EFFECT OF INJECTOR OPENING PRESSURES ON THE PERFORMANCE, EMISSION AND COMBUSTION CHARACTERISTICS OF DI DIESEL ENGINE RUNNING ON HONNE OIL AND DIESEL FUEL BLEND

by

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Original scientific paper
UDC: 621.43.041.6:662.756.3
DOI: 10.2298/TSCI10041051B

The present work examines the use of a non-edible vegetable oil namely honne oil, a new possible source of alternative fuel for diesel engine. Highly viscous honne oil can be reduced by blending it with diesel fuel. A direct injection diesel engine typically used in agricultural sector was operated on neat diesel and a blend of 50% honne oil with 50% diesel fuel (H50). Injector opening pressure was changed to study the performance, emission and combustion characteristics. It was observed that increasing the injector opening pressure with H50 from the rated injector opening pressure (200 bar) increased the brake thermal efficiency and reduced CO, HC, and smoke opacity emissions. However, NO_x emission was increased. With H50, ignition delay decreased as injector opening pressure increased. Improved premixed heat release rate were observed with H50 when the injector opening pressure was advanced. The best injector opening pressure was 240 bar for H50 based on brake thermal efficiency and emissions.

Key words: *honne oil, diesel engine, blending, injector opening pressure, performance, emissions*

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 particulate matter (PM), smoke density, and NO_x, and there is inherent trade off between them [1]. For the

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reduction of exhaust emissions, few researchers used alternative fuels in the form of fumigation [2-4] and diesel fuel additives [5].

The compressibility effect of the vegetable oil causes an earlier injection of fuel in to the engine cylinder as compared to diesel fuel [6, 7].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 [8]. The cetane number of vegetable oil, which is little lower compared to the diesel fuel [9], does not play an important role, as there is small differences in their premixed combustion phase [8, 10].The major difference occurs in the atomisation process, *i. e.*, the mean droplet size of vegetable oil is much higher than diesel fuel [11, 12]. This is because the high viscosity 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 [8, 13]. 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 [14]. Hence, only a partial replacement of diesel fuel is possible.

Table 1. Comparison of values of properties of karanja oil used in diesel engine by different investigators

Properties	Unit	Researcher [15]	Researcher [16]	Researcher [17]
Density at 15 °C	kgm^{-3}	912	913	938
Viscosity at 40 °C	cSt	27.84	27.84	35.98
Lower heating value	kJkg^{-1}	34,000	37,304	41,660

Nishimura [18] reported that the basic mechanism involved in the formation of pollutants inside the direct ignition (DI) diesel combustion chamber, is the mixing and combustion of injected fuel. Kouremenos *et al.*, [19] reported that physical properties have a considerable effect on both mixing and combustion of injected fuel. Another important finding from Kouremenos *et al.*, [19] 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. Properties like, viscosity, density, surface tension and heating values depend upon the origin of the oil (tab. 1). 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 [20]. 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 spray tip penetration [21, 22]. Nishimura [18] concluded that pressure level of the injected fuel has a significance effect on the performance and formation of pollutants inside the DI diesel engine combustion. Alriksson *et al.*, [23] reported that high charge air pressure and high injection pressure are important parameters for achieving low emissions. 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 during the ignition delay period, HC and smoke level will reduce [24-26]. Hountalas *et al.*, [27] found that the increment of injection pressure results to higher maximum rate of heat release and faster combustion (reduced duration). Higher differences are observed when increasing injection pressure from 1040 to 1200 bar, and lower ones from 1200 to 1700 bar. Venkanna *et al.*, [28, 29] reported that performance and emissions with vegetable oil/diesel fuel blend – honge oil 30% + diesel fuel 70% (H30) and rice bran oil 30% + diesel fuel 70% (R30) – are even better than neat diesel fuel (ND) at enhanced injector opening pressure (IOP). Improved premixed heat release rate were noticed with H30 and R30 when the IOP is enhanced.

Several investigators [16, 28-31] have reported experimental works on different ND oil and vegetable oil blendes with diesel fuel in DI diesel engine without varying IOP and Venkanna *et al*., [28, 29] carried out with varying IOP. The performance of the 10% karanja vegetable oil fuelled engine was marginally better than the ND in terms of brake thermal efficiency (BTE), smoke opacity (SO), and exhaust emissions, including NO_x emission, for a range of operations [15]. It was demonstrated that use of 100% vegetable oil is possible in DI diesel engine and CO, HC, CO_2, specific fuel consumption were increased and NO_x and SO decreased over a range of operation [30, 31].

Use of ethanol/bio-diesel/diesel fuel blend on a heavy duty diesel engine showed a significant reduction in PM emissions, 2%-14% increase of NO_x emissions and decrease in total HC under most tested conditions [32]. It was concluded that blends ERO2.5 (2.5% ethanol by volume, 97.5% rapeseed oil by volume), PRO2.5 (2.5% petrol by volume and 97.5% rapeseed oil by volume), and EPRO5-7.5 (5-7.5% ethanol, 5-7.5% petrol and 95-92.5% diesel fuel in such a way that both ethanol and petrol are in equal proportions) improved performance efficiency of a fully loaded engine and could be used for unmodified diesel engines fuelling [33]. Rakopoulos *et al*. [34] concluded that use of ethanol and diesel fuel blends in diesel engine significantly reduced smoke density, NO_x emissions remained the same or very slightly reduced, CO emissions were equal or slightly reduced and unburned hydrocarbon (UHB) emissions were increased. It was concluded that the tested ethanol-diesel blends could be used safely and advantageously in the present bus diesel engine, at least in small blending ratios.

Experiments have been conducted to study the effect of nozzle opening pressure on the combustion process and exhaust emissions of a direct injection diesel engine fueled with orange skin powder diesel solution (OSPDS) and concluded that the performance of the engine at 235 bar nozzle opening pressure was better with reduction in emissions except NO_x than other nozzle opening pressures [35]. For the reduction of exhaust emissions and improvement of performance few researchers used methyl esters of vegetable oil (biodiesel) and biodiesel/diesel fuel blends in diesel engine and concluded that biodiesel/diesel fuel improves performance and exhaust emissions. It is also concluded that biodiesel/diesel fuel blend can be used in diesel engine without much modification to the engine [36-40].

From the literature review it is concluded that the injection and atomization characteristics of the fuel are mainly dependent on the viscosity in turn vegetable oil. If viscosity is high spray will not disperse properly as it comes out of the nozzle. This leads to poor mixture formation with air. This will lead to slower combustion, lower BTE, higher emissions. The said problems can be overcome by (1) blending diesel with vegetable oil which will reduce the viscosity, (2) injecting vegetable oil/diesel fuel blend at high pressure which in turn increases the atomization process by increasing dispersion of vegetable oil/diesel blend spray in turn better mixing process and there by releasing more heat. Generally, carbon residue of vegetable oil is very high which can lead to high smoke level and injector coking in turn poor fuel atomization. It is also concluded that very high injection pressure will lead to fine droplet and this can adversely affect fuel distribution in air.

The objective of the present work is to study through experiments the influence of IOP on the performance, emission and combustion characteristics of H50 in DI diesel engine. A description of honne tree (*Caulophyllum linophilum bin*)is available in our previous work [41].

Materials and methods

Fuel characterisation

Table 2. Properties of the fuel

Properties	Units	Methods BIS 1448	ND	H100	H50
Density at 15 °C	kgm^{-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	---
Lower heating value	kJkg^{-1}	P:6	43,000	39,100	41,104

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 Bureau of Indian Standards (BIS) and are tabulated in tab. 2.

Experimental set up and plan

Experimental tests were conducted on a DI diesel engine, typically used in agricultural sector. The specifications of the engine are given in tab. 3. The photograph and schematic diagram of the experimental set is shown in figs. 1 and 2. The exhaust gas composition was analysed by using exhaust gas analyzer and SO was measured using SO meter. The specifications of exhaust gas analyzer and uncertainties of measured values are given in the tab. 4. The standard principle of measurement for NO_x and HC is chemiluminiscent and flame ionization, respectively. However, in the present work the principle of measurement for NO_x and HC is electrochemical and NDIR, respectively. Two fuel tanks were used in the present investigation with

Table 3. Engine specifications

Manufacturer	Kirloskar Oil Engines Ltd., India
Model	TV_SR II, naturally aspirated
Engine	Single cylinder, direct injection diesel engine
Bore / stroke / compression ratio	80 mm / 110 mm / 16.5:1
Piston crown shape	Bowl-in-piston
Speed	1500 rpm, constant
Injection pressure / advance	200 bar / 23° bTDC
Number of nozzle holes	Three
Type of sensor and maximum pressure	Piezo electric (5000 psi for Cp and 10000 psi for Fp
Resolution	0.1 bar for Cp / 1 bar for Fp
Response time	4 micro seconds
Sampling resolution	1 degree crank angle
Crank angle sensor	360 °CA encoder with a resolution of 1 degree

Figure 1. Photograph of the experimental set-up

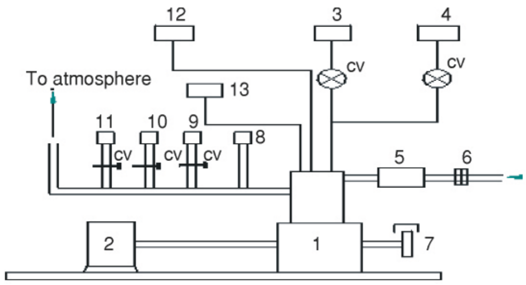

Figure 2. Schematic diagram of the experimental set-up
(1) – engine, (2) – eddycurent dynamometer, (3) – diesel tank, (4) – honne oil tank, (5) – air tank, (6) – orifice meter, (7) – speed pick up, (8) – EGT, (9) – smoke meter, (10) – exhaust gas analyzer, (11) – SO_2 meter, (12) – computer, display unit (PV, Pθ, NHRR, etc.), (13) – lubricating oil temperature, cv – control valvel

switch over arrangement, so that supply of fuel can be changed without stopping the engine operation. The engine was started with diesel fuel and the data was collected after attaining steady-state. Then the experiment was switched over to H50. The engine tests were conducted for the entire load range (0 to 100% in steps of 25%) at constant speed of 1500 rpm. The cooling water temperature was maintained constant (70 to 75 °C) by controlling the flow rate of water. The engine parameters, such as fuel consumption, air consumption, exhaust gas temperature (EGT) and exhaust gas emissions were measured using each fuel sample (ND and H50) thrice and averaged.

The manufacturer specified injector opening pressure is 200 bar. Tests were carried out with H50 to optimize the IOP. These experiments were carried out at different IOP of 200, 220, 240, and 260 bar. The IOP was set by adjusting the spring of the injector. In cylinder pressure and top dead centre (TDC) signals were acquired and stored on a high speed computer based digital data acquisition system. The data from 100 consecutive cycles were recorded. These were processed with specially developed software to obtain combustion parameters .

Table 4. Exhaust gas analyzer and smoke opacity specifications and uncertainties of measured data

Exhaust gas	Principle of measurement	Range	Resolution	Accuracy
O_2	Electrochemical	0-22 vol.%	0.01 vol.%	±0.2 vol.%
NO_x	Electrochemical	0-5,000 ppm	1 ppm	±10 ppm
CO	NDIR	0-10 vol.%	0.01 vol.%	±0.03 vol.%
CO_2	NDIR	0-16 vol.%	0.1 vol.%	±0.7 vol.%
HC	NDIR	0-20,000 ppm	1 ppm	±5 ppm
Standard deviation				±2%
Measured data		Uncertainty [%]		
Speed		±1		
Fuel volumetric rate		±1		

Results and discussion

Fuel properties and characteristics

The viscosity of H100 and H50 at 40 °C is 32.47 cSt and 9.75 cSt, respectively. It shows that viscosity of H50 is much less than H100. Density of H100 and H50 is higher than ND. The flash point of H100 and H50 is better than ND for the engine application. Presence of oxygen in oil improves combustion and reduces emissions but decreases the heating value of the oil. Heating value of H100 oil is approximately 90% of the value of ND but is comparable with other vegetable oils as reported by Rakapoulos *et al*. [9].

Effect on performance parameters

The results of the experiments carried out on DI diesel engine using ND and H50 are presented and discussed.

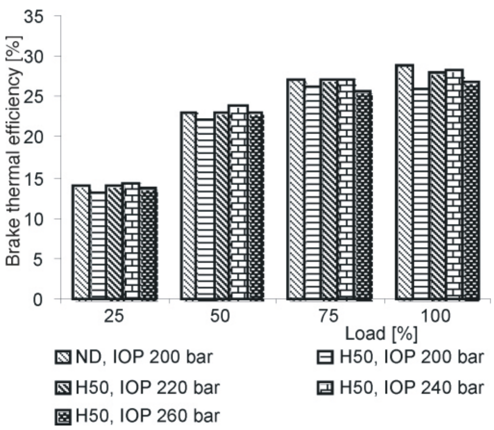

Figure 3. Variation of BTE

Figure 3 shows the BTE for ND and H50 at different loads at different IOP. For the entire load, the BTE for H50 at IOP 200 bar is less than that of ND. With H50, the results show that increasing IOP from 200 to 260 bar is advantageous for increasing BTE over the entire load range (except corresponding to IOP 260 bar and 75% load), however increase is more in the low and medium load regions (25% and 50% load) and this is higher than ND. Generally, in diesel engine air to fuel ratio is high in the low and medium load regions compared to full load. With H50, due to inherent oxygen air to fuel ratio is still high compared to ND. Even though viscosity of H50 is higher than ND, high air to fuel ratio and high IOP improves atomisation, vaporisation, mixing with air leading to better combustion. It indicates improved premixed combustion phase when the IOP is increased. This improves BTE. It is also to be noted that the oxygen contained in the H50 takes part in combustion which enhances the combustion process.

With H50 and IOP of 260 bar, BTE decreased compared to IOP of 240 bar, over the entire load range, which is in agreement with the findings of other researchers [27-29]. As IOP increased drop let size decreased. A smaller droplet will have lesser momentum; affect fuel distribution in air, and its relative velocity decrease in air resulting in its partial suffocation by its own products of combustion leading to incomplete combustion.

Variation in EGT with loads at different IOP is shown in fig. 4. EGT of H50 is highest at 200 bar when the BTE becomes lowest. This is due to sluggish combustion at lower IOP which leads to increased EGT. During premixed combustion phase, low heat release rate is observed (fig. 10). Major portion of the heat is released during the diffusion combustion phase which could not be converted into work. With H50, EGT decreases with increasing IOP compared to H50 at IOP 200 bar. This is due to improved premixed combustion phase in turn improved BTE results in lower EGT.

Effect on emission parameters

The CO emissions of both fuels (ND and H50) were lower in partial engine load, however, increased at higher engine load as shown in fig. 5. This is due to relatively less oxygen available for the reaction when more fuel is injected in to the engine cylinder at higher engine load.

For the entire load, the CO and HC (fig. 6) for H50 at IOP 200 bar are higher than that of ND. It is observed that CO and HC emissions of H50 drops as IOP increases, reaches to a least at 240 bar and this is lower than ND (except 75% and 100% load), however decrease is more in the low and medium load regions. The reason may be due to (1) inherent oxygen and (2) high IOP. Even though viscosity of H50 is higher than ND, high IOP improves spray characteristics hence leads to a shorter physical delay period. This will enhance the performance with H50, which normally have a long ignition delay on account of their high viscosity. The improved spray also leads to better mixing of fuel and air in turn fast combustion. This result is comparable to the reported values [28, 29]. With H50, the highest IOP *i. e.*, 260 bar leads to an increase in the CO and HC level as compared to IOP of 240 bar over the entire load range. This is in accordance with the result of Venkanna *et al.*, [28, 29]

Figure 7 shows that SO of H50 steadily drops with increase in the IOP from 200 to 240 bar, reaches to a least at 240 bar, and this is lower than ND, however decrease is more in the low and medium load regions, which is in agreement with the findings of other researcher [42]. This is due to improvement in spray hence improved mixture formation, also due to inherent oxygen present in H50 and less aromatics. Alriksson *et al.*, [23] and Hountalas *et al.*, [27] found very low soot emissions with high IOP. With H50, SO at 260 bar is higher compared to

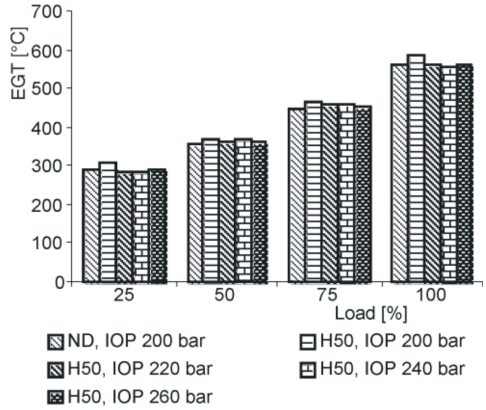

Figure 4. Variation of EGT with load

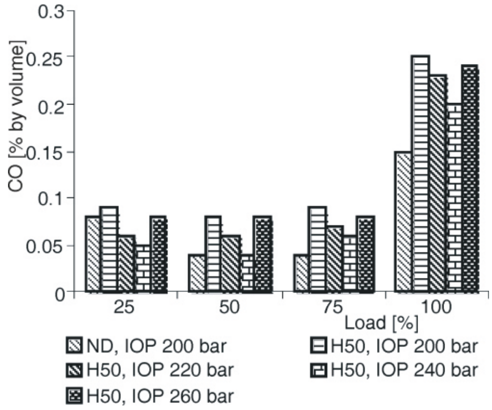

Figure 5. Variation of CO emissions

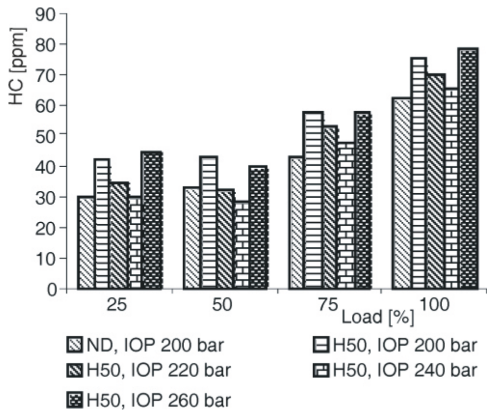

Figure 6. Variation of HC emissions

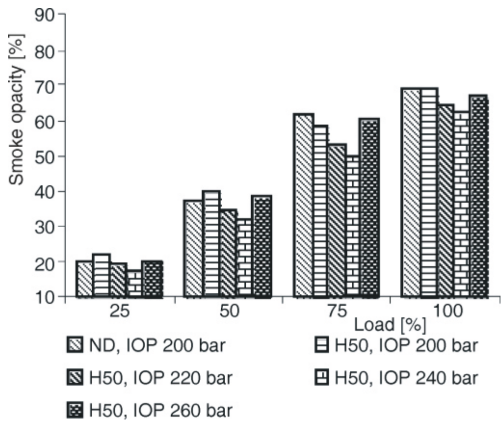

Figure 7. Variation of SO emissions

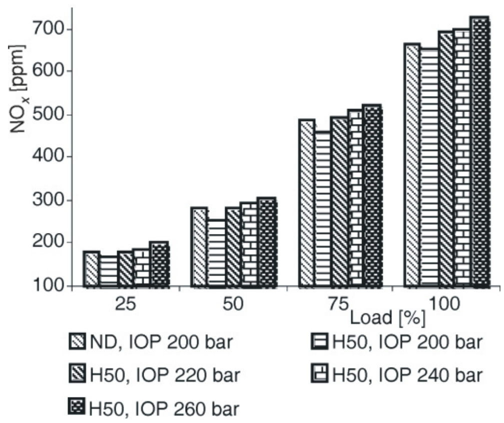

Figure 8. Variation of NO_x emissions

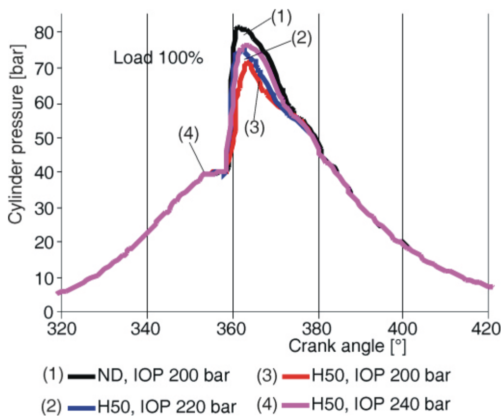

Figure 9. Variation of cylinder pressure (color image see on our web site)

IOP 240 bar, over the entire load range. The reason is explained in previous section.

Figure 8 shows the NO_x emissions at different IOP at different loads. For both the fuels, NO_x emission increases with load as expected due to increase in cylinder temperature. With H50, NO_x emission increases with increasing IOP over the entire load range, however increase is more at 75% and 100% load. This is due to better combustion and dominant premixed combustion phase leads to increase in cylinder pressure and temperature, which is in agreement with the findings of other researcher [42]. Even though EGT of H50 at 200 bar is high, NO_x is least. Higher EGT is due to sluggish combustion *i. e.*, major portion of heat is released during later part of diffusion phase combustion.

Combustion characteristics

Results corresponding to IOP 260 bar are not shown in figs. 9 and 10. Cylinder pressure crank angle variation at maximum load with ND and H50 at different IOP is given in fig. 9. Pressure diagram for H50 at different IOP follow the trend similar to the ND pressure diagram at rated IOP. The cylinder peak pressure is highest with ND followed by H50 at IOP 240, 220, 200 bar, which is in agreement with the findings of other researcher [27]. With H50, increase in peak pressure is purely due to increase in IOP in turn fast combustion.

Variation of net heat release rate crank angle with ND and H50 at different IOP at maximum load is shown in fig. 10. With H50, it indicates improved premixed combustion phase when the IOP is enhanced. For a given viscosity (for a given fuel) increase in IOP leads to better fuel atomisation, vaporisation, and mixing with air in turn fast combustion. High IOP is predominant than viscosity. With H50, the peak net heat release rate increases from 64 to 75.7 J per °CA with an IOP change from 200 bar to 240 bar. Improvement in combustion can be seen as IOP increases from 220 bar and above. This was seen in the case of performance and emissions also. Reduced smoke levels and increased brake thermal efficiency and NO_x emissions are observed when the IOP is increased. As the IOP increased from 200 bar, premixed combustion phase improves, but ignition delay is almost same.

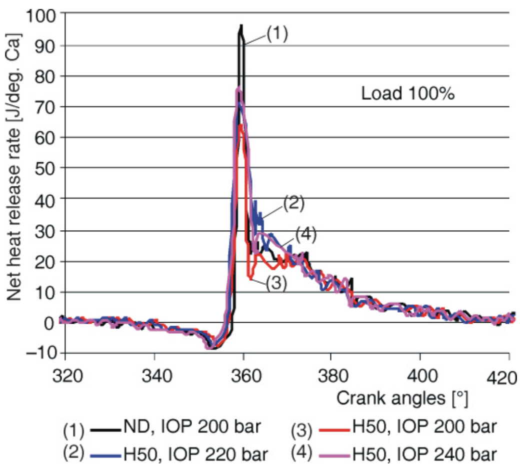

Figure 10. Variation of net heat release rate (color image see on our web site)

Conclusions

In the present work, an experimental investigation has been conducted to examine the effect of injection pressure level on the performance and pollutant emissions of a DI diesel engine using ND and H50 as fuel. From the results it is revealed in general that the increase of injection pressure:

- increases BTE as IOP increase from 200 to 240 bar; increase is higher at low and medium load regions and this is higher than ND,
- decreases CO, HC, and SO emissions as IOP increase from 200 to 240 bar,
- decrease is higher at part load and this is lower than ND,
- increases NO_x emissions as IOP increase from 200 to 260 bar, and
- leads to a faster heat release (combustion), improved premixed combustion, almost same ignition delay.

Acknowledgments

The DI diesel engine test rig, exhaust gas analyzer and smoke meter used in this work are procured with fund of Technical Education Quality Improvement Program (TEQIP Phase I) (World Bank Assisted Program). TEQIP and the Management of Sri B. V. V. Sangha, Bagalkot, India, and are gratefully acknowledged. Our special thanks are due to the Principal, Basaveshwar Engineering College and H.O.D, Mechanical Engineering for their continuous encouragement and support. Our special thanks are also due to Dr. P. B. Gangavati, Professor, Department of Mechanical Engineering for his timely valuable suggestions, discussion and editing the paper.

Acronyms

bTDC	–	before top dead centre
BTE	–	brake thermal efficiency
Cp	–	cylinder pressure
DI	–	direct injection
EGT	–	exhaust gas temperature
Fp	–	fuel line pressure
IOP	–	injector opening pressure
ND	–	neat diesel fuel
H100	–	neat honne oil
SO	–	smoke opacity
TDC	–	top dead centre
H50	–	50% diesel fuel + 50% honne oil by volume
UHC	–	unburned hydrocarbon

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Paper submitted: February 28, 2010
Paper revised: April 30, 2010
Paper accepted: June 27, 2010