects of injection timing on the performance, emission and combustion characteristics of B20 fueled DI diesel engine. The tests were performed at standard injection pressure of 200 bar with diesel and B20 at different injection timings viz. 20° bTDC, 21° bTDC, 22° bTDC, and 24° bTDC. The results were compared with that of B20 and diesel operated standard engine to decide on the proper injection timing for biodiesel fueled engine. From the experimental results the following conclusions can be drawn.

1. It was observed that the performance of the engine was initially improved and then decreased with retarded injection timings i.e. BTE increased marginally and BSFC were slightly decreased with retarding the injection timing from 23° to 21° bTDC. Further retardation of injection timing to 20° bTDC was found not so beneficial, moreover advancement of injection timing to 24° bTDC was not desirable as it led to drop in thermal efficiency and increase in BSFC of the engine.
2. CO, UBHC and smoke intensity for the engine was marginally increased with retarded injection timing due to poor initial phase of combustion.
3. Retarding the injection timing significantly decreased NO_x emission due to lower in-cylinder temperature as a result of poor premixed combustion phase caused by shorter ignition delay.

4. It was found that retarding the injection timing further lowered ignition delay, maximum peak in-cylinder pressure and maximum heat release rate.

The present investigation showed that the performance, combustion and emission characteristics of biodiesel fueled engine can be improved by suitably varying the injection timing. The engine operated with the retarded injection timing of 21° bTDC was found to be superior in terms of performance, combustion and exhaust emissions improvement over the standard, other retarded and advanced injection timings. Compared to the engine operated at standard injection timing of 23° bTDC, the retarded injection timing of 21° bTDC provided a better performance of 2.27% and 3.4% in terms of BTE and BSFC respectively and NO_x emission level improvement of 4.5%. However CO, UBHC and smoke emission levels were slightly deteriorated.

References

[1] K. Agarwal and L. M. Das, "Bio-diesel development and characterization for use as a fuel in compression ignition engines," Journal of Engineering for Gas Turbine and Power Transactions of the ASME 123, 440-447 (2001).

[2] K. Agarwal, J. Bijwe and L. M. Das, "Effect of bio-diesel utilization of wear of vital parts in compression ignition engine," Journal of Engineering for Gas Turbine and Power Transactions of the ASME 125, 604-611 (2003).

[3] R. Altin, S. Cetinkaya and H.S. Yucesu, "The potential of using vegetable oil fuel as fuel for diesel engines," Energy Conversion and Management 42, 529-538 (2001).

[4] A.S. Ramadhas, S. Jayaraj and C. Muraleedharan, "Use of vegetable oils as I.C. engine fuel- a review," Renewable Energy, 29(5), 727-742 (2004).

[5] M. Balat H. Balat, "A critical review of bio-diesel as a vehicular fuel," Energy Conversion and Management 49, 2727 – 2741 (2008).

[6] Murugesan, C. Umarani, R. Subramanian and N. Nedunchezhian, "Bio-diesel as an alternative fuel for diesel engines-A review," Renewable and Sustainable Energy Reviews 13, 653–662 (2009).

[7] M. A. Kalam and H. H. Masjuki, "Potential and properties of palm diesel as alternative fuel for automotive engines," International Energy Journal 9, 37–42 (2008).

[8] Pichalai, "The role of Thai energy policy and strategies in sustainable development," The Journal of the Royal Institute of Thailand 30 (3), 717–731 (2005).

[9] Pichalai, "Thailand's energy conservation program and the role of new and renewable energy in energy conservation," The Journal of the Royal Institute of Thailand 32 (1), 125–133 (2007).

[10] A.K. Agarwal, "Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines," Progress in Energy and Combustion Science 33, 233–271 (2007).
[11] A. Srivastava, R. Prasad, "Triglycerides-based diesel fuels," Renewable and Sustainable Energy Reviews 4, 111–133 (2000).
[12] K. Babu and D. Devaradjane, "Vegetable oils and their derivates as fuels for CI engines. An overview," SAE Paper No 2003-01-0767 (2003).
[13] K. Barnwal and M. P. Sharma, "Prospects of bio diesel production from vegetable oils in India," Renewable and Sustainable Energy Reviews 9, 363–378 (2005).
[14] S. Sundarapandian and G. Devaradjane, "Experimental investigation of the performance on vegetable oil operated CI engine," Proceedings of the 19th National Conference on I.C. engine and combustion, Annamalai University, Chidambaram, December 21–23, 87–94 (2005).
[15] T. W. Ryan, L. G. Dodge and T. J. Callahan, "The effects of vegetable oil properties on injection and combustion in two different diesel engines," Journal of the American Oil Chemists' Society 60, 1610–1619 (1984).
[16] Report of the committee on development of 'Biofuel' planning commission, Government of India, New Delhi, 2003.
[17] S. C. Bhupendra, K. Naveen and M. C. Haeng, "A study on the performance and emission of a diesel engine fueled with jatropha biodiesel oil and its blends," Energy, 37, 616–622 (2012).
[18] Baiju, M.K. Naik and L.M. Das, "A comparative evaluation of compression ignition engine characteristics using methyl and ethyl esters of Karanja oil," Renewable Energy 34(6), 1616-1621 (2009).
[19] P.K Devan and N.V. Mahalakshmi, "Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels," Fuel Processing Technology 90(4), 513-519 (2009).
[20] K.K. Radha, S.N. Sarada, K. Rajagopal and E.L. Nagesh, "Performance and emission characteristics of CI engine operated on vegetable oils as alternate fuels," International Journal of Automotive and Mechanical Engineering, 4, 414-427 (2011).
[21] P.K. Sahoo and L.M. Das, "Combustion analysis of jatropha, karanja and polanga based biodiesel as fuel in a diesel engine," Fuel, 88(6), 994–999 (2009).
[22] C.E. Goering, A.W. Schwab, M.J. Daugherty, E.H. Pryde and A.J Heakin, "Fuel properties of eleven vegetable oils," Transactions of ASAE, 25(6), 1472-1477 (1982).
[23] Kouremenos, D. T. Hountalas and A. D. Kouremenos, "Experimental investigation of the effect of fuel composition on the formation of pollutants in direct injection diesel engines," SAE Paper No 1999-01-0189 (1999).

[24] Flavio, “Impact of biodiesel bulk modulus on injection pressure and injection timing: the effect of residual pressure,” Fuel 90(2), 477-485 (2011).
[25] V. L. Michal, P. Martin and B. Alexander, “Experimental investigation of the behavior of non-esterified rapeseed oil in a diesel engine mechanical fuel injection system,” Fuel 94, 157-165 (2012).
[26] Challen and R. Barnescu, Diesel Engine Reference Book, Society of Automotive Engineers, (Bath Press, England, 1999).
[27] V. Ganesan, Internal Combustion Engines, 2nd ed. (Tata McGraw Hill Publishers, New Delhi, 1998), pp. 295–355.
[28] J. B. Heywood, Internal Combustion Engine fundamentals, (McGraw Hill Publications, New York, 1988), pp.682–692.
[29] T. Leevijit, G. Prateepchaikul, “Comparative performance and emissions of IDI turbo automobile diesel engine operated using degummed, de-acidified mixed crude palm oil-diesel blends,” Fuel 90(4), 1487-1491 (2011).
[30] S. Saravanan, G. Nagarajan, R.G. Lakshmi Narayana and S. Sampath, “Combustion characteristics of a stationary diesel engine fueled with a blend of crude rice bran oil methyl ester and diesel,” Energy 35(1), 94-100 (2010).
[31] K. Ali, Y. Abdulkadir, G. Metin and A. Duran, “Usage of methyl ester of tall oil fatty acids and resinic acids as alternative diesel fuel,” Energy Conversion and Management 51(12), 2863-2868 (2010).
[32] M. M. Musthafa, S. P. Sivapirakasam and M. Udayakumar, “Comparative studies on fly ash coated low heat rejection diesel engine on performance and emission characteristics fueled by rice bran and pongamia methyl ester and their blend with diesel” Energy 36(5), 2343-2351 (2011).
[33] A. L. Boehma, D. Morris and J Szybist, “The impact of the bulk modulus of diesel fuels on fuel injection timing,” Energy & Fuels 18(6), 1877-1882 (2004).
[34] Monyem, J. H. V. Gerpen and M. Canakci, “The effect of timing and oxidation on emissions from biodiesel fueled engines,” Transactions of the ASAE 44(1), 35-42 (2001).
[35] M. E. Tat, J. H. V. Gerpen, S. Soylu, M. Canakci, A. Monyem and S. Wormley, “The speed of sound and isentropic bulk modulus of biodiesel at 21°C from atmospheric pressure to 35 MPa,” Journal of the American Oil Chemists Society 77(3), 285-289 (2000).
[36] A. K. Yadav and V. Krishna, “Sustainable energy production from Jatropha bio-diesel,” International Journal of Advancements in Research & Technology, 1(5), 1-6 (2012).
[37] M. Sahu, V.K.Gour and S. Gupta, “Jatropha oıl: an eco-frıendly sustaınable bıo-fuel source,” Journal of Industrial Pollution Control 24 (2), 177-182 (2008).

[38] Y. Ali and M. A. Hanna, "Alternative diesel fuels from vegetable oils," Bioresource Technology 50, 153–163 (1994).
[39] N. J. Barsic and A. L. Humke, "Performance and emissions characteristics of a naturally aspirated diesel engine with vegetable oil fuels," SAE Paper No 810262 (1981).
[40] D. Hsu, Practical Diesel Engine Combustion Analysis, 1st ed. (Society of Automotive Engineers Inc., Warrendale, PA, pp. 21-26 (2002).