Performance, emission and combustion characteristics of direct injection diesel engine running on calophyllum inophyllum linn oil (honne oil)

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Abstract: 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. A Direct Injection (DI) diesel engine typically used in agricultural sector was operated on Neat Diesel (ND) and neat honne oil (H100). At maximum load, with H100, brake thermal efficiency and NO_x emission decreased where as emissions like CO, HC, smoke opacity increased. With H100, peak cylinder pressure and maximum rate of pressure rise decreased compared to ND. With H100, occurrence of peak pressure is away from top dead center compared to ND. With H100, ignition delay and combustion duration increased compared to ND.

Key words: non edible vegetable oil, neat honne oil, diesel engine, performance, emissions, combustion

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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 PM/smoke density and NO_x, and there is inherent trade off between them[1].

The compressibility effect of the vegetable oil causes an earlier injection of fuel into the engine cylinder as compared to diesel fuel[2,3]. This earlier injection does not plays an important role, as this injection advance difference is at maximum 1°CA even for the neat vegetable oil[4]. The cetane number of vegetable oil, which is a little lower compared to the diesel fuel[5], does not plays an important role, as there is small differences in their premixed combustion phase[4,6]. The major difference occurs in the atomization process, i.e., the mean droplet size of vegetable oil is much higher than diesel fuel[7,8].

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[4,14].

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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].

Table 1 Comparison of properties of diesel fuel, honne oil and few vegetable oils [5,9,10]

Properties	Units	ND	Honne oil	Cotton seed oil	Soybean oil	Corn oil	Olive oil	Honge oil	Rice bran oil
Density at 15 ℃	/kg.m^{-3}	830	910	910	925	915	925	924	901
Kinematic viscosity at 40℃	/cSt	3.12	32.47	34	33	35	32	45.23	42.55
Lower heating value	/kJ.kg^{-1}	43,000	39,100	36,800	37,000	36.300	37.000	30,440	38,952

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. Properties like viscosity, density, surface tension and heating values depend upon the origin of the oil (Table 2). It is reported that the injection and atomization characteristics of the vegetable oils are significantly different from 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 spray tip penetration[19,20].

Table 2 Comparison of values of properties of Karanja oil used in diesel engine by different investigators

Properties	Units	Researcher I [11]	Researcher II [12]	Researcher III [13]
Density at 15℃	/Kg.m^{-3}	912	913	938
Viscosity at 40℃	/cSt	27.84	27.84	35.98
Lower heating value	/kJ.kg^{-1}	34,000	37,304	41,660

Several investigators[9,10,13,21-28] have reported experimental work on different neat vegetable oil and vegetable oil blends with diesel fuel in DI diesel engine.

1.1 Previous work on use of neat vegetable oils in diesel engine

Performance and emission characteristics of neat Karanja oil and its blends were found to be comparable to that of mineral diesel[13]. It was observed that for neat orange oil the emissions of HC, CO, smoke opacity were reduced whereas NO_x emissions were decreased as compared to ND[21]. Herchel et al.,[23] used neat vegetable oil and concluded that smoke opacity and NO_x lowered while CO and HC increased. Silvio et al.[24] 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 decreased over a range of operation. With vegetable oil, the emissions of CO, HC and SO_x were found to be higher, whereas NO_x and PM emissions were lower compared to ND[25,26]. Wang et al.[27] conducted experiment on vegetable oil. They have reported that at maximum load there were higher exhaust gas temperature and HC, lower CO and NO_x as compared to ND. The use of 100% vegetable oil results in increased brake specific fuel consumption and emissions of CO, HC, and CO_2 increased at maximum load[28].

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, and higher emissions.

1.2 Present work

As per the present authors' knowledge use of neat honne oil (H100) in diesel engine is not reported in the literature. The objective of the present work is to study through experiments on the performance, emission and combustion characteristics of (H100) in direct injection (DI) diesel engine. A description of honne tree is reported in the authors' previous work[29].

2 Materials and methods

2.1 Fuel characterization

The properties of H100 and ND were determined as per the methods approved by Bureau of Indian Standards.

2.2 Experimental setup and plan

The engine used in the present tests at Basaveshwar Engineering College is a Kirloskar, single-cylinder oil engine. It consists of a test-bed, a diesel engine, an eddy current dynamometer, three fuel tanks with a stirrer (one tank is fitted with thermostat controlled heater), a data acquisition system, a computer, an operation panel, the exhaust emission analyzers, a smoke meter, a SO_x meter, and the various sensors to measure the lubricating oil temperature, the exhaust temperature at the manifold, a pressure sensor to measure in-cylinder pressure, a pressure sensor to measure fuel line pressure (placed very near to injector). Two filters are installed: one at the exit of the tank and the other one at the fuel pump. These filters had to be changed every H100 of operation, because they are clogged. The fuel system is modified by adding an additional three-way, hand operated, two position directional control valve which allowed rapid switching between the diesel used as a standard and the test fuels. Fuel is fed to the injector pump under gravity. Lubricating oil temperature is measured by using a thermocouple. The cooling water temperature is maintained constant (65 to 70℃) throughout the research work by controlling the flow rate of

Table 3 Engine specifications

Manufacturer	Kirloskar Oil Engines Ltd., India,
Model	TV–SR II, naturally aspirated
Engine	Single cylinder, DI
Bore / stroke /	80 /mm —110 /mm
Compression ratio	16.5:1
Speed	1500 r/min, constant
Injection pressure	2×10^7Pa
Injection advance	23°bTDC
Cylinder pressure (Cp) / line pressure (Fp) before the injector)	0-2 $\times10^7$Pa / 0-2$\times10^8$Pa (fixed at 45 mm
Resolution	1×10^4Pa for Cp / 1×10^5Pa for Fp
Type of sensor	Piezo electric (5×000 psi for Cp
Response time	and 10,000 psi for Fp)
Sampling resolution	4 micro seconds
Crank angle sensor	1 degree crank angle
resolution of 1 degree	360 degree encoder with a resolution of 1 degree

The exhaust gas composition was analysed by using exhaust gas analyzer (make: MRU, Germany, model: DELTA 1,600 S) and smoke opacity (make: MRU, Germany, model: Optrans 1,600) was measured using smoke opacity meter. The specifications of exhaust gas analyzer and uncertainties are given in the Table 4.

Table 4 Exhaust gas analyzer and smoke opacity specificationsanduncertaintyof measured values (1 ppm= 10^{-6} =1 μL/L)

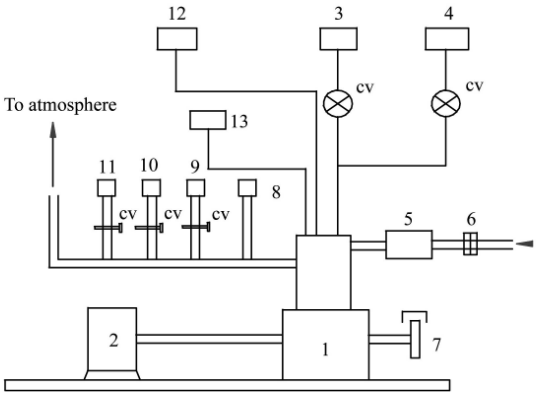
Exhaust gas	Principle of measurement	Range	Resolution	Accuracy
O_2	Electrochemical	0-22 vol.%	0.01 vol.%	±0.2 vol.%
NO_x	Electrochemical	0-5,000 ppm	1 ppm	±10 ppm
CO	NDIR	0-10 vol.%	0.01 vol.%	±0.03 vol.%
CO_2	NDIR	0-16 vol.%	0.1 vol.%	±0.7 vol.%
HC	NDIR	0-20,000 ppm	1 ppm	±5 ppm
SD				±2%

Measured data	Uncertainty/%
Speed	±1
Fuel volumetric rate	±1
Torque	±1
EGT	±1

Figure 1 Photograph of the experimental setup

The engine was started with diesel fuel and data were collected after attaining steady state. Then the experiment was switched over to H100. 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 1,500 r/min. The engine parameters, such as fuel consumption, air consumption, Exhaust Gas Temperature (EGT) and exhaust gas emissions were measured using each fuel sample (ND, H100) thrice and averaged.

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 H100 consecutive cycles were recorded (hardware is designed to take the data up to 300 consecutive cycles). These were processed with specially developed software to obtain combustion parameters like, rate of pressure rise, occurrence of rate of pressure rise, net heat release rate, occurrence of net heat release rate, second derivative of rate of pressure rise, start of combustion, estimated end of combustion, delay period and combustion duration.



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

Figure 2 Line diagram of the test setup

3 Results and discussion

In this section the experiments conducted using ND and H100 are reported and discussed.

3.1 Fuel properties and characteristics

The proprieties of the honne oil, diesel fuel and H100 were determined and the results are shown in Table 5. The composition of H100 oil is reported in the authors' previous work [15]. The viscosity of honne oil is 32.47 cSt at 40℃ whereas at 100℃ the viscosity is 9.09 cSt. At high temperature the viscosity falls to below 10 cSt which reduces the atomization problem. Density of honne oil is slightly higher than ND. The flash point of honne 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 honne oil is approximately 90% of the value of ND but is comparable with other vegetable oils as reported by Rakopoulos et al.,[30].

Table 5 Properties of the fuel

Properties	Units	Methods IS 1,448	D100	H100
Density at 30℃	$kg \cdot m^{-3}$	P:16	830	910
Flash point	℃	P:69	56	224
Kinematic viscosity at 40℃	cSt	P:25	3.12	32.47
Kinematic viscosity at 100℃	cSt	P:25	—	9.09
Heating value	$kJ \cdot kg^{-1}$	P:6	43,000	39,100

3.2 Effect on performance parameters

The effect of load on the brake thermal efficiency for ND and H100 is shown in Figure 3. There is a steady increase in brake thermal efficiency as load increases in ND and H100 operation. Honne oil results in decreased brake thermal efficiency as compared to ND over the entire load range. Oxygen present in the honne oil molecules improves the combustion characteristics but high viscosity, surface tension and poor volatility result in poor atomization and poor spray characteristics. The poor spray pattern may affect the homogeneity of air fuel mixture which in turn lower the heat released rate thereby reduction in brake thermal efficiency than ND. Also the lower heating value of H100 leads to injection of higher quantities of fuel as compared to ND for the same load conditions hence, decrease in brake thermal efficiency. The maximum brake thermal efficiency with H100 is 25.01% at 100% load whereas it is 29.20% with ND.

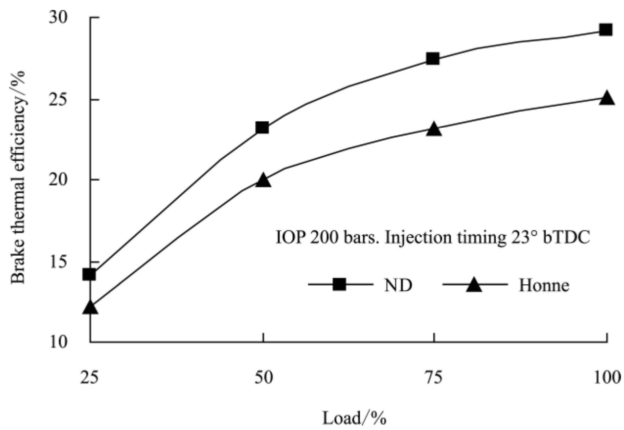


Figure 3 Variations of brake thermal efficiency

EGT, shown in Figure 4, is higher when the load is increased and it is greater for H100 than ND, particularly at high loads. This could be due to low volatility and high viscosity of H100, which affects the spray formation in combustion chamber and thus leads to a more dominant diffusion combustion phase than ND. The heat released during the late combustion could not be converted into work and appeared as heat. This is the reason for lower thermal efficiency (Figure 3).

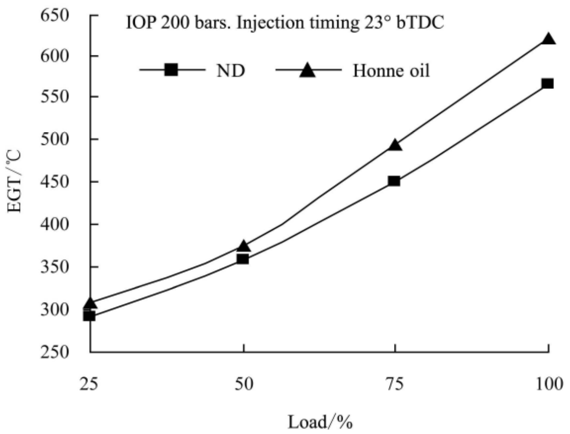


Figure 4 Variations of exhaust gas temperature

3.3 Effect on emission parameters

The effects of load on CO and HC emissions for both H100 and ND are shown in Figure 5 and 6, respectively. The CO and HC emissions increased with the increase of engine load, as expected. The CO emissions of both fuels were lower in partial engine load, however, increased at higher engine load. 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. The CO and HC emissions are higher with H100 compared to ND over the entire engine load. Poor volatility, high viscosity and the poor spray characteristics of H100 resulting in poor mixing, rich pockets formed in combustion chamber, and consequently, poor combustion leads to lower combustion efficiency.

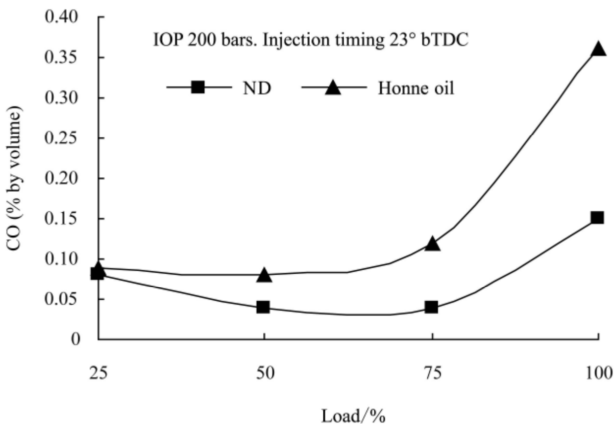


Figure 5 Variations of CO emissions

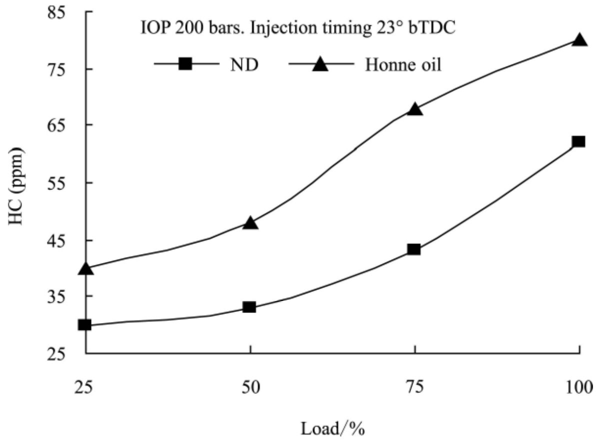


Figure 6 Variations of HC emissions

Figure 7 shows the variation of smoke opacity emission with load. Smoke opacity increased with the increase of engine load, as expected. For H100 smoke opacity is on higher side for entire range of operation. Increase in smoke opacity is more, particularly at higher loads. The heavier molecular structure and higher viscosity of H100 lead to poor atomization result in higher smoke opacity than ND.

The variation of NO_x emission with load is shown in Figure 8. The NO_x emission increased as the engine load increased, due to combustion temperature increased. This proves that the emission of NO_x is significantly influenced by the cylinder gas temperature and the availability of oxygen during combustion. It is observed that H100 produces lower NO_x compared to ND over the entire load range. Decrease in NO_x is low in lower loads and more in higher loads. The reduction in NO_x emission is due to reduced premixed burning rate (low heat release rate) leads to lower cylinder temperature.

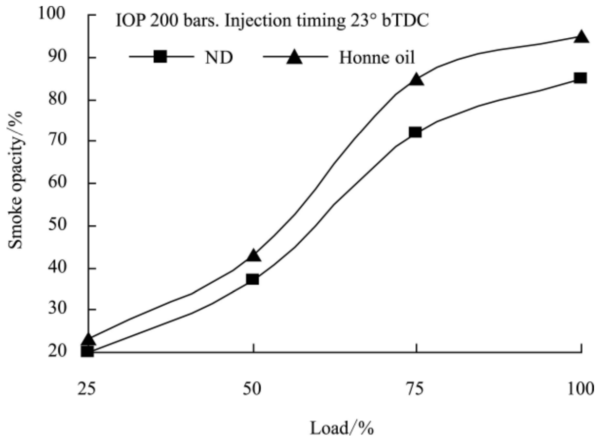


Figure 7 Variations of smoke opacity emissions

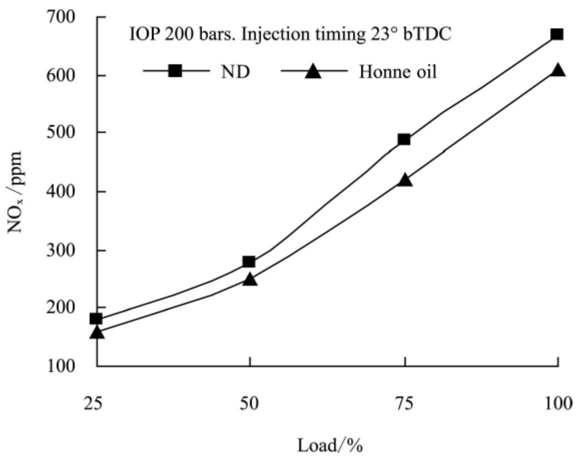


Figure 8 Variations of NO_x emissions

Figure 9 and 10 show CO_2 and O_2 emissions respectively. Data show that with H100 CO_2 emissions increased and O_2 emissions decreased significantly compared to ND. Vegetable oil contains oxygen contents in it, so the carbon content is relatively lower in the same volume of fuel consumed at the same engine load, due to this CO_2 emissions would have been decreased compared to ND but in the present work CO_2 emissions increased. This requires further investigations.

In a CI engine, cylinder pressure depends on the fraction of fuel burned during the premixed burning phase. Cylinder pressure crank angle variation at maximum load with ND and H100 is given in Figure 11. Honne oil follows the trend, similar to ND pressure diagram. Same trend is followed for other loads. Pressure diagram for other loads is not shown. The cylinder peak pressure is highest with ND followed by H100. It is observed that the occurrence of peak pressure moves away with H100 compared to ND. This indicates that the ignition delay is longer with H100 compared to ND. Longer ignition delay means more fuel is injected. Due to high viscosity, poor volatility, poor spray characteristics and lower heating value of H100 leads to less fuel being prepared for rapid combustion result in lower peak pressure compared to ND. This is also a reason for reduction in maximum rate of pressure raise (MRPR) with H100 as shown in Figure 12. The peak pressure with load for ND and H100 is shown in Figure 13.

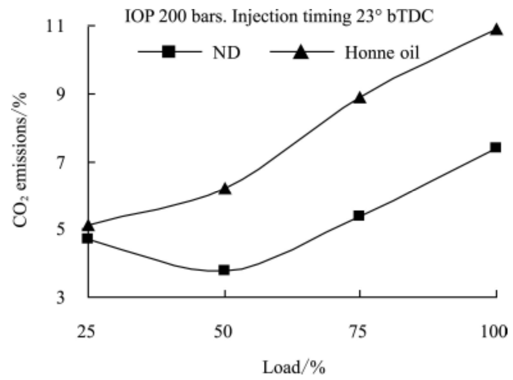


Figure 9 Variations of CO_2 emissions

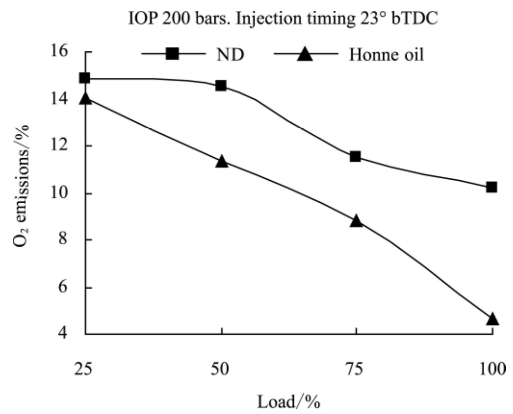


Figure 10 Variations of O_2 emissions

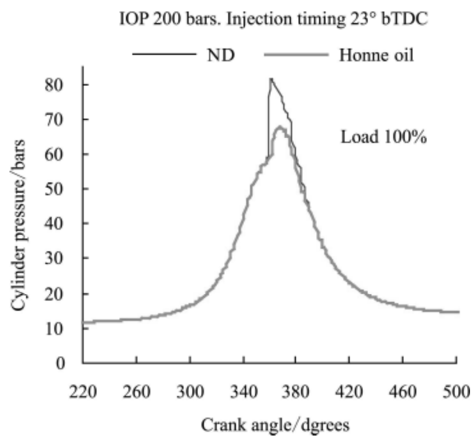


Figure 11 Variations of cylinder pressure

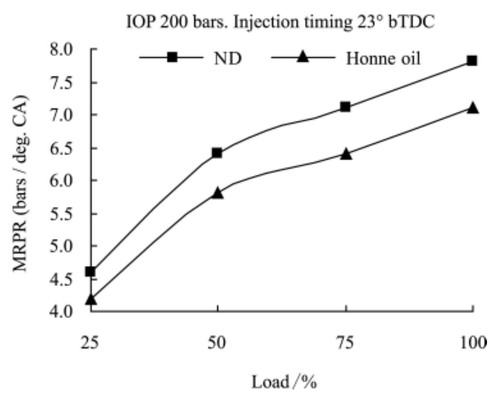


Figure 12 Variations of MRPR

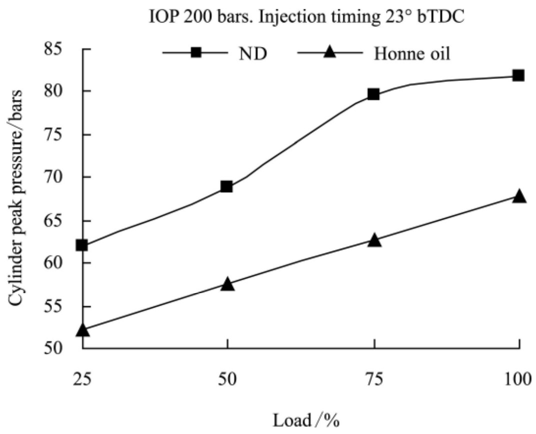


Figure 13 Variations of cylinder peak pressure

3.4 Combustion characteristics

The variation of ignition delay is shown in Figure 14. The ignition delay is longer with H100 compared to ND over the entire load range. This is due to the low cetane number of H100 (not measured).

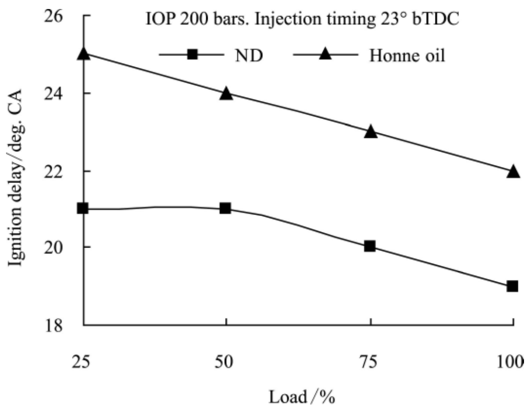


Figure 14 Variations of ignition delay

Figure 15 shows the effect of crank angel on net heat release rate at maximum load for both ND and H100. It is observed that the premixed burning is more dominant with ND as expected. This could be the reason for the higher thermal efficiency of ND (Figure 3). Honne oil shows lower heat release rate during premixed burning phase compared to ND. The high viscosity and poor volatility of H100 result in poor atomization and fuel air mixing rates. Hence, more burning occurs in the diffusion phase.

Figure 16 shows the variation of combustion duration (CD). The CD increased with the increase of engine load for both the fuels, as expected. This is due to an increase in the quantity of fuel injected with load. Longer CD is observed with H100 compared to ND. Due to lower heating value of H100, more quantity of oil is injected for the same load compared to ND. Less fuel being prepared during premixed burning phase after ignition delay, remaining fuel is burned during diffusion combustion phase; hence diffusion combustion phase is more dominant with H100 than ND. This leads to more EGT (Figure 4).

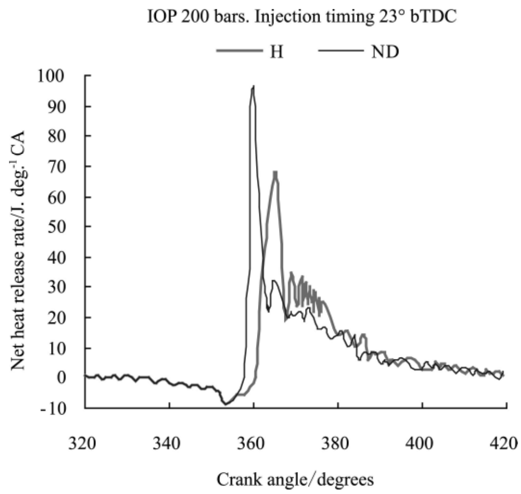


Figure 15 Variations of net heat release rate

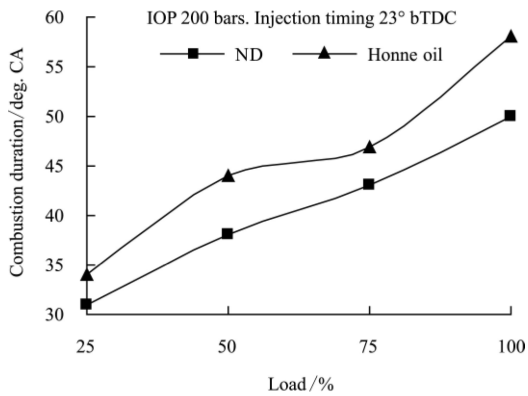


Figure 16 Variations of combustion duration

4 Conclusions

Use of a non-edible oil namely honne oil is considered as a new possible source of alternative fuel for diesel engine. No difficulty was faced at the time of starting the engine and the engine ran smoothly over the range of engine speed. Based on the experimental work with H100, at maximum load, the following conclusions are drawn.

- Brake thermal efficiency of H100 is 25.01% compared to 29.20% with ND.

- EGT of H100 is 620℃ compared to 565℃ with ND.
- CO emission of H100 is 0.36% (by volume) compared to 0.15% (by volume) with ND.
- HC emission of H100 is 80 ppm (μL/L) compared to 62 ppm(μL/L) with ND.
- Smoke opacity of H100 is 95% compared to 84.8% with ND
- NO_x emission of H100 is 550 ppm (μL/L) compared to 667 ppm (μL/L) with ND.

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