Injection Timing Impact on *Calophyllum inophyllum linn* oil (Honne Oil) / Diesel Fuelled Diesel Engine

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Abstract – *The present work examines the use of a non-edible vegetable oil namely honne oil, a new possible alternative fuel for diesel engine. Viscosity of honne oil can be reduced by blending it with diesel fuel. A direct injection (DI) diesel engine typically used in agricultural sector was operated on neat diesel (ND) and a blend of 50% honne oil with 50% diesel fuel (H50). Injection timing was changed to study the performance, emission and combustion characteristics. It was observed that advancing the injection timing with H50 from the rated injection timing (23* ^{o}*bTDC) increased the brake thermal efficiency and reduced CO, HC and smoke opacity emissions. However,* NO_x *emission was increased. The ignition delay with H50 was higher than that with ND for all the injection timing under consideration. Improved premixed heat release rates were observed with H50 when the injection timing was advanced. The best injection timing was found to be 27*^{o} *bTDC for H50 based on brake thermal efficiency (BTE).*

Keywords – Blending, combustion, emissions, injection timing, performance, vegetable oil.

1. INTRODUCTION

The continuous rise in global prices of crude oil, increasing threat to environment due to exhaust emissions, the problem of global warming and the threat of supply fuel oil instabilities have adversely impacted the developing countries, more so to the petroleum importing countries like India. From the point of view of long term energy security, it is necessary to develop alternative fuels with properties comparable to petroleum based fuels. Vegetable oils are one such alternative source. Diesel engines have the advantages of better fuel economy, lower emissions of HC and CO. However, diesel engines suffered from high emissions of particle matter / smoke density and NO_x, and there is inherent tradeoff between them [1]. For the reduction of exhaust emissions, few researchers used alternative fuels in the form of fumigation [2]-[4] and diesel fuel additives [5].

It is reported that use of 100% vegetable oil is also possible in diesel engine as they have a cetane number with heating value close to diesel fuel but show inferior performance and emissions compared to ND [6]. The compressibility effect of the vegetable oil causes an earlier injection of fuel in to the engine cylinder as compared to diesel fuel [7], [8]. This earlier injection does not play an important role, as this injection advance difference is at maximum 1°CA even for the neat vegetable oil [9]. The cetane number of vegetable oil, which is little lower compared to the diesel fuel [10], does not play an important role, as there is small differences in their premixed combustion phase [9], [11]. The major difference occurs in the atomisation process, *i.e.*, the mean droplet size of vegetable oil is much higher than diesel fuel [12], [13]. This is because the high viscosity (Table 1) and low volatility of vegetable oils lead to difficulty in atomizing the fuel and in mixing it with air. This fact and the much slower evaporation process for the vegetable oil could considerably affect the combustion process [9], [14]. Further, gum formation, piston sticking under long-term use due to the presence of oxygen in their molecules and the reactivity of the unsaturated HC chains are the problems with vegetable oils [15]. Hence, only a partial replacement of diesel fuel is possible.

Nishimura [16] reported that the basic mechanism involved in the formation of pollutants inside the DI diesel combustion chamber, is the mixing and combustion of injected fuel. Kouremenos *et al.* [17] reported that physical properties have a considerable effect on both mixing and combustion of injected fuel. Another important finding from Kouremenos *et al.* [17] was the serious effect of fuel physical properties and especially viscosity and density on the performance of the fuel injection system, injector opening pressure and injection timing. It is reported that the injection and atomization characteristics of the vegetable oils are significantly different than those of petroleum-derived diesel fuels, mainly as the result of their high viscosities [18]. Hence, performance, emission and combustion characteristics of each vegetable oil depend upon the mixing process in turn the fuel injection system, injector opening pressure and injection timing. High viscosity and surface tension of vegetable oil affect atomization by increasing the droplet size which in turn increases the spry tip penetration [19], [20].

It was reported that the engine performance and exhaust emission [CO, HC, smoke opacity (SO)] characteristics of the engine operating on ND / vegetable oil / bio diesel / diesel-biodiesel blends at advanced injection timing were improved [21]-[27] and better than when operating at increased injection pressure [28]. The reason might be due to more landing time (due to

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injection advance) of the fuel particle resulting in a more dispersion of fuel particle in turn better vaporization hence better mixing of air and fuel. An increase of injection pressure is found to enhance the atomization, reducing fuel particle diameter at the nozzle out, resulting in a more dispersion of fuel particle in turn better vaporization hence better mixing of air and fuel resulting in improved performance and emissions characteristics [29]-[31]. Injection advance is more predominant than enhanced injection pressure, because, due to more time available, more quantity of fuel participates in vaporisation leads to better air fuel mixture in larger part of the combustion chamber. Whereas in case of enhanced injection pressure, due to smaller droplet size of the fuel, improves vaporisation in turn locally better air fuel mixture.

Table 1. Comparison of properties of diesel fuel, honne oil and few vegetable oils.

Properties	Units	ND	Honne oil	Cottonseed oil[a]	Soybean oil[a]	Corn oil[a]	Olive oil[a]	Honge oil[b]	Rice bean oil[c]
Density at 15°C	Kg/m^3	830	910	910	925	915	925	924	901
Kinematic viscosity at 40°C	cSt	3.12	32.47	34	33	35	32	45.23	42.55
Lower heating value	kJ/kg	43,000	39,100	36,800	37,000	36,300	37,000	39,440	38,952

[a] [10], [b][40], [c][41]

Several investigators [32]-[44] have reported experimental works on different neat vegetable oil and vegetable oil blends with diesel fuel in DI diesel engine without varying injection timing and reported mixed opinion on performance and emission characteristics.

Use of a vegetable oil (putranjiva oil) and diesel fuel blending in diesel engine have demonstrated that blends of vegetable oil upto 30% and diesel fuel reduce the emissions such as CO, NO$_x$, smoke, particulates and the BTE is comparable to ND [32]. Performance and emission characteristics of karanja oil and its blends have been found to be comparable to that of mineral diesel [33]. The performance of 10% blend karanja vegetable oil fuelled engine appeared marginally better than the ND in terms of BTE, smoke opacity, and exhaust emissions, including NO$_x$ emission, for a range of operations [34]. It is observed that for neat orange oil emissions of HC, CO, smoke opacity get reduced whereas NO$_x$ emissions decrease as compared to ND [35]. Herchel *et al.* [36] used neat vegetable oil and concluded that smoke opacity and NO$_x$ lowered while CO and HC increased. Silvio *et al.* [6] demonstrated that use of 100% vegetable oil was possible in DI diesel engine and CO, HC, CO$_2$, specific fuel consumption were increased and NO$_x$ decreased over a range of operation. In other study, emissions of CO, HC and SO$_x$ were increased, where as NO$_x$ and PM emissions were decreased for blended vegetable oil with diesel fuel as compared to diesel fuel [37], [38]. Wang *et al.* [39] conducted experiment on blended vegetable oil with diesel fuel and observed that higher exhaust gas temperature were attained with very small changes in CO and lower NO$_x$ as compared to diesel fuel. Venkanna *et al.* [40], [41] reported that performance and emissions with vegetable oil/diesel fuel blend (honge oil 30% + diesel fuel 70% (H30) and rice barn oil 30% +diesel fuel 70% (R30)) are comparable with ND. It was reported that BTE of honne oil / diesel fuel / kerosene was higher as compared to ND and there was a good trade off between NO$_x$ and SO [42]. It was concluded that performance and emission characteristics of preheated honne oil / diesel fuel blends (10% to 50%) were better than unheated honne oil blends [43]. It was observed that increasing the IOP with honne oil +50% diesel fuel from the rated injector opening pressure (200 bar) increased the BTE and reduced CO, HC and SO emissions [44].

From the literature review it was concluded that the injection and atomization characteristics of the fuel are mainly dependent on the viscosity of the fuel. Hence, performance, emission and combustion characteristics of diesel fuel (each vegetable oil) depend upon the mixing process in turn the fuel injection system, injector opening pressure and injection timing. It was also concluded that advanced injection timing was better than when operated at increased injector opening pressure. For each vegetable oil injector timing and injector opening pressure is to be optimized to get maximum efficiency and minimum emissions.

The objective of the present work is to study, through experiments, the influence of injection timing on the performance, emissions and combustion characteristics of H50 fed DI diesel engine. A description of honne tree is available in the literature [45].

2. MATERIALS AND METHODS

Fuel Characterization

The properties of neat honne oil (H100), ND and H50 (50% honne oil + 50% diesel fuel on volume basis) were determined as per the methods approved by the Bureau of Indian Standards and the results are given in Table 2.

Table 2. Properties of the fuel.

Properties	Units	Methods IS 1448	ND	H100	H50
Density at 15°C	Kg/m^3	P:16	830	910	872
Flash point	°C	P:69	56	224	72
Kinematic viscosity at 40°C	cSt	P:25	3.12	32.47	9.75
Kinematic viscosity at 100°C	cSt	P:25	----	9.09	4.39
Lower heating value	kJ/kg	P:6	43000	39100	41104

Table 3. Engine specifications.

Manufacturer	Kirloskar Oil Engines Ltd., India
Model	TV_SR II, naturally aspirated
Engine	Single cylinder, DIdiesel engine
Bore / stroke	80 mm / 110 mm
Compression ratio	16.5:1
Speed	1500 rpm, constant
Injection pressure	200 bar
Injection timing	23° bTDC
Shape of piston	Bowl-in-piston
Dynamometer	Eddy current (Make: Dynaspeed)
Air flow measurement	Air box with U tube
EGT	RTD thermocouple.
Governor	Mechanical governing (centrifugal)
Pressure transducers	
Resolution	bar for cylinder pressure (Cp)/ 1 bar for fuel line pressure (Fp)
Type of sensor and maximum pressure	Piezo electric (5000 PSI for Cp and 10000 PSI for Fp)
Response time	4 micro seconds
Sampling resolution	1 degree crank angle
Crank angle sensor	360 degree encoder

Table 4. Exhaust gas analyzer and smoke opacity specifications and uncertainty of measured values.

Exhaust gas	Principle of measurement	Range	Resolution	Accuracy
O2	Electrochemical	0-22 vol.%	0.01 vol.%	±0.2 vol.%
NOX	Electrochemical	0-5,000 ppm	1 ppm	±10 ppm
CO	NDIR	0-10 vol.%	0.01 vol.%	±0.03 vol.%
CO	NDIR	0-16 vol.%	0.1 vol%	±0.7 vol%
HC	NDIR	0-20,000 ppm	1 ppm	±5 ppm
Smoke opacity				± 2%
Measured data		Uncertainty		
Speed		± 1		
Fuel volumetric rate		± 1		
Torque		± 1		
EGT		± 1		

Experimental Set Up and Plan

Experimental tests were conducted on a DI diesel engine, typically used in agricultural sector. Two fuel tanks were used in the present investigation with switch over arrangement, so that supply of fuel can be changed without stopping the engine operation. The specifications of the engine are given in Table 3. The photograph of the experimental set up is shown in Figure 1.

The engine tests were conducted for the entire load range (0 to 100% *i.e.*, 0 to 5 hp in steps of 25%) at constant speed of 1500 rpm. The engine parameters, such as fuel consumption, air consumption, exhaust gas temperature (EGT) and exhaust gas emissions were measured for both fuel samples (ND and H50) thrice and averaged. The engine was started with diesel fuel and the data was collected after attaining steady state. Then the experiment was switched over to blend of honne oil and diesel fuel.

The manufacturer specified static injection timing is 23° bTDC. Experiments were carried out with H50 to optimize the static injection timing. These experiments were carried out at different static injection timings of 23, 25, 27 and 28° bTDC. Static injection timing was varied by using shims in the fuel pump. The exhaust gas composition was analysed by using exhaust gas analyzer (make: MRU, Germany, model: DELTA 1600 S) and smoke opacity was measured using smoke opacity meter (make: MRU, Germany, model: Optrans 1600). The specifications of exhaust gas analyzer and uncertainties of measured values are given in the Table 4.

Fig. 1. Photograph of the experimental set up.

3. RESULTS AND DISCUSSION

Fuel Properties and Characteristics

The composition of honne oil is reported in the literature [45]. The viscosity of honne oil is 32.47 cSt at 40°C whereas at 100°C the viscosity is 9.09 cSt. At high temperatures the viscosity falls to below 10 cSt which reduces the atomisation problem. Density of honne oil is slightly higher than ND. The flash point of honne oil is better than ND. Presence of oxygen in oil improves combustion and reduces emissions but decreases the heating value of the oil. The heating value of honne oil is approximately 90% of the value of ND but is comparable with other vegetable oils as reported by Rakopoulos *et al*. [10].

Effect on Performance Parameters

The BTE increases with the increase in engine loads as expected and this is shown in Figure 2. It was observed that the injection timing of 23° bTDC (engine manufacturer data) was the best for ND based on the BTE. The engine performance with H50 is observed at different timings. It is observed that the injection timing of 23° bTDC as the worst for H50 based on BTE. The combustion was slow with H50 on account of its high viscosity which leads to a poor spray and mixture with air. The BTE increased when the injection timing was advanced. If start of injection is advanced, cylinder temperatures and pressures are lower, increasing ignition delay. In the combustion chamber more time is available for physical processes like, fuel heating, vaporizing, and mixes with cylinder air. If ignition delay increases, the amount of fuel and air mixture ready for combustion increases. This results in a higher rate of heat release, causing higher cylinder temperatures and pressures. Higher cylinder temperature and pressure leads to higher BTE. It appeared that H50 yielded better BTE at 27° bTDC injection timing in comparison to 23° bTDC timing. For H50, 27° bTDC is considered as the best injection timing based on the BTE. The BTE of H50 with advanced injection timing is still lower than that of ND for the entire load under consideration. Nwafor *et al*. [46] reported that rapeseed oil operation at 3000 rpm with standard timing produced the highest BTE and there was no significant difference noted between the diesel fuels and advanced timing unit at low and intermediate load levels.

Figure 3 compares the exhaust gas temperature (EGT) for various operations. The diesel fuel operations showed the lowest values at static injection of 23° bTDC. With H50, the advanced injection timing produced the highest EGT. Due to high viscosity and low volatility, there are some rich pockets of fuel air mixture which burned in the later part of the combustion. Also the late burning of injected honne oil results in lower combustion and, consequently, a higher EGT. The heat released during the late combustion could not be converted into work and appeared as heat. This is the reason for lower BTE than that of ND (Figure 1).

Effect on Emission Parameters

With H50, CO emission is least at 28° bTDC injection timing and HC emissions are least with the best injection timing namely 27°bTDC compared to other injection timings at all loads as seen in Figures 4 and 5. This is due to: (1) longer ignition delay causes more fuel to accumulate before ignition and part of the accumulated fuel causes higher wall adherence or local over leaning and (2) improved combustion (increase in in-cylinder pressure and temperature). The CO and HC levels with H50 the said best injection timing is still higher than ND. Nwafor *et al*. [46] concluded that advanced injection unit showed a marginal increase in HC emissions over the standard injection timing unit at the speed of 3000 rpm.

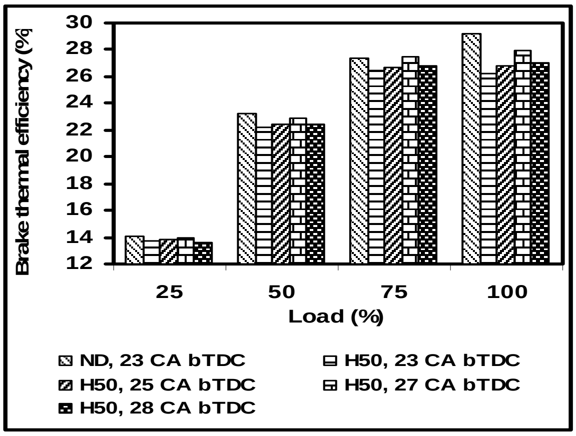

Fig. 2. Variation of brake thermal efficiency.

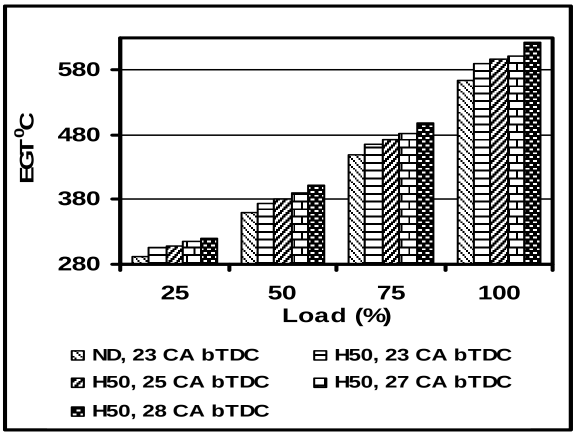

Fig. 3. Variation of exhaust gas temperature.

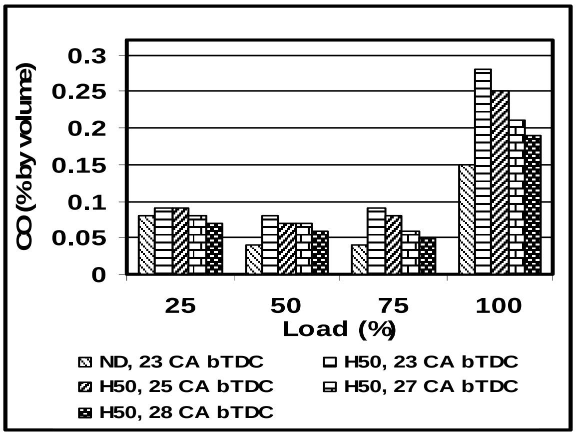

Fig. 4. Variation of CO emissions.

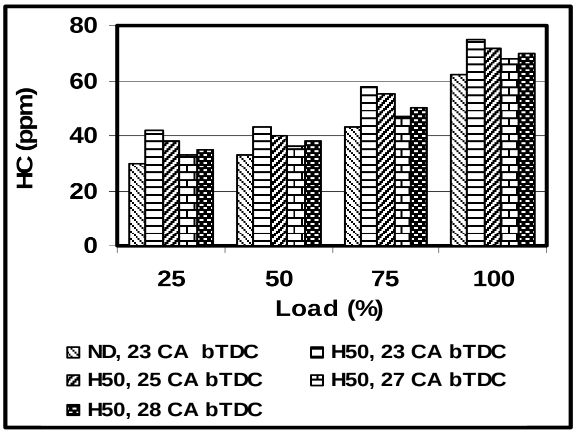

Fig. 5. Variation of HC emissions.

The SO with ND and H50 increase with increase in engine loads as expected and this is shown in Figure 6. Smoke opacity level with H50 decreases as the injection timing is advanced as is normal in diesel engines because of the predominance of the premixed combustion phase. A least SO is obtained at 28^{o} bTDC and this is almost equal to ND.

Figure 7 shows the NO_x emissions for ND and H50. NO_x emissions increased with load. With increasing load, fuel consumption rate increases and hence more heat is released during burning. NO_x emission increases with increasing temperature of combustion chamber. Another main factor is injection timing. The NO_x emission level increases as the injection timing is advanced as expected. This is due to the dominance of the premixed combustion phase leading to higher peak pressure in turn higher cylinder temperature. With H50, NO_x emission is highest at 28^{o} bTDC injection timing compared to other injection timings and ND. Both ND and H50 are tested with the same injection time of 28^{o} bTDC. Thus the injection timing of 28^{o} bTDC of ND produced high temperature yielding more NO_x as compared to H50.

Combustion Characteristics

Cylinder pressure crank angle variation at maximum load with ND and H50 at different injection timing is given in Figure 8. H50 at different injection timings follows the trend similar to the ND pressure diagram. The cylinder peak pressure is highest with ND followed by H50 at injection timings of 28^{o} bTDC and 27^{o} bTDC. Peak cylinder pressure occurred at 361^{o} with ND, whereas it occurred at 362^{o} and 363^{o} with H50 at injection timings of 27^{o} and 28^{o} bTDC respectively. If injection is too early (more than 28^{o} bTDC) incomplete combustion occurred and the peak temperature and peak pressure lowered.

The variation of net heat release rates with ND and H50 at different injection timing are given in Figure 9. The peak net heat release rate with H50 is always lower than ND. The start of combustion for the same injection timing appeared to be delayed indicating an increase in the ignition delay with H50. With H50, as injection timing is advanced, the ignition delay increased because fuel is injected earlier in the compression process. This lead to more accumulation of the fuel in the ignition delay period and lead to a more predominant initial phase of combustion, the premixed combustion. This is the reason for the improved thermal efficiency. This also says that the diffusion combustion portion became less significant and thus smoke is reduced (Figure 5). Too advance ignition timing of 28^{o} bTDC increased the ignition delay to a larger value leading to poor combustion and the BTE is reduced.

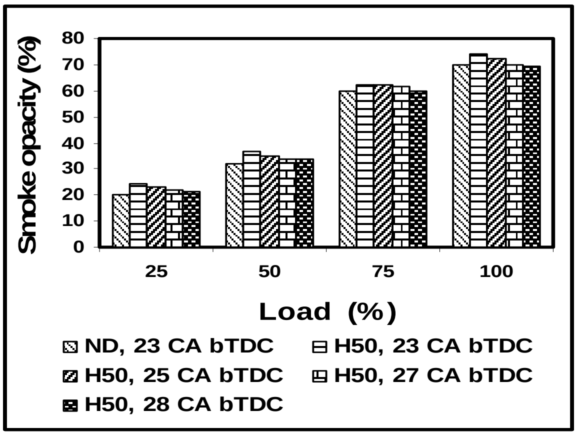

Fig. 6. Variation of smoke opacity emissions.

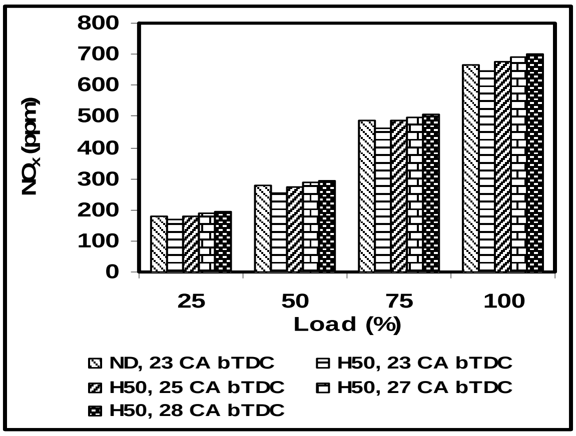

Fig. 7. Variation of NO_x emissions.

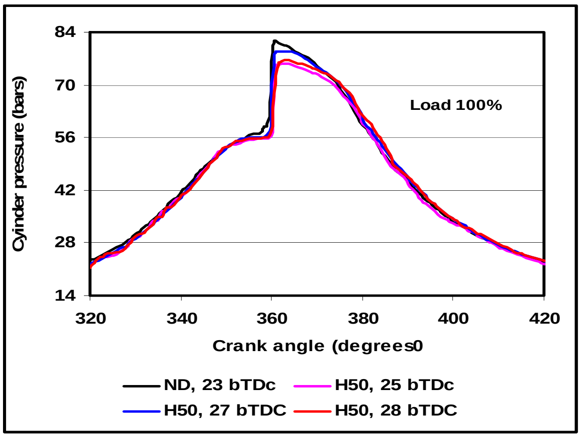

Fig. 8. Variation of cylinder pressure.

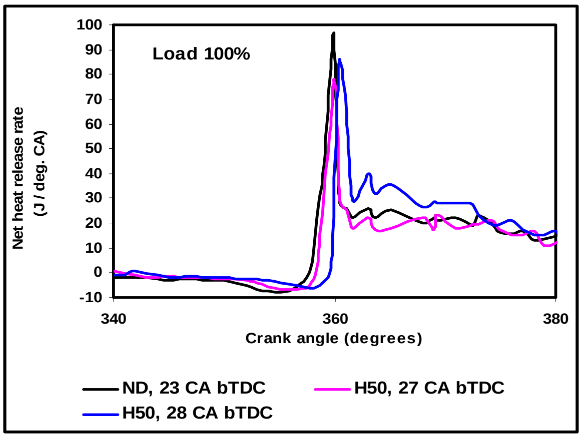

Fig. 9. Variation of net heat release rate.

4. CONCLUSIONS

Based on the experimental work with ND and H50 the following conclusions are drawn. It is found that the injection timing of 23^{o} bTDC (specified by the manufacturer) was the best for ND based on BTE. In case of H50 the injection timing has to be advanced as compared to ND. It was observed that advancing the injection timing with H50 from the rated injection timing (23 ^{o}bTDC) increased the BTE and reduced CO, HC and smoke opacity emissions. However, NO_x emission was increased. Advanced injection timing increased the ignition delay and lead to a dominant premixed combustion phase. Improved premixed heat release rates were observed with H50 when the injection timing was advanced. The best injection timing based on brake thermal efficiency is 27^{o} bTDC. With H50, at 27^{o} bTDC, at maximum load, resulted in the following improvements as compared to 23^{o} bTDC injection timing.

- Increase in BTE from 26.26% to 27.98%.
- EGT increased from 590^{O}C to 602^{O}C.
- Reduction in the CO from 0.28% to 0.21%
- Reduction in HC from 75 ppm to 68 ppm
- Reduction in SO from 74% to 69.5%
- Increase in NO_x from 648 ppm to 689 ppm.

To get maximum efficiency and least emissions, each diesel engine fuel should be optimized for injection advance and injector opening pressure. Hence it is recommended to carry out work to get maximum efficiency and emissions by optimizing injection advance and injector opening pressure.

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